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Hard Ionization, Soft Ionization, and Byproduct Formation in Indoor Air Treatment

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Abstract

Electrical air-cleaning technologies are often grouped under the term ionization, but their operating mechanisms and emissions can differ. Dielectric barrier discharge and other non-thermal plasma processes can generate reactive species that transform volatile organic compounds (VOCs) and produce secondary byproducts under some conditions [1, 2, 3]. Indoor studies illustrate why contaminant removal and unintended chemistry both need evaluation [5, 6]. In mass spectrometry, hard and soft ionization describe the degree of molecular fragmentation during ion formation [7, 8]. This paper uses that terminology as an analogy for AEIRO's design objective: controlled positive and negative ion delivery rather than intentional gas-phase oxidation. A design objective does not establish a product's emissions profile. Ozone, other byproducts and treatment performance require applicable model-specific testing under stated conditions.

1. Introduction

The word "ionization" is often used too broadly in indoor air quality discussions. A dielectric barrier discharge reactor, a corona discharge ozone generator, a non-thermal plasma VOC abatement system, an electrostatic precipitator, and a tunable bipolar ionization system may all involve charged species, but they do not necessarily operate by the same chemistry.

The most important distinction is the amount of energy delivered into the gas phase. High-energy discharge systems can dissociate molecules and create reactive species. These systems are often intentionally used for VOC decomposition because they can generate oxidants and radicals that attack organic compounds. Reviews of dielectric

barrier discharge and non-thermal plasma VOC abatement describe the formation of ozone and reactive oxygen species as central to the VOC degradation process [1, 2, 3].

This chemistry can be useful in industrial exhaust treatment, where the objective is to chemically destroy contaminants inside a controlled reactor. In occupied indoor spaces, incomplete VOC conversion can leave secondary products rather than only carbon dioxide and water [1, 2]. A residential ion-generator study demonstrates the importance of evaluating device emissions [5], while research on ozone reactions with fragranced personal care products provides context for secondary indoor chemistry [6].

In mass spectrometry, soft ionization generally seeks to preserve molecular-ion information by minimizing fragmentation. AEIRO describes TBPI as a soft-ionization design because its intended function is controlled ion delivery rather than intentional VOC decomposition. That description explains the design approach; it does not by itself demonstrate the absence of ozone, reactive species or secondary byproducts in an installed product.

2. Hard Ionization

Hard ionization refers to an ionization process that deposits enough energy into a molecule to cause fragmentation. In mass spectrometry, the classic example is electron ionization, commonly performed at 70 electron volts. This technique intentionally produces molecular fragments, creating repeatable spectra used for compound identification. Mass spectrometry literature distinguishes hard ionization from soft ionization based on the degree of molecular fragmentation produced during ion formation [7, 8].

This distinction is directly relevant to air treatment. If an electrical discharge produces electrons, streamers, or microdischarges with enough energy to dissociate oxygen, nitrogen, water vapor, or VOCs, the process is no longer simply charging molecules or particles. It becomes a reactive chemical process [1, 2, 3].

In air, hard ionization can produce:

- atomic oxygen;
- ozone;
- hydroxyl radicals;
- superoxide;
- nitrogen oxides;

- excited oxygen and nitrogen species;
- fragmented VOC radicals;
- oxidized VOC intermediates;
- secondary organic aerosol precursors.

These species are useful when the goal is chemical destruction of pollutants, but they are not automatically desirable in occupied environments. A technology that is energetic enough to fragment VOCs can also create partial oxidation products that must be measured and controlled [2, 5, 6].

3. Dielectric Barrier Discharge as a Hard Ionization Process

Dielectric barrier discharge is a common form of non-thermal plasma. It uses high voltage across a dielectric barrier to create many short-lived microdischarges. Although the bulk air temperature may remain near room temperature, the electrons generated in the discharge can have enough energy to initiate strong chemical reactions [1, 3].

DBD systems are widely studied for VOC abatement because they can generate reactive species capable of oxidizing organic compounds. Reviews of DBD VOC treatment describe the role of plasma-generated oxidants, including ozone and other reactive oxygen species, in VOC degradation [1, 2].

DBD is also a common ozone-generation method. DBD ozone generators work by dissociating oxygen molecules and allowing oxygen atoms to recombine with molecular oxygen to form ozone. A recent DBD ozone-generator study describes high-energy electron excitation and oxygen dissociation as part of the ozone-generation process [4].

