Food Science Institute

KANSAS STATE UNIVERSITY

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"In the aggregate, the existent knowledge on the chemical action of ultraviolet constitutes a very considerable mass of facts. These, however, are scattered over so wide a field that their coordination and correlation is by no means a simple task." -- Carleton Ellis and Alfred A. Wells, "The Chemical Action of Ultraviolet Rays, 1925.

Overview: The goals of management of Indoor Environment Quality (IEQ) are multiple: improvement of productivity in the work environment, occupant and worker health, and quality of sensitive products; protection of furnishings and décor, building HVAC equipment components; and building security; and reduction of building maintenance, energy costs, and fire hazards. Improvements in the health of building occupants are associated with cost savings in building operations. An ordered hierarchy of management strategies includes: source control, exposure control, ventilation, and air purification. Purification of indoor air environments of bioaerosols (*) by enhanced photocatalytic processes is the focus of this paper.

I. Indoor Environmental Quality (Statement of the Problem).

Indoor Environmental Quality (IEQ) defines living and working conditions within building environments that directly affect the health, safety, and comfort of building occupants. Air must be safe to breathe, water safe to drink, food safe to consume, and wastes safe to dispose. Management of both airborne and surface constituents must be considered during all phases of building design, construction, operation, and demolition.

Air is mixture of major, minor, and trace constituents in various physical, chemical, and biological forms. Major constituents include: nitrogen, oxygen, carbon dioxide, and water. Minor constituents include: ammonia, nitrogen oxides, carbon monoxide, and inert gases. Trace constituents include: Volatile Organic Compounds (VOCs); Particulate Matter (PM_x); and BioAerosols (BAs). These constituents may become airborne as gases, vapors, or suspended particles; or become deposited and attached to building structures and building occupants.

The indoor air environment is dynamic and constantly changing. Individual constituents are continually being created, removed, and transformed. Sources of indoor air constituents are primarily emissions, i.e. releases of volatiles or resuspension of particulates from building surfaces and furnishings. They can be byproducts of building HVAC operation, manufacturing, and cleaning, operations; and "bioeffluents" from occupants. Constituents are also transported between indoor and outdoor sources by air-handling systems for heating and cooling, ventilating, conditioning, and for purification ("HVAC+" systems). Individual constituents can be created and/or destroyed by natural atmospheric reactions or by engineered purification processes.

A given air constituent may be essential, nonessential, and/or hazardous to human health. It all depends on how much, where and when, does what, to whom. **Risk assessment** requires knowledge of both the degree of **effect** and the degree of **exposure** that both determine **hazard**. Effects depend upon chemical, physical, and biological properties of the constituent; exposures depend upon concentrations and durations, and how the constituent is transported. Routes of exposure include respiration of air, ingestion of food and water, and direct skin contact

Risk management requires decisions on how to reduce or eliminate the hazard posed by an undesired "air contaminant". Control technologies are selected based on cost and on the level of control that is dictated by both environmental health demands and by cost to implement. Conventional technologies may range from simple removal and disposal, to partial reduction or elimination of harmful effects, or to complete destruction and elimination. Advanced technologies involve application of specific process for oxidation of VOCs, agglomeration of PM_x, and inactivation of BAs.

Proactive (preventive) technologies restrict accumulation of volatiles, deposition of particles, and proliferation of microbes on surfaces. **Reactive** (mitigative) technologies destroy volatiles, agglomerate particulates, and inactivate airborne and surface-bound microbes. The combined approach to air purification is to practice both "before" and "after" the fact.

(*) **"BioAerosols" (BAs)** are airborne particles of biological origin ubiquitous to indoor and outdoor environments. Viable (living) forms can cause infections or disease; non-viable (dead) forms can cause allergies and toxic reactions. Bioaerosols include both prokaryotes (bacteria) and eukaryotes (fungii, protozoa, algae), and particulate fragments of higher plants and animals. Pollen, mold, and dander are common bioaerosols. Antibiotic-resistant microorganisms represent the other extreme. An excellent short review is found at HYPERLINK "http://aerosol.ees.ufl.edu/Bioaerosol/Section01-3.html" http://aerosol.ees.ufl.edu/Bioaerosol/Section01-3.html

II. Air and Surface Purification (Solution to the Problem).

The **purification** of (1) air circulating through rooms in buildings, and the purification of (2) extended surfaces that comprise the structure and furnishings of a building are often thought to be separate applications to be treated by distinctly different technologies. One is directed at treating a gas while the other is directed at treating a solid.

