THE UNIVERSITY of ADELAIDE

Final Technical Report

Evaluation of the PlasmaShield Air Purification System for Mitigation of Volatile Organic Compounds, Airborne Particles, Nitrogen Dioxide and Ozone Emissions

A Review of Single Pass and Test Room Experimentation,
with Occupational Hygiene Considerations

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1. Executive Summary

In a previous Interim Report (AESHDP0122), Adelaide Exposure Science and Health (University of Adelaide) reviewed selected experimental data pertaining to the PlasmaShield Air Purification System (PAPS) and provided commentary on air purification from an occupational hygiene perspective. This report presents findings from an independent empirical study by the author of the performance of the PAPS system in a test room environment. Consistent with the Interim Report, an occupational hygiene perspective has been used to interpret the findings.

Background and Objectives

The objectives given below complement the work done by Mondial Advisory/Airpure, and, to some extent, previous work by the AESH laboratory at the University of Adelaide (VOCs) and InterTek (ozone).

The Mondial Advisory/Airpure report demonstrated that PAPS could significantly reduce particle concentrations but its scope did not include ultrafine particles (less than 0.1 µm). The report assessed mitigation of cigarette smoke which has an ultrafine component, and ambient airborne particulate matter which also has an ultrafine component, e.g. from diesel exhaust emissions.
The InterTek report demonstrated that PAPS generates insignificant levels of ozone. However, ozone production as a result of breakdown of air contaminants coming into the unit was not assessed, as it is not within the scope of internationally recognised standards.
The University of Adelaide AESH report (OEHC1084) demonstrated VOC reduction for a range of individual volatile organic compounds, but the use of GC-FID limited the ability to assess breakdown products of toluene, which can theoretically arise when toluene is subjected to an electron beam. However, a recently published paper by Zhao and Alwahabi in the University of Adelaide's School of Chemical Engineering noted that PAPS generates excited N_2 and NO only within a narrow region around the discharge electrode tip (with peak intensity below 100 µm from the tip). These excited species are unlikely to travel far from the point of generation. The study also showed no presence of excited OH*, O*, and other radicals.
Finally, given that nitrogen and oxygen are the main constituents of air, it would be important to know if low levels of nitrogen dioxide are being produced by the PlasmaShield system. This had not been previously reported, and is pertinent given that the Australian National Environment Protection Measure (ambient air quality 1 hr average of 80 ppb) is tighter than the World Health Organization guideline (100 ppb). The odour threshold (100 - 400 ppb) also exceeds the NEPM, meaning it has poor warning properties (SCOEL, 2014).

Methods

Experiments were conducted in a test room.
The first set of experiments related to the PAPS mitigation of fine and ultrafine airborne particles, generated by two different systems, i.e. hot block generation of theatrical smoke, and low temperature aerosolisation of diethylhexylsebacate (DEHS).
The second set of experiments evaluated whether the PAPS system generated ozone via its own mode of action, or indeed reduced ozone when ozone was deliberately introduced into the test room.
The third set of experiments assessed whether nitrogen dioxide was produced by the PAPS mode of action.
The final experiment assessed VOCs at the PAPS outlet following toluene and limonene vapour introduction into the test room.

Main Findings

Averaged fine particle reduction (comparison of inlet and outlet readings)

Theatrical smoke, particle count with AeroTrak (size):
1µm 87%; 3µm 93%

DEHS aerosol, particle count with AeroTrak (size):
1µm 90%; 3µm 95%

Averaged ultrafine particle reduction
Theatrical smoke: 87%

Ozone
Self-generated ozone: maximum of 0.002 ppm
With ozone being artificially generated in the room ,ozone at PAPS outlet was <0.002 ppm.

Nitrogen dioxide
Self-generated nitrogen dioxide: not detected (<0.002 ppm)

VOCs at the PAPS outlet following toluene and limonene vapour introduction at the inlet
Inlet toluene concentration: 2.1 mg/m3; Outlet: 0.2 mg/m^3 (about 90% efficiency)
D-limonene concentration at inlet: 56 µg/m3; Outlet: not detected (<30µg/m3)

Formation of by-products
No additional VOCs were detected under these conditions or when toluene was introduced at at a higher concentration of 55 mg/m^3.

Interpretation of findings

Particles
The particle reduction experiments show that the PAPS is effective for both fine and ultrafine particles. The extent of reduction was somewhat less than that reported by Mondial Advisory. In that experimentation, a post-filter was used, and so the results are not directly comparable. In addition, particle concentrations generated in the test room were higher, typically 1-2 mg/m^3 for DEHS aerosol and 1-10 mg/m^3 for theatrical smoke as PM_1. The extent of particle reduction may depend on the type of particle. However, the PAPS has now been tested with theatrical smoke, DEHS, cigarette smoke and ambient air particles, across a range of particle sizes. DEHS aerosol may be unusual as it is generated at room temperature under pressure, rather than high temperature conditions (e.g. combustion aerosols which are more commonly found).
PAPS particle reduction **even without a post filter** may approach that of popular HEPA-based systems. Testing with a free standing air purifier (Samsung AX 7000) showed approximately 94-98% PM_1 reduction and 92% for ultrafines (using theatrical smoke as above).

Ozone
It is evident that the PAPS does not self-generate appreciable quantities of ozone. Ozone reduction at low ambient ozone concentrations occurs even if the PAPS is not powered up, presumably dues to the CuO/MnO_2 catalytic converter placed after the exit stage of the reactor.

Nitrogen dioxide
It is also evident that PAPS does not self-generate nitrogen dioxide.

Volatile organic compounds
The previous AESH report indicated that the PAPS is able to significantly reduce low to moderate concentrations of toluene. At low (realistic odour threshold) concentrations the data in this report also indicate good efficiency. Importantly, there appeared to be no breakdown products of toluene when present at a higher concentration of 55 mg/m^3. This is still not definitive as there could be breakdown products not detected in the 73 compound GC-MS scan. However, when present in the room during the various experiments the author did not notice any new smell or irritation when the PAPS system was turned on with D-limonene-spiked toluene. From an occupational hygiene perspective and considering the findings of Zhao and Alwahabi the weight of evidence suggests that reactive species inducing acute airway effects are not generated to any significant extent by the PlasmaShield system. The experience of persons working in areas serviced by the PAPS would be diagnostic.

Bioaerosols
Most researchers would consider generic particle reduction in the micron and submicron size ranges to be a proxy for bioaerosol reduction. That said, independent studies of the PAPS by Flinders University have been conducted and published demonstrating actual microbial inactivation across a range of agents. The key finding were as follows:
PAPS statistically significantly ($p<0.05$) reduced airborne *Escherichia coli, Staphylococcus epidermidis*, Bacteriophage MS2 and *Cladosporium* sp. compared with the negative control. The maximum removal achieved was estimated to be 4 x $\log_{10}$ *E. coli* (99.99% removal), 4 x $\log_{10}$ *S. epidermidis* (99.97% removal), 7 x $\log_{10}$ MS2 (99.99998% removal) and 5 x $\log_{10}$ *Cladosporium* sp. (99.999% removal). Scanning electron microscope images of the surviving microorganisms showed that the PAPS damaged the cell membrane of these model microorganisms.

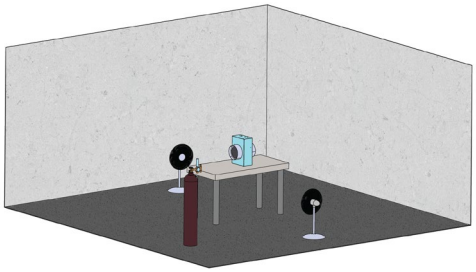
Conclusions

The new empirical work conducted by the author is consistent with Interim Technical Report (Appendix 1). The investigations involving fine and ultrafine particles, ozone, nitrogen dioxide, toluene and limonene in test room conditions indicate that PAPS is capable of simultaneously mitigating a range of air contaminants, without introducing others.
The results confirm that the effective multi-contaminant clean air delivery rate approximates that of the volumetric air flow of the PAPS system.

Overall, the PlasmaShield Air Purification System represents an advanced form of air purification that would suit indoor environments where air disinfection is necessary or important. It would also suit settings whether there is a confluence of work/worker/workplace risk factors for disease, productivity, vigilance or critical decision-making. This includes health and aged care, and certain military, high security, transport, educational, research and commercial environments.

2. Experimental Conditions and Test Room Characteristics

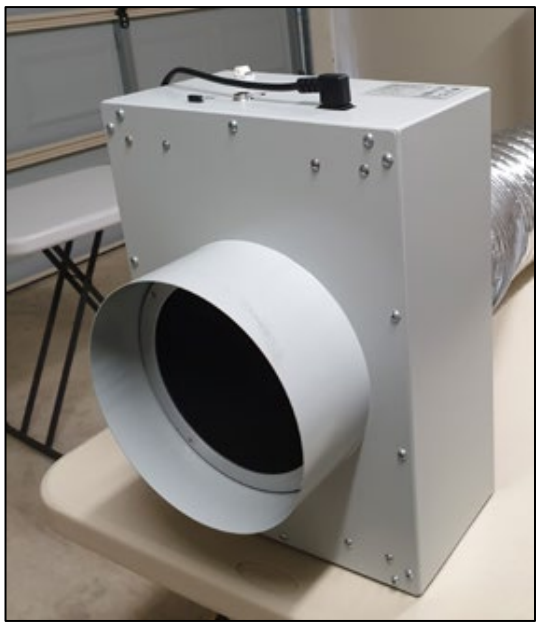
A MD250 PlasmaShield unit (30W) coupled with an in-line fan (producing approximately 320 m^3/hr) was mounted on a bench in the centre of a naturally ventilated test room (89 m^3 and approximately 1 air change per hour, as measured by the carbon dioxide and acetone vapour decay methods). A datalogging TSI Q-Trak 8551 was used for carbon dioxide measurements.



Test room (5.7m x 5.8 m x 2.7m height)

Measuring air exchange in test room using the carbon dioxide decay method

No post filter was used for the PAPS unit.
Note that in practice, a post filter (e.g. MERV-11) is used in conjunction with the PAPS unit. The experiments in this Report were conducted to assess the intrinsic abilities of the MD250 PlasmaShield unit.



MD250 PlasmaShield unit (30W) illustrating the outlet without post-filter.

3. Airborne Particles (Theatrical smoke and DEHS aerosol)

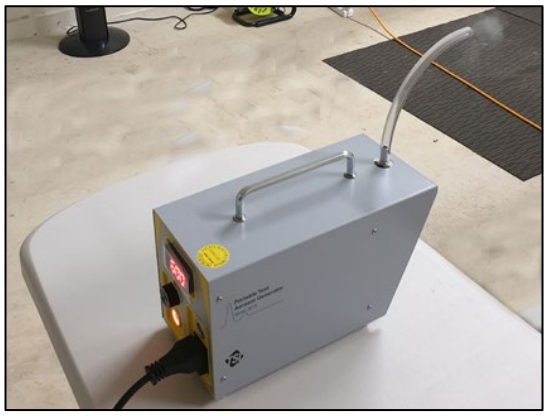
Measurement methods

Aerosol concentrations were measured in equivalent gravimetric (TSI DustTrak DRX 8534 laser photometer, and DustTrak 8520) and number methods (TSI AeroTrak 9306-V2 particle counter).
Ultrafine particle concentrations were assessed with a TSI P-Trak condensation nuclei counter.

Generation and characterisation of airborne particulate

Diethylhexyl-sebacate (DEHS) aerosol and theatrical smoke were used to assess aerosol mitigation by the PAPS. Particle concentrations generated in the test room were typically 1-2 mg/m^3 for DEHS aerosol and 1-10 mg/m^3 for theatrical smoke as PM_1.

DEHS aerosol was generated in the test room with a TSI 3073 portable test aerosol generator.
This is room temperature aerosolization.



Portable test aerosol generator (note aerosol on top right of image)

Theatrical smoke was produced by a Rave professional fog machine (AF-1214) using a heavy fog liquid (AF-1212).
Theatrical smoke involves hot block generation.

