Novaerus Gaseous Plasma Discharge Technology for Air Disinfection: Review and Discussion

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Abstract

This report aims to provide a succinct review of the state of the art in gaseous plasma discharge technology, specifically focussing on air disinfection. The antimicrobial and anti-viral efficacy of plasma technology as reported in the literature is assessed and a brief examination of the underlying deactivation mechanisms is discussed. Finally, some relevant embodiments, particularly pertaining to the dielectric barrier discharge / corona discharge configurations will be discussed as these pertain to the current Novaerus plasma coil design.

1. Background

In recent years there has been a significant emergence of interest in plasma technology in medicine, particularly for device sterilization and disinfection. Plasma's, which include UV photons, chemically reactive radicals, and energetic charged species that can bombard a microorganism, are a rich source of agents which can contribute to the disinfection process. There is a range of possible embodiments of suitable plasma sources and configurations, ranging from thermal to non-thermal, direct contact or indirect (afterglow), depending on the specific application.

Atmospheric pressure plasmas relevant to this report are non-equilibrium entities, wherein the free electrons in the plasma bulk are at a relatively high temperature with respect to the neutrals and ionic species also present in the plasma bulk. The enhanced chemistry of the non-equilibrium plasma is driven primarily by the electrons, which absorb most of the energy from the power source, while the heavier particles remain at lower temperatures. The electron energy distribution in the plasma can be strongly influenced by the method in which the electrical energy is applied to the plasma. For example, a pulsed power system tends to shift the electron energy distribution function to the high energy tail. A separate family of atmospheric pressure plasmas are thermal plasmas, where a local equilibrium exists between the electrons and the heavier particles present in the plasma. Examples include spraying and welding, which are beyond the scope of this report.

Within the medical and health fields, plasma is seen as an elegant and emerging disinfection technique, particularly for temperature sensitive surfaces such as plastics and fabrics, as would commonly be found in the clinical environment. In the recent literature several proposed plasma sterilisation and disinfection arrangements have been proposed – both at low-pressure and atmospheric pressure using a variety of energising sources – and invariably these techniques have proven to be highly effective in destroying micro-organisms.

A key advantage of the non-thermal nature of atmospheric pressure plasmas is that it readily lends itself suitable for incorporation into relative low cost product embodiments, where heat dissipation and power consumption would otherwise be a significantly complicating factor. Additionally, atmospheric pressure plasmas do not require the complex, bulky and expensive vacuum equipment required for the more traditional low pressure plasma systems and they can operate at low powers, sometimes as low as a few watts.

The most common embodiments of stable, low power atmospheric pressure plasma discharges are the dielectric barrier discharge, the corona discharge and the plasma jet.

2. Mechanisms

In non-thermal plasma discharges, the micro-organism destruction mechanism is believed to be due to several factors, including UV radiation generated by de-excitation processes within the plasma, the removal of material from the cells (etching) due to the presence of reactive species created by the plasma, and the physical bombardment of the micro-organisms due to the presence of energetic particles that emerge from the plasma and bombard the surface (e.g. sputtering). The relative contribution of the different mechanisms depends on the precise configuration of the plasma source and the chemistry of the plasma discharge.

In non-equilibrium atmospheric pressure plasmas, of which Novaerus' technology is one, UV is not considered to be the primary deactivation agent, however it inhibits the microorganisms' ability to replicate by interacting with the organisms DNA. For example the UV disrupts DNA base pairing causing thymine-thymine dimers leading to death of exposed bacteria. UV is known to inactivate cells if its wavelength is within the germicidal range (220nm - 280nm) and doses of several mWs/cm^2 are known to be very effective. Atmospheric pressure plasmas with air as the source gas tend to produce emission within the germicidal range, however the intensity of the radiation can be relatively low, depending on the plasma operating conditions. The Novaerus device does produce UV radiation albeit at low intensity and its likely this contributes to, rather than dominates, the deactivation processes. For example figure 1 presents an image of the light emission from an energised Novaerus plasma coil when viewed side-on.

