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June 21, 2023

Open-Panel Adsorption: Volatile Organic Compound Mitigation in Ambient Air using Activated Carbon

Keywords: adsorption, open panel adsorption, activated carbon, VOCs, air pollution, ambient air; thermal desorption; environmental justice

Abstract

The threat to human health posed by Volatile Organic Compounds- carcinogenic substances for which the EPA has set no safe threshold exposure levels- is profound¹. Despite international², national and state air quality standards, and greatly improved air quality monitoring, exposure remains a health hazard. Open panel adsorption, an open-source technical solution to mitigate ambient VOCs, uses small screened panels of commodity granulated activated carbon placed in locations polluted with VOC aerosols. After pollutants are adsorbed, the panels are desorbed by pyrolysis or thermal oxidation and contaminants incinerated, and the material is reactivated. Alternative methods such as electrochemical treatment or microwave desorption are under development. A simple adsorption system for ambient air is faced with atmospheric humidity, the erratic mixing ratio of ambient air, and diffusion in the low partial pressure of pollutants in ambient air. Adsorption systems use closed reactor beds and a closely controlled and specified cubic feet per minute inlet to hasten mass transfer to breakthrough (saturation and dynamic equilibrium). OPA relies on 1) repeated flows to the adsorbent material, achieving saturation over a much longer duration; 2) deployment locations carefully chosen in order to maximize persistent and episodic acute air pollutant concentrations; and 3) increasing the adsorbent surface area by designing panels open to the air. Adsorption panels should be placed in locations where pollutants are dense, preferably where air flow is laminar with low friction (because of impermeable adjacent vertical walls, for instance) to facilitate adsorption. This design thus alternately utilizes the relatively passive diffusion of batch adsorption systems, and effusion under pressure used by the more prevalent tubular or plug flow or column reactor adsorption system. Timed jar tests utilize AC sorbent material in VOC-saturated air, with a handheld Ion Science Cub Photo-Ionization Detector unit placed into a 2.3 cubic Liter Rubbermaid Brilliance container. These tests have indicated favorable adsorption with repeated introductions of TVOC (nail polish remover), as well as rapid adsorbance under varying light, RH, and air turbulence conditions. Another initial experiment used screened panels of 4x8 mesh coconut-shell AC, adjacent to a six-lane arterial urban route. Tested by TD-GC-MS analysis using a modified EPA Method TO-17 protocol, the panels evidenced significant hydrocarbon species. Crucially, the AC was not blinded by PM 2.5, nor did competition from adsorbed H2O hinder adsorption of VOCs. Panels attached to buildings and hardscape, regularly desorbed, could offer public health co-benefits in an environmental justice context.

1. Introduction: Problem and a Prospective Solution

¹ Propper, Ralph¹ rpropper@arb.ca.gov Wong, Patrick et al. "Ambient and Emission Trends of Toxic Air Contaminants in California. Environmental Science & Technology. 10/6/2015, Vol. 49 Issue 19, p11329-11339.

² Air quality guidelines for Europe: second edition. WHO Regional publications. European series No 91.

The threat to human health posed by Volatile Organic Compounds- carcinogenic substances for which the EPA has set no safe threshold exposure levels- is profound ³. Despite international ⁴, national and state air quality standards, and greatly improved air quality monitoring, exposure remains a health hazard. Most remediative methods set policy at national or state level, at the source, for instance through treatment of tailpipe exhaust, or mandated alteration in the composition of gasoline itself. However, effective enforcement is the exception rather than the rule.

An economical, local solution is needed. Micromitigation, or Open Panel Adsorption, is an environmental remediation method which uses physisorption by granular activated carbon in open 'adsorption panels' to mitigate ambient VOCs at emissions hotspots. This citizen science initiative seeks to establish a universally accessible open-source protocol for the abatement of VOC pollution in environmental justice communities in California and beyond. Adsorption is widely used in industrial emissions systems, and we seek to adopt this technology in an ambient setting. The Micromitigation Working Group, a bi-monthly Meetup hosted since April 2021 by the open science Counter Culture Labs in Oakland, California, is working to develop OPA to complement to the established regulatory point source-based and facility-based approach to emissions.

2. Definition and Health Effects of VOCs

Volatile Organic Compounds are easily volatilized ⁵, non-methane hydrocarbons (NMHC)- that is organic carbon chain or ring-based compounds- with a vapor pressure over 2mm mercury HG, (0.27kPa) at 25 degrees Celsius. The US EPA's definition is more precise: "Volatile organic compounds (VOCs) are defined as any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions" ^{6,7}. Zhang et al.'s 2017 survey article indicates that while the definition of VOC varies across nations and agencies, it is still voluminous, totaling more than 300 species of VOCs ⁸.

The dangers of volatile organic compounds are well-known^{9,10}. The 189 federal Hazardous Air

³ Propper, Ralph¹ rpropper@arb.ca.gov Wong, Patrick et al. "Ambient and Emission Trends of Toxic Air Contaminants in California. Environmental Science & Technology. 10/6/2015, Vol. 49 Issue 19, p11329-11339.

⁴ Air quality guidelines for Europe: second edition. WHO Regional publications. European series No 91.

⁵ Volatile organic compounds (VOCs) are also defined as those which have a Reid vapor pressure above 10.3 Pa at ambient temperature (293.15 K) and pressure (101.325 kPa).

⁶ https://archive.epa.gov/ttn/ozone/web/html/def_voc.html.

⁷ [EPA - TTN NAAQS - Ozone Implementation - Technical Resources - Definition of Volatile Organic Compounds \(VOC\)](#).

⁸ Zhang et. al. 2017 p102.

⁹ World Health Organization. WHO Guidelines for Indoor Air Quality: selected pollutants. WHO: Copenhagen, Denmark. 2010.

¹⁰ Shumin Cheng et al." Global Research trends in Health Effects of Volatile organic compounds during the last 16 Years: a Bibliometric analysis". [Aerosol and Air Quality Research](#) 19. 2019: 1834-1843.

Pollutants, for which the EPA has set no safe threshold level of exposure¹¹, are also referred to as Toxic Air Contaminants (TACs)¹² by California's Air Resources Board. VOCs are lipo-philic, readily dissolving in fat, oil, or non-polar solvents, and are thus readily absorbed by lungs, skin, and gastrointestinal tract. These are not innocuous bad odors, but serious carcinogens for which no minimum level has been determined to be safe^{13, 14}. VOCs cause any number of severe health problems^{15, 16}, as well as sub-clinical conditions. These include neurological effects (toluene, in nail products); irregular heartbeat and myeloid leukemia (benzene); CNS disorders (styrene), irritation of respiratory tract and eyes (ketones, alcohols, formaldehyde, undecane and nonane), and peripheral neuropathy (hexane). TVOCs, such as the cocktail of contaminants in 'sick buildings', contribute to sensory irritation, headache and fatigue¹⁷. The U.S. National Air Toxics Assessment recognizes formaldehyde, 1,3-butadiene, and benzene as national cancer risk drivers and contributors¹⁸. In addition to household products such as HCOH in cleaning supplies and IAQ, most people encounter VOCs through proximity to ICE engine vehicles. The Agency for Toxic Substances and Disease Registry at the Centers for Disease Control maintains exhaustive online epidemiological data for each TAC. TACs are tracked by the California EPA's Office of Environmental Health Hazards Assessment (OEHHA), as well as by the EU and the WHO. They are well-understood in environmental health, and increasingly studied^{19, 20}. Yet much of their regulation is overseen and enforced, in a mottled and uneven manner, at the state and local levels. VOCs are an increasing threat in a world with secular trend of higher tempera-

¹¹ <https://www.epa.gov/haps>

¹² <https://ww2.arb.ca.gov/resources/documents/carb-identified-toxic-air-contaminants>. Also https://leginfo.ca.gov/faces/codes_displaySection.xhtml?sectionNum=39655&law-Code=HSC, and <https://oehha.ca.gov/air/general-info/toxic-air-contaminant-list-staff-reportsexecutive-summaries>.