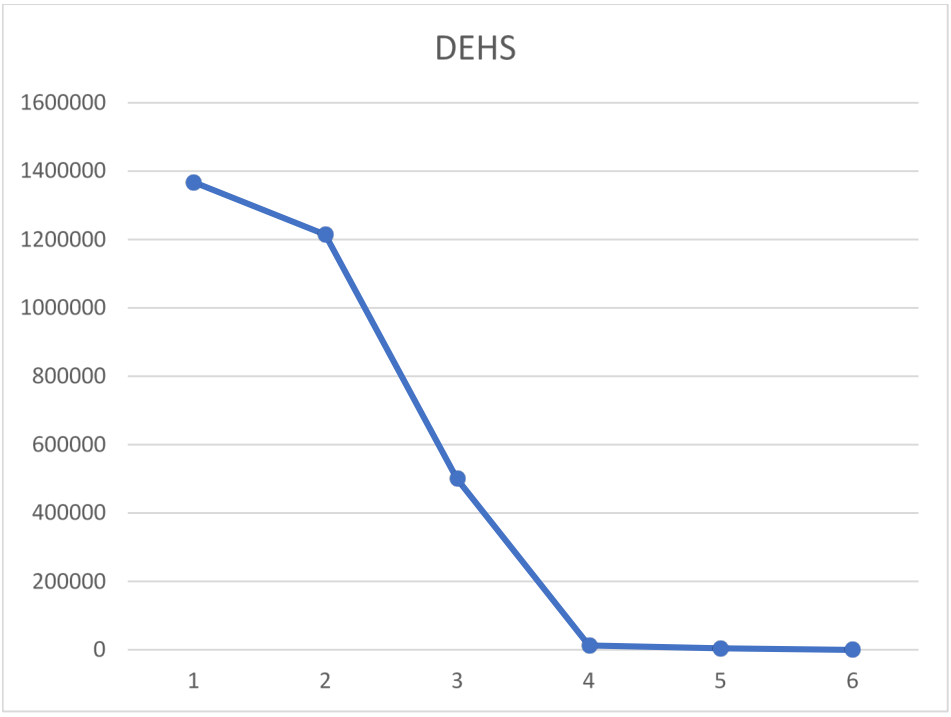
Theatrical smoke generator - Rave professional fog machine (AF-1214)

Both methods produce aerosols in the size range relevant for exhalation (vocalisation, breathing) reported by Archer et al (2022).

The size distribution was measured and illustrated as follows.

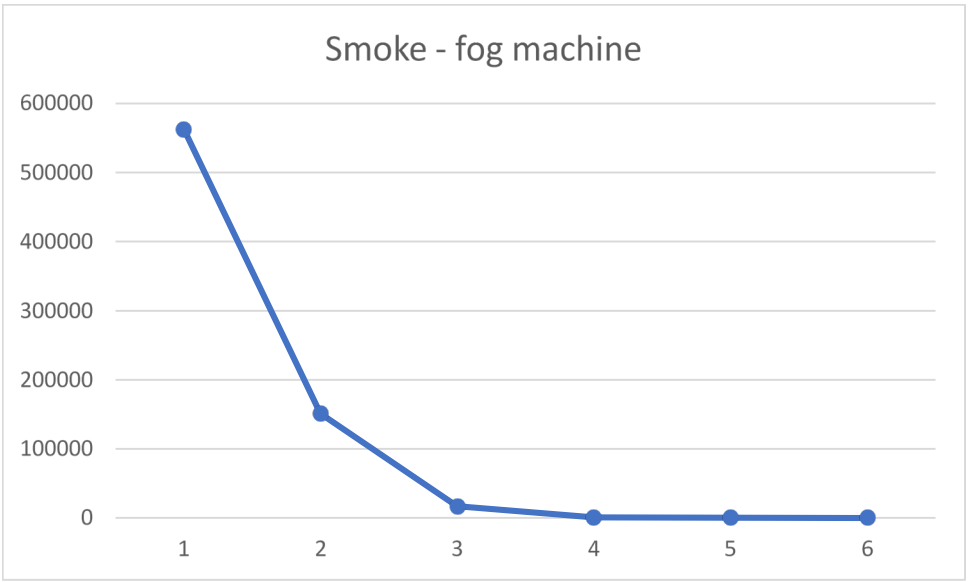
Relative particle count of different size fractions

TSI AeroTrak (arbitrary y axis)



DEHS = Diethylhexylsebacate

X axis categories : 1 = 0.3 um, 2 = 0.5 um, 3 = 1um, 4 = 3 um, 5 = 5 um, 6 = 10 um



X axis categories : 1 = 0.3 um, 2 = 0.5 um, 3 = 1um, 4 = 3 um, 5 = 5 um, 6 = 10 um

The theatrical smoke is essentially all submicron, with an appreciable ultrafine component, as measured with the TSI P-Trak condensation nuclei counter.

DEHS aerosol is more representative of vocalisation. Archer and co-workers (2022) reported a bi-modal distribution of exhaled particles. For all activities involving vocalization, the mode of smaller particle size was centred around 0.50–0.64 µm diameter, indicative of particles generated within the lower respiratory tract. The larger-sized mode was between 1.39 and 1.94 µm diameter during vocalization, representative of particles formed in the larynx.

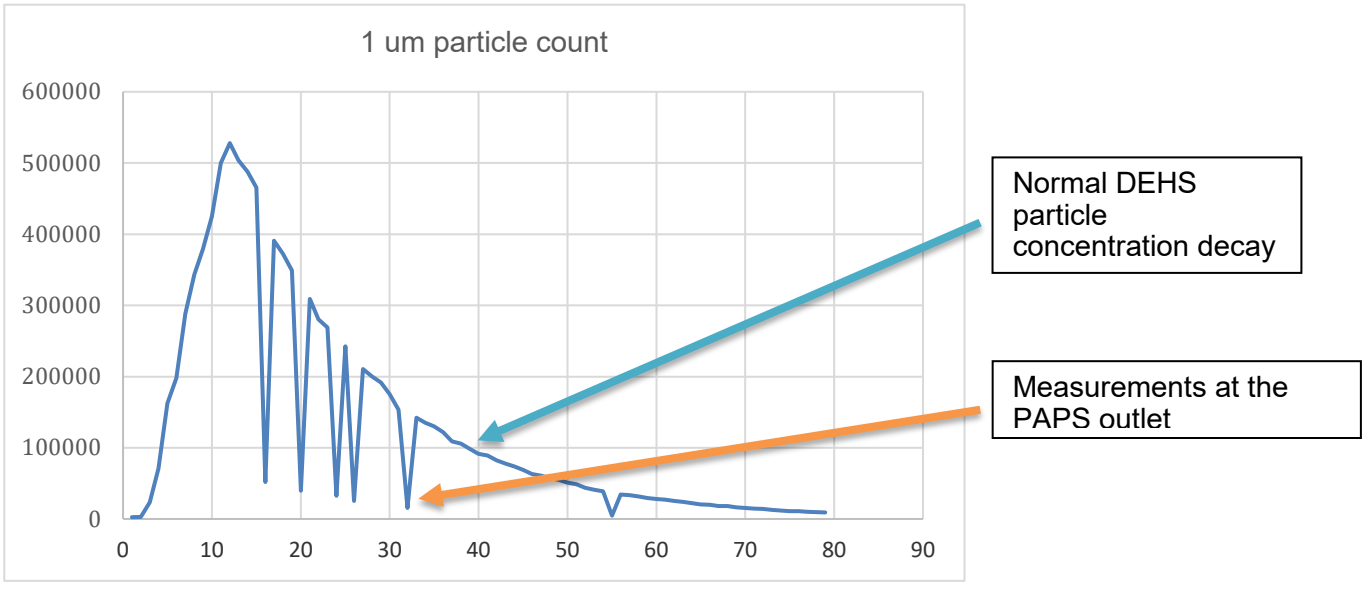
Aerosol mitigation by PlasmaShield

Single pass measurements were taken at the inlet and outlet of the PAPS unit repeatedly and sequentially.

DEHS aerosol

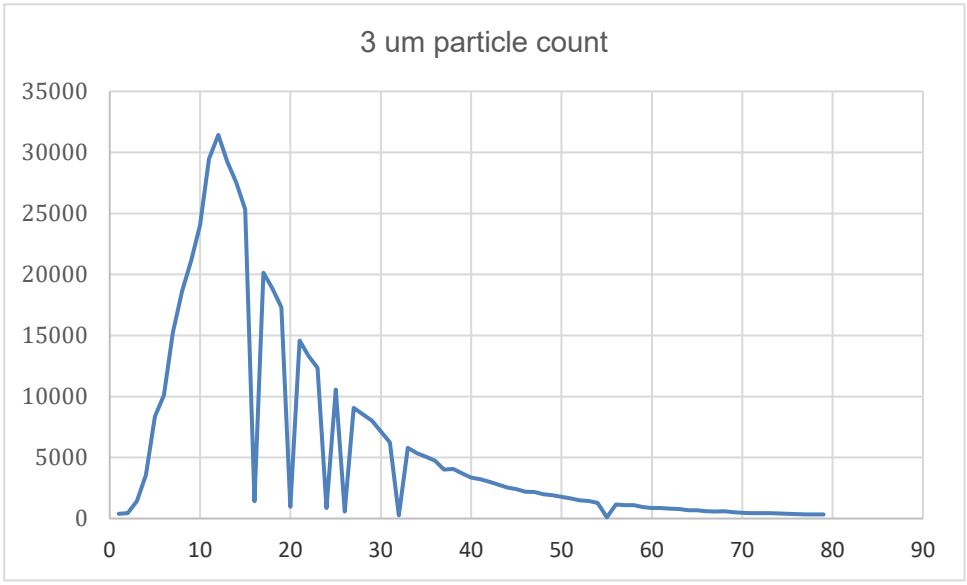
AeroTrak data

The reduction of particle number concentration (1 um) is illustrated below. The graph is a combination of the decay profile of DEHS when introduced into the room and the particle counts as periodically measured at the outlet of the PAPS unit.
The first ten minutes represent the buildup of particles in the test room. The dips at 16, 20, 23, 26, 32 and 55 minutes illustrate the mitigation. The average reduction is 90%.



Reduction of 1um particle concentration (cumulative #) at various time points (minutes)

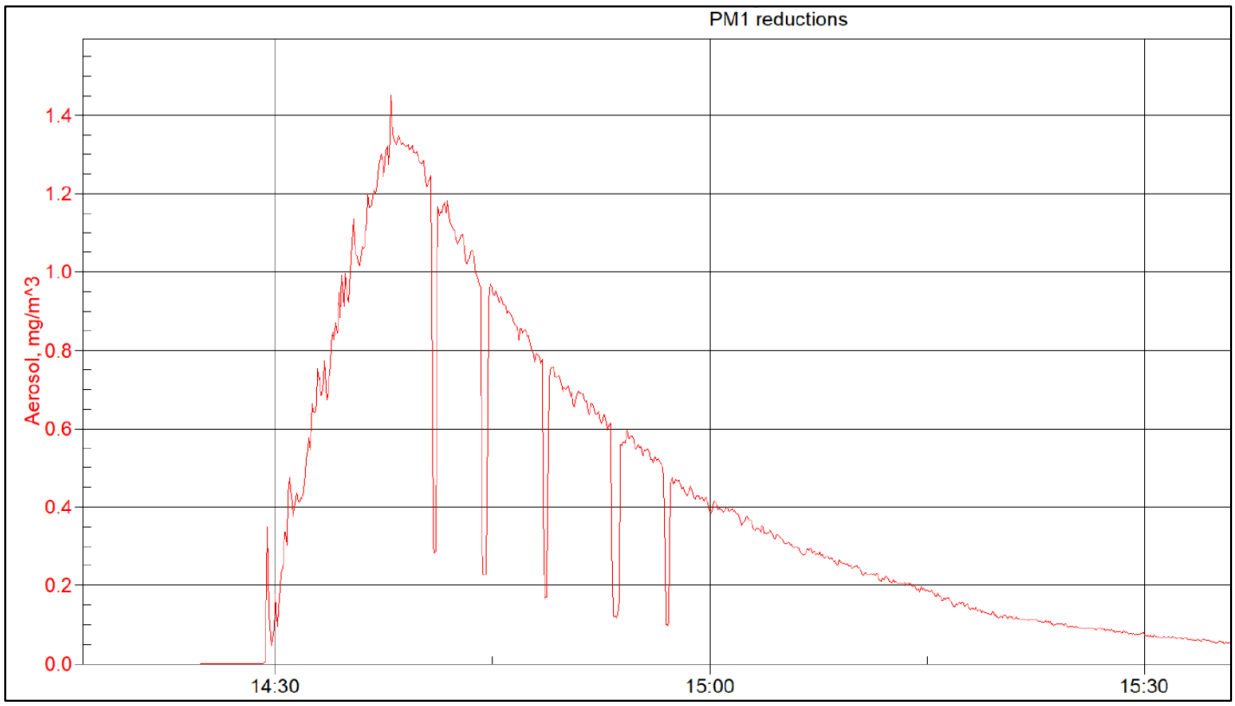
The reduction of particle number concentration (3 um) is given below. The first ten minutes represent the buildup of particles in the test room. The dips at 16, 20, 23, 26, 32 and 55 minutes illustrate the mitigation. The average reduction is 95%.