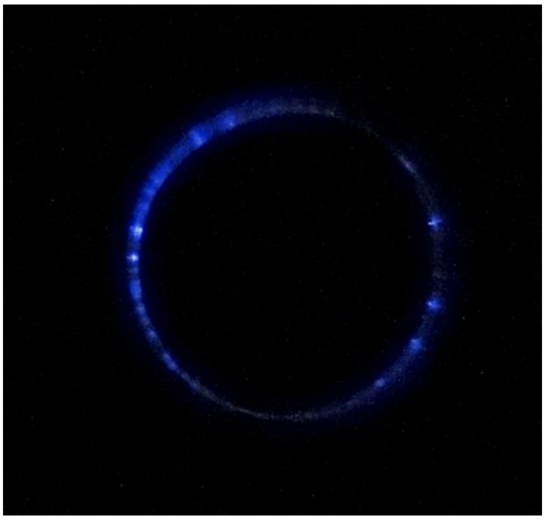


Figure 1: Light Emission from the Novaerus Plasma Coil

Reactive species in atmospheric pressure plasmas are generated primarily through electron impact ionisation and dissociation. In the non-equilibrium plasmas of interest here, the primary radicals generated in air are oxygen and nitrogen based species, including atomic oxygen, ozone (O_3), NO, NO_2, and OH, all of which have an impact on the cells of microorganisms. The outer membrane of cells are made of lipid bilayers which contain fatty acids, that gives the membrane a gel-like structure, allowing the transport of biochemical products across the membrane. These fatty acids in particular are susceptible to attacks by the hydroxyl radical (OH) which in turn compromises the function of the membrane lipids, and hence the transport of compounds in and out of the cell is disrupted. Protein molecules are also present in the cell lipid bilayer. The aminoacids in the proteins are susceptible to oxidation from the plasma-produced radicals which play a crucial role in the overall inactivation process. Figure 2 shows an optical emission spectrum of an air dielectric barrier discharge. The spectrum is dominated by N_2 and NO transitions, with little observable germicidal radiation but evidence of reasonable densities of useful radicals.

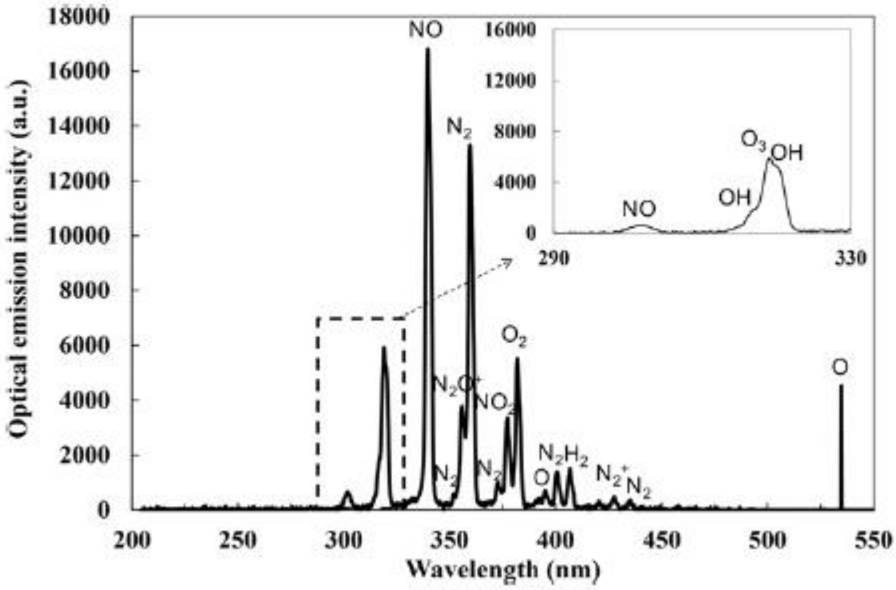


Figure 2: Typical Optical Emission Spectrometer Reading from an Air Dielectric Barrier Discharge

