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Method for estimating the volatility of aerosols using the Piezobalance: examples from vaping e-cigarette and marijuana liquids

Running title: Method for estimating volatility of aerosols

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Abstract

We present a new method to estimate the fraction of an aerosol mixture that is volatile, as well as the time required for evaporation from a collecting surface. The method depends on an instrument (the Piezobalance) designed to measure the accumulated mass on a quartz crystal that can also measure the subsequent loss of mass due to evaporation. Commercially available e-liquids or marijuana liquids were heated using an e-cigarette device or a vapor pen, inhaled, and exhaled into a closed unventilated room (volume = 43 and 33 m^3) in each of two residences. From a set of 88 measurements on an e-liquid containing 99.7% "vegetable glycerin" (VG), we estimate the fraction of the e-cigarette aerosol that is volatile to be 88% (95% confidence interval (CI) 77-99%). We also estimate the time to reach 95% of the total loss of the volatile material from the crystal to be 47 minutes (CI 33-60 minutes). For pure propylene glycol (PG) liquid, we measured extremely high rates of evaporation, finding that the exhaled plume did not create high exposures beyond about 0.65 m distance. From 124 experiments on three types of marijuana cartridges, the corresponding estimates of the volatile fraction of exhaled marijuana aerosol were normally 5-7% for liquids heated to moderate temperatures (N = 106), but 25-34% for liquids heated to high temperatures (N = 18). In the latter case, the time to reach 95% of the total loss of volatile material was on the order of 5-10 hours. This indicates the importance of volatility considerations in affecting exposure to indoor aerosols from these two common sources. Secondhand exposures to $PM_{2.5}$ from e-cigarette aerosols are likely to be short-lived for most scenarios, whereas we show that secondhand $PM_{2.5}$ exposures from marijuana vaping aerosols can be substantial and long-lived after a single puff.

Practical implications

The method presented here is general and can be used on almost any aerosol mixtures. It has the advantage of requiring a single instrument that can measure both the source strength and decay rates of the aerosol created by the source and also the fraction of collected material that is volatile. The method identified a major difference in the expected exposure to e-cigarettes vs. marijuana aerosols from vaping. The method should be of interest to investigators who study particulate air pollution and to companies that manufacture air monitoring systems. A number of important sources of indoor aerosol mixtures (e.g., cooking, candle use, incense, etc.) remain to be investigated for volatility effects using this method.

1. Introduction

Volatile aerosols present a problem to persons attempting to determine particulate matter (PM) mass concentrations using the accepted gravimetric method of collection on a filter, since the material partially evaporates from the filter during or after collection. A portion of both primary organic aerosol (POA) emitted directly from sources and secondary organic aerosol (SOA) created by photochemical processes is semivolatile (Turpin and Huntzicker 1995). A well-known example is ammonium nitrate, sometimes a substantial component of ambient air PM (Lunden et al., 2003). Both positive and negative artifacts can occur in ambient monitoring networks using quartz fiber filters (Maimone et al., 2011). Indoor air has been shown to have

higher concentrations of organic aerosol than outdoor air (Hodas et al., 2012; Polidori et al., 2006). Not only gravimetric methods, but also the alternative piezoelectric methods such as the tapered element oscillating microbalance (TEOM) have also encountered this problem. Later versions of the TEOM have developed ways to measure the amount of volatile material lost during collection (Thermofisher Scientific, https://www.thermofisher.com/order/catalog/product/TEOM1405). However, the TEOM is large and expensive (>$20K) and not an easily workable method for environmental scientists engaged in studying indoor air quality or personal exposure to PM. For example, it is quite bulky and is usually installed at fixed air monitoring stations, unable to be moved from room to room as in normal indoor air studies. Its normal operation also requires a total flow rate of 16.67 L/min compared to the 1 Lpm flow rate of the less expensive piezoelectric monitor known as the Piezobalance (Kanomax USA, Inc. https://www.kanomax-usa.com/) with a concomitant increase in noise. TEOMs equipped with a filter dynamic measurement system (FDMS) require two alternating cycles, one of which uses clean air passed across a filter to determine the mass loss due to volatility. They also require Nafion dryers to control humidity. These requirements lead to a high price tag. In contrast, the Piezobalance weighs 1.8 kg (approximately 4 pounds) is easily portable and battery-operated, allowing operation in any location.

Here we propose a method using the Piezobalance, which can be adapted to estimate the volatile fraction of aerosols of any composition. We illustrate the method using Piezobalances to estimate the volatility of two aerosol mixtures of considerable recent interest: aerosols produced from e-cigarettes and aerosols produced by marijuana liquid vaping.