¹³ Galezowska, G., M. Chraniuk, I. Wolska. "In vitro assays as a tool for determination of VOCs' toxic effect on respiratory system: a critical review". *Trac-Trend Anal. Chem.* 77 (2016) 14-22.

¹⁴ B. Huang, C. Lei, C. Wei, G. Zeng. "Chlorinated volatile organic compounds (Cl-VOCs) in environment- sources, potential human health impacts and current remediation technologies". *Environ. Int.* 71 (2014) 118-138.

¹⁵ P. Patnaik, *A Comprehensive Guide to the Hazardous Properties of Chemical Substances*. John Wiley & Sons. 2007.

¹⁶ Zhang et al 2017 has an excellent summary on health effects of VOCs.

¹⁷ Godish, p412.

¹⁸ www.epa.gov/nata.

¹⁹ K. Ard. "Trends in exposure to industrial air toxins for different racial and socioeconomic groups: a spatial and temporal examination of environmental inequality in the U.S. from 1995 to 2004". *Soc Sci Res*, 53. 2015: 375-390.

²⁰ K. Zwickl, M Ash, and K Boyce. "Regional Variation in environmental inequality: industrial air toxics exposure in U.S. Cities". *Ecol. Econ.* 2014. 107: 494-509.

tures. Moreover, as Ozone precursors they contribute to O₃ production as a secondary aerosol in the presence of NO and sunlight ²¹.

Mitigation of VOCs is typically accomplished through regulation at the source. This accomplishes the task, in many cases. For instance, essentially banning usage of the cleaning solvent Perc in California and the gasoline additive MTBE in the United States, as longitudinal MATES studies by the California Air Resources Board and the South Coast Air Quality Management District have shown, has been extremely productive in reducing TAC exposure ²².

Yet regulation at the source does not suffice. The world is full of smogging "grand polluters", two-stroke engine vehicles, outdoor food preparation and car and motorbike repair, and many other sources of VOC emissions at close proximity to human work and residence²³. An economical and effective local solution is needed.

As indicated, OPA uses commodity activated carbon, in small panels in ambient settings, to adsorb ambient VOCs. These are then desorbed. We will briefly go over the properties of Activated carbon and other adsorbent materials, following which we will describe the design of OPA relative to traditional chemical reactors.

3. Adsorption Separation Processes and Materials

Physisorption, Surface Chemistry and Kinetics, and Adsorbent AC

Adsorption, or *physisorption* is a basic "process by means of which gases are taken in but do not chemically combine with the substrate which they interact with"²⁴. In physical adsorption, electrons are not shared or transferred; the chemical species remain individual²⁵. Adsorption is also defined as "a process by which material accumulates at the interface between two phases".²⁶ These phases may be liquid-liquid, liquid-solid, gas-liquid, or gas-solid. We are

²¹ R Atkinson Gas-phase tropospheric chemistry of volatile organic compounds: 1. Alkanes and alkenes". J Phys Chem Ref Data 26 (1997) 215-290.

²² MATES: Multiple Air Toxics Exposure Study in the South Coast AQMD. Final Report. August 2021.SCAQMD. Diamond Bar, CA.

²³ American Lung Association. State of the Air Report. Lerner, Steve. Sacrifice Zones. 2010. UN Habitat. State of the World's Cities 2010/2011: Bridging the Urban Divide. Overview and Key Findings.

²⁴ Gabelman, Alan. P.E. "Adsorption Basics: Part 1". American Institute of Chemical Engineers. aiche.org/cep. August 2017.
Gabelman, Alan. P.E. "Adsorption Basics: Part 2". American Institute of Chemical Engineers. aiche.org/cep. August 2017.

²⁵ Process Engineering Associates, Activated Carbon- parts 1 and 2.

²⁶ Noll, Kenneth E.; Vassilos Gounaris, and Hou, Wai-Sun. Adsorption Technology for Air and Water Pollution Control. Chelsea, MI: Lewis Publishers. 1992, p1.

mostly concerned with the latter ²⁷. Adsorption is canonical in chemical engineering²⁸ and ubiquitous in molecular separation in the chemical, natural gas, mining, petroleum, food, and environmental emissions industries ²⁹. Industrial processes for stationary source (e.g., emissions) control typically use adsorptive materials in fluidized reactor beds ³⁰.

Surface Chemistry and Kinetics

The adhesion of molecules in adsorption is an interfacial or surface phenomenon. The associated bonding is based on weak electrostatic attractive van der Waals forces³¹ rather than ionic or covalent bonding. The phenomenon relies on London dispersion or induced dipole forces rather than dipole attraction, which explains its reversibility. VOCs will desorb thermally starting at 300 Fahrenheit. The fundamental action of the process is diffusion ³² which may be understood through Le Chatelier's principle (although as a thermodynamic depiction this does not explain the kinetics), or Henry's Law. This may be enhanced by convection and dispersion in the mobile, that is gas, phase as implemented in adsorber reactor design ³³.

The physical process of adsorption, as the molecules move through the adsorbent material, is one of mass transfer. Isotherm equations for adsorption were first described by Irving Langmuir in 1916, in work for which he subsequently won the 1932 Nobel Prize in Chemistry. The Langmuir isotherm's assumptions assume a monolayer adsorbent material. In its derivation the Langmuir isotherm refers to homogenous adsorption in which each molecule possesses constant enthalpies and sorption activation energy: "all sites possess equal affinity for the adsorbate, with no transmigration of the adsorbate in the plane of the surface"³⁴.

The more recent Freundlich isotherm does not assume a monolayer, and "is widely applied in heterogeneous systems especially for organic compounds or highly interactive species on activated carbon and molecular sieves."³⁵. The linear isotherm, expressing partial pressure and Henry's Law, is simpler and embodies relative humidity, temperature, and partial pressure in-

²⁷ In contrast, in *absorption* is mass transfer to another phase. The medium into which the contaminant is absorbed, often a liquid or filter paper, combines chemically with said contaminant.

²⁸ Dobbs, Jimenez, Wankat. Denn, Morton M. Chemical Engineering: an Introduction. New York: Cambridge University Press. 2012.

²⁹ Marquez, P., A. Benitez, J. Hidalgo-Carrillo, F.J. Urbano, A. Caballero, J.A. Siles, M.A. Martin." Simple and eco-friendly thermal regeneration of granular activated carbon from the odour control system of a full-scale WWTP: study of the process in oxidizing atmosphere". Separation and purification technology. 255. Jan 2021. 117782. 1-11.