Atmospheric pressure plasmas of relevance here are very low density, with the proportion of neutral species several orders of magnitude greater than the charged species. However, the charged species in the plasma are believed to play a significant role in the rupture of the outer surface of cell membranes. The energy of the ion species is typically low – close to room temperature so physical etching due to ion bombardment is likely to be low. However, the electrostatic force caused by the accumulation of charge on the outer surface of the cell membrane can overcome the tensile strength of the cell membrane, causing it to rupture. While this mechanism isn't fully understood by the scientific community, there is enough empirical evidence to suggest that this is an important mechanism of cell inactivation. Note that the precise mechanisms for deactivation of gram-positive and gram negative organisms are likely to be different, with the more irregular outer surface of gram-negative cells more likely to lead to a stronger effect.

The simultaneous and synergistic exposure of biological material to the above 'mechanisms' is believed to be the reason why plasmas such as Novaerus are so effective at deactivation of airborne microorganisms. A cartoon illustrating theses effects is given in figure 3.

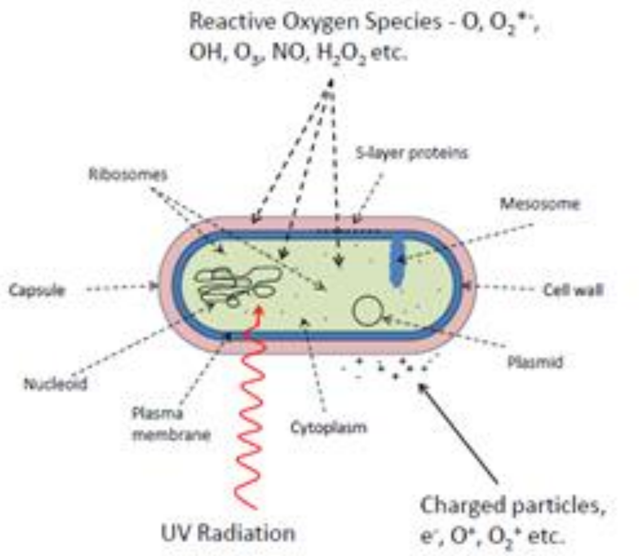


Figure 3: Synergistic Effect of Multiple Deactivation Mechanisms in a Plasma

(Courtesy N O'Connor, DCU)

3. Efficacy

Reports in the literature on the efficacy of atmospheric pressure plasmas vary greatly, in particular in connection with the timescale required for inactivation. This is accounted for by the fact that there is a myriad of corona, barrier, and hollow cathode discharges of varying dimensions, materials, and power/electrical characteristics. It is also important to carefully interpret the reported microbiological data as the interference on the surface, and the recovery mechanisms are not always uniform or correctly reported. It is also important to note that disinfection strategies using plasma can use direct plasma exposure, indirect plasma exposure – where the radicals produced by the plasma have diffused away from the immediate vicinity of the plasma, or a hybrid of both.

In practical terms, most embodiments of plasma decontamination systems will through design or otherwise use a combination of direct exposure and indirect exposure when decontaminating an environment – this is believed to the case with the Novaerus device.

The survivability curve for a given scenario will depend on the degree of packing density, biofilm formation, isolated and uncovered organisms, availability of other matter (e.g. proteinaceous material), and the proximity to the irradiating UV. An illustration from Moisan [1] of a typical (3-phase) survival curve for a plasma exposed spore colony is given in figure 4.