Volatility of these aerosols is of interest, particularly if evaporation from filters could affect gravimetric measurements. We consider two modes of volatility:

1) While airborne, particle numbers may change according to at least three loss mechanisms: air exchange, deposition, and evaporation. The first two mechanisms (usually denoted by $a + k$) are generally considered to be approximately constant over a short period of time. Evaporation rates, however, may increase over time. This would appear as an increase in the decay rate, which can be detected by optical monitors as we illustrate in this paper.

2) After collection on a filter, particles may continue to evaporate. The rate of evaporation can be estimated by monitoring the filter mass continuously, which is possible using the Piezobalance.

1.1 Electronic cigarettes

Electronic cigarettes (e-cigarettes) are gaining rapidly in use worldwide. They offer a way to reduce dependence on tobacco cigarettes by providing nicotine but without creating combustion particles responsible for most of the cardiovascular and cardiorespiratory mortality of cigarette smokers. This has led to a recommendation in the UK that doctors advise smokers of the potential life-saving effects of e-cigarettes (Royal College of Physicians, 2016). Some studies estimate reductions in mortality of some millions of cases over the next 40 years (Levy et al., 2018). However, there is also fear that youthful nonsmokers may develop an addiction to

nicotine that could lead to smoking tobacco cigarettes. In 2018, 14%, 29%, and 34% of 16 million 8th, 10th, and 12th grade high school students, respectively, reported vaping nicotine (Johnston et al., 2019). On September 12, 2018, the US Food and Drug Administration gave notice to five companies that they need to show adherence to the laws prohibiting youth under the age of 18 or 21 from buying e-cigarettes (USFDA, 2018).

Multiple studies have been performed of the composition and particle dynamics of e-cigarette aerosol as emitted from an e-cigarette device. A fundamental analysis of the effects of e-cigarette fluid composition on the gas-particle ratio is provided by Pankow (2017). Volatility and rate of evaporation of the pure compounds is mainly controlled by their vapor pressure. The vapor pressure of 100% propylene glycol at room temperature is a bit less than 0.1 mm Hg (Lyondell basell https://www.lyondellbasell.com/globalassets/documents/chemicals-technical-literature/lyondellbasell-chemicals-technicalliterature-vapor-pressure-of-aqueous-propylene-glycol-solutions-2518.pdf). The vapor pressure of pure glycerin at room temperature is more than 100 times less, at 1.68 X 10-4 mm Hg (Pubchem https://pubchem.ncbi.nlm.nih.gov/compound/Glycerol#section=Vapor-Pressure). Therefore we expect PG to evaporate far more rapidly than VG. But the addition of as little as 10% water to a pure PG compound increases the vapor pressure by a factor of 60 (Lyondell basell https://www.lyondellbasell.com/globalassets/documents/chemicals-technical-literature/lyondellbasell-chemicals-technicalliterature-vapor-pressure-of-aqueous-propylene-glycol-solutions-2518.pdf). This is relevant because most PG/VG solutions also include some water.

Wright et al., (2016) measured the evaporation kinetics of glycerin, finding that the modeled times required to evaporate a 350 nm diameter glycerin particle to half its mass varied between 3 and 200 s depending on the amount of water vapor present. Oldham et al., (2018) studied the particle distributions from 20 e-cigarette fluids sampled at the beginning, middle, and near the end of the consumption of the cartridge volume. Oldham also examined the fluid composition and found the sum of VG and PG to be around 80-90% of the total volume; water accounted for 8-16% of the remainder, with nicotine at about 2-4%. Pratte et al., (2016) also measured size distributions of four e-cigarette formulations using two different methods of sampling the aerosol. One method required a delay of 3.4 s compared to the second method. In this short time, coagulation and evaporation/condensation processes resulted in increasing the MMAD from a range of 0.18-0.20 μm to a larger range of 0.22-0.29 μm. Zhao et al., (2016) measured heating coil temperatures in four e-cigarette devices and found a range from 152.3 to 216.8 °C. Williams et al., (2013) dissected 22 cartomizers and determined that the filaments consisted of a thin nickel-chromium wire coupled to a thicker copper wire coated with silver. There were four tin solder joints coupling the copper-silver wire to the air tube and mouthpiece. The aerosol contained particles >1 μm comprised of tin, silver, iron, nickel, aluminum and silicate, together with nanoparticles of tin, chromium and nickel. Saffari et al., (2014) also compared particulate metals from e-cigarettes and tobacco cigarettes.