Conventional air purification involves the removal of **particulates** and **bioaerosols** by filtration; or the adsorption of **gases** and **volatiles** from the air. Traditionally, room air is (1) passed through disposable high-efficiency particulate air (HEPA) filters to remove particulate matter of prescribed sizes, or (2) through packed beds of activated carbon to scrub out unspecified odors and organic vapors ("gas-phase filtration"). The former requires the replacement of units; the latter requires the replacement or regeneration of units, and the disposal of wastes.

Non-engineered controls of surface contaminants are prescriptive and passive. Conventional processes for surface purification or the disinfection of bioaerosols attached to exposed surfaces include hand washing and scrubbing of exposed surfaces with topical disinfectants is prescribed to reduce microbial contamination. These processes have historically required storage and use of hazardous chemicals, such as water solutions of phenol, formaldehyde, hexachlorophene, isopropyl alcohol, quaternary ammonium salts, and sodium hypochlorite; or gases, such as ozone, hydrogen peroxide, and ethylene oxide.

Conventional air purification technologies generally target high levels of broad classes of air contaminants. **Enhanced air purification** technologies are designed to use specific processes to target specific groups of contaminants, such as oxidation of VOCs, agglomeration of PMx, or inactivation of bioaerosols. Greater levels of control also can be achieved by applying multiple technologies in sequence. Technologies can also be applied according to demand during periods of high building occupancy or during the course of special building operations.

Engineered controls of specific air contaminant classes, such as VOCs, PM_x, and BAs, are more proactive and responsive to changing conditions. They were originally designed and operated to air flow, temperature, and humidity. Ventilation is the historic approach for control of airborne contaminants. It is essentially a dilution of contaminated "dirty" air with fresh "clean" air, and/or separation and venting of "dirty" air. Air cleaning, or purification, by contrast, involves the removal and/or conversion of individual classes of air contaminants into less noxious or hazardous forms.

Evolution of technology (for air purification involving engineered systems) is a continual process. Electronic and photo-catalytic air cleaners comprise a diverse group of engineered devices that are significantly different in their functionalities, modes of operation, and targeted efficiencies. Bipolar air ionization is contrasted from both electrostatic precipitation and ozone generation. In air ionization, PM_x is electrically neutralized by direct contact with "cluster ions", as opposed to attraction to electrically-charged surfaces as in electrostatic precipitation. In air ionization, the primary active species are clusters of negative and/or positive air ions, and not ozone in the case of ozone generation. Enhanced photocatalytic technology has combined many of the features of early devices to greatly increase its utility in IEQ.

III. Enhanced Photocatalytic Technology (Description of the Process).

Explanation of photocatalytic technology requires a definition for **plasma** - the fourth state of matter - the others being gas, liquid, and solid. A plasma is formed by exposing electrically-neutral gas molecules, that make up most of normal air, to a high energy source, such as electricity or ultraviolet light. A very small number of the many oxygen molecules each gain an electron and are reduced to **negatively-charged "air ions"**. Likewise, a very small number of the many nitrogen molecules each lose an electron and are oxidized to **positively-charged "air ions"**. Enhanced photocatalysis involves many different chemical and physical species interacting in homogeneous and heterogeneous reactions (*).

These **"air ions"** are highly energized, but the bulk of the surrounding gas molecules remains un-ionized and the mixture remains at essentially room temperature. These simple "air ions" are relatively short-lived and prefer to revert to their original un-ionized forms, or alternatively, combine with water molecules to form larger hydrated **"cluster ions"**, which have multiple electrical charges, and which may exist for several hundred seconds.

This enhanced technology of **"cluster ions"** has intriguing properties. Those containing **"reactive oxygen species" (ROS)** are very chemically active and can convert most VOCs into simpler products of complete oxidation like carbon dioxide and water. Those containing **"reactive charged species" (RCS)** are very physically active and can agglomerate fine particulate matter PM_x into larger clumps that are more easily removed from the surrounding air.

Air molecules become ionized when exposed to thermal, electrical, or light energies. Physicochemical reactions are accelerated on the surface of a photoactive solid exposed to light [typically titanium dioxide (TiO_2) exposed to ultraviolet (UV) light]. This reaction generates free hydroxyl radicals (•OH) that react further to form various ROS and RCS. Photocatalysis is very efficient and does not require high energies or result in high temperatures and loss as heat

Weston Scientific LLC currently uses this enhanced technology (*) and is building on this foundation. The energy source is a broad-spectrum, high-efficiency dual-wavelength UV X lamp (253.7 & 185.4 nm). A unique honeycomb matrix is used to maximize surface exposure available to promote photocatalysis. Rates of the most desirable reactions are further increased by applying the UV light directly and reflecting it indirectly onto the photocatalyst matrix to greatly enhance the ionization of air passing across the cell. The accumulation of undesirable films on the catalyst is also minimized. A proprietary six-metal hydrophobic coating of the lamp further enhances the production of preferable reactive oxygen species while eliminating the formation of undesirable ozone and nitrogen oxides. Free radical reactions with water vapor promote the formation of hydroxyl, superoxide, and hydroperoxy radicals that create an aggressive atmosphere of reactive oxygen species and reactive charged species. The ionized cloud of ROS and RCS are then directed into an enclosed space or room where they can have a pronounced bactericidal effect on bioaerosols.