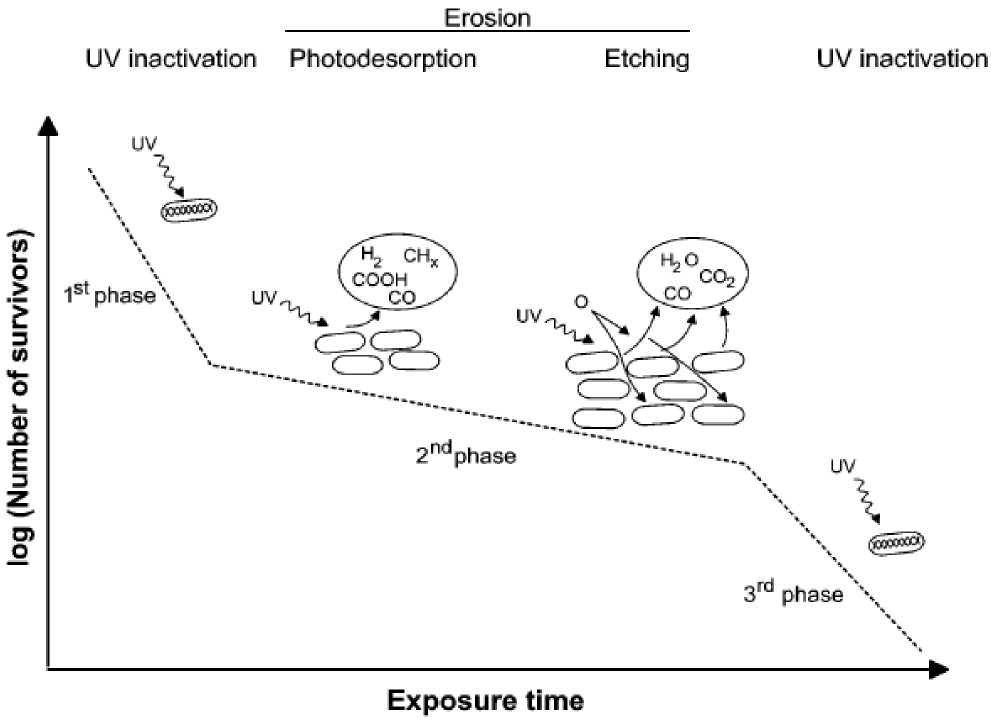


Figure 4: 3-Illustration of 3 Phase Survival Curve for Plasma Exposed Spore Colony

While the efficacy of plasma technology for microbial deactivation is undisputed in the literature, the precise underlying mechanisms are still not fully understood and there is no universally agreed optimum configuration for antimicrobial applications [7]. In general terms however, for a given microbiology, a given plasma gas and approximate power density, the order of magnitude of the survival rate depends on whether or not the interaction with the microorganisms is direct or indirect.

The Novaerus device can be classified as a type of dielectric barrier discharge with air as the feedstock gas. Figure 5 below shows data from an air based dielectric barrier discharge where the disinfection mechanism is reliant purely on the by-products of the plasma reactions that take place elsewhere, i.e. indirect plasma exposure. Here it can be seen that effective disinfection only occurs after several minutes exposure. Note here that in this case the microorganisms being treated were in biofilm form.