Ingebrethsen et al., (2012) used two methods to study e-cigarettes in an undiluted state and under normal conditions of high dilution. They found an order of magnitude less mass in the latter (normal) condition suggesting significant evaporation taking place on a time-scale of minutes. Fuoco et al., (2014) analyzed volatility at three temperatures (37, 100, 170 C) and found the

particle number decreased by about half between the low and high temperatures, suggesting rapid evaporation. Feng et al., (2015) applied a computational fluid dynamics model to both conventional and e-cigarettes as they move through the first 3 bifurcations in a lung deposition model. They found that the e-cigarette droplets, being more hygroscopic than the conventional tobacco aerosol, increased in size more rapidly on encountering the humid environment of the lung. Mikheev et al., (2016) applied high-time-resolution spectroscopy to characterize particle size distributions of e-cigarette mainstream smoke and found a bimodal distribution between nanoparticles at about 11-25 nm count median diameter (CMD) and larger particles of 96-175 CMD. They found the highest concentration of nanoparticles occurring in the first 0.3-0.5 s of the puff. They found increased metal content in the nanoparticles that was attributed (in part) to contact of the liquid with the heated coils of the atomizer. Li et al., (2020) tested e-liquids with different PG/VG ratios, introducing the smoke into a 0.46 m3 chamber. Half-lives for the number and mass loss rates ranged from 15-24 minutes and 6-12 minutes, respectively.

We note that studies using smoking machines are unable to measure the impact on non-vapers of nearby vaping. For that, we require a human to inhale the e-cigarette aerosol into his lungs and exhale it into a room. Because almost no sidestream aerosol is produced by an e-cigarette, the exhaled aerosol is the only contributor to indoor concentrations and personal exposures. These aerosols will undergo changes in the lungs and will mix with gases from the bloodstream to form a new mixture quite different in humidity, temperature, composition, and particle size from the aerosols directly created by the e-cigarette before inhalation (Martuzevicius et al., 2018). Long et al., (2014) collected exhaled aerosols from human subjects and determined that the distribution and mass balance of exhaled e-cigarette aerosol composition was greater than 99.9% water and glycerin (about 75% water, 25% glycerin). Exposure to e-cigarette aerosol exhaled by human subjects has been studied by several investigators (Baassiri et al., 2017; Logue et al., 2017; Sleiman et al., 2016; Zhao et al., 2018; Schripp et al., 2013; Czogala et al., 2014; Ruprecht et al., 2014, 2017; and Ballbé et al., 2014). Zhao et al., (2017) studied 13 smokers in a large room and employed several monitors to measure the proximity effect. Other studies considering passive vaping are available Geiss et al., 2015; Grana et al., 2014; Hess et al., 2016; Maloney et al., 2016; McAuley et al., 2012; O'Connell et al., 2015). Useful studies of the "topography" of vaping e-cigarettes (frequency of inhalation, amount of vapor inhaled, length of time the vapor is inhaled and exhaled, etc.) have been provided (Robinson et al., 2015; Dautzenberg et al., 2015; Hitchman et al., 2014; Talih et al., 2015; Public Health England, 2016).

1.2 Marijuana liquid

Vaping marijuana has emerged as a popular method of delivering marijuana. This method heats marijuana in liquid form to the point of vaporization, avoiding combustion. The marijuana is thus delivered without the accompanying products of combustion. In 2018, 6%, 14%, and 16% of 16 million 8^{th}, 10^{th}, and 12^{th} grade high school students, respectively, reported vaping marijuana (Johnston et al., 2019). Goodwin et al., (2018) reported increases of marijuana use in homes with children from 4.9% in 2002 to 6.8% in 2015. The composition of mainstream and sidestream marijuana smoke, including concentrations, particle size distributions, and chemical species has been studied by several investigators, almost all using machine-smoked marijuana cigarettes (Hiller et al., 1984; Moir et al., 2008).

However, as with e-cigarettes, most passive exposure to vaped marijuana smoke will come from the exhaled breath of smokers. In the case of vaping marijuana liquid, 100% of the passive exposure will be from exhaled breath since there is no sidestream aerosol. The aerosol emerging from exhaled breath will be different in many respects from the inhaled aerosol, due to lung deposition, humidification, growth, and coagulation, so it is important to test exposure under real-world conditions using human smokers/vapers. One recent study included 193 persons, of whom about 22%, 15%, and 13% were tobacco, marijuana, and e-cigarette users, respectively (Klepeis et al., 2017). The authors found that nonsmokers exposed to persons smoking either tobacco or marijuana cigarettes had roughly twice the exposure to fine particles as nonexposed nonsmokers. On the other hand, e-cigarettes produced no measurable increase. As part of the same study, Posis et al., (2019) studied 298 homes with at least one cigarette smoker and at least one child under the age of 14. In 29 homes, marijuana smoking was reported. Homes with only marijuana smoking during weekly measurements using Dylos monitors had particle number concentrations about 50% higher than in homes with no smoking of any kind. The Dylos monitors used in both of these studies were not calibrated by comparison to gravimetric levels, so the investigators could not estimate $PM_{2.5}$ exposures or source strengths. A later study has found that vaping marijuana at a rate of one puff per hour for 16 hours per day can produce secondhand $PM_{2.5}$ exposures comparable to those from smoking tobacco cigarettes (Wallace et al., 2020). This same study found that increasing the time heating the marijuana liquid to higher temperatures produced higher source emissions. A companion study determined source strengths (mg/puff) for four methods of inhaling marijuana: joints, bongs, glass pipes, and vaping (Ott et al., 2021).