This is the central problem with using hard ionization chemistry in occupied indoor air. If the process has enough energy to dissociate oxygen and form ozone, it may also have enough energy to fragment VOCs and initiate secondary chemistry [1, 2, 4].

4. VOC Fragmentation and Secondary Byproducts

VOC removal by non-thermal plasma is rarely a simple one-step conversion of the VOC into carbon dioxide and water. Instead, it is a chain of reactions involving energetic electrons, radicals, ions, excited species, and oxidants. These reactions can break chemical bonds, abstract hydrogen atoms, add oxygen, and form unstable radical intermediates. Those intermediates can then react further to form secondary byproducts [1, 2, 3].

Potential byproducts from hard plasma VOC treatment can include:

- formaldehyde;
- acetaldehyde;
- formic acid;
- acetic acid;
- carbon monoxide;
- ozone;
- nitrogen oxides;
- oxidized VOCs;
- ultrafine particles;
- secondary organic aerosols.

The plasma-catalysis literature is useful here because it shows that researchers often add catalysts to non-thermal plasma systems specifically to improve selectivity, reduce ozone slip, and reduce undesirable byproducts. Reviews of plasma-catalytic VOC removal discuss both the mechanisms of VOC destruction and the importance of controlling byproduct formation [2, 3].

This is an important distinction for indoor air treatment. A hard plasma system may reduce the concentration of a target VOC, but target VOC reduction alone does not prove that the air is cleaner. A complete evaluation should also measure ozone, aldehydes, oxidized VOCs, acids, nitrogen oxides, particles, and other secondary products [5, 6].

Waring and Siegel evaluated a portable ion generator in a residential room and found that operation could increase ozone and potentially aldehydes under the tested conditions [5]. Wu and colleagues studied emissions from fragranced personal care products and their reactions in the presence of ozone, including oxidized vapors and

new particle formation [6]. The latter study provides background on indoor secondary chemistry; it did not test emissions from an air-cleaning device.

5. The Mass Spectrometry Analogy

Mass spectrometry provides a useful analogy for distinguishing ion formation with extensive fragmentation from methods that preserve more molecular-ion information. Its terminology is not an indoor-air-cleaner safety classification.

In hard ionization, such as conventional 70 eV electron ionization, the molecule receives enough excess energy to fragment. This produces a mass spectrum containing multiple fragment ions. Those fragments are useful because they help identify the original compound. Reviews of small-molecule mass spectrometry describe electron ionization as a hard ionization method and contrast it with softer methods used to preserve molecular-ion information [7, 8].

In soft ionization, the goal is different. The goal is to ionize, protonate, deprotonate, charge-transfer, or cluster the molecule while minimizing fragmentation. Soft ionization is preferred when the analyst wants to observe the intact molecular ion or molecular adduct rather than a cloud of fragments [7, 8].

For air-cleaning applications, this analogy can help explain design intent, provided the actual device chemistry is evaluated separately:

Processes designed to fragment or oxidize gases may form reactive species and secondary products. Their outcomes depend on the reactor, energy input, target compounds and operating conditions [1, 2, 3, 5, 6].

A charge-delivery design aims to create and transport ions without deliberately decomposing VOCs. The intention to limit fragmentation still requires verification of actual emissions.

TBPI is described by AEIRO as soft ionization because its design objective is low-energy, controlled ion delivery. The mass-spectrometry analogy does not establish the energy distribution or emissions of a particular air-cleaning model.

6. TBPI as a Soft Ionization Technology

Targeted Bipolar Pulsed Ionization is designed to deliver controlled ion output without operating as a high-energy plasma reactor. Unlike dielectric barrier discharge and aggressive corona discharge systems, TBPI is not intended to decompose VOCs by creating a highly reactive oxidation environment.

The key TBPI principles are:

Polarity control

TBPI can control whether positive or negative ions are generated, allowing the system to bias ion output toward the contaminant being targeted.

Pulsed bipolar operation

TBPI can alternate polarity with a delay between outputs. This is intended to reduce immediate ion recombination and preserve useful downstream ion availability. The size of any benefit depends on operating conditions and should be established by measurement.

Targeted contaminant interaction

TBPI is intended to use electrostatic attraction and ion-contaminant interactions rather than indiscriminate chemical oxidation.