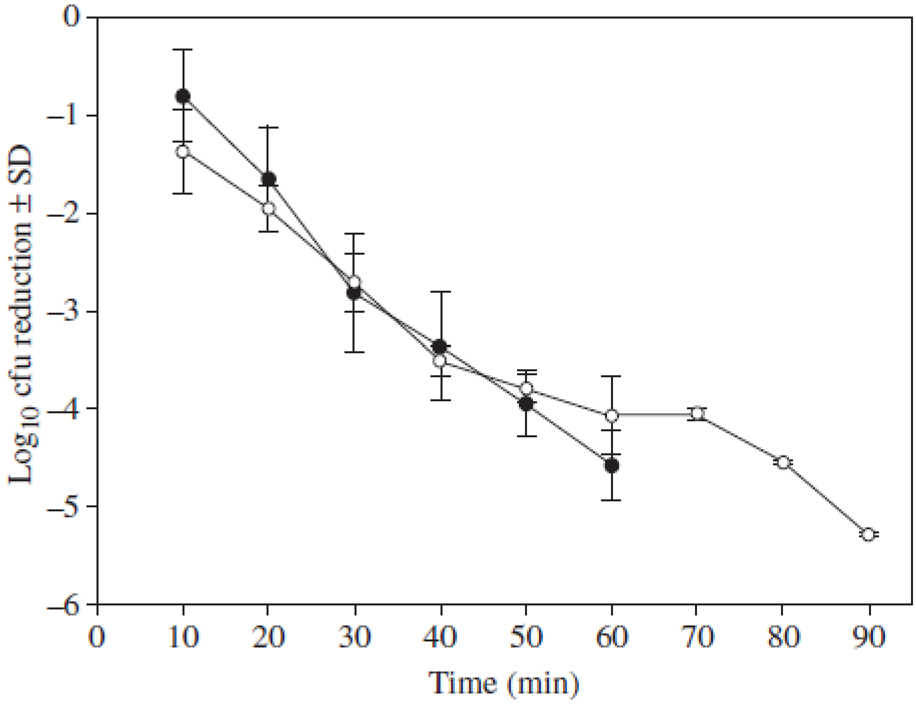


Figure 5: Survival curves for biofilms of S. epidermidis (C) and meticillin-resistant Staphylococcus aureus (B) exposed to dielectric barrier discharge plasma byproducts (Cotter et al) [8].

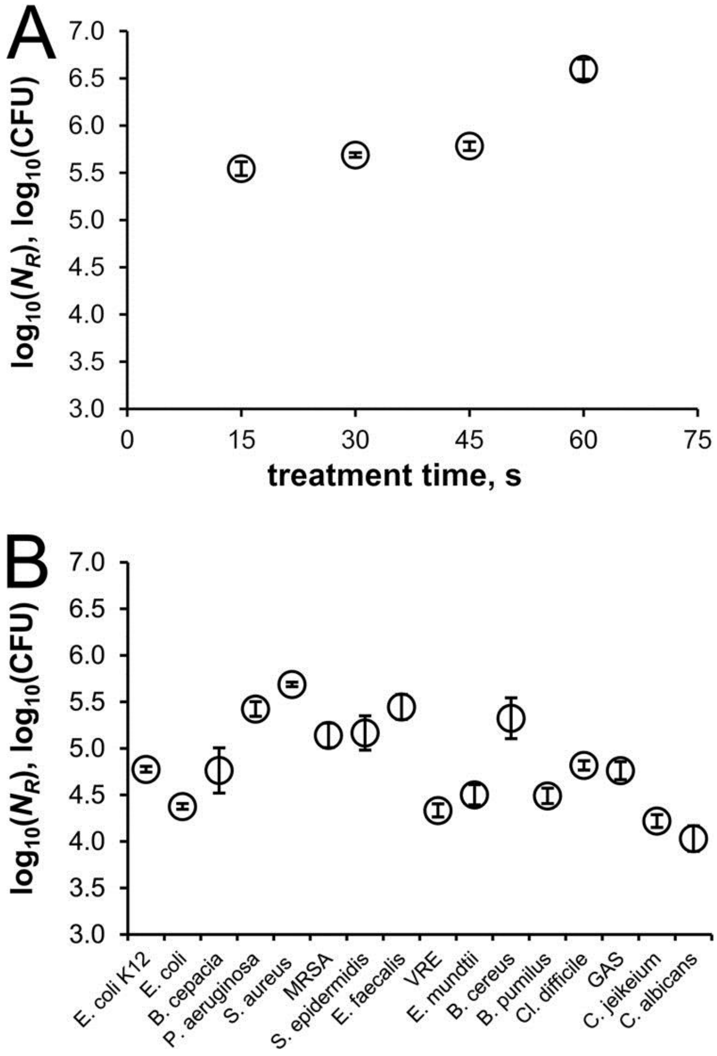


Figure 6 Microorganism Log Reduction When Exposed to Air Plasma, *Klamph et al*

On the other hand, for direct plasma exposure the deactivation time is considerably shorter. For example, figure 6 is taken from Klamph et al [2] and shows the log reduction for a variety of microorganisms following direct exposure to an air based dielectric barrier discharge. Note in this case the driving frequency was higher than that used in the Novaerus device (1 KHz in this case), but the results are still representative.

There is little in the literature on the deactivation of viruses using low temperature plasma technology. This is surprising given that based on our understanding of plasma interaction with microorganisms, as described earlier, the plasma is likely to be effective at deactivating viruses. A recent paper by Xing-Min Shi et al [3] examine the use of a non-thermal dielectric barrier discharge for deactivating the hepatitis B virus by exposing serum (extracted for HPV contaminated patient blood samples) to the plasma and detecting the alteration of the virus DNA after treatment with a plasma for various exposure times. The main experimental result from this paper is given in figure 7, where one can see that the results are rapid and substantial.