Reduction of 3 um particle concentration (cumulative #) with at various time points (minutes)

DustTrak data

The reduction of PM_1 concentration is given below. The first ten minutes represent the buildup of particles in the test room. The dips at 14:40, 14:44, 14:49, 14:54 and 14:57 illustrate the mitigation. The average reduction is 80%.



Reduction of PM_1 particle concentration at various time points

Theatrical smoke

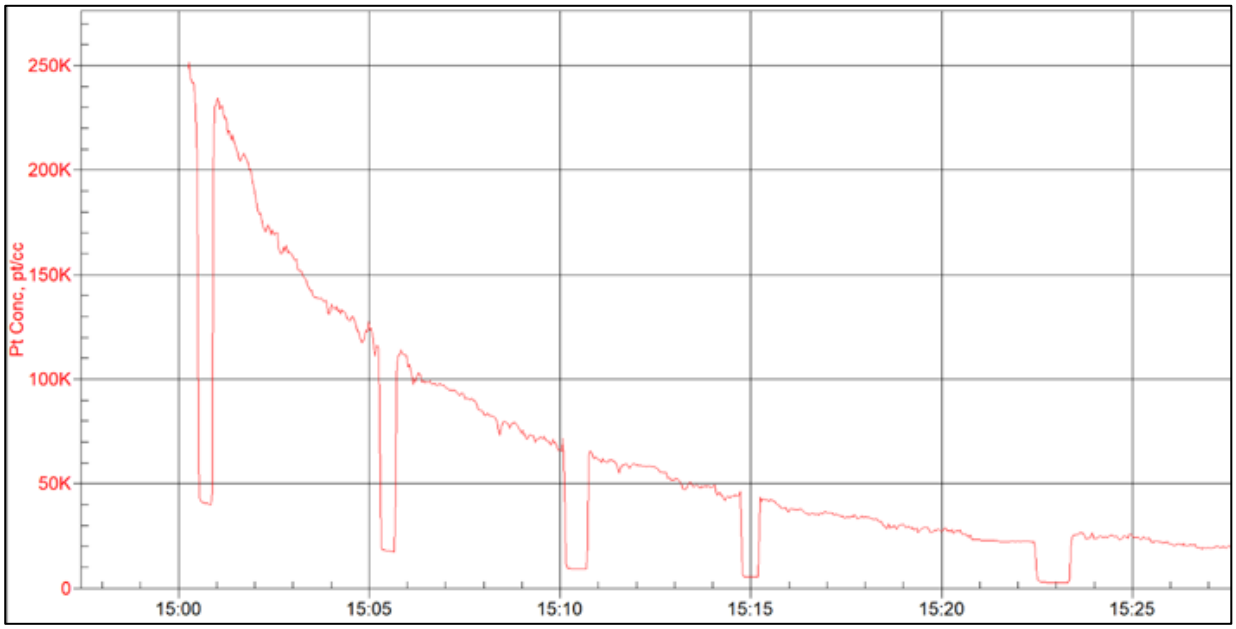
The corresponding average reduction of particle number concentrations were:
87% (1 um) and 93% (3 um)

The corresponding average reduction of PM_1 was 92%.

Ultrafine particle reduction

The graph below illustrates the extent of mitigation of ultrafine particles (<0.1 um) from theatrical smoke.

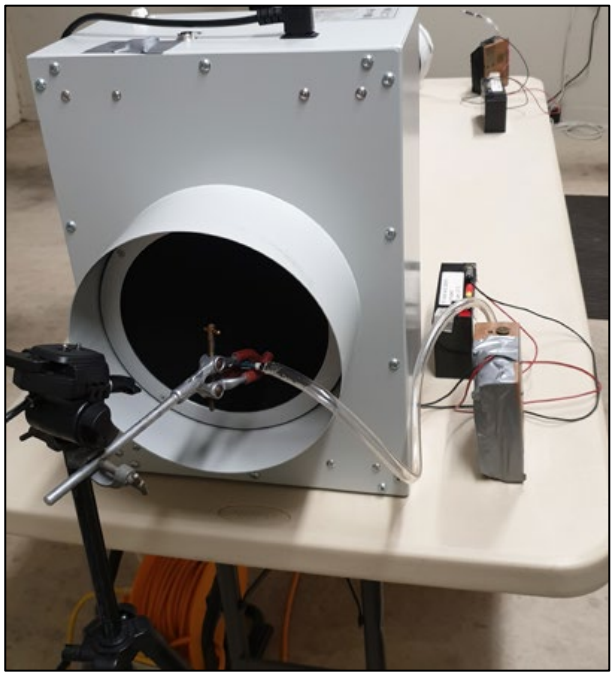
The average reduction is 87%.



Reduction of ultrafine particle number concentration at various time points

4. Volatile Organic Compounds – semi-quantitative assessments

Toluene and D-limonene vapour were generated by blowing air over toluene/limonene mixtures in a large glass dish, with the room concentration being monitored with a RAE Systems ppbRAE 3000 photoionisation detector. Volatile organic compounds were measured with modified SKC air sampling pumps (1.0 L/min) and charcoal tubes (SKC 226-09). Measurements were taken at the inlet and outlet of the PAPS unit simultaneously over a known period in excess of 2 hrs. GC-MS analyses were conducted by TestSafe Australia (73 reported compounds VOC scan, WCA 207). Front and back sections were separately analysed.



Sampling for VOCs at the inlet and outlet of the PAPS unit.

Findings

(TestSafe Australia reference 2022-0874)

VOCs at the PAPS outlet following toluene and limonene vapour introduction at the inlet
Inlet toluene concentration: 2.1 mg/m3; Outlet: 0.2 mg/m^3 (about 90% efficiency)
D-limonene concentration at inlet: 56 µg/m3; Outlet: not detected (<30µg/m3)

Formation of by-products
No additional VOCs were detected under these conditions or when toluene was introduced at at a higher concentration of 55 mg/m^3.

5. Nitrogen dioxide

An Aeroqual 500 instrument with separate sampling modules were used for ozone and nitrogen dioxide measurements, i.e. nitrogen dioxide (0-1 ppm) and ozone (0 - 0.05 ppm). Measurements were taken at the inlet and outlet of the PAPS unit repeatedly and sequentially.

Finding

No nitrogen dioxide was detected at the outlet of the PlasmaShield unit (<0.002 ppm).

Nitrogen dioxide measurement at the outlet

Although the detector had a certificate of calibration (Certificate 56742, 23 November 2021), the sensor was checked with a gas torch, as illustrated below.
The reading of 0.003 ppm demonstrated sensor functionality.

Test of instrument detector to demonstrate functionality

6. Ozone

Measurements were taken at the inlet and outlet of the PAPS unit repeatedly and sequentially.

Findings

Self-generated ozone: maximum of 0.002 ppm

An experiment was conducted to see if the PAPS unit could reduce ozone in a pre-existing ozone contaminated room.

Ozone contamination in the test room was generated with a UV lamp system with integrated fan blower (Ultra Violet Products (Aust.) Pty Ltd Ultra Zone 03-40FS).

Findings

Ozone at PAPS inlet (up to 0.05 ppm, with strong associated smell).
Ozone at PAPS outlet: <0.002 ppm.

7. Interpretation of the Findings

Particles
The particle reduction experiments show that the PAPS is effective for both fine and ultrafine particles. The extent of reduction was somewhat less than that reported by Mondial Advisory. In that experimentation, a post-filter was used, and so the results are not directly comparable. In addition, particle concentrations generated in the test room were higher, typically 1-2 mg/m^3 for DEHS aerosol and 1-10 mg/m^3 for theatrical smoke as PM_1. The extent of particle reduction may depend on the type of particle. However, the PAPS has now been tested with theatrical smoke, DEHS, cigarette smoke and ambient air particles, across a range of particle sizes. DEHS aerosol may be unusual as it is generated at room temperature under pressure, rather than high temperature conditions (e.g. combustion aerosols which are more commonly found).
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It is also evident that PAPS does not self-generate nitrogen dioxide.

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Most researchers would consider generic particle reduction in the micron and submicron size ranges to be a proxy for bioaerosol reduction. That said, independent studies of the PAPS by Flinders University have been conducted and published demonstrating actual microbial inactivation across a range of agents. The key finding were as follows:
PAPS statistically significantly ($p<0.05$) reduced airborne *Escherichia coli, Staphylococcus epidermidis*, Bacteriophage MS2 and *Cladosporium* sp. compared with the negative control. The maximum removal achieved was estimated to be 4 x $\log_{10}$ *E. coli* (99.99% removal), 4 x $\log_{10}$ *S. epidermidis* (99.97% removal), 7 x $\log_{10}$ MS2 (99.99998% removal) and 5 x $\log_{10}$ *Cladosporium* sp. (99.999% removal). Scanning electron microscope images of the surviving microorganisms showed that the PAPS damaged the cell membrane of these model microorganisms.

Collectively, the independent generic and specific biological particle reduction investigations, under simulated and laboratory conditions, demonstrate that PAPS is an efficient air disinfection system.

Recent issues identified in the scientific literature on airborne disease transmission

Tan et al (2022) have progressed risk assessment for airborne disease transmission.
What this paper describes is the risk distribution (probability function) rather than an average or point risk estimate.
The message is that the spatial characteristics (air flow patterns) of the room are important, especially the height of the room. This has implications for social distancing. It is evident that one needs to understand/assess the spatial complexity of the room (e.g. relatively open space versus crowded with partitions, furniture etc.).

As the room height increases, the risk decreases, but the potential for conventional mechanical ventilation to disrupt the thermal stratification decreases due to the increased distance between the inlet and the ground. Mechanical ventilation is therefore not ideal for high ceilings, and the limitations are often addressed by lowering the height of the diffusers (Eames and Flor, 2022).

In another paper, Shah et al (2021), using a reasonably well-mixed arrangement (artificially created by an air purifier), showed that the buildup of airborne virus was significantly reduced if air purifiers are used. The results demonstrated that ventilation air-exchange or purification is effective in decreasing both the final viral saturation concentration and the time required to reach the saturation state
The additional “effective” ventilation (with portable air purifiers or supplemented HVAC) gives more reliability in risk reduction, when dealing with complex or non-complex spaces.
PlasmaShield provides the greatest reliability as it is multimodal air contaminant mitigation technology. It lends itself to situations where air quality, in a broader sense, is important.
Air purifiers do not eliminate short range transmission, but in conjunction with an understanding of room complexity may allow for better specification of social distancing requirements, even in the absence of masks.

8. Conclusions

The new empirical work conducted by the author is consistent with the Interim Technical Report. The investigations involving fine and ultrafine particles, ozone, nitrogen dioxide, toluene and limonene in test room conditions indicate that PAPS is capable of simultaneously mitigating a range of hazardous air contaminants, without introducing others.
Recent peer-reviewed work by Flinders University has demonstrated air disinfection efficiency. In addition, peer-reviewed work by the University of Adelaide addressing the basic mode of action of PAPS shows that the plasma irradiation has sufficient energy to break bonds as well as the ability to charge and agglomerate particles, which then improves particle collection efficiency for a post-filter.