(*) **Enhanced Photocatalysis** of Biological, Chemical, and Physical Constituents is described in detail in the Appendix.

Microorganisms in indoor environments can be present both as particulates (cells, spores) and can produce natural microbial VOCs (MVOCs). Mitigation, therefore, may require combinations of processes to effect removal and destruction. Microbes prefer to attach to almost any surface. Traditionally, attempts have been made to create and maintain "sanitary", microbially-clean surfaces, e.g. painted and tiled surfaces, and smooth ducts and piping. No surface is ever completely free of microbes, although special laboratories and biologically "clean" rooms for handling potent disease agents approach "zero" limits. Sterilization can be thermal (heating, freezing), chemical (disinfectants, germicides), physicochemical (surface antimicrobials), or photochemical (UV germicidal irradiation).

Bioaerosols (BAs) are different from inanimate particulate matter (PM_x) in that they are associated with living organisms that are capable of metabolizing, growing, and reproducing, and causing adverse effects upon higher organisms. In indoor air purification it is particularly desirable to control populations of bacteria which are implicated as the cause of hospital-acquired illnesses (nosocomial infections) attributed to antibiotic-resistant species ("Superbugs"), and outbreaks of food poisoning in restaurants attributed to accidental contamination. The airborne transmission of viruses, bacteria, fungal spores, and other bioaerosols is of major concern.

Traditional non-engineered controls of aerosols and surface contaminants are prescriptive and passive. Conventional processes for surface purification or the disinfection of bioaerosols attached to exposed surfaces include hand washing and scrubbing of exposed surfaces. Topical disinfectants is prescribed to reduce microbial contamination. These processes have historically required storage and handling of hazardous chemicals.

Disinfection of building surfaces is broadly defined as the partial inactivation of microorganisms (or their toxins or vectors) and rendering them incapable of causing adverse effects upon human health. The process is not usually intended to kill all microorganisms, especially not bacterial spores, which are more resistant than whole cells. Rather, it results in a greatly reduced population of microorganisms that is much less likely to spread infection and disease.

Sterilization is a much more extreme physical and/or chemical process intended to achieve asepsis, a sterile microbial environment, such as operating rooms, surgical instruments, medications, and biological culture media, where complete elimination of all types of life is required. Sterilization is accomplished by application of heat, chemicals, irradiation, high pressure, and filtration, or various combinations.

Cell walls of bacteria provide structural support and protection of the cellular membrane and the cytoplasm. Depending upon the species, bacterial cell walls may contain peptidoglycan, a polymer of sugars and amino acids, and lipopolysaccharides, containing lipids and polysaccharides. These and other chemical components make up one or more layers of the bacterial cell wall, which can have different configurations and thicknesses for different classes of bacteria.(*) The exteriors of non-bacterial bioaerosol cells and particles can have different definitions. (Further elucidation of the mechanism of inactivation by enhanced photocatalysis further collaborative research.

The usual mechanisms invoked to explain nonspecific disinfection and sterilization of most microorganisms by commonly used technologies (like heat, steam, chemical agents, etc.) involves the complete destruction of the cell wall and/or disruption of internal cellular structures. Dead and disintegrated cells appear in photomicrographs as shriveled "prunes".

The mechanism that might be invoked to explain specific **inactivation** of bioaerosols by "cluster ions" (ROS and RCS), however, may be quite different. The dead cells in photomicrographs appear as "pincushions" struck by tiny invisible arrows. The use of the word "target" seems apropos. Damage by ROS appears to be confined to the structures of the cell wall and no internal structures appear to be adversely affected. This has consequence in that RNA and DNA in the interiors of the cells do not appear to be affected. Selective neutralization of net surface charges by RCS on the outer cell wall may be involved as well in the agglomeration of dead cells.