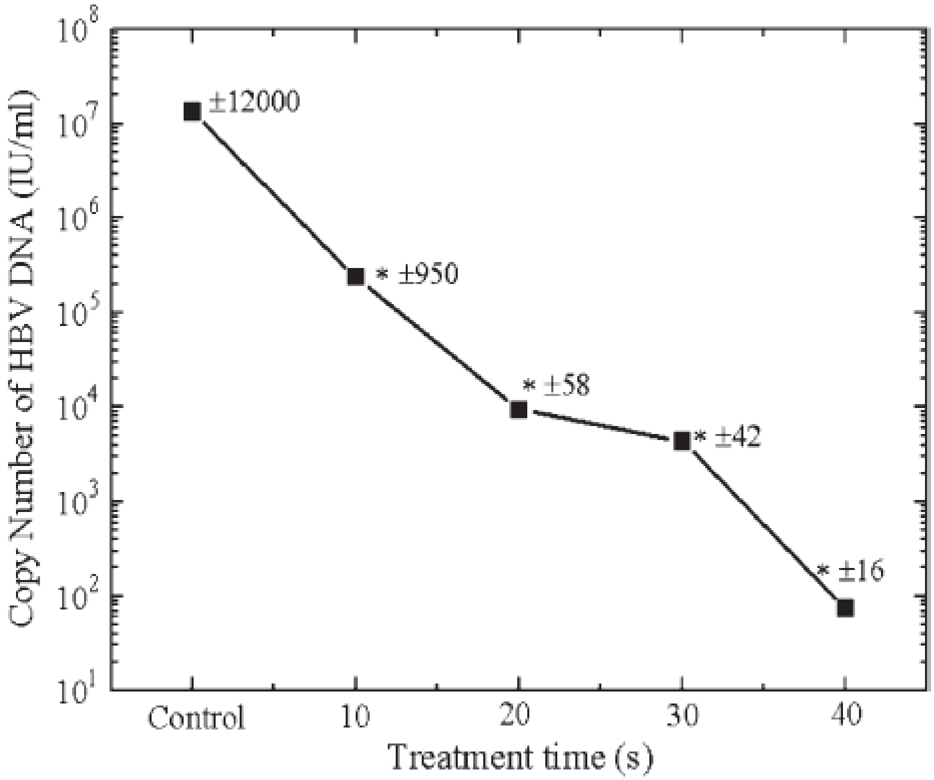


Figure 7: Deactivation results of HBV DNA in serum samples, *taken from [3]*

There is also evidence in the literature for the abatement of odors using non-thermal plasma technology, this will be the basis of a discussion elsewhere [4].

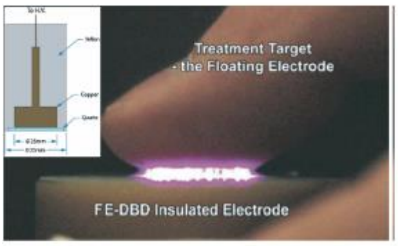
Recently there has been an increased interested in treating and disinfecting air using plasma, mostly driven by needs in food processing and healthcare. In these applications the volume of air to be treated is passed in close proximity to the plasma source. However, unlike in the case of the surface treatment applications discussed earlier, the single-pass exposure time of the microorganisms is limited to the transit time (τ) of the organisms through the plasma region. For a typical geometry and air-flow rate through a device, τ can be of the order of ms. Remarkably however, the relatively short τ is enough time for the airborne microorganisms to have a significant interaction with the plasma; enough to deactivate a significant proportion of the microorganisms on a single pass through the plasma. Gallagher et al at Drexel [5] experimented with single pass nebulized e-coli through a DBD discharge with a τ of circa 0.75ms and they observed a log reduction of about Log1.5 for a single pass, with a log reduction of Log3 if the organisms were subsequently (and briefly) exposed to low-intensity ozone. This study justified these numbers with a rudimentary but reasonable physical model based on the reaction rate constants of each plasma factor with the microorganisms. Very recent work by Yongdong Liang et al [6] at Peking showed similar results and they additionally deployed molecular techniques to understand DNA affects and they observed cell membrane rupturing.