Overall, the results indicate that the effective multi-contaminant clean air delivery rate approximates that of the volumetric air flow of the PAPS system. In other words, the effective room air exchange is significantly increased. Being mounted in the ceiling space, the PAPS unit is also likely to be quiet in operation and may (with adjustment of diffusers) potentially provide better control of airflow than free-standing air purifiers.

With respect to SARS-CoV-2 variants that may be measles-like in their contagiousness, risk modelling scenarios in prototypical classrooms and barracks suggest that conventional entrainment ventilation systems (ceiling air supply and return) should be supplemented with air disinfection or HEPA (Mikszewski et al, 2021). However, the latter does not remove VOCs or destroy microbial pathogens.
The WHO Guidance on ventilation for COVID-19 (WHO, 2021) recommends 60-160 L/s per person of outside/clean air for healthcare settings and 10L/s per person in other settings. These criteria can be met with the PAPS unit as an add-on to an existing HVAC system, or fitted as part of a new system.

Thus, PAPS represents an advanced form of air purification that would suit indoor environments where air disinfection is necessary or important. It would also suit settings whether there is a confluence of work/worker/workplace risk factors for disease, productivity, vigilance or critical decision-making. This includes health and aged care, and certain military, high security, transport, educational, research and commercial environments.

9. References

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Appendix: Interim Technical Report (AESHDP0122)

1. Executive Summary

Adelaide Exposure Science and Health (University of Adelaide) was asked by PlasmaShield Ltd to review selected experimental data pertaining to the PlasmaShield Air Purification System (PAPS) and provide commentary on air purification from an occupational hygiene perspective.
The occupational hygiene approach utilised several conceptual frameworks relating to risk factors, exposure mechanisms and target control.
Design criteria for room air purifiers were critically examined and their role as adjuncts to ventilation considered.
A detailed review was made of PAPS experimentation related to volatile organic compound mitigation and ozone emissions. There was a further review of experiments and associated data relating to airborne particle mitigation, microbial mitigation and energy efficiency.
Practical issues with air purifiers were highlighted, with reference to recent scientific literature.

Comparison was made of the PAPS with portable air purifiers having combination HEPA and charcoal filters.

Compared with free standing HEPA-based portable air purifiers, the evidence suggests some specific benefits of the PAPS unit. These include

- Microbial destruction rather than simple capture on a filter
- HEPA-like particle removal (with MERV-13 filter) with less backpressure
- Selected (and long term) VOC reduction, with no obvious release of reactive gases
- Lower operating costs, and fewer maintenance issues
- Being mounted in the ceiling space, the PAPS unit is likely to be quiet in operation and may potentially provide better control of airflow, interrupting the source to receiver pathway

2. Purpose

The purpose of this report is to review selected experimental data pertaining to the PlasmaShield Air Purification System (PAPS) and provide commentary on air purification from an occupational hygiene perspective.
It is an interim report, subject to further in-house experimentation by AESH clarifying ultrafine particle filtration performance, VOC mitigation and ozone production/mitigation of a high power unit in a test room.

Notes:

The request for review and commentary was made by PlasmaShield Ltd.
In so doing, a PlasmaShield unit was kindly made available to AESH for observations and simple tests. Similar observations and tests had been made with a range of HEPA-based portable air purifiers, supplied independently of PlasmaShield Ltd.
This enables comparison of the PAPS with the portable air purifiers.
The term “air purifier” here is considered equivalent to “air cleaner”. PAPS is also a form of “air disinfection” or “air sterilisation”. (UK SAGE, 2020)

This is a thematic review of PAPS data, based on occupational hygiene principles for the identification, evaluation and control of airborne contaminants.

The occupational hygiene discipline uses several conceptual frameworks for risk management of airborne contaminants. For example, health risk analysis considers “work, worker, workplace”- related factors as well as a “source, path, receiver” exposure model.
The hierarchy of hazard control (Section 36 of Australian model WHS legislation) is then considered for contextualisation of controls.

3. About AESH and the Author

Adelaide Exposure Science and Health (formerly the Occupational and Environmental Hygiene Laboratory) is an internationally recognised university research laboratory, established in 1987. It conducts research, funded by a variety of agencies; provides external occupational and environmental hygiene laboratory and field services; and educational services.
It has strong links with government agencies and professional bodies. It provides evidence-based input into policy and regulation.
Although it supports industry and the general community, AESH does NOT endorse any commercial products. Rather, it generates evidence, and reviews evidence that can underpin decision-making. AESH is staffed by experienced laboratory scientists, using a wide range of fixed instrumentation and portable environmental monitoring equipment.

There are no competing or conflicting interests to declare, and welcomes any scientific scrutiny of AESH-generated data.

Professor Dino Pisaniello is a distinguished health and safety professional. He recently retired as Director of AESH, after more than 25 years in the role. He served as Chief Technical Advice Coordinator (CBRN) for the South Australian emergency agencies from 1997-2021. Dino is a Past President of the Australian Institute of Occupational Hygienists and, from 2001 - 2005 was the Chairman of the Australian Congress of Occupational Safety and Health Association Presidents. He served two terms as Australian Secretary of the International Commission on Occupational Health. Dino is a Fellow of the Australian Institute of Occupational Hygienists, the Australian Institute of Health and Safety and the Royal Australian Chemical Institute. He is a certified industrial hygienist (American Board of Industrial Hygiene), a chartered chemist (RACI) and chartered OHS professional (AIHS).

Dino has published in excess of 250 scientific papers, book chapters and technical reports. His publications address hazards in mining, manufacturing, defence, healthcare, agriculture, domestic and office environments, work and vision and climate change impacts on health. He has expertise in chemical hazard risk assessment and management, occupational and environmental epidemiology, intervention research, and health and safety education.
A Researcher Profile is at
http://researchers.adelaide.edu.au/profile/dino.pisaniello

4. **PlasmaShield Air Purification System** (Air disinfection and filtration)

PAPS uses a combination of high intensity electric fields and low energy electron beam irradiation. The electric field induces irreversible electroporation (electropermeabilization). High-speed electron bombardment ruptures/penetrates microbial cell membranes and damages internal contents. The combination inactivates viruses and micro-organisms. The beam irradiation may also break chemical bonds in airborne chemical contaminants decomposing them into simpler species such as carbon dioxide, nitrogen and water.

5. Contextualisation of the PlasmaShield System within the management of airborne health hazards for humans

It is instructive to situate PAPS, as a control measure, within the hierarchy of hazard control. PAPS is a form of engineering control for indoor air contaminants, allied to mechanical or natural ventilation of an occupied space. It is a higher order (and preferred) control compared with administrative controls or PPE. However, in the case of communicable disease where humans are the hazard source, and where the mode of transmission is mainly via the airborne route face to face, administrative controls and personal respiratory protection assume great importance.
It is not feasible to recreate spray booth conditions in an office or classroom to interrupt the source to receiver pathway in proximity!
That said, PAPS, portable air purifiers and systems such as upper level germicidal UV units are considered to be important supplements to the provision of clean outside air by heating, ventilation and air conditioning (HVAC) systems and windows. They act to increase the effective clean air delivery rate, and in the case of PAPS and portable air purifiers may modify flows so that contaminated air is directed away from the breathing zone of susceptible persons. However, owing to the diversity of portable air purifier outlet configurations care must be taken in their placement to avoid unwanted turbulence.

The benefits of clean (and non-odorous) indoor air can be seen in the increasing evidence for improved productivity, educational performance, job satisfaction and the reduction of adverse health impacts from episodic natural and anthropogenic air pollution events, e.g. bushfire and wood heater smoke, temperature inversions, dust storms etc. (Wyon 2004; Pulimeno et al, 2020) There is also now the realisation that seasonal colds and flu transmission can also be reduced by better infection prevention, including better indoor air treatment.
However, existing HVAC systems in most buildings were designed for thermal comfort and some airborne particle removal. Given the recent bushfire events and COVID-19, it is now accepted by architects and engineers that future buildings will need to incorporate more outside air, better air purification and air flows in the overall ventilation design to mitigate health risks.
In existing high health risk settings such as healthcare or aged care, the current arrangements would potentially need upgraded or supplementation.

With regard to “work, worker, workplace” risk factors, indoor air health risk analysis helps us to understand where PAPS and ventilation supplements would be most beneficial and suggests the following:

Work:
There are numerous examples in this category. Tasks that involves increased breathing rates or vocalisation entail more risk, e.g. exercise in gyms. Work that entails frequent or close physical contact with others would entail more risk, e.g. clinical/healthcare tasks, hairdressing, customer service etc. Work requiring high vigilance, involve high visual load and critical decision making can also be adversely impacted by poor indoor air quality.

Worker (individual):
Certain individuals may be hypersusceptible to air contaminants, due to genetic, gender and age-related factors, multi-morbidities and pre-existing medical conditions, personal habits or use of medications.

Workplace:
Indoor environments that are confined (with small volumes) entail more risk for a given internal emission of airborne contaminant. Workplaces that are in industrial areas, in CBD settings with high traffic entail greater risk for, and complaints from, occupants due to external contamination being dragged in through the ventilation system.

Using the abovementioned risk analysis, PAPS would be most beneficial in settings where there is a confluence of risk factors. This includes health and aged care, and certain military, high security, transport, educational, research and commercial environments.

Beyond the human health risks, there are applications of such air purification systems in food product protection, animal and plant protection and valuable artifacts.

6. What are the indoor air contaminants of concern?

These can be broadly classified as gases/vapours and particles. Microbial contaminants are generally particles, but there may be volatile organic compounds arising from certain microbes.
Not all contaminants can be monitored in practice (especially low levels of odourous compounds). The WHO Indoor Air Quality Guidelines refer to selected contaminants.
Tables 3.1-3.6 of the Australian Building Codes Board (ABCB) Indoor Air Quality Handbook illustrate common air contaminants, their sources and potential health effects.
Airborne fungal profiles in office buildings in metropolitan Adelaide, South Australia: Background levels, diversity and seasonal variation (Taylor et al, 2014) have been examined.

7. Design Considerations for a room air purifying system – an occupational hygiene perspective

Air purifiers should remove potentially harmful air contaminants (as above), but not introduce contaminants at a level that would cause harm or discomfort.

According to the ABCB Indoor Air Quality Handbook (p45)

> *Some air cleaning devices are marketed with little evidence to support their actual operating effectiveness or their actual efficiency at removing specific air contaminants. To be relied on for an air contaminant control strategy, air cleaning devices need to be able to demonstrate the following key performance factors:*
>
> - *They can remove the specified gaseous or particulate air contaminant from the air, with a level of efficiency that is known (tested) and repeatable over time.*
> - *The test method used is transparent, repeatable and publicly available.*
> - *That the air flow rates and operating characteristics used in the testing of the device are consistent with the parameters under which the air cleaner is typically applied.*
> - *The action of the device does not create new or secondary air contaminants.*
>
> *For example, some air cleaning treatments produce ozone as a by-product of their process.*
>
> *Independent testing to a publicly available peer-reviewed test specification is generally preferable to (and provides greater assurance than) internal manufacturer or supplier performed tests with bespoke test methods.*

Whilst such criteria seem reasonable, they tend to reflect engineering criteria of effectiveness rather than broader occupational hygiene considerations that are more relevant for health. The latter include the role of the device in the overall strategy for health hazard control, practical maintenance issues and potential hazards in maintenance, noise, and user experience. (Niu et al, 2020; Curtius et al, 2021)
Well conducted occupational hygiene investigations may well address non-standard issues as part of research. They may appear as peer-reviewed publications in high ranking journals, without being associated with a test specification as such.

Finally, it should be remembered that common air purification units are an adjunct to ventilation systems that provide outside air, and do not normally remove carbon dioxide, a by-product of human respiration (UK SAGE, 2020) The exception would be self-contained life support systems such as in spacecraft or submarines. Radon and carbon monoxide are other examples of indoor air contaminant that normally depend on dilution for control, rather than air purification.

What are the airborne chemical concentrations that would not cause harm or discomfort?