2. Methods and Materials

The Piezobalance is manufactured by Kanomax, Inc. Japan, and for a time was licensed for sale in the US by TSI Inc, Shoreview, MN. Piezobalances used in this study included models from both Kanomax USA Inc. (Andover NJ, Model 3511), and TSI, Model 8510. The instrument employs a vibrating quartz crystal exposed to a steady flow rate (1 L/minute) that has passed through an electrically charged $PM_{2.5}$ impactor (Sem et al., 1977). A reference crystal not influenced by ambient air vibrates at a different (higher) frequency. As the exposed crystal collects particles, its oscillation frequency decreases due to the piezoelectric principle, and within a certain frequency range the change in frequency is proportional to the amount of material collected on the exposed crystal. The proportionality depends on the crystal's properties and is set by the manufacturer. The frequency change during each measured time interval is then multiplied by the factory-set conversion factor G to give an estimate of the amount of mass collected during the time interval (see Supplemental Information). For any given aerosol source such as tobacco cigarettes, the mass usually continues to accumulate on the Piezobalance crystal, and the frequency of the exposed crystal decreases proportionally due to the piezoelectric effect. This causes the *difference* in frequency between the unexposed and exposed crystals to increase. When the frequency difference increases beyond an upper threshold limit, the surface of the crystal must be cleaned manually with a sponge and soap solution. Any decrease in the frequency difference would indicate the crystal is losing mass.

The aerosol from an e-cigarette consists mostly of a liquid aerosol. As the e-cigarette's aerosol accumulates on the Piezobalance crystal while it is also evaporating, the addition to the mass still causes the frequency difference to increase for a while. Eventually, however, the rate of evaporation exceeds the rate of accumulation, and successive one-minute Piezobalance frequency differences begin to decrease instead of increasing. This turns out to be a highly valuable property, since it allows a quantitative estimate to be made of the fraction of the e-cigarette vapor that is volatile. When the Piezobalances used in this study were purchased, we requested that a special connector be added by the seller (see details in Supplementary Information). This modification allows the frequency difference between the exposed and unexposed crystals to be output each minute to a computer where it can be logged, and, using the monitor's conversion factor, the amount of $PM_{2.5}$ mass accumulated or lost in units of ng/minute can be computed externally and stored. A newer version of the Piezobalance includes automatic datalogging for up to 500 measurements (https://www.kanomax-usa.com/product/piezobalance-dust-monitor-3520-series/). It is not clear, however, whether this newer model can log the crystal's frequency or send the frequency readings to an external data logger. A design modification might allow this important feature to be included in a future model.

The SidePak™ (TSI, Model AM510) uses a laser to sense particles as they pass through a chamber. The scattered light is collected and used to estimate particle volume applying Mie scattering formulae. The SidePak is calibrated using ISO 12103-1 Test Dust (formerly Arizona Test Dust; specific gravity 2.6). As with all optical monitors, it is recommended that the particular aerosol mixture being studied be analyzed using gravimetric methods, so that a calibration factor can be determined for that aerosol. For example, the calibration factor for the SidePak has been found to be about 0.32 for tobacco smoke (Dacunto et al., 2013). For the e-cigarette, we have not found it possible to collect enough particles to determine a SidePak calibration factor for a reason to be discussed below. Therefore, for e-cigarettes we report the SidePak values exactly as recorded (calibration factor CF = 1.0). The calibration factor (CF) is the ratio of the mass concentration obtained by the "gold standard" of a filter-and-laboratory-microbalance to the mass concentration reported by the monitor by itself. Depending on the density, humidity, and refraction and reflection index of the exhaled e-cigarette vapor, it is likely that the SidePak is overestimating the actual concentration. During the study, both monitor types were zeroed, the impactors were cleaned and regreased, and the flow rates were checked.

2.1 e-cigarettes

Two e-liquids were obtained commercially. One contained propylene glycol (PG) at 100% concentration (Aphrodite's Affair, Zeusjuice, https://www.zeusjuiceonline.com/). The second e-liquid contained glycerin or "vegetable glycerin" (VG) at 99.7% concentration (Vape Wild, company out of business as of Sept 9, 2020). No nicotine was present in the two e-liquids. PG is more than 100 times more volatile than VG (vapor pressure of ~0.1 mm Hg vs. 1.68×10^{-4} mm Hg at 25 °C).

Between May 7 and August 8, 2018, 88 experiments were carried out on the 99.7%VG e-cigarette fluid in two locations. One location was a 43 m^3 room in a residence in Redwood City, CA. The other location was a 30 m^3 room in a residence in Santa Rosa, CA. Rooms were sealed

off from the remainder of the home. The HVAC system in Santa Rosa was on and the floor registers sealed. The HVAC system in Redwood City was off and floor registers unsealed. In the Redwood City location, 54 experiments were performed using four co-located Piezobalances. (In all, 6 Piezobalances were tested.) In the Santa Rosa location, 34 experiments were carried out using two Piezobalances. The two locations were chosen partly in order to maximize the number of different Piezobalances in case different quartz surfaces might have different effects on measured volatility. Also the room sizes were quite different, with the larger room almost 50% larger. This would affect the time to reach good mixing, and in fact we showed that for marijuana vaping, mixing was achieved in less than an hour, but for e-cigarettes even the smaller room could not reach well-mixed conditions.

The commercial vaping device we used is designed with a tank to hold the vape liquid. This was heated by an electric coil activated by pressing a button on the device, called a Reactor (HaloCigs https://www.halocigs.com/) . The power could be set by the operator and varied between 10 to 50 watts. A slit could be opened to allow more or less air to mix with the heated vapor. Most experiments used a fully open slit, which was found to produce the largest quantities of vapor. The inhale period was shown on the Reactor's display for each inhalation, and normally ranged between 2 and 3 seconds.

In all experiments, from 1 to 5 puffs were inhaled over 2-3 seconds per inhalation and exhaled after holding in mouth and lungs for 1-2 seconds. The rooms were sometimes equipped with a small table fan to promote mixing, but a number of experiments used no fan. Because we expected that PG would evaporate far more rapidly than VG based on their vapor pressures, we carried out a sequence of experiments vaping 100% PG at various distances from the Piezobalance ranging from 0.3-3 m. All distances were recorded. The variation of these distances is important because the rapidity of the evaporation ensures that the room has no time to become well-mixed.

Room concentrations were monitored at 1-minute time intervals. Sufficient time was allotted after each experiment for the room to return to the background value before another experiment was attempted. This allowed the decay rates to be determined for the Piezobalance.

2.2 Marijuana vaping

Several commercial marijuana liquids were acquired with a range of CBD/THC ratios including 2:1, 8:1 and 18:1 (Care By Design, www.cbd.org)). A battery and heating coil in the vaping pen provided the energy to heat the attached liquid-containing cartridge. The vaping pen was obtained from AbsoluteXtracts (ABX; https://www.abx.org). Like the Reactor for the e-cigarette, the vaping pen was an electronic device that could be controlled by a button on its side. Background concentrations were collected for at least 5 minutes before taking a puff of the marijuana liquid. For the first 105 tests, a single protocol (Protocol I) was followed. This protocol included a 2-3-second heating period (caused by pressing and holding down the power button on the vaping pen), followed by a 2-3-second inhalation and an immediate exhalation. The number of puffs varied from 1 ($N = 54$) to 2 ($N = 31$) to 3 ($N = 14$) to 4 ($N = 6$). Later we

wished to test the effect of higher temperatures on the amount of aerosol exhaled, so we adopted Protocol II. Only one puff per test ($N = 19$) was employed. In this protocol, we first pressed and held down the power button for 6 seconds, paused for a few seconds, and then pressed and held down the power button again for 6 more seconds, keeping it pressed while inhaling for 3 additional seconds, and then exhaling as before. The reason for the pause midway through Protocol II was to prevent the automatic shutoff of power that occurs after the button is pressed for 10 consecutive seconds. Thus, Protocol II resulted in heating the liquid for about 15 seconds, compared to 4-6 seconds for Protocol I.

Concentrations were measured for a number of hours after each test. Because of the slow release of material from the Piezobalance crystal, some experiments lasted as long as 18-21 hours.

2.2.1 Gravimetric tests

Gravimetric tests could not be carried out on the e-cigarettes due to inability to collect enough material on the filter. In contrast, gravimetric studies were possible for marijuana vaping because the particles remain suspended for hours instead of minutes. Eight tests were carried out at the Redwood City location using a 2:1 CBD/THC liquid, resulting in an estimated Piezobalance calibration factor of CF = 0.97 (SD 0.03) for $PM_{2.5}$.(Zhao et al., 2020).

2.3 Decay rates, deposition rates, and air exchange rates

We define decay rates as the rate of total mass loss over time after a peak in mass concentration occurring shortly after a source is turned off. At least three loss mechanisms are involved in this decay: air exchange rates, rates of deposition on surfaces, and evaporation rates. We determined air exchange rates at the Santa Rosa site by releasing carbon monoxide from cylinders containing 10% CO and plotting the decline of CO concentrations in the room using the Langan CO Measurer Model T15, (Langan Instruments, San Francisco) capable of measuring sub-ppm concentrations. A correction factor for the temperature was applied. We used SidePaks and low-cost PurpleAir monitors to measure the initial PM2.5 decay rates due to deposition and air exchange combined. And we used the Piezobalance to measure the increases in decay rates due to evaporation over time.

Decay rates are important to calculate for at least three reasons. 1) The length of time to return to background is a crucial parameter in estimating exposure. 2) The decay rates after an initial period of poor mixing can be used to estimate the source strength, another crucial parameter, in a method developed by Ott (2007). 3) A change in the decay rates can indicate other processes affecting aerosol loss mechanisms such as coagulation and (particularly for our purposes) evaporation. For the Piezobalance, a “decay rate” is not a decline in aerosol concentration; it is a rate of mass accumulation, in units such as ng/minute. Without evaporation, the rate of mass accumulation is a constant multiple of the aerosol concentration. With evaporation from the crystal, the rate of mass accumulation is slowed, and the decay rate (slope of the mass accumulation) appears to accelerate. If the rate of mass loss from the crystal exceeds the rate of mass accumulation, the mass accumulation rate becomes negative. The time integral over this

negative interval represents the total mass loss. This can be compared to the total mass gain from the beginning of the experimental period to determine the fractional mass loss (volatility).

2.4 Temperature and relative humidity (RH)

At the Santa Rosa site, temperature and RH were measured every minute using Hobo Onset data logger Model UX100-011. An HVAC system kept the temperature controlled to 24 (±2) ºC. Although the RH was not controlled, the variation over any particular experiment was not expected to be large.

3.1 Volatility calculations

Two equivalent methods were developed for calculating the volatile fraction of the exhaled vapor (fraction lost to evaporation). Method 1 is direct observation of the frequency change over time. The frequency change increases from a baseline to a peak value, and then decreases as the crystal loses mass. The amount of the decrease divided by the amount of the increase over a period of time following the peak is the fraction $F(t)$ of the aerosol that is lost during that time. If the decay is followed long enough for the frequency to achieve an asymptotic (steady-state) value, then this ratio is the total volatile fraction F_∞. If we have a series of measurements of the observed fraction $F(t)$ ending at different times t, then we can fit an asymptotic curve of the form

$$F(t) = F_\infty(1-\exp(-t/\tau))$$

to estimate the two unknown parameters F_∞ (total fraction of material that evaporates) and time constant τ (time from the beginning of the decay period to reach $1-1/e$ of the final concentration). If different substances were tested during these experiments, the point estimates of F_∞ and τ would represent typical values for the ensemble as a whole, while the range of results would reflect, in part, different possible values for the different substances tested. This formula can also be used during a single experiment to estimate F_∞ and τ for the particular vaping liquid used in that experiment.

Method 2 uses the minute-by-minute direct measure of the mass gained or lost. Each positive concentration value recorded by the Piezobalance following the puff is a measure of the additional mass collected on the crystal. For our specific Piezobalances, the mass gain (or loss) is measured in ng/minute. However, it is only the *net* additional mass, reduced by any losses occurring that minute due to evaporation. After a time, the positive values change to negative values. This happens when the evaporative loss exceeds the additional mass collected during that minute. Since we know the Piezobalance flow rate (1 L/min), we can interpret a negative value as the amount of mass (in ng) lost during that minute. Thus, we can add the consecutive measured positive concentrations to obtain an estimate of the total mass collected by the instrument. We can then add the negative values during the "loss time" (time when the Piezobalance is reading negative values) to obtain an estimate of the total amount of mass lost from the crystal due to evaporation. The absolute value of the ratio of the mass lost to the mass gained over a time t measured from the beginning of the decay period is the volatile fraction $F(t)$.

If the period of time extends to a time when the Piezobalance is no longer recording negative values, we have a direct measurement of the total fraction F_∞ of the aerosol that is volatile.

The two methods are completely equivalent, since the frequency change over time is directly related to the mass gained or lost during that time. The frequency method is convenient and easier than the concentration summation method, but the latter has the advantage of being more relatable to the observed concentrations.

4.1 Results

4.1.1 e-cigarettes

A total of 88 experiments on the e-liquid containing 99.7% VG were carried out comparing the fraction $F(t)$ of material volatilized over a given period of time (i.e., the period we call "loss time" when the Piezobalance is showing net losses of material) ranging from 3 to 99 minutes. A nonlinear estimate of the asymptotic fraction F_∞ is 0.88 (95% CI 0.77-0.99) (Figure 2). The characteristic time τ was 15.7 minutes (95% CI 11.3-20.1 minutes). The time to reach 95% evaporation is 3τ or 47 (CI 34-60) minutes. The estimate of 88% volatile material is in reasonable agreement with the findings of Long (2014) that about 75% of the material in exhaled breath following e-cigarette (VG) inhalation is water.

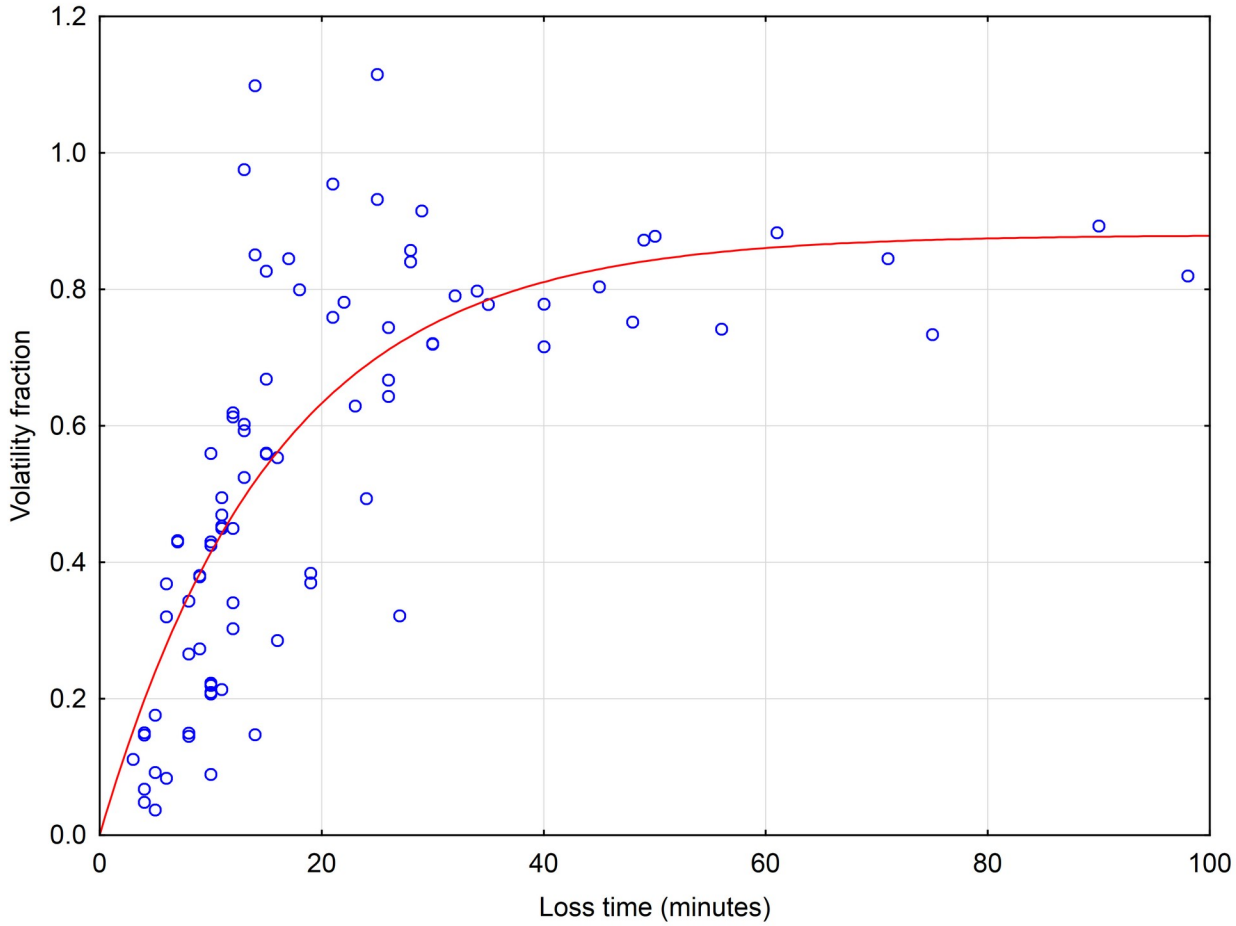

Figure 1. Fraction of Piezobalance particle mass evaporated over the time the Piezobalance is losing mass (the "loss time"). All 88 experimental results are shown. The dozen longest experiments all lie within the 70-90% range. The asymptotic fraction F_∞ is 88% (CI 77-99%), and the time to reach 95% of the total is 3τ = 47 minutes (CI 33-60 minutes).

An experiment on 5/12/2018 illustrates the two methods of determining the volatile fraction $F(t)$ for an e-cigarette (Figure 2). On this day, four puffs of an e-cigarette consisting of 99.7% VG were taken in rapid succession, and the decay was followed for 99 minutes after the peak concentration was achieved. As shown by the curve and text shown in blue on the figure, the frequency difference between the exposed and unexposed crystals increased from 2609 Hz to a peak of 5362 Hz over a 10-minute period. The frequency then declined to a new apparent steady state of 3132 Hz over the next 99 minutes (the loss time shown in Figure 1). The ratio of the frequency loss to the frequency gain was 0.81, indicating that 81% of the aerosol was volatilized after 99 minutes ($F(99) = 0.81$). This estimate agrees perfectly with the one obtained from adding up the 99 negative readings and comparing to the sum of the 10 positive readings at the beginning of the experiment, which is illustrated by the red curve and text shown on this figure. The blue curve and numbers on Figure 1 illustrate Method 1, and the red curve and numbers illustrate Method 2 of analyzing the Piezobalance decay rates. Both methods yielded the same volatility estimate of 81%.

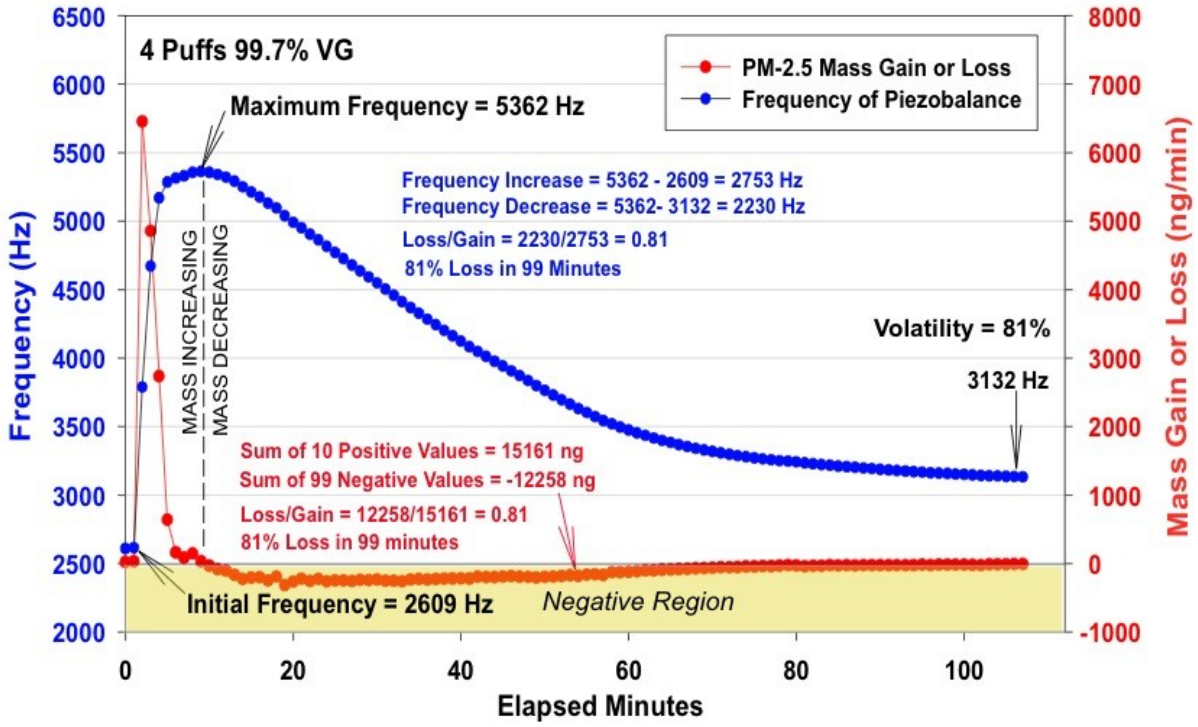

Figure 2. Experiment showing loss of volatile material from the e-cigarette vapor as a function of time. Change in frequency (blue) and mass accumulation (red) of the Piezobalance following 4 puffs from an e-cigarette. Methods 1 and 2 show the same volatility of 81%.

An example of a single daily experimental session at the Redwood City site comparing the mean concentrations of 99.7% VG aerosol recorded by 3 Piezobalances is provided (Figure S1). It is also possible to fit a single experimental result using the same approach. Measuring from the frequency maximum, one calculates for each time step the fraction $F(t)$ of the total frequency gain ($F_{peak} - F(0)$) that is lost during that time step. Nonlinear estimation can then be used to determine the two parameters F_∞ and τ. An example is provided (Figure 3).