There is an ongoing collaboration between researchers at Dublin City University, NASA AMES in the US, and Novaerus, where the efficacy of the Novaerus disinfection system for a range of microorganisms is being investigated as well as a study of the fundamental underlying deactivation mechanisms. Results so far indicate the Novaerus system is of comparative efficacy for a single pass through the system, which is very encouraging in light of the fact that the Novaerus system operates a very low power compared to other devices.

The underlying deactivation mechanisms are currently under investigation with an emphasis on E coli and Staphylococcus Aureus. Characterisation methods include fluorescence microscopy (cell wall integrity), atomic force microscopy, and Surface enhanced raman spectroscopy (SERS) to study the spectral finger print of untreated and treated microorganisms.

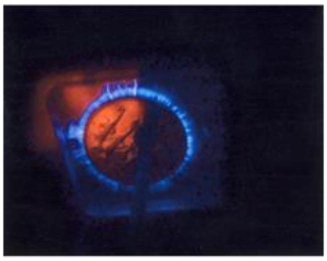
4. Embodiments

As mentioned previously, there are a multitude of possible embodiments of non-thermal atmospheric pressure discharges, however the they can be broadly classified into three 'families', : the dielectric barrier discharge, the corona discharge, and the plasma jet, as illustrated in figure 8 below. This classification is reasonable for the purposes of this report however there are other possible variants and the literature is populated with hundreds of possible embodiments.



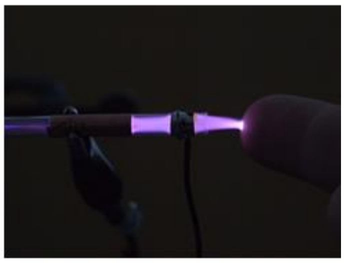
Dielectric Barrier Discharge

(Friedman et al 2006)



Corona Discharge

(D Balchin 2007)



Plasma Jet

(N O'Connor 2011)

Figure 8: Popular Atmospheric Pressure Discharge Construction

The construction most relevant to the Novaerus technology is the dielectric barrier discharge (DBD) and the corona discharge. DBD is a general term for a discharge that uses a dielectric material as a plasma stabilizer. The main feature of a DBD is the dielectric layer, which covers at least one of the electrodes. Typically, materials with a high dielectric constant and high breakdown voltage (ceramics or glass) are used. The dielectric material must be capable of avoiding any damage caused due to the stress induced by the discharge. The properties of the discharge are strongly dependent on the thickness of the dielectric. There are other factors such as dimension of the coils, mesh size and wire radius (if relevant), and electrode material, which can also influence the discharge properties and contributes to the efficiency and stability of the DBD device under study.

Tuning various external parameters can be used to optimize the discharge parameters, for example:

- (i) The operating voltage of the discharge affects the magnitude of the electric field, and hence the energy of the charged particles in the plasma.
- (ii) The power controls the ionization density per second and hence is an approximate control variable for the plasma density. It is also a possible control variable for the energy of the plasma constituents.
- (iii) The gas pressure controls the electron collision frequency and the mean free paths of all plasma constituents.
- (iv) The type of gas controls the ionization potential, and thus the energy required to produce an electron-ion pair in the plasma.
- (v) The geometry of the electrodes can affect the energy input by altering the electric field, through changing the geometry of the anode-cathode configuration.
- (vi) Cathode characteristics, such as the secondary emission coefficient, or the capability of thermo-ionic emission can also affect the discharge characteristics.

Example embodiments of DBD configurations taken from Kogelschatz are given in Figure 9.