³⁰ "the application of adsorption technology or pollution control usually deals with the control of organic compounds. VOCs, pesticides, PCBs, phenolics, and complex synthetic organics are typical adsorbates." Noll p1.

³¹ only X joules in electrical strength.

³² D.T. Tefera et. Al. "Two-dimensional modeling of VOC adsorption onto beaded activated carbon". *Environ Sci Technol*. 47 (2013): 11700-11710. "...the main mass transport takes place by diffusion of the adsorbate in the porous adsorbent particles", p 11702.

³³ Ibid, p 11702.

³⁴ Foo and Hameed 2010, p4.

³⁵ Foo and Hameed 2010, p4.

puts. More recently, new variables have been added, including chemical potential additions to isotherms to address adsorption post-surface adsorption. Physisorption is the main mechanism involved, but “multilayer adsorption takes place: interlayer and intralayer interactions between the adsorbed molecules”³⁶. Adsorption heat produced diminishes as the saturation progresses. Saturation is also increased by capillary condensation, within the micropores. Gibbs free energy associated with the unbound valence electrons at the surface decreases as post-surface adsorption takes place within layers. This enthalpy of the reaction is also specific to the specific heat capacity of different adsorbed species. In practice, empirical isotherms can characterize input and output, at given pressures and temperatures, without close characterization of the thermodynamics that pertain when different species are adsorbed.

Post-adsorption, Van der Waals attachment is temperature-independent³⁷. As sorbate molecules attach at all layers, surface free energy decreases- conversely, adsorption works more readily on high SFE substances. When saturation is complete, at breakthrough, a dynamic chemical equilibrium between adsorbate and adsorbent is reached, and adsorption and desorption rates are equal^{38, 39}. In an ambient rather than controlled laboratory test, the surface chemistry would be heterogeneous with respect to the different species in each sample of VOC ambient air. Since this varies so much, it would seem difficult to characterize.

Materials used in Adsorption

Materials used in adsorption vary significantly by size, shape, and polarity⁴⁰. However, they share the common feature of extensive porous structures and hydrophobicity. By minimizing resistance in the mass transfer process, these molecular features enhance adsorption kinetics, and welcome rather than discourage diffusion.

Zeolite alumino-silicate, SiO₂, and molecular sieves, are also widely used for adsorption, as are Metal Oxide Frameworks⁴¹. These substances are relatively discriminating in species adsorbed, due to their uniform-Angstrom external apertures. Other polymer adsorbents and molecular sieves are made from coal and include non-woven synthetic fiber filtration media and silica gel (hydrous oxide, SiO₂ in other media⁴²).

³⁶ N. Mohan et al.” Breakthrough of toluene vapors in granulated activated carbon filled packed bed reactor”. *Journal of Hazardous Materials* 168 (2009): 777-781.

³⁷ Noll Ch 13.

³⁸ Foo and Hameed 2010 p3.

In addition, the founding work: I Langmuir "The Constitutional and Fundamental properties of solids and liquids". *J Am Chem Soc* 38 11 1916 2221- 2295.

³⁹ Foo and Hameed 2010

⁴⁰ Li, Xiuquan, Li Zhang, Zhongqing Yang, Peng Wang, Yunfei Yan, and Jingyu Ran." Adsorption materials for volatile organic compounds (VOCs) and the key factors for VOCs adsorption process: a review". *Separation and Purification Technology*. 235 (2020). 116213.

⁴¹ Li, Xiuquan, Li Zhang, Zhongqing Yang, Peng Wang, Yunfei Yan, and Jingyu Ran." Adsorption materials for volatile organic compounds (VOCs) and the key factors for VOCs adsorption process: a review". *Separation and Purification Technology*. 235 (2020). 116213, p3.

⁴² Gu, Xuexian et al. "New activated carbon with high thermal conductivity". *Journal of Wuhan University of Technology*. Materials science edition. Volume: 31, 2. April 2016: 328.

Activated carbon is still the most widely used adsorptive material and the choice of OPA, because of its short diffusion path, high mass transfer rate, and heterogeneous adsorbent quality^{43, 44}. The tetrahedral carbon atom, which allows the formation of covalent compounds in many contexts, lends itself to adsorption of a wide range of gas phase molecules. The surface for adsorptive activity is increased by the burning off (pyrolysis, or anaerobic thermal decomposition) of tar and ash from carbonaceous material at 800 to 1000 degrees C⁴⁵. VOC species are removed, and extensive internal micro-pores are created in this activation process⁴⁶. The surface area can range up from 500-2000 m²/g and will attract a wide range of organic (and inorganic) molecules.

Materials used in gas phase adsorption include coal and coconut shell, but also new materials such as peat, bamboo, nut shells, fruit stones such as olive pits, durian seed, and petroleum residue, in the form of activated carbon granules, powder and mesh. These materials, many of them agricultural byproducts such as "bamboo dust, peat, chitosan, lignite, fungi, moss, bark husk, chitin, coir pith, maize cob, pinewood sawdust, rice husk, sugar cane bagasse, tea leaves, and sago waste"⁴⁷, as well as economical waste by-products of agricultural processes, or bio-allergenic wastes from vegetable tanning⁴⁸, strongly indicate that adsorption can be extremely modest in price.

4. Canonical Adsorption Reactor Design, and Proposed OPA Ambient Adsorption system

The Design of Adsorption Systems

Given that the input materials to adsorption may be economical, how can this advantage be complemented by economical capital equipment implementation? Canonical design is imple-

⁴³ According to the EPA's Engineering Bulletin: "Adsorption by activated carbon has a long history of use as a treatment for municipal, industrial and hazardous waste streams... GAC is a relatively non-specific adsorbent and is effective for removing many organic and some inorganic contaminants from liquid and gaseous streams."

⁴⁴ Broom, Darren." Characterizing Adsorbents for Gas Separation". Reprinted with permission from *Chemical Engineering Progress (CEP)*, March 2018. Copyright © 2018 American Institute of Chemical Engineers (AIChE).

⁴⁵ Gabelman Part 2, p38.

⁴⁶ EPA Engineering Bulletin 1991, p3.

⁴⁷ Foo and Hameed 2010 p2.

⁴⁸ R.R. Gil, B Ruiz, et al." VOCs removal by adsorption onto activated carbons from bioallergenic wastes of vegetable tanning". Chemical engineering journal. v 245, 1. June 2014: 80-88.

mented in industrial processes using a columnar reactor^{49,50, 51, 52}. The major distinction in adsorption system design is that between Batch and Plug flow or tubular adsorption⁵³. In both cases, the systems are closed but not isolated, and the ingress of fluid flow with contaminants is adiabatic, through a pipe.

Batch Reactor

The batch reactor, "in which the adsorbent [usually Powdered activated carbon] is mixed with the polluted stream and the system is allowed to approach equilibrium..." is used in fluid streams. However, it is not generally looked upon favorably:

"the use of a single batch reactor results in low removal efficiency and requires the use of pure carbon... because the desired high effluent quality equilibrates with a low solids concentration."⁵⁴

The weakness of this design is its passivity so to speak, as it relies on diffusion when the stronger medicine of effusion and pressure swings are available. Another variant, less often mentioned, is constant stir reactor (CSTR). The constant stir reactor (steady state; well mixed), improves on batch processing's weaknesses in a similar physical format, albeit with an open rather than closed system^{55 56}.