For an indoor air environment where workers are not deemed to be occupationally exposed to airborne chemicals as per a risk assessment, comparison with the Safe Work Australia Exposure Standards would not be appropriate. In the absence of any other regulated indoor air quality standards the comparison point for concentrations of concern would be the odour/sensory thresholds, or old NHMRC guidelines (NHMRC recommended Interim National Indoor Air Quality Goals, rescinded in March 2002).

By way of examples, the sensory thresholds for formaldehyde and toluene are as follows.

Formaldehyde 0.1 ppm [0.12 mg/m^3]
(Golden, 2011)
This is similar to the Australian Building Codes Board 2021 ABCB Guidelines, adopted from WHO 2010).

Toluene – approximately 1 ppm [3.8 mg/m^3] would be detectable
https://oehha.ca.gov/media/downloads/crnr/toluenerel082020.pdf
ABCB has 0.5 mg/m^3 for total volatile organic compounds.

The corresponding current Workplace Exposure Standards are

Formaldehyde 1 ppm [1.2 mg/m^3] (as an 8-hr Time weighted average)
Toluene – 50 ppm [191 mg/m^3] (TWA)

What are the air concentrations of airborne microbial agents that would not cause harm or discomfort?

Dose-response relationships from which to derive acceptable levels are generally not available (Douwes et al, 2003) A systematic review (Walser et al, 2015) on the issue concluded none of the analyzed studies provided suitable dose-response relationships for derivation of exposure limits. The main reasons were: (1) lack of studies with valid dose-response data; (2) diversity of employed measuring methods for microorganisms and bioaerosol-emitting facilities; (3) heterogeneity of health effects; (4) insufficient exposure assessment.
Arbitrary levels have been set, e.g. for operating theatres, and clean rooms.

8. Review of Selected Experimental Data Relating to PAPS

Only two reports are reviewed here (see Appendices 1 and 2).

PlasmaShield Ltd also provided experimental data from:

- Mondial Advisory (particle and microbial reduction performance of a high power version of PAPS, November 2021)
- Flinders University (microbial reduction validation study, June 2019)
- University of South Australia (energy and economic evaluation, December 2019)

The author has sighted those three above but no comment is made, other than the methodology appears appropriate and results from the first two indicate significant contaminant reduction in single pass and test room experiments.

Evaluation of PAPS with Common Air Contaminants - University of Adelaide

Appendix 1 is a 2018 Occupational Hygiene Report on the ability of PAPS to reduce selected air contaminants in a single pass.
Note that the author of this report had no involvement with any of the measurements. The author simply provides peer review and commentary.

The laboratory setup simulated a ducted system in practice. The selection of contaminants was based on what might be considered common air contaminants, with a variety of chemical structures (aldehyde, aromatic hydrocarbon, alcohol and amine). Testing was carried out

using low and high concentrations of the chosen air contaminants. Standard occupational hygiene chemical detection methods were used at two test points. In the case of toluene two separate detection methods were used.
What is important here is the relative concentrations upstream and downstream of the PAPS unit, rather than absolute values. Experiments were conducted by experienced professional hygienists who have a track record of publication in peer-reviewed journals.
Under the experimental conditions, it is evident that the PAPS is very effective in the removal of toluene, formaldehyde and isopropanol for the air stream. It is less effective for ammonia.
No toluene breakdown products were noted by Dr Crea in the GC-FID chromatograms.

The clean air delivery rate for the removal of selected VOCs i.e. Toluene, Formaldehyde and Isopropyl Alcohol is 180 m^3/hr, suitable for a medium sized room (50 m^3).
In a perfectly mixed room of 50 m^3 with no further contaminant introduction, this could reduce toluene, formaldehyde and isopropanol levels by 90% in about 15 minutes and 99% in 30 minutes.

By way of comparison, it should be noted that charcoal-based purifiers lose efficiency quite quickly, and early observations of a portable air purifier indicated about 50% loss of efficiency after less than a week of operation (Photoionisation detector readings at the inlet and outlet of the purifier in a contaminated test room).
This issue has been raised in an AIRAH Guide for classrooms (page 32).

> *Most portable devices using carbon filtration have a small amount of active surface area carbon filtration, which quickly becomes saturated with humidity and/or absorbed contaminants, rendering the devices ineffective and requiring rapid replacement of the media, creating unnecessary expense with no benefit.*

It is also consistent with occupational hygiene experience with organic vapour filter cartridges for respirators.
Thus the evidence suggests that PAPS provides better long term control of various volatile organic compounds exposure to which may have toxicological or psychosomatic sequelae.

Ozone Emissions Report - Intertek

Appendix 2 is an Ozone Emissions Report prepared by an independent accredited testing company in June 2021.
It evaluated emissions from PAPS Model MD250 (high and low fan speeds [1.0 and 1.8 m/s, CADR approximately 180 and 320 m^3/hr], and operation without the fan). The protocol was in accordance with UL 867, with a calibrated and sensitive ozone monitor.
The PAPS equipment was found to meet the criteria for emittance of ozone not exceeding a concentration of 0.050 ppm. Maximum values were 0.002 ppm. Thus, the data demonstrate that PAPS does not self-generate ozone to any significant extent.

By way of comparison, the WHO outdoor air quality guideline (2021) for ozone is 0.03 ppm (60 ug/m^3 in the peak season) and the Australian ambient exposure guideline is 0.08 ppm (4 hr value).

The Intertek report relates to single pass and chamber-accumulation of ozone after 8 hr of operation but does not consider ozone production as a result of break down of air contaminants coming into the unit.

However, when the author operated a PAPS unit in a room filled with theatrical smoke (5 mg/m^3 of PM1.0), there was no detectable odour of ozone at the outlet. The odour threshold for ozone has been reported to be about 0.02 ppm, with significant inter-individual variability (Cain et al, 2007).

In addition, the design of the PAPS mitigates ozone emission by virtue of the reactor geometry which generates ozone only in the entry stage of the reactor. The exit stage of the reactor is designed to eliminate and destroy ozone; a CuO/MnO2 catalytic converter placed after the exit stage of the reactor converts any residual ozone to oxygen.
Whilst the potential for emission of primary or secondary reactive species remains, there appears a shortage of evidence of adverse health effects. Carslaw et al (2017), cited in UK SAGE (2020) argued “that there is a clear need to carry out careful assessments of the effect on human health of air cleaner technology in a range of indoor environments, so that any gains through biological pathogen removal can be weighed up against the adverse effects that may arise from the formation of chemical contaminants”.
In their small scale study, Carslaw el al (2017) did not provide any health data. In a computer room they utilised a commercially available air cleaning device, with no further details of manufacturer, and in the presence of a surface cleaning agent containing limonene. It was stated that “the air cleaning device generated ozone internally in the presence of excess limonene to rapidly produce OH radicals”. The odour of limonene was detectable close to the instrument. The results from this study show that a range of secondary pollutants can be produced following cleaning. However. “the concentrations of the secondary species do not reach particularly high concentrations” and the cleaning activities were of short duration.
Nørgaard et al (2014) conducted near-realistic emission testing of two common consumer products, a kitchen cleaning agent and a plug-in air freshener, in a walk-in climate chamber in the presence of 50 ppb ozone. They showed the formation of oxidation products of which some raise concern about possible contribution to acute airway effects. This study did not utilise an air purifier and demonstrates that oxidation products can be produced at high ambient levels of ozone with the use of cleaning agents and air fresheners. The authors conclude “Testing under realistic conditions that mimic user pattern behavior is warranted to obtain acute and longer-term exposure data at realistic indoor ozone concentrations.”

In this somewhat complex and confusing area of indoor atmospheric chemistry, all researchers appear to recommend further research under real world conditions. The levels of the primary and secondary reactive species appear to be low, and dependent on the levels of other chemicals used in short term cleaning tasks.

9. Conclusions

Compared with free standing HEPA-based portable air purifiers, the evidence suggests some specific benefits of the PAPS unit. These include

- Microbial destruction rather than simple capture on a filter (Flinders University reports)
- HEPA-like particle removal (with MERV-13 filter) with less backpressure – Mondial Advisory Report
- Selected (and long term) VOC reduction, with no obvious release of reactive gases (University of Adelaide report and observations)
- Lower operating costs, and fewer maintenance issues (University of South Australia report)
- Being mounted in the ceiling space, the PAPS unit is likely to be quiet in operation and may potentially provide better control of airflow, interrupting the source to receiver pathway.

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Appendices:

Appendix 1: AESH Report 2018 Mitigation of Common Air Contaminants (OEHC1084)

Appendix 2: Intertek Ozone Emissions Report (Report No: 210304019GZU-001)

RF OEHC1084

Bogdan Duszynski
Commercialisation Manager
Plasma Shield Pty Ltd
Mawson Lakes
South Australia 5095

Date: 26 October 2018

Dear Bogdan

Re: Testing Conditions for the Evaluation of plasmaSHIELD™ Non-Thermal Plasma Air Purification and Disinfection System with Common Air Contaminants

Please find attached the report on the testing of the plasmaSHIELD Non-Thermal Plasma Air Purification and Disinfection System with Volatile Organic Compounds (VOC); toluene, isopropyl alcohol and formaldehyde and non-VOC; ammonia.

Yours sincerely

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THE UNIVERSITY of ADELAIDE

RESEARCH REVIEW DOCUMENT

Testing Conditions for the Evaluation of plasmaSHIELD™ Non-Thermal Plasma Air Purification and Disinfection System with Common Air Contaminants

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Adelaide Exposure Science and Health Laboratory (formally Occupational & Environmental Hygiene Laboratory)
The University of Adelaide, 28 Anderson Street THEBARTON SA 5031, Adelaide, Australia

Duration of Research: April – August 2018
Research Report Date: October, 2018

SCOPE

The purpose of this study was to independently evaluate the performance of a Non-Thermal Plasma Technology (plasmaSHIELD™), in compliance with applicable Medical, Commercial and Industrial standards, on the removal of Volatile Organic Compounds (VOC) and air harmful contaminants.

The test protocol was to create a realistic and standard environment as for Heating, Ventilation, and Air Conditioning (HVAC) setup requirements. The technology acceptance testing and validation was carried out in the environment for which the technology is intended to be used.

Testing and analysis undertaken by the Exposure Science and Health Laboratory at The University of Adelaide has been impartial and subject to a systematic evidence-based assessment process. There are no competing or conflicting interests to declare.

TESTED AIR POLLUTANTS

Volatile Organic Compounds (VOCs)

- Toluene: is a common solvent in paints and adhesives, nail polish remover and correction fluids.
- Formaldehyde: is commonly found in indoor air and has wide industrial applications, such as building materials (e.g. particle board), adhesives and insulation materials. It is also used in the health care industry as a disinfectant and biocide and a tissue fixative and embalming agent.
- Isopropyl Alcohol: is widely used in as cleaning solvent and disinfectant

Other non-VOCs

- Ammonia: has many applications in industry as a refrigerant gas, manufacture of plastics, pesticides, dyes and other chemicals. It is also found in many cleaning solutions.

plasmaShield SYSTEM TEST CONDITIONS

The apparatus used for the test was a plasmaSHIELD Unit (Model MD250, Serial No. PS0012) for the effectiveness of the removal of air contaminants is shown in Figure 1.
The plasmaShield unit was placed in line using 250 mm diameter flexible HVAC ducting.

The plasmaShield Unit was tested with the air flow set at 1.0 metre/second (180 m^3/hr or 104 CFM) using a Blauberg Turbo 250 G inline fan unit. Testing was carried out using low and high concentrations of the chosen air contaminants. The exhaust air from the inline fan unit was fed into an operating Laboratory fume cupboard.

The temperature and operating conditions have remained consistent throughout all experiments and test processes.

Vapour/gas concentrations were collected/measured at 0.3m before unit and 2.5m after the plasmaShield unit from inside the flexible ducts.
The pressure drop from pre-plasmaShield to post-plasmaShield, at the airflow of 1.0 m/s ranged from 24.7 Pa to 26.5 Pa.