Low-energy ion generation

TBPI is designed for controlled ion generation rather than intentional oxygen dissociation or VOC breakdown. References on mass spectrometry explain the hard/soft terminology [7, 8]; applicable device testing is needed to characterize ozone, other emissions and ion delivery.

Occupied-space compatibility

Suitability for occupied spaces depends on model-specific emissions, electrical safety, installation, maintenance and demonstrated treatment performance. A design that does not intentionally oxidize VOCs should not be assumed to be universally safer or more effective than a different technology.

7. Ozone as an Indicator of Hard Ionization Chemistry

Ozone is one of the clearest indicators that a discharge process is energetic enough to alter air chemistry. To form ozone from oxygen, the process must create reactive oxygen pathways, commonly through oxygen dissociation followed by recombination. DBD ozone generators are designed around this mechanism [4].

In an occupied indoor environment, ozone is undesirable for two reasons. First, ozone itself is a respiratory irritant. Second, ozone reacts with common indoor VOCs, including terpenes from cleaning products, fragrances, and building materials. These reactions can form formaldehyde, ultrafine particles, organic acids, and other oxidized

compounds. Indoor chemistry studies have repeatedly identified ozone-initiated chemistry as an important source of secondary indoor pollutants [5, 6].

Therefore, avoiding ozone generation is not only a regulatory consideration; it can also reduce one important pathway for downstream secondary chemistry. TBPI is designed as a low-energy soft ionization system rather than a high-energy plasma oxidation process. However, demonstrating low or non-detectable ozone does not by itself prove the absence of every possible VOC transformation or secondary byproduct. Claims about aldehydes, oxidized VOCs, particles, acids, nitrogen oxides, or other emissions should be based on applicable model-specific emissions testing under defined operating conditions.

8. Design Intent and Byproduct Verification

The aim of soft ionization is to create charged species while limiting fragmentation. In mass spectrometry, that aim is evaluated through the resulting spectra [7, 8]. In indoor air treatment, the relevant evidence is measurement of the air cleaner's emissions and performance under defined conditions.

In practical terms, TBPI is not intended to:

- split oxygen molecules;
- generate ozone;
- fragment VOCs;
- oxidize terpenes;
- create aldehydes;
- create organic acids;
- generate nitrogen oxides;
- form secondary organic aerosol.

Instead, TBPI is intended to:

- generate controlled ions;
- tune polarity based on contaminant type;
- reduce ion recombination;
- improve ion delivery;
- influence particles and contaminants through charge effects;
- support contaminant control without destructive gas-phase chemistry.

The useful distinction is between an intended charge-delivery mechanism and intentional chemical decomposition. Actual emissions may not follow a technology label alone.

TBPI is designed to avoid the energy regime associated with molecular fragmentation and ozone-forming plasma chemistry. Product-specific ozone testing can characterize ozone emissions for the tested model and conditions. Broader claims about VOC fragmentation or secondary byproducts require applicable emissions testing for those specific compounds or endpoints.

9. Conclusion

Hard ionization and soft ionization are not the same. Hard ionization deposits enough energy into molecules to fragment them. In mass spectrometry, this is useful because fragmentation helps identify chemicals [7, 8]. In indoor air treatment, however, the same principle can create unwanted chemistry.

Dielectric barrier discharge and other plasma processes can transform gases and VOCs and may form secondary products [1, 2, 3]. Photocatalytic oxidation is a different mechanism and should be assessed on its own design and test evidence. The outcome of either approach cannot be inferred solely from a broad technology category.

TBPI is designed to control ion polarity and timing rather than deliberately oxidize VOCs. That is a mechanism-level distinction. It should not be presented as proof that every implementation is free of ozone or other byproducts.

The design intent of TBPI is to use controlled, low-energy ion generation rather than high-energy gas-phase oxidation chemistry. That design distinction supports evaluating TBPI separately from plasma systems that intentionally generate reactive species. Actual ozone and other emissions performance should be established for each applicable product through appropriate testing rather than inferred solely from the soft-ionization design concept.

References and source types

Research citations provide background for the stated mechanisms and tested systems. They do not automatically validate AEIRO product performance. Manufacturer literature, public guidance and internal references are labeled separately. Product claims require evidence for the relevant model, endpoint and operating conditions.

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