Plug Flow Reactor

The prevailing model is the plug flow reactor (PFR), sometimes called continuous tubular reactor, CTR, or piston flow reactor. Its major design assumptions are relatively low resistance or drag- that is a low Reynold's number- laminar flow with no axial mixing, and a single homogeneous reaction taking place in the column. To enhance the partial pressure discrepancy, PFR design relies on effusion as the physical configuration which facilitates partial pressure discrepancy and hence equilibrium.

The columnar continuous plug flow configuration consists of a canister or tank or other 'column'- an enclosed cylinder with a bed of carbon at various thicknesses- and an inlet and outlet⁵⁷. Adsorption onto the AC adsorbent material continues to equilibrium between the contaminant aerosol (or fluid) stream and the adsorbent material. The moving boundary of the ad-

⁴⁹

⁵⁰ Noll, Kenneth E.; Vassilos Gounaris, and Hou, Wai-Sun. Adsorption Technology for Air and Water Pollution Control. Chelsea, MI: Lewis Publishers. 1992.

Ruthven, Douglas M. Principles of adsorption and adsorption processes New York: Wiley, 1984.

⁵¹ U.S. Army Corps of Engineers. Design Guide 1110-1-2. Engineering and Design Adsorption Guide. March 1, 2001.

⁵² Perry's Chemical Engineering Handbook. 8th Edition, 2008.

⁵³ Kevin Dunn, McMaster U Adsorption Lesson.

⁵⁴ Noll p8

⁵⁵ Jimenez, J.L. "Introduction to Flow Reactors". Advanced Atmospheric Chemistry (CHEM 5152) Spring 2015. http://ocw.mit.edu/courses/chemical-engineering/10-37-chemical-and-biological-reaction-engineering-spring-2007/lecture-notes/lec05_02212007_g.pdf.

⁵⁶ Denn 2012 regarding CSTR and other reactor formats.

⁵⁷ *ibid.*, p9.

sorption mass transfer process, as the molecules move through the reactor bed or vessel, is called the mass transfer zone (MTZ). Pressure drop occurs as the contaminant is adsorbed by the adsorbent material. As the MTZ reaches the far end of the reactor bed or column, breakthrough is reached and the system achieves a steady state of dynamic equilibrium. Saturation is gauged when the inlet and outlet have the same pressure and contaminant concentrations. Column testing is used for comparative gauging of the saturation process over time, and to measure heat evolved, as this is an exothermic process.

Such a system often has a temperature swing (TSA) or pressure swing phase (PSA) component, with desorption built in. Packed fixed beds, with a separate effluent stream from the reactor 'bed'- i.e., cylinder- are prevalent for industrial air pollution control^{58, 59}. Such a system typically comprises two reactor column beds that are regularly exchanged, so that one is always in use. Two small beds, rather than one large one, may be used to assuage the dangers associated with exothermic processes. However, these are usually cautioned when GAC is used in a closed space or with peroxides or ketones. Another common feature is a heat exchanger to alleviate the degradation of adsorption capacity associated with relative humidity above 50%. Under exposure to extreme high temperature VOCs (e.g., 60°C⁶⁰), in the adiabatic column, there is a possibility of ignition for activated carbon⁶¹. In this case, additional features to cool air are implemented.

Open Panel Adsorption Design

A simple adsorption system for ambient air is faced with atmospheric humidity, the erratic mixing ratio of ambient air, and diffusion in the low partial pressure of pollutants in ambient air. Adsorption systems use closed reactor beds and a closely controlled and specified cubic feet per minute inlet to hasten mass transfer to breakthrough (saturation and dynamic equilibrium). OPA relies on 1) repeated flows to the adsorbent material, achieving saturation over a much longer duration; 2) deployment locations carefully chosen in order to maximize persistent and episodic acute air pollutant concentrations; and 3) increasing the adsorbent surface area by designing panels open to the air. Adsorption panels should be placed in locations where pollutants are dense, preferably where air-flow is laminar with low friction (because of impermeable adjacent vertical walls, for instance) to facilitate adsorption. This design thus alternately utilizes the relatively passive diffusion of batch adsorption systems, and effusion under pressure used by the more prevalent tubular or plug flow or column reactor adsorption system.

Thus we wish to implement the simplest of adsorption systems using commodity AC. This will use diffusion and ambient air, over time, rather than the established plug flow reactor adsorption mechanism, or pressure-swing or temperature swing adsorption (PSA and TSA) methods.

5. Experiments in Ambient Adsorption

Hypothesizing that ambient adsorption is an effective means of VOC mitigation, we carried out two experiments. The first showed that adsorption did indeed take place in an ambient setting, despite lack of extreme changes in temperature or pressure, and despite the presence of high ambient relative humidity. The second indicated that as expected, the kinetics of adsorption

⁵⁸ "GAC treatment of contaminated gas streams is carried out almost exclusively in fixed-bed reactors. EPA Engineering Bulletin

⁵⁹ Fluidized reactor beds (FRB), with onboard desorption utilizing pressure or temperature swing, are more expensive and will not be considered further here.

⁶⁰ Delage et. al, Nantes paper.

⁶¹ Twumasi, E., M. Forslund, P. Norberg, C. Sjostrom. " Carbon-silica composites prepared by the precipitation method", J. Porous Matter. 19 (2012): 333-343.

are rapid, and repeated episodes of intermittent adsorption are effective. The first provides a material balance, in this case semi-quantitative rather than precise, but no rate equation given the duration of placement of panels. The second provides the opposite- a rate equation without material balance.

Ambient Test with GC/MS

Our initial experiment used adsorption panels, screened containers of 4x8 mesh coconut-shell AC, purchased from an online mass retailer. The 4 x 8 mesh designation means that 90% of the granules are no larger than 4.75mm or .187 inch (No. 4), and no smaller than 2.360 mm or .0929 (No. 8) inches. We are concerned with gaining proximity to pollutants which have not yet been dispersed by vertical transport from buoyancy and turbulence and horizontal transport from winds. We placed several cloth bags of 100 grams of AC in inconspicuous locations adjacent to car traffic (approximately 3 meters) immediately north of a Bart commuter train overpass on a busy six-lane arterial street adjacent to multifamily residences ⁶², for three weeks⁶³.

The first sample of the adsorbed AC was tested at an analytical laboratory by GC-MS analysis through thermal desorption (TD GC-MS), using a modified EPA Method TO-17 protocol. The results indicated significant hydrocarbons, although we realize that we did not specify desorption at a sufficiently high temperature to desorb the VOCs at a higher Celsius. The results should have been higher. Yet even these preliminary desorption reports indicate that passive ambient adsorption over a period of time does work. Despite our apprehension, the AC was not blinded by PM 2.5 nor did competition from adsorbed H2O preclude adsorption of VOCs.

Timed Jar Tests

In the second experiment, timed jar tests utilize AC sorbent material in VOC-saturated air, with adsorption over time measured. The most rudimentary measure is the characterization of adsorption by GAC of TVOC in air. An empirical test combines a handheld commercial Ion Science Cub Photo-Ionization TVOC detector with a 10.6 eV bulb, with an airtight food storage box. The PID unit is placed into a transparent 2.3 cubic Liter (9.6 cup) Rubbermaid Brilliance container, along with 70 grams of 4x8 mesh granulated activated carbon, and observed until ppm dropped to 1.0.

For the TVOC species, the experiment used nail polish remover, the listed ingredients of which are acetone (CH_3CO), the simplest and smallest ketone; benzophenone ($\text{C}_6\text{H}_5\text{CO}$); propylene carbonate ($\text{C}_4\text{H}_6\text{O}_3$); and dimethyl glutarate ($\text{C}_7\text{H}_{12}\text{O}_4$). All of these are VOCs, although all compounds are VOC exempt compounds⁶⁴. However, the ionization energy for the reference species isobutylene differs from the ionization energy of acetone. Yet according to EPA Technical Note TN-106 and Ion Science Cub's technical documents, the correction factor for acetone, with a 10.6 eV bulb, is 1.17. No CFs are given for the other species. While the PPM readings should be slightly higher given the correction factor, the rate equation would be the same.

⁶² These deployments taught us something about maintaining the panels. Subsequent rains obliterated many of these panels at a time when the Covid Omnicron surge made going out to fetch them almost impossible.

⁶³ The testing time also needs to be determined. EPA method 325B used for BTEX analysis in fenceline locations, recommends two weeks. We started, however, with a much longer time period.

⁶⁴ Propylene carbonate is not regulated as a volatile organic compound (VOC) because it does not contribute significantly to the formation of smog and because its vapor is not known or suspected to cause cancer or other toxic effects. VOC exempt solvents are organic compounds which are exempt from restrictions placed on most (VOCs) in the United State.

Variegating Conditions for Adsorbance

The empirical conditions under which OPA will be carried out will consist of deployments of relatively long duration, which are uneven in adsorbate concentration. This approach to implementation contrasts with circumstances more typically characterizing industrial processes, with a single instance of aerosol input to see how rapidly adsorbent GAC works in adsorption.

Our tests attempted to simulate these variegated conditions, including a variety of jar tests including physical abiotic criteria for which we can control. This does not include all physical parameters, certainly. Air pressure in the ambient tropospheric range does not vary significantly, certainly not given that pressure swing is a typical design method by which to enhance speed of breakthrough in adsorption reactors.

Testing the Instrumentation

A preliminary test addressed the verisimilitude of the instruments. Is the store-bought container, intended for food storage, airtight? We considered this by adding TVOC, in the form of 0.25mL nail polish remover to a 4" x 2 1/2" (10.2 x 6.35cm) section of cheesecloth- but did not add activated carbon- and then sealed the lid. The ppm reading in the container peaked at a maximum of 3190, then dropped to 2950 within thirty minutes and stayed at or above this level for the next seven and a half hours. After eight hours, at which time the instrument had lost 6.865% of its peak reading, the Cub PID was turned off. Another, shorter test, showed that the TVOC does not offgas to the container itself after hours of testing (See Attachment B).

6. Results of the Timed Jar Tests

Preliminary results of the timed jar tests have indicated favorable adsorption with repeated introductions of TVOC. In addition, we conducted tests in which rapid adsorbance took place under varying light, RH, and air turbulence conditions. Rapid kinetics were seen in the dramatic drop in ambient ppm in the chamber, as the TVOC is adsorbed. As there is one major ingredient- acetone- in the nail polish remover, the rate equation is first order and thus a simple slope mass over time (M/t).

The initial rate equation used was the maximum to the first measurement under 1.0 ppm. In this case, the M/t, or ppm max to ppm at 1.0, was between 9 and 25 ppm per minute in most cases. However, another examination of the CSV data files indicated that the adsorption level lingered at a low ppm level between 5.0ppm and 1.0 ppm for as long as several hours, before reaching 1.0 ppm. Thus, we calculated the rate equations from the maximum reading down to 5.0 ppm. In every case, this figure was less than one hour. The M/t in these cases was between 25 and 63 ppm reduced per minute. Because 5PPM is below STEL for WHAT VOCS, this is more perspicacious regarding the heavy lifting of the ambient adsorption, so to speak. Invariably, it seems to take place rapidly.

Other findings include that moderate sunlight was more effective than adsorption in darkness, and adsorption moderately less effective at about 50%RH (see Attachment C and Appendix 1).

Repeated Adsorption

Ultimately, the most consequential test is that of repeated adsorption (See Appendix 2, and Attachment D). A dozen tests indicated that repeated adsorption remained effective, albeit in all but one case less so than the first-round of ambient adsorption. The sticking probability does not seem to decrease with the second application, or apparently, with the third application.

Cost

We calculated cost for the first TVOC removal test (See Attachment A, 11.30.2022, and Appendix 3). The rate equation of 1969.8 ppm removed over 135 minutes is 14.5911, that is 14.5911 ppm removed per minute. Alternatively, one could say that the 50 grams of AC with a

delta of 1969.8 ppm, removes 39.396 ppm of TVOC per gram of Activated Carbon, over two and one-quarter hours. Since GAC cost \$22.99 for five pounds, the 50 grams of AC, at 0.11.231 lb., cost 50 cents (0.506842). At one penny per gram, or about 40 cents to remove 39.393ppm TVOC, this is modest in price. This would be more emphatically the case with the most rapid rate equations- those for the first round of adsorption, in sunlight, from the maximum reading to 5.0ppm. In such cases, with a higher rate equation of per-minute adsorption, the cost would be less than one gram, or one penny, per minute as 14.5911ppm TVOC is removed. The cost per-ppm adsorbance metric is significant for the case for OPA, which is intended for circumstances in which and constituencies for whom time is less dear than money.

These preliminary findings affirm the working hypothesis: ambient diffusion will do the job of adsorption, and a columnar reactor with no PSA or TSA mechanism exerted. Ambient adsorption using only diffusion may not complete its work optimally, but well enough for the circumstances for which OPA is intended.

7. The Desorption, Decomposition, and Regeneration of Spent Activated Carbon

The entirety of open panel adsorption works only if the reverse logistics are thorough in desorbing and decomposing VOC contaminants: micromitigation is only as good as the entirety of its desorption processes. The centrality of these processes to the larger integrity of MM having been established, both conventional pyrolysis and more chemically sophisticated desorption and regeneration methods are under development.

Decomposition Methods: Combustion and Pyrolysis

Physi-sorption is a reversible physical process- and desorption is its reverse complement. Saturated carbon desorption (and reactivation) is usually carried out in a multiple-hearth kiln at spent carbon reactivation facilities. (Alternative techniques will be addressed momentarily). The processes include drying; anaerobic thermal desorption, which subjects the materials to temperatures elevated to at least eight hundred degrees (often as high as 1100 f.), then steam. The process is carefully managed to avoid oxidation of the GAC under a closed environment. Steam creates positive pressure, helping to ensure against oxidation. This process volatilizes the organic compounds which have been adsorbed onto the carbon. The chemical reaction incinerates VOCs and gases by pyrolysis. Thermal decomposition essentially completes the combustion process which was not completed when the hydrocarbon was first burned and remained volatile. Alternatively, some contaminants can be recaptured and reused.

Desorption and Decomposition by Pyrolysis

Pyrolysis, thermal decomposition of biomass occurring in the absence of oxygen, is an ancient process historically used to create charcoal ⁶⁵. This endothermic process differs from combustion (exothermic, with O₂) and gasification (also exothermic with O₂). Slow pyrolysis for volatiles takes place through multi-step heating, with a residence time between five and thirty minutes ⁶⁶. At 600 to 800 Centigrade, long chain alkane hydrocarbons decompose to short-lived free radicals and short chain gaseous hydrocarbons as C-H and C-C bonds are ruptured. These can be reused as organic chemical raw materials. The intermediate reactant products of slow pyrolysis

⁶⁵ Mohammad Jahirul et al. "Biofuels Production through biomass pyrolysis: a technological review". *Energies* 2012, 5, 4952-5001.

⁶⁶ Mario Lanzetta and Colomba Di Blasi, "Pyrolysis kinetics of wheat and corn straw". *Journal of Analytical and Applied pyrolysis*. 44 (1998): 181-192.

may require catalytic cracking, an intrinsically problematic process in oil and gas refineries.⁶⁷ Thermal desorption appears to be less environmentally problematic than solvent desorption⁶⁸, and can work at lower temperatures as well⁶⁹ While some research indicates that sulfur- and nitrogen-containing compounds can hinder the regeneration process, this is not indicated for hydrocarbons strictly speaking^{70, 71, 72}.

The instance of pyrolysis of aromatic ring HCs and chlorinated HCs could be addressed by using cleaner decomposition and regeneration technologies. Aromatic ring structure Hydrocarbons pyrolyze into aryl radicals, which can re-form as biphenyl. Moreover, pyrolysis of C4 hydrocarbon 1,3 butadiene and propyne can result in intermediate formation of polycyclic hydrocarbons. However, PAH formation is far less at temperatures below or equal to 800 C⁷³. For refineries, pyrolysis engenders intermediate recombination of reactants, and requires the process of catalytic cracking⁷⁴, better avoided if possible.

Alternative technologies for desorption are desirable and under development. Another possibility would be using recently developed fast pyrolysis, characterized by "high heat transfer and heating rate, very short vapor residence time, rapid cooling of vapors and aerosol... and good control of reaction temperature"⁷⁵.

Capital Equipment for Carbon Regeneration

Most regeneration- as distinguished from desorption- is carried out by thermal facilities, using multi-hearth furnaces and rotary kilns. The former last longer and have greater capacity. Alternatively, a rotary kiln requires less skill to operate, requires more fuel, and can manage smaller

⁶⁷ Conesa, Juan A., Nuria Ortuno, and Damia Palmer." Estimation of industrial emissions during pyrolysis and combustion of Different Wastes Using Laboratory Data". Nature Research Scientific Reports. 2020. 10: 6750.

⁶⁸ Ramirez, Noelia et al." Comparative study of solvent extraction and thermal desorption methods for determining a wide range of VOCs in ambient air". Talanta. 82, 2. July 2010: 719-727.

⁶⁹ Marquez, P., A. Benitez, J. Hidalgo-Carrillo, F.J. Urbano, A. Caballero, J.A. Siles, M.A. Martin." Simple and eco-friendly thermal regeneration of granular activated carbon from the odour control system of a full-scale WWTP: study of the process in oxidizing atmosphere". Separation and purification technology. 255. Jan 2021. 117782. 1-11.

⁷⁰ Xue Han, Hongfei Lin, Ying Zhen." Regeneration methods to restore carbon adsorptive capacity of dibenzothiophene and neutral nitrogen heteroaromatic compounds". Chem Engineering Journal. 243 (2014): 315-325.

⁷¹ U.S. EPA. Robert S. Kerr Environmental Research Laboratory. Thermal Regeneration of Activated Carbon. 600-2-78-103. EPA May 1978.

⁷² Conesa, Juan A., Nuria Ortuno, and Damia Palmer." Estimation of industrial emissions during pyrolysis and combustion of Different Wastes Using Laboratory Data". Nature Research Scientific Reports. 2020. 10: 6750.

⁷³ " Polycyclic aromatic hydrocarbons from the co-pyrolysis of 1,3-butadiene and propyne". Proceedings of the Combustion Institute 14 Sept 2013. 1775-1783.

⁷⁴ Environmental Protection Agency, Feb 9 2005. 40 CFR Part 63, National Emission Standards for Hazardous Air Pollutants for Petroleum Refineries: Catalytic Cracking Units, Catalytic Reforming Units, and Sulfur Recovery Units; Final Rule and Proposed Rule.

⁷⁵ PG&E Gas R&D and Innovation Technical Analysis: Pyrolysis 5.14.2018. p5.

batches. More sophisticated regeneration facilities include kilns or furnaces equipped with SCADA-controlled sensors to ensure avoiding LEL and UEL oxygen levels in the enclosed space of the facility, as well as exhaust handling system to control emissions. Economies of scale, given the sheer expense of a hearth or kiln, would be advantageous to MM in practice. The most sophisticated and doubtless the most expensive kilns used in metallurgical processes in Germany and South Africa advertise a lean burn with minimal emissions. Wide implementation of MM would bring downward price pressure on the thermal desorption process as well. Notwithstanding this, the process for regeneration, or desorption, of the mesh, granules, and cartridges once used is well-defined technically and well-regulated in the U.S. by governmental agencies ⁷⁶.

Alternative Desorption, Decomposition, and Regeneration Technologies

Perhaps a dozen alternative treatments for desorption from AC (and from other adsorbent substrates) have been developed during the past decade. The most fully developed of these methods include Microwave treatment^{77 78 79}, electrochemical decomposition and regeneration, catalytic oxidation, Fenton's reaction, ozonization, UV light, H₂O₂, solvents, ultrasound (produces free radicals through cavitation at critical temperature or pressure), and bioregenerative solubilization with surfactants⁸⁰. These have various advantages and detriments.

⁷⁶ Spent carbon regeneration facilities fall under the purview of the Environmental Protection Agency throughout the USA, and by the Department of Toxic Substances Control in California. The 1976 Resource Conservation and Recovery Act provides authority for the EPA and state agencies to regulate carbon disposal and to regulate the regeneration of such carbon materials. Both entities require certification that the spent carbon is not hazardous waste. EPA standards and DTSC procedures define this term according to 40 CFR Part 261.3 and Title 22 of the California Code of Regulations, respectively. Characteristics of hazardous waste according to the EPA's Hazard Codes are: ignitable (with flash point less than 140 degrees Fahrenheit); corrosive (acidic or basic); reactive (unstable under normal conditions), toxic (containing mercury, lead, DDT, PCBs), and acute hazardous waste or toxic waste.

In addition to following the EPA standards, the DTSC requires the specification of the non-hazardous- or hazardous nature of such wastes. This includes a number of specified wastes: F list (various manufacturing and industrial processes); K list (specific industries, petroleum and pesticides); P list (industrial chemicals), U list (discarded commercial chemical products), and M-list (mercury). Activated carbon granules and cartridges from ambient AQ collection would appear to fall into none of these forbidden categories, according to the detailed spec sheets for California Carbon.

⁷⁷ Foo and Hameed 2009.

⁷⁸ Yang, Hui et. al. "Microwave Desorption and regeneration methods". *Adsorption: journal of the International Adsorption Society*. 25, 2. Feb 2019: 173-185.

⁷⁹ Tamer M. Alsilaibi, Ismail Abustan, Mohd Azmier Ahmad, and Ahmad Abu Foul. "A review: production of activated carbon from agricultural byproducts via conventional and microwave heating". *J. Chem Techno Biotechnol*. 2013, 88: 1183-1190.

⁸⁰ With micelles, which form in colloidal suspension, which form according to polar charge.

Desorption by Microwave

The alternative non-thermal process of microwave-assisted desorption and regeneration, is encouraging as it offers extremely rapid heating, requires less energy and allows a high level of AC regeneration^{81, 82, 83}. In experiments with adsorbed radon, it works with effective desorption and high regeneration capacity (>90%), at relatively low temperature (150 c), and relatively quickly (nine minutes)⁸⁴.

Desorption requires essential elements of heat, leading to pyrolysis and volatilization, carried out in either a rotary kiln or a multi hearth kiln. References in industry sources vary as to the temperature and timing of the regeneration and reactivation processes. Perry's Chemical Engineer's Handbook 8th Edition 2008 covers this topic in detail⁸⁵. Foo and Hameed (2009) indicate problems relating to regeneration and reactivation, and present the case for the usage of microwave energy for both desorption and reactivation.

Moreover, experimental studies of the process, such as Foo and Hameed's 2012 experiments, have used modified home microwave ovens. These can be purchased for less than one hundred dollars in the United States, and seem to have practically speaking no resale value. Thus the capital equipment for such technique may be very economical. Could this method possibly be widely implemented at a small scale, by local environmental regulatory agencies or municipal facilities or community biolabs?

Another significant improvement is the usage of microwaves combined with UV light at 185 nm to facilitate the decomposition of Chlorine-containing species, especially when aided by O₃^{86, 87}. This significantly ameliorated trouble with intermediate pyrolysis products. The chlorine in question is found in pharmaceutical products, which end up in the water, and is thus less of a concern with aerosols and with the typical HC TACs found near roadways. The photolysis produced by UV light on its own, as per Santos et al., is not particularly impressive as a decomposition or regeneration method.

Desorption and Decomposition by Electro-Chemical Means

Another possibility is electro-chemical decomposition and regeneration of saturated AC. Saturated AC is placed in an electrolytic cell containing an electrolyte solution, to which potential cur-

⁸¹ Foo and Hameed 2009.

⁸² K.Y. Foo, B.H. Hameed. " Microwave-assisted regeneration of activated carbon." Bioresource Technology 119 (2012) 234–240.

⁸³ E. Claisan, et al." Low temperature regeneration of activated carbons using microwaves: Revising conventional wisdom". J Environmental Management. 2012, 102: 134-140. Indicates that microwave regeneration is not a universal panacea for all contaminants. After microwave regeneration of adsorbed pharmaceutical compounds, regeneration capacity was negatively affected.

⁸⁴ Yang, Hui et. al." Microwave Desorption and regeneration methods". Adsorption: Journal of the International Adsorption Society. 25, 2. Feb 2019: 173-185.

⁸⁵ p16-63 to 16-66.

⁸⁶ Yanlong Sun, Bo Zhang, Tong Zheng, and Peng Wang." regeneration of activated carbon saturated with chloramphenicol by microwave and ultraviolet irradiation". Chemical Engineering Journal 2017: 264-270.

⁸⁷ Y Sun et. al., 2017 p267.

rent is applied⁸⁸. This method has high regeneration capacity, and less modification to the pore structure of the AC than other methods. Because of the design of the process, it may simply be less challenging in terms of heating time and temperature regulation. Unlike thermal kiln or hearths, this machinery also can in some circumstances be deployed in situ.

Catalytic Oxidation

Catalytic oxidation requires the presence of mostly metallic catalytic materials- noble metal, non-metal, and mixed-metal catalysts⁸⁹, but can be carried out at a lower temperature than thermal desorption, decomposition, and regeneration⁹⁰.

Decomposition by Fenton's Reaction

Fenton's reaction entails the oxidation of Fe⁺ ions by hydrogen peroxide (H₂O₂) and the resulting production of the hydroxyl radical, in the process decomposing contaminants. It appears to preserve AC for subsequent regeneration extremely well ⁹¹. Reducing agents can be added to further facilitate the process.

Currently these methods are too novel to be carried out economically, and this in turn is a prerequisite for scaling. At the first round, OPA will have to be implemented using the available thermal desorption facilities. It is encouraging to see a great deal of concern for less polluting methods by which to carry out AC desorption thermally, chemically, and using different EMF effects on molecular bonds. The countries in which this research and development work is most vigorously pursued, judging by the technical literature, are Brazil, Spain, China, and Malaysia. Probably not coincidentally, these nations have both strong agricultural and heavy industry sectors, and considerable state influence over economic development. Intensive development of desorption and regeneration methods that do not require combustion would bring the cost down. This would require industrial policies expressly devoted to environmental remediation.

8. Empirical Testing of Metrics for Air Intake combined with an Activated Carbon Adsorption Panel

The project must proceed from testing in an airtight container to testing in a real-world setting. An initial challenge is deploying panels for the correct time duration, rather than gratuitously later than breakthrough. Given the dramatic gradient witnessed in the first timed jar test, it appears that breakthrough is often complete within an hour. However, adsorption will be intermittent in implementation.

Beyond the time duration, tests should systematically alter different values of concerning deployment location variables. These attributes include: adsorption panel dimensions; ambient humidity; light exposure (measured in lumens, from a smartphone app); the panel's proximity to emissions; stronger or weaker air flow (measured with an anemometer); laminar or turbulent flow; and ambient temperature. Of these factors, ambient temperature and humidity are given rather than controlled. At present, simply testing these attributes as binary rather than ordinal variables seems to be the most economical option.

⁸⁸ Zanella, Tessaro and Feris 2014.

⁸⁹ M.S. Kamal, S.A. Razzak, M.M. Hossain." Catalytic oxidation of volatile organic compounds (VOCs): A review". *Atmospheric Environment*. 140 (2016): 117-134.

⁹⁰ M.S. Kamal, S.A. Razzak, M.M. Hossain." Catalytic oxidation of volatile organic compounds (VOCs): A review". *Atmos Envir*. 140 (2016): 117-134.

⁹¹ Santos et al., " Saturated activated carbon regeneration by UV Light, H₂O₂ and Fenton reaction", p6.

The MMWG will leave adsorption panels in wire mesh protective screened cages, in different canonical weather patterns, specifically damp, cool weather and warm sultry weather. Given the same temperature and humidity, we will alter proximity to the emissions source, with one panel approximately 18 inches (45cm) away and the other one meter away, while trying to keep air flow similar between the three panels. Vehicle tailpipes are usually about one foot (30.48 cm) above the ground; varies 8 to 18 inches (20 to 45cm). Exothermic reactions take place at far higher than ambient temperatures⁹², but we are trying to see if sunlight, at far lower ambient temperatures, will affect adsorption.

Locations for the close-proximity panels will be utility poles or guardrails immediately next to parking lanes. Locations for the further proximity panels will be not much further away- probably simply higher on the utility pole or across the sidewalk. We will use two small panels, one very near the emissions source and one a meter or so away. A third larger panel will also be deployed near the emissions source. The smaller panel will be approximately 8x6", or about 20x15 cm, and the larger panel will be 12x8" (30x20 cm). Please see Figure A- PHOTOGRAPH OF UTILITY POLE STREETSIDE. In a second test, we will alter light exposure while trying to hold proximity to emissions steady.