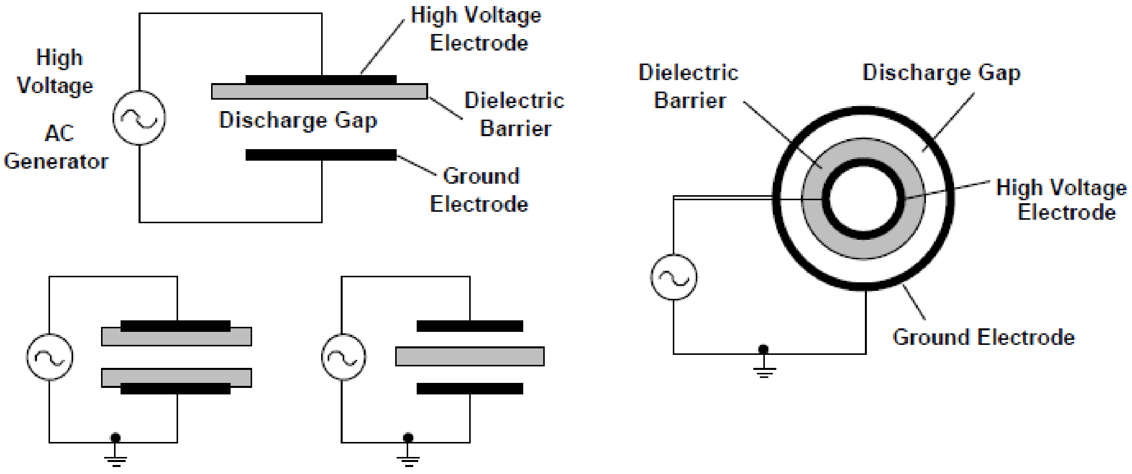


Figure 9: Example DBD Configurations

5. Innovation & Conclusion

The Novaerus technology is protected by US 8,211,374 B2 with the title 'Air Cleaning Device' and US 7,449,053 B2 with the title 'Air Filtration Device'. There are key features of the Novaerus intellectual property (in particular the electrical characteristics) that are significant in terms of device safety, efficacy, and manufacturing complexity than give Novaerus a competitive advantage over competing solutions.

In summary, there is a large quantity of data that supports the fact that plasma is an effective sterilization technology for surface and airborne microorganisms. The Novaerus plasma technology, a low-power, atmospheric DBD-type plasma generator, has achieved comparable levels of microbial deactivation to the state-of-the-art in the literature. The Novaerus generation principle is similar to many of the plasma generators that form the underlying basis for these studies, and has proven in multiple laboratory tests and clinical trials to be a highly effective anti-microbial disinfection technology.

The author is unaware of any other commercial plasma-based system for air disinfection with comparable efficacy on the market today. Based on our understanding of plasma and the available data it is highly likely that the Novaerus device will substantially reduce the levels of airborne microbial contamination in a healthcare environment.

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About the Author

Dr. Stephen Daniels is a senior faculty member in the School of Electronic Engineering at DCU and is Executive Director of Irish National Centre for Plasma Science and Technology (NCPST). He is widely published in the field of Technological Applications of Plasma with over 70 peer reviewed journal publications, over 100 conference contributions (including several invited lectures at international meetings) and 10 patents. He leads or has a leadership role in several large research awards, including the Precision Research Cluster (http://www.ncpst.ie/precision/), the Biomedical Diagnostics Institute, (http://bdisurfacescience.weebly.com/index.html), and the SFI-HRB Translational Research Award (https://sites.google.com/site/plasmahcai/). Dr Daniels leads a large multidisciplinary research group and collaborates widely, including a fruitful collaboration with Prof. Hilary Humphreys from the Royal College of Surgeons in Ireland in the area of healthcare associate infections. Recently he has collaborated with Novaerus in developing an understanding of the physics underlying the device, how to characterise and optimize its performance, and is part of the collaboration with NASA AMES.

The Irish National Centre for Plasma Science and Technology (NCPST) is a strong multidisciplinary research centre with research staff from a variety of scientific and engineering disciplines. The Centre is considered to be one of the leading academic research centres in its field in the world, and consists of approximately 80 members with well funded scientific plasma research programmes in modeling and simulation of fundamental processes, technological applications and industrial collaborations.