Guidance Data used to test VOCs

The concentration range selected for this study used the following guidelines;
'*Safework Australia Workplace Exposure Standard For Airborne Contaminants'*

'The ANSI/ASHRAE Standard 62.1-2010, 'Ventilation for Acceptable Indoor Air Quality'

Generating Concentrations of the VOCs

A Sage Model 341A syringe pump was used to generate toluene and isopropyl alcohol vapour concentrations. Analytical reagent grade toluene and isopropyl alcohol (>99%) were used.
The injection rates on the pump were selected to control the desired vapour concentrations generated. Gas tight luer lock 1 mL, 5 mL and 10 mL syringes were used (Figure 2a).

The testing of the plasmaShield unit was carried out by generating a continuous steady concentration of the VOCs. Testing was done as a single pass continuous test.

The contaminant liquid was injected onto a filter paper located just inside the inlet manifold (see Figure 2b). The air flow through the rig in Figure 1 evaporated the liquid and the vapour travelled through the HVAC flexible duct, through the plasmaShield Unit and was drawn out through the Blauberg inline fan located in the fume cupboard. No air contaminant vapour was detected inside the laboratory during the test procedures.

MEASUREMENT OF VOCs

Toluene

Two calibrated PhoCheck Tiger Photo Ionisation Detector (PIDs) were used with correction factors to establish qualitatively the concentrations of toluene generated.
These instruments were calibrated with 100 ppm iso-butylene with a 10.6eV lamp and the limit detection was 1 ppm.
The testing was carried out at room temperature (22°C to 24°C) and RH of 40% to 44%
Personal sampling pumps and SKC 226-09 charcoal tubes were used to collect toluene samples pre and post the plasmaShield unit for quantitative determination of toluene concentrations at the rate of 1.0 L/min.

The sampling tubes were desorbed using a solution of Carbon Disulphide (3.0 ml) containing an internal standard nonane. The samples were allowed to stand for 60 minutes with occasional agitation prior to analysis.

The samples were analysed by a verified method for Volatile Organic Compounds (VOCs); '*Health & Safety Executive (HSE), Method for Determination of Hazardous Substances (MDHS) 88 and 96; Volatile organic compounds in air*'. This method utilises a Gas Chromatography technique with a Flame Ionization Detector (FID).

Isopropanol

Testing for isopropyl alcohol was carried out as a single pass continuous test at room temperature using one calibrated PhoCheck Tiger Photo Ionisation Detector (PID).
This instrument was calibrated with 100ppm iso-butylene with a 10.6eV lamp and the limit detection was1ppm.

The PID was used with correction factor to quantitative measure the concentrations of isopropanol generated and the effect of the plasmaShield unit on the generated isopropanol concentrations.
The testing was carried out at room temperature (22^{o}C to 24^{o}C) and RH of 40% to 44%

Formaldehyde

For formaldehyde, a pre-weighed amount of paraformaldehyde was placed in an aluminium tray inside an insulated open ended steel chamber with a glass wool filter over the end to stop any paraformaldehyde dust being released (Figure 3).

The paraformaldehyde was heated using a heating block at set temperatures to be able to generate the required concentrations of formaldehyde in the flexible ducting.

Samples of air were collected onto 2,4 dinitrophenyl hydrazine coated glass fibre filters connected to personal air sampling pumps set to 1.0 L/min flow rates to measure the concentration of formaldehyde vapour inside (at about the centre) the flexible duct.

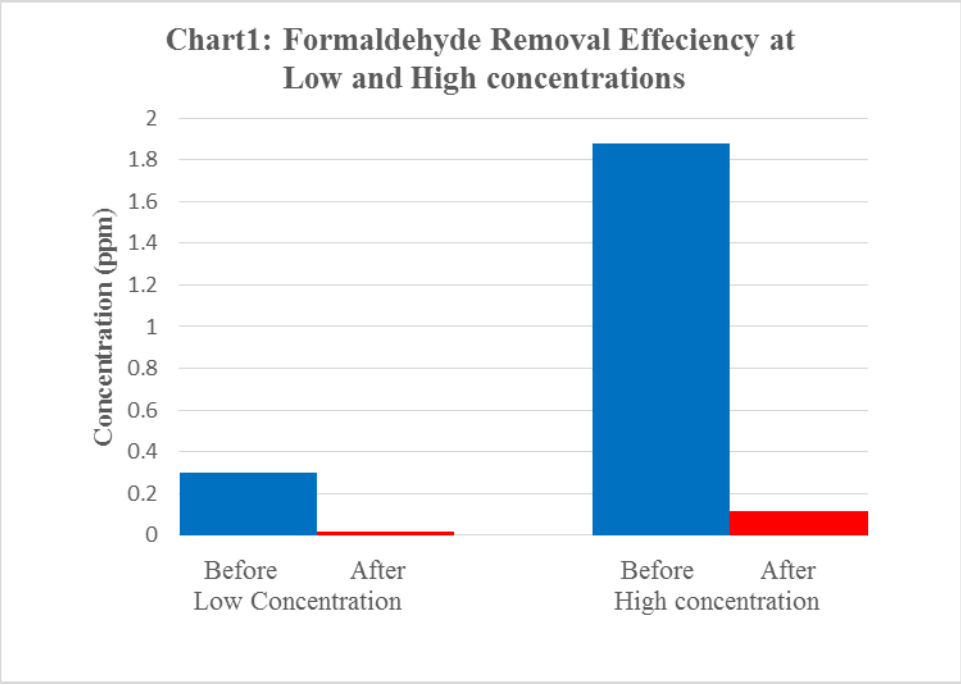
The analysis of the collected formaldehyde samples was carried out by a verified method for formaldehyde; *'Health & Safety Executive (HSE), Method for determination of Aldehydes in air (MDHS 102)'* that utilises a High performance Liquid Chromatography *(*HPLC) Ultraviolet (UV) analysis.
The testing was carried out at room temperature (22^{o}C to 24^{o}C) and RH of 40% to 44%

TEST RESULTS TABLES AND CHARTS OF VOC

Formaldehyde

Table 1: Single pass Formaldehyde removal efficiency test (continuous flow at 1 m/s flowrate)

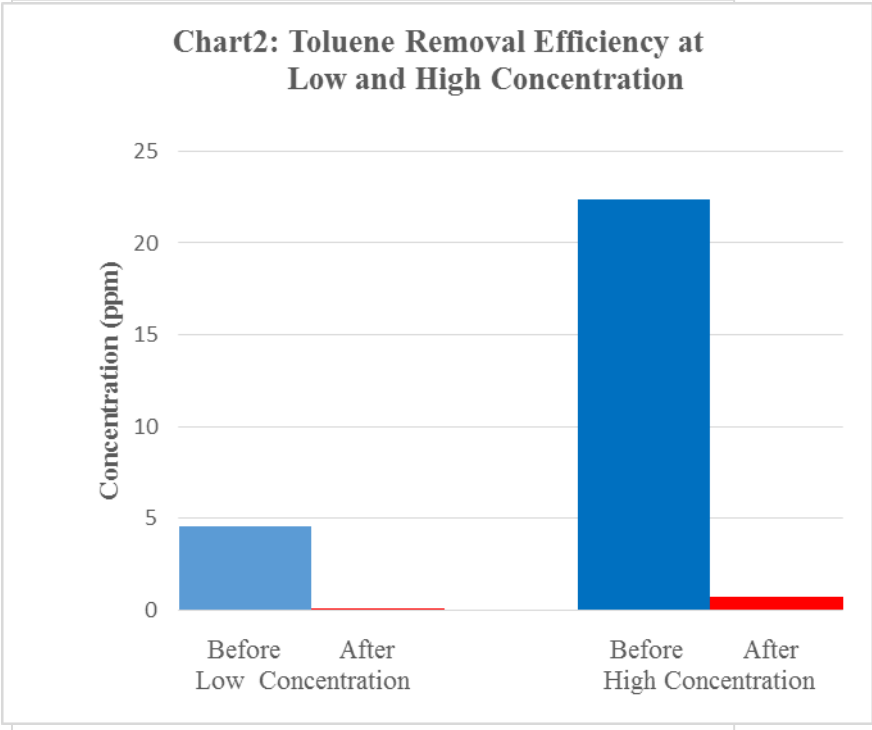
Sample	Sampling time (min)	Formaldehyde Concentration (ppm)	% Reduction
Low Concentration			
Before plasmaSHIELD unit	5	0.30	93%
After plasmaSHIELD unit		0.02	
High Concentration			
Before plasmaSHIELD unit	5	1.88	94%
After plasmaSHIELD unit		0.114	



Toluene

Table 2: Single pass Toluene removal efficiency test (continuous flow at 1 m/s flowrate)

Sample	Sampling Time (min)	Concentration[a] Toluene (ppm)	% Reduction
Low Concentration			
Before plasmaSHIELD unit	26	4.6	98%
After plasmaSHIELD unit	26	<0.1[a]	
High concentration			
Before plasmaSHIELD unit	5	22.4	97%
After plasmaSHIELD unit	5	0.7	

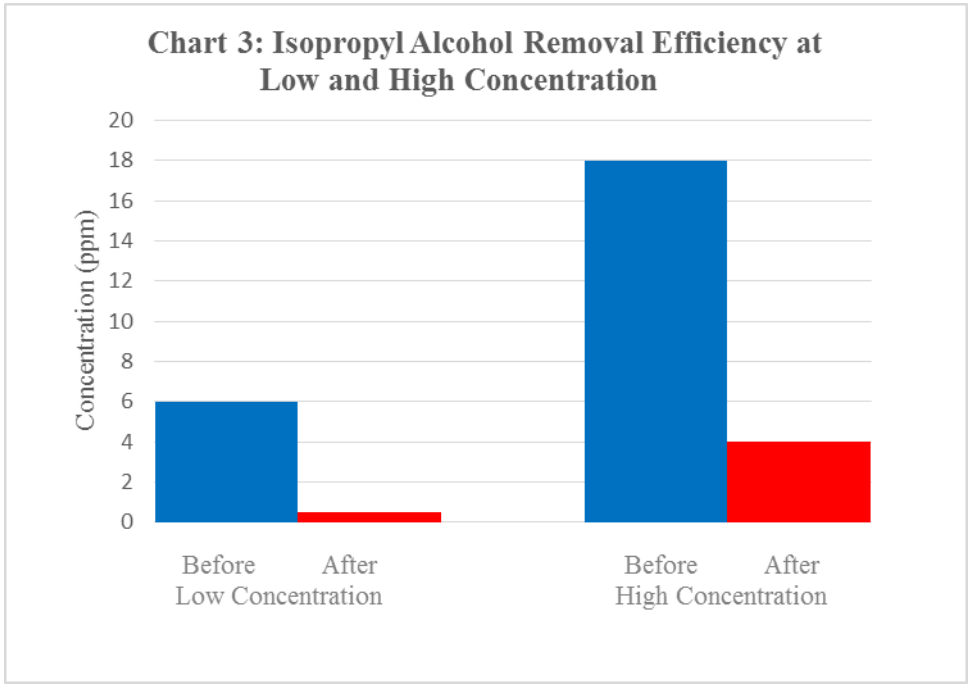


Isopropyl Alcohol

Table3: Single pass Isopropyl Alcohol removal efficiency test (continuous flow at 1 m/s flowrate)

Sample	Sampling Time (min)	Concentration[a] isopropyl alcohol (ppm)	% Reduction
Low Concentration			
Before plasmaSHIELD unit	5	6	92%
After plasmaSHIELD unit		0.5	
High Concentration			
Before plasmaSHIELD unit	5	18	78%
After plasmaSHIELD unit		4	

[a] measurements made with PID (10.6ev lamp)



MEASUREMENT OF OTHER NON VOCS

Ammonia

The ammonia gas was generated using a concentrated ammonia solution in a syringe using a Sage Model 341A syringe pump. The injection rates on the pump were selected to control the desired ammonia concentrations generated using gas tight luer lock, 1 mL and 5 mL syringes.

The ammonia concentration before and after the plasmaShield unit was measured using a calibrated direct reading instrument, MX6 Ibrid meter fitted with an ammonia sensor. The instrument was calibrated with 50 ppm ammonia gas and the limit of detection is 1 ppm.

The testing was carried out at room temperature (22°C to 24°C) and RH of 40% to 44%

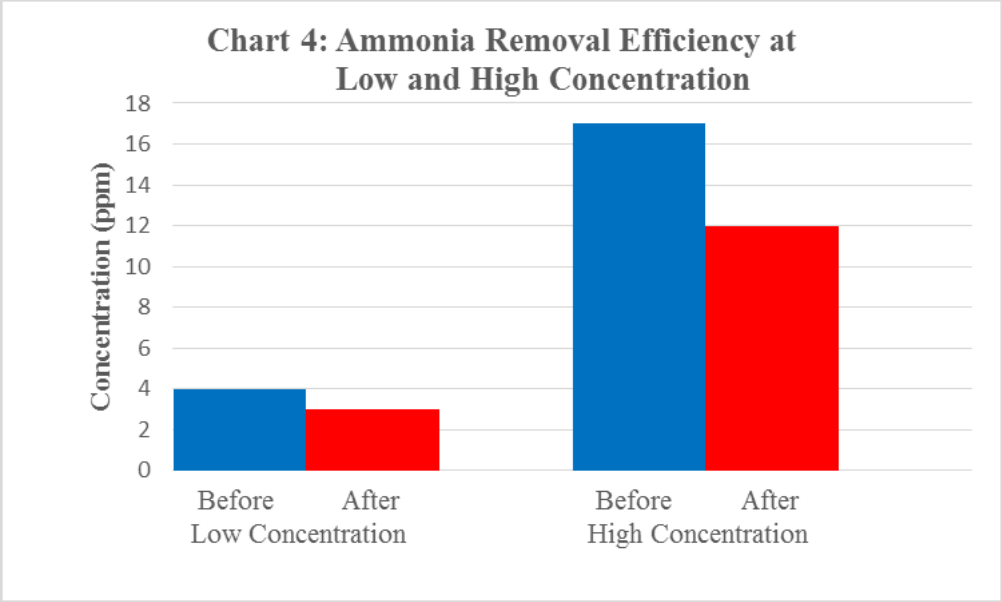
TEST RESULTS TABLES AND CHARTS OF NON-VOC

Ammonia

Table 4: Single pass Ammonia removal efficiency test (continuous flow at 1 m/s flowrate)

Sample	Sampling Time (min)	Concentration[a] Ammonia (ppm)	% Reduction
Low Concentration			
Before plasmaSHIELD unit	5	4	25%
After plasmaSHIELD unit		3	
High Concentration			
Before plasmaSHIELD unit	5	17	
After plasmaSHIELD unit		12	29%

[a] Concentration measured with Ammonia direct reading instrument



CONCLUSIONS

COMMENTS ON RESULTS FOR-VOCS

Results for Formaldehyde, Toluene and Isopropyl Alcohol for a continuous single pass test at 1 m/s flowrate

The system/technology demonstrates very high efficiency in removal of Formaldehyde As demonstrated in Table 1, Chart 1 of this document, the system achieves a reduction rate of at least 93% in a continuous single-pass test with air velocity of 1 m/sec (180 m^3/hr).

The rate of Toluene removal under the same operating conditions is even more effective with the system / technology achieving a reduction rate of at least 97%. The results are demonstrated in Table 2, Chart 2 of this document.

The Isopropyl Alcohol removal rate was also highly effective, with the system/technology achieving a consistent reduction rate of at least 92% in single-pass continuous test. The results are demonstrated in Table 3, Chart 3 of this document.

COMMENTS ON RESULTS FOR NON-VOCS

Results for Ammonia

The removal rate of Ammonia has achieved an efficiency of 23% to 29% at single-pass continuous flow rate of 1 m/sec air velocity. The results are demonstrated in Table 4, Chart 4 of this document.

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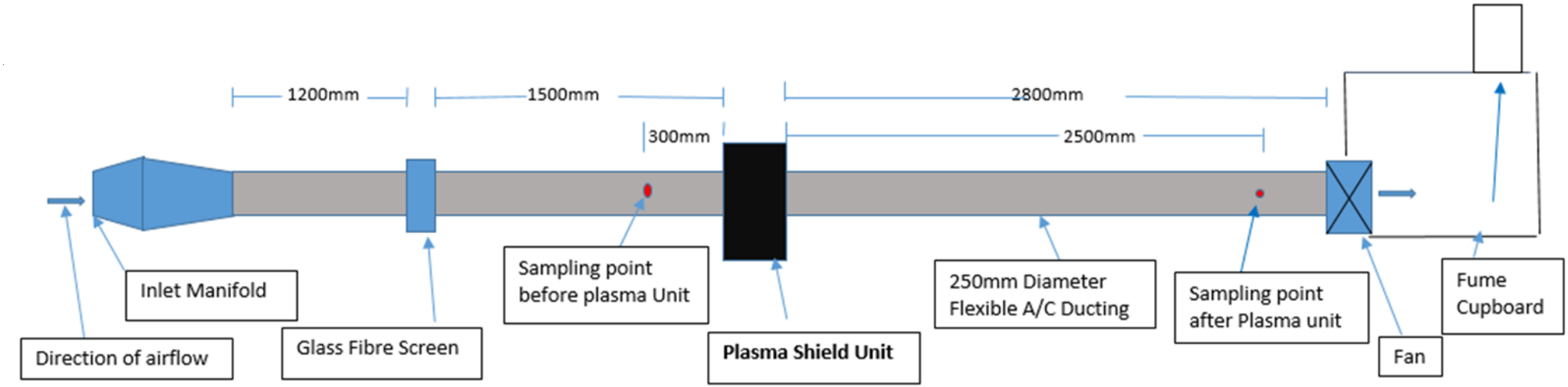

Fume Cupboard **Fan** **Direction of Airflow** **plasmaSHIELD Unit** **Inlet Manifold**

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APPENDIX

Figure 2 and 3: plasmaShield Unit: Experimental Set-up

Figure 2a: Syringe pump

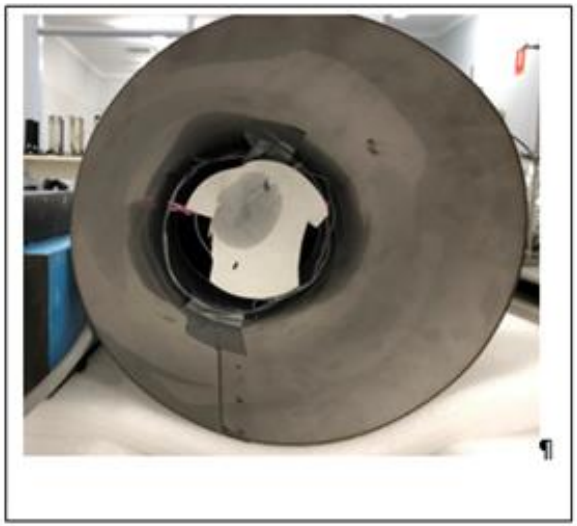

Figure 2b: Injected solvent onto filter paper

Figure 3: Formaldehyde vapour Generation (heating Paraformaldehyde on hotplate)

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PLASMA SHIELD PTY LTD

OZONE TEST REPORT

SCOPE OF WORK
Ozone Emissions Testing of s Treatment System for Model: MD250

REPORT NUMBER
210304019GZU-001

ISSUE DATE
18-Jun-2021

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QUOTE NUMBER
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Report No.: 210304019GZU-001
Date: June 18, 2021

Contact Name: SAEID VOSSOUGHI
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Phone: +61 451559870
Email: svossoughi@plasmashield.com.au

SECTION 1

SUMMARY

The representative sample(s) have been tested, investigated, and found to comply with the requirements of standards:

*Electrostatic Air Cleaners, UL 867, **Section 40**, Fifth Edition, August 4, 2011 revision: AUGUST 7, 2018.*

The equipment identified in this report has been found to meet the criteria for emittance of ozone not exceeding a concentration of 0.050 ppm. Furthermore, a second sample was not required to be tested, according to UL 867, as the first sample's maximum emissions were less than 0.030 ppm, which satisfies item a) in the Section 40.1.1.

This report completes our evaluation covered by Intertek Project Number 210304019GZU which has been authorized by Intertek quote number: QGZ201106028. If there are any questions regarding the results contained in this report, or any of the other services offered by Intertek, please do not hesitate to contact the above signed.

OZONE EMISSIONS SUMMARY

FAN SPEED	FILTER(S)	03/VOLTAGE SETTING	$C(t)_{max}$ [ppm]
Highest	Permanent Filter	-	0.002
Lowest	Permanent Filter	-	0.002
No Fan	Permanent Filter	-	0.001

Completed by:	Yuxuan Huang/Sunny Zhou	Reviewed by:	Jacob Langenbacher
Title:	Engineer/Assistant Technical Manager	Title:	Engineer
Signature:		Signature:	
Date:	Jun. 7, 2021	Date:	June 18, 2021

SECTION 2

INDEX

Section Names	PAGE
1: Summary/Signatures	2
2: Index/ Chamber Equipment Information	3
3: Unit under test information	4
4: Peak test	5
5: Max Test(s) Information	7
6: Appendices	10
7: Revisions	13

CHAMBER EQUIPMENT INFORMATION

TEST EQUIPMENT LIST

Instrument	Model	Intertek Ctrl #	Cal Due Date
Teledyne – Advanced Pollution Instrumentation Ozone Calibrator	T703	SA054-14	17-Dec-2021
Teledyne – Advanced Pollution Instrumentation Ozone Monitor	T400	SA054-17	*
Teledyne – Advanced Pollution Instrumentation Ozone Monitor	T400	SA054-13	*
Vaisala – Temperature & Humidity Transducer	H2120047	SA054-12	4-Jun-2021
QI XING HUA CHUANG – Mass flowmeter	D07-23FM	SA054-12-03	8-Jul-2022

* The T400 Ozone Monitor is calibrated using the T703 calibrator.

SECTION 3

UNIT UNDER TEST INFORMATION

MODEL INFORMATION			
Manufacturer:	PLASMA SHIELD PTY LTD	Pre-Filter:	No
Model Number:	MD250	HEPA Filter:	No
Production/Prototype/ Design	Prototype	ESP Filter:	No
Fan Speeds:	3	Permanent filter:	Yes
O3/Voltage Settings:	NA	UV Light:	No
O3 Monitor:	NA	Ionizer:	Yes
Model Notes:	Brand Name: PURITII Permanent filter (These filters are interlocked. The interlock was accepted as safety interlock during the safety test.). 3 Fan Speed (No Fan, Low Speed and High Speed). Measure the air velocity at the center of the device OUTLET and adjust the fan SPEED CONTROL knob to get the following air velocities. 1.75m/s ~ 1.8m/s air velocity: High-Fan speed for plasmaSHIELD model MD250 0.9m/s ~ 1m/s air velocity: Low Fan speed for plasmaSHIELD model MD250 Ionizer (Can work without the fan operating); NO UV Light; No auto mode; No sleep mode. The product has two installation options. One is ducted ceiling installation. Another is unducted ceiling installation. Conducted on unducted ceiling installation to cover ducted ceilling installtion.		

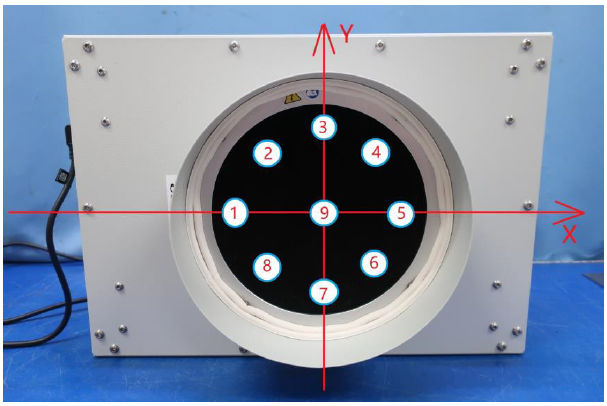
RUN-IN TEST			
FIRST SAMPLE			
Run-in Start:	Apr. 5, 2021 9: 00	Run-in End:	Apr. 8, 2021 9: 00
Run-in Temperature:	25±5°C	Tracking Number	S210304019-001
Serial Number:	NA		
Sample Notes:			
SECOND SAMPLE			
Run-in Start:	NA	Run-in End:	NA
Run-in Temperature:	NA	Tracking Number	S210304019-002
Serial Number	NA		
Sample Notes:			

SECTION 4

PEAK OZONE TEST z

GRILL AND AIR PERIPHERY DIMENSIONS			
		Date of Test:	Apr. 17, 2021; Apr. 18, 2021; Apr. 22, 2021
Grill:	Diameter 250 mm	Air Periphery:	Diameter 250 mm
Estimated Grill Area:	Approx. 49062.5mm ^2	Est. Air Periphery Area:	Approx. 49062.5mm ^2
Notes:	Ionizer cannot be observed through the air outlet.		

PEAK LOCATION



Loc.	X	Y
-	[mm]	[mm]
1	-81	0
2	-57	57
3	0	81
4	57	57
5	81	0
6	57	-57
7	0	-81
8	-57	-57
9	0	0

* Location measurements are coordinates in reference to the center point.

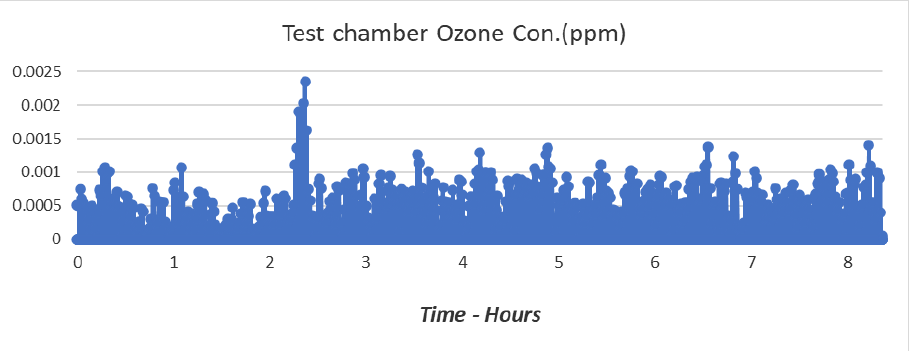
PEAK OZONE CONCENTRATIONS (ppm)				
Location	*With Filter(s)*			
	Highest	Lowest	No Fan	--
1	0.0010	**0.0012**	0.0002	**--**
2	0.0013	0.0008	0.0000	--
3	**0.0017**	0.0006	0.0004	--
4	0.0013	0.0008	0.0003	--
5	0.0014	0.0011	**0.0007**	**--**
6	0.0013	0.0008	0.0002	--
7	0.0013	0.0002	0.0004	--
8	0.0003	0.0006	0.0004	--
9	0.0009	0.0007	0.0002	--

Note: Result is minus background.

SECTION 5

MAX OZONE TEST

START DATE OF TEST: 25- Apr-2021
SAMPLE: S210304019-001
FAN SPEED: Highest
FILTER(S): Permanent filter installed
Ionizer on

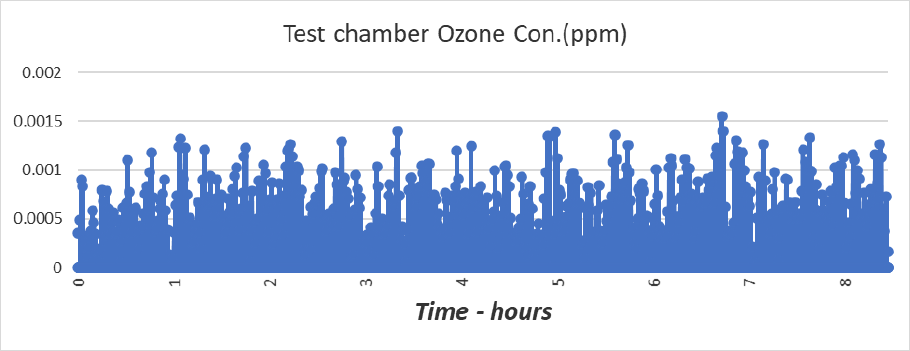


MAXIMUM OZONE TEST RESULTS							
	UL Ref.	Pass/Fail	Mean	Min	Max	Delta	Units
Background C(t) O3:	40.4.3	PASS	0.000	0.000	0.001	0.001	[ppm]
Test 1min C(t) O3:	40.1.2	PASS	0.002	0.000	**0.002**	0.002	[ppm]
Test 5min C(t) O3:	40.1.2	PASS	0.002	0.000	0.002	0.002	[ppm]
Chamber Temperature:	40.4.2	PASS	24.25	23.26	24.51	1.26	[degC]
Chamber Humidity:	40.4.2	PASS	46.46	45.06	51.14	6.08	[%RH]
Chamber Static Pressure:	-	PASS	5.52	3.10	6.50	3.40	[Pa]
Chamber Supply Air Flow:	-	-	34.00	33.96	34.02	0.06	[m3/h]
Required to Test 2nd Sample:	40.1.1	NO					
Test Duration:	40.4.6	8 hours					

NOTES: Peak Test Location 3.
According to a) of 40.4.6, 24 hours testing is not needed.

MAX OZONE TEST

START DATE OF TEST: 26- Apr -2021
SAMPLE: S210304019-001
FAN SPEED: Lowest
FILTER(S): Permanent filter installed
Ionizer on

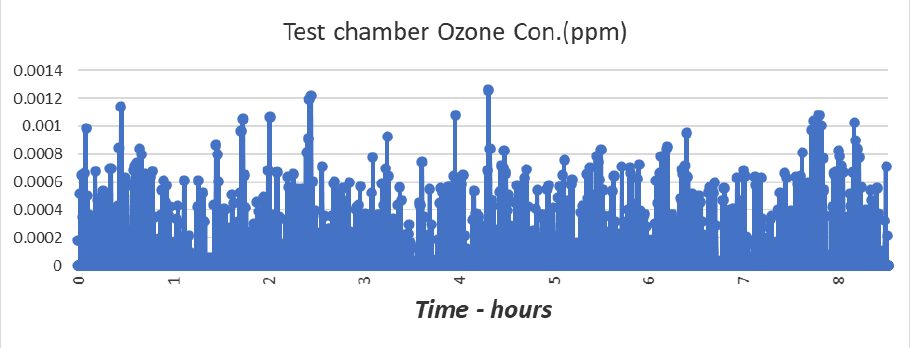


MAXIMUM OZONE TEST RESULTS							
	UL Ref.	Pass/Fail	Mean	Min	Max	Delta	Units
Background C(t) O3:	40.4.3	PASS	0.000	0.000	0.001	0.001	[ppm]
Test 1min C(t) O3:	40.1.2	PASS	0.002	0.000	**0.002**	0.002	[ppm]
Test 5min C(t) O3:	40.1.2	PASS	0.001	0.000	0.002	0.002	[ppm]
Chamber Temperature:	40.4.2	PASS	24.10	23.90	24.35	0.45	[degC]
Chamber Humidity:	40.4.2	PASS	49.18	48.61	49.65	1.04	[%RH]
Chamber Static Pressure:	-	PASS	5.52	4.70	5.90	1.20	[Pa]
Chamber Supply Air Flow:	-	-	34.00	33.97	34.02	0.05	[m3/h]
Required to Test 2nd Sample:	40.1.1	NO					
Test Duration:	40.4.6	8 hours					

NOTES: Peak Test Location 1.
According to a) of 40.4.6, 24 hours testing is not needed.

MAX OZONE TEST

START DATE OF TEST: 23- Apr -2021
SAMPLE: S210304019-001
FAN SPEED: No Fan
FILTER(S): Permanent filter installed
Ionizer on



MAXIMUM OZONE TEST RESULTS							
	UL Ref.	Pass/Fail	Mean	Min	Max	Delta	Units
Background C(t) O3:	40.4.3	PASS	0.000	0.000	0.001	0.001	[ppm]
Test 1min C(t) O3:	40.1.2	PASS	0.001	0.000	**0.001**	0.001	[ppm]
Test 5min C(t) O3:	40.1.2	PASS	0.001	0.000	0.001	0.001	[ppm]
Chamber Temperature:	40.4.2	PASS	24.65	24.51	24.77	0.26	[degC]
Chamber Humidity:	40.4.2	PASS	50.50	50.10	51.04	0.94	[%RH]
Chamber Static Pressure:	-	PASS	5.52	0.90	13.80	12.90	[Pa]
Chamber Supply Air Flow:	-	-	34.00	33.97	34.14	0.17	[m3/h]
Required to Test 2nd Sample:	40.1.1	NO					
Test Duration:	40.4.6	8 hours					

NOTES: Peak Test Location 5.
According to a) of 40.4.6, 24 hours testing is not needed.

SECTION 6

APPENDIX

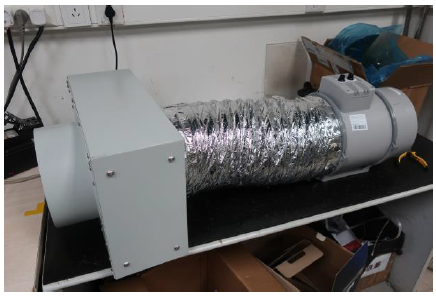
DATA FILES

TEST NAME	RAW DATA FILE
Half Life Test	RawData-halflife-2021-4-22.xls
Max Ozone: High w/ Filter	RawData-Max-Filter- Highest.xls
Max Ozone: Low w/ Filter	RawData-Max-Filter- Lowest.xls
Max Ozone: No Fan w/ Filter	RawData-Max-Filter- No Fan.xls

ATTACHMENT DOCUMENTS

DOCUMENT	SOFT-COPY FILE NAME
ARB Application	ARB Application.pdf
Chain of Custody: Sample 1	COC- S210304019-001&002.pdf
Chain of Custody: Sample 2	COC- S210304019-001&002.pdf

UUT PHOTOGRAPHS



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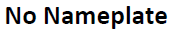
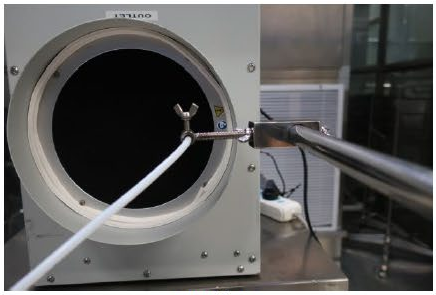


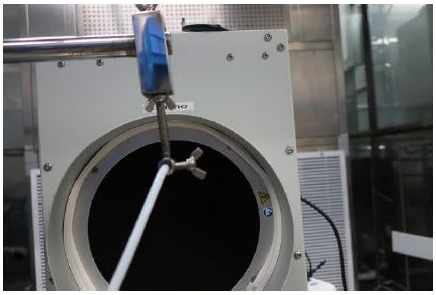
Nameplate

UUT PHOTOGRAPHS: PEAK TEST



Location 3

H w/ FILTER



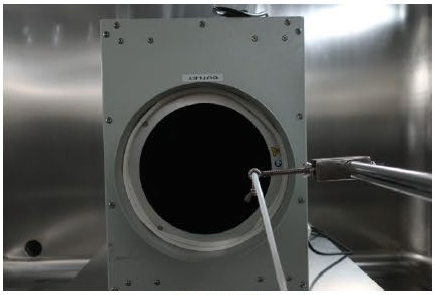
Location 1

L w/ FILTER

Location 5

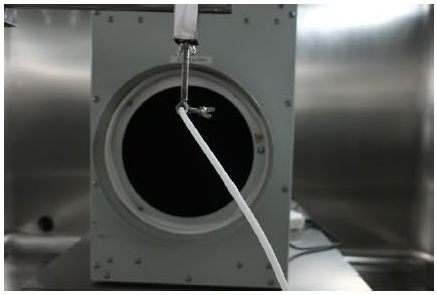
No Fan w FILTER

UUT PHOTOGRAPHS: MAX OZONE TESTS



Location 3

H w/ FILTER



Location 1

L w/ FILTER

Location 5

No Fan w FILTER

7.0 REVISION SUMMARY

Date/Proj # Site ID	Project Handler/ Reviewer	Section	Description of Change