We will have the results tested by thermal desorption and gas chromatography-mass spectrometry (EPA Method TO-17, TD GC/MS analysis) in order to see re semi-quantitative quantity and composition of adsorbed chemical species. Ambient adsorption over time will rely on numerous VOC events, so this does not yield a rate equation. But it will provide empirical data on relatively better ways to deploy panels. These results with an air flow meter, will allow us to have some means to characterize material balances.

9. Conclusion

Open Panel Adsorption or Micromitigation could be consequential for environmental justice communities, and should be further investigated with field experiments and TO-17 (TD GC/MS) testing. Our goal is micromitigation technology, described by open online protocol and developed by a distributed online working group which meets by WhatsApp or Zoom call. The possibilities of such 'vernacular mitigation' are far-flung.

In America's neglected communities and in countries with weak AQ standards and enforcement towns or neighborhoods, OPA could be initiated autonomously, including by a person or group, with limited means and technical expertise.

Acknowledgements

Micromitigation/ Open Panel Adsorption could not have been developed without the unique environment of the Counter Culture Labs. The CCL is the first home of the Open Insulin Project, as well as ongoing work on Mycology, Vegan Cheese, Kombucha genomics; and Open Bioprinter, among other projects.

RES particularly acknowledges Dr. Emmanuel Chiedu (Federal Institute of Industrial Research, Lagos, Nigeria) who advised on the batch adsorption test with photoionization detector.

This research has benefitted from critique and discussions with Drs. Pete Palmer (SFSU), Bill Horn (UC Davis), Patrik D'Haseleer (CCL and Lawrence Livermore National Laboratory), Deep Sengupta (UC Berkeley), as well as Peter Fitchen (Google), and Ken McGary (Clarity.io), and Roshni Sirvani.

APPENDIX 1

APRIL 13 IN SUNLIGHT 14.7c 31%RH

2023 less 0.993/ 10 00 53 to 12 30 53 **2022.007/ 150**

Mass ppm adsorbed/ minute:

⁹² Delage, U. Nantes research, re 60c needed for dangerous exothermic reaction.

13.4800

APRIL 13 IN SUNLIGHT

2023 less 4.958/ 10 00 53 to 10 38 08 **2018.042/ 37:15 Mass ppm adsorbed/ minute:**
54.1756

APRIL 11-12 DARKNESS 14.1c 34%RH

1463 less 1/ 21 56 53 to 00 23 53 **1462/147 Mass ppm adsorbed/ minute:**
9.9455

APRIL 11-12 DARKNESS

1463 less 4.966/ 21 56 53 to 22 50 23 **1458.034/ 53:30 = 53.50 Mass ppm adsorbed/ minute:**
25.2529

APRIL 17 HIGH RELATIVE HUMIDITY

526 less 4.868/ 12:21:51 to 12:36:36 **521.132/ 14:45 Mass ppm adsorbed/ minute:**
35.3309

APRIL 17 HIGH RELATIVE HUMIDITY

526 less 0.992/ 12 21 to 13 02 36 **525.008/ 41:36**
Mass ppm adsorbed/ minute:
12.6477

APPENDIX 2

MAY 8

MAY 8 THIRD W SAME SAMPLE OF ACTIVATED CARBON 266.918/ 13 45
= 19.412218

MAY 5 SECOND W SAME SAMPLE OF ACTIVATED CARBON 258.709/ 21.25
= 12.1745

MAY 4 FIRST ROUND 38.5% RH, 17.3C; 676.007/ 43.50
= 15.54039080

MAY 8 THIRD WITH SAME SAMPLE OF ACTIVATED CARBON T 5.0PPM

Max less 5.0ppm/ time 267.9 less 4.57 / 10 45 23 to 10 53 08 263.33/ 7:45 = 7.75
= 33.9780

MAY 5 SECOND WITH SAME SAMPLE OF ACTIVATED CARBON

Max less 5.0ppm/ time 259.7 less 4.667/ 12 57 47 to 13 07 17 255.023/ 09:30 = 09.50
26.8423

MAY 4 FIRST ROUND 38.5% RH, 17.3C;

Max less 5.0ppm/ time 677 less 4.933 / 12 30 50 to 12 49 20 672.067/ 18.50 =
36.32794

MAY 2

MAY 2 THIRD ROUND WITH SAME SAMPLE OF ACTIVATED CARBON

476.8 less 0.98/ 10 24 45 to 10 43 45 475.82/ 19 Mass ppm adsorbed/ minute:
25.0431

APRIL 24 SECOND ROUND WITH SAME SAMPLE OF ACTIVATED CARBON

910.2 at 10 06 00 910.2 less 0.992/ 10 06 07 less 10 51 52 909.208/ 45m 45s
Mass ppm adsorbed/ minute:
19.87339

APRIL 21 FIRST ROUND WITH SAMPLE ACTIVATED CARBON

710 less 0.987/ 13:49 to 14:14:15 709.013 / 27 Mass ppm adsorbed/ minute:
26.2597

MAY 2 THIRD ROUND WITH SAME SAMPLE OF ACTIVATED CARBON

**476.8 less 4.971/ 10 24 45 to 10 33 45 471.831/ 9 Mass ppm adsorbed/ minute:
52.4256**

APRIL 24 SECOND ROUND WITH SAME SAMPLE OF ACTIVATED CARBON

910.2 at 10 06 00 910.2 less 4.956/ 10:06:07 less 10:22:07 **905.244/ 16 MIN = 56.5777**

Mass ppm adsorbed/ minute:

56.5777

APRIL 21 FIRST ROUND WITH SAMPLE ACTIVATED CARBON

710 less 4.989/ 13:49 to 14:01:29 **705.111 / 12:15 Mass ppm adsorbed/ minute:**

57.5600

APRIL 5

APRIL 5 FIRST ROUND WITH SAMPLE ACTIVATED CARBON

1640 less 0.982/ 09:10:24 to 09:57:39 **1639.018/ 47:15 Mass ppm adsorbed/ minute:**

34.6882

APRIL 5 SECOND ROUND WITH SAME SAMPLE OF ACTIVATED CARBON

1160 less 1.044/ 11:15:09 to 16:49:09 **1158.56/ 334m Mass ppm adsorbed/ minute:**

3.468

APRIL 5 FIRST ROUND WITH SAMPLE ACTIVATED CARBON

1640 less 4.926/ 09:10:24 to 09:31:54 **1635.074/ 25:54 = 63.13027 Mass ppm adsorbed/ minute:**

63.13027

APRIL 5 SECOND ROUND WITH SAME SAMPLE OF ACTIVATED CARBON

1160 less 4.9/ 11:15:09 to 11:58:54 **1155.1/ 43:45 = 43.75 Mass ppm adsorbed/ minute:**

26.4022

APRIL 3 SECOND ROUND

1512 AT 12:18 12 4.956 AT 12:34:29 **1507.009/ 16:15 = 16.25**

Mass ppm adsorbed/ minute:

92.739

APRIL 3 FIRST ROUND

512.2 AT 07:50:42 4.991 AT 08:00:12 **507.209 / 9:27 = 9.50**

Mass ppm adsorbed/ minute:

53.390