(*) **Bacteria** can be differentiated as (G+ and G-) based on reactions to the differential Gram staining technique.
G+ : *Bacillus, Clostridia, Staphylococcus, Enterococcus, Micrococcus, Sarcina, Listeria, Streptococcus spp.*
G- : *Pseudomonas, Escherichia, Serratia, Shigella, Legionella, Salmonella, Enterobacter, Helicobacter, Neisseria* spp.
HYPERLINK "http://en.wikipedia.org/wiki/Gram-negative_bacteria" http://en.wikipedia.org/wiki/Gram-negative_bacteria HYPERLINK "http://en.wikipedia.org/wiki/Gram-positive_bacteria" http://en.wikipedia.org/wiki/Gram-positive_bacteria

V. Environmental Evaluation (Operation and Safety).

Proper **operation** of enhanced air purification systems to improve IEQ requires optimization of process variables describing both the air handling system and the air quality demand. The process control unit should be centrally located. Inputs are set manually, based on fixed design parameters, or set automatically, based on monitored demand parameters. Manual inputs include: power capacity, and airflow area, and desired levels of air ions. The latter may be monitored indirectly through applied power levels. Electronic inputs might include: airflow, humidity, outside air quality, return air quality, and detection of specific VOCs. Sensors measure volumetric airflow and humidity.

Air quality sensors placed in the return air duct and in the outside air intake can be used to measure VOCs and PM**x**. Another air quality sensor can be used to monitor ozone, to ensure that any ozone present in the outside air is below the recommended ASHRAE limit (50 ppb). A third type of air quality sensor can be used to measure relative levels of certain size fractions of particulate matter (PMx). Signals from the sensors can be logged by a personal computer or transmitted by modem to an internet data center. Performance of the system then can be visually displayed in real-time plots and stored for archival retrieval or real-time viewing using a standard web browser. Collectively, the population of all charged species in the air environment contributes to a net negative, or positive, "space charge" that can be monitored

Safety of any new technology applied for the purification of indoor air constituents must insure safe operation within the occupied spaces of a living/ working building environment. Acceptance of photocatalytic technology, therefore, involves gaining a basic understanding of underlying chemistry and physics, and then learning how to best apply its features to the control of bioaerosols, especially in industries like food processing and healthcare that are sensitive to public opinion.

Weston Scientific Technology (*)

ROS and ROS generated by the **Weston Scientific Technology** are not considered to pose significant hazards to human health. Any risks attributable to ROS or RCS are considered much less than those associated with the trace air contaminants. The ROS and RCS generated by the **Weston Scientific Technology** mimics natural formation of similar species in the atmosphere. There is a considerable body of literature that describes the beneficial effects of negative air ions. A natural low-level background of "air ions" is present in the atmosphere that is increased during periods of electric storms. There is a growing literature on the beneficial effects of "air ions" to enhance the IEQ of living and working environments.

The Weston Scientific **Technology** is applied for the purification of **both room air and building surfaces**. It involves the generation of hydrated "cluster ions" using photocatalytic devices installed directly in rooms or air-handling systems. The "cluster ions" are generated *in situ* and immediately react with the targeted air contaminants. Any unreacted "cluster ions" revert back to their original state within a short time.

The Weston Scientific Technology was evaluated under laboratory conditions to determine if any undesired byproducts were formed. Analyses (GC/MS) confirmed that ozone and hydrogen peroxide were within acceptable limits. Some VOCs detected at low levels were attributed to materials used to construct the test chamber. Residual levels of other oxides and nitrogen oxides were below detectable levels. There is no direct exposure to UV radiation with the Weston Scientific technology.

The alternate use of chemical disinfectants applied in the extreme may require vacating a building until any residues are neutralized or purged to eliminate residues. There are no unused reactants to dispose of using photocatalytic processes. The only residues upon the application of the **Weston Scientific Technology** are considered to be the terminal products of oxidation like water and carbon dioxide. Agglomerated particulates are removed by conventional filters in HVAC units.

References.

Daniels, Stacy L., "On The Ionization of Air for Removal of Noxious Effluvia" (Air Ionization of Indoor Environments for Control of Volatile and Particulate Contaminants with Nonthermal Plasmas Generated by Dielectric Barrier Discharge, Special Issue on Nonthermal Medical/Biological Treatments Using Electromagnetic Fields and Ionized Gases, IEEE Trans. Plasma Sci. 30(4), 1471-81 (August 2002).

Daniels, Stacy L., "On the Qualities of the Air as Affected by Radiant Energies (Photocatalytic Ionization Processes for Remediation of Indoor Environments)", J. Env. Eng. Sci. 6(3), 329-42 (May 2007).

Tupman, David, Enhanced Photo-Catalytic Cells, U.S. Pat. Apps. 20120058006, 8 Mar 2012; 20120141320, 7 Jun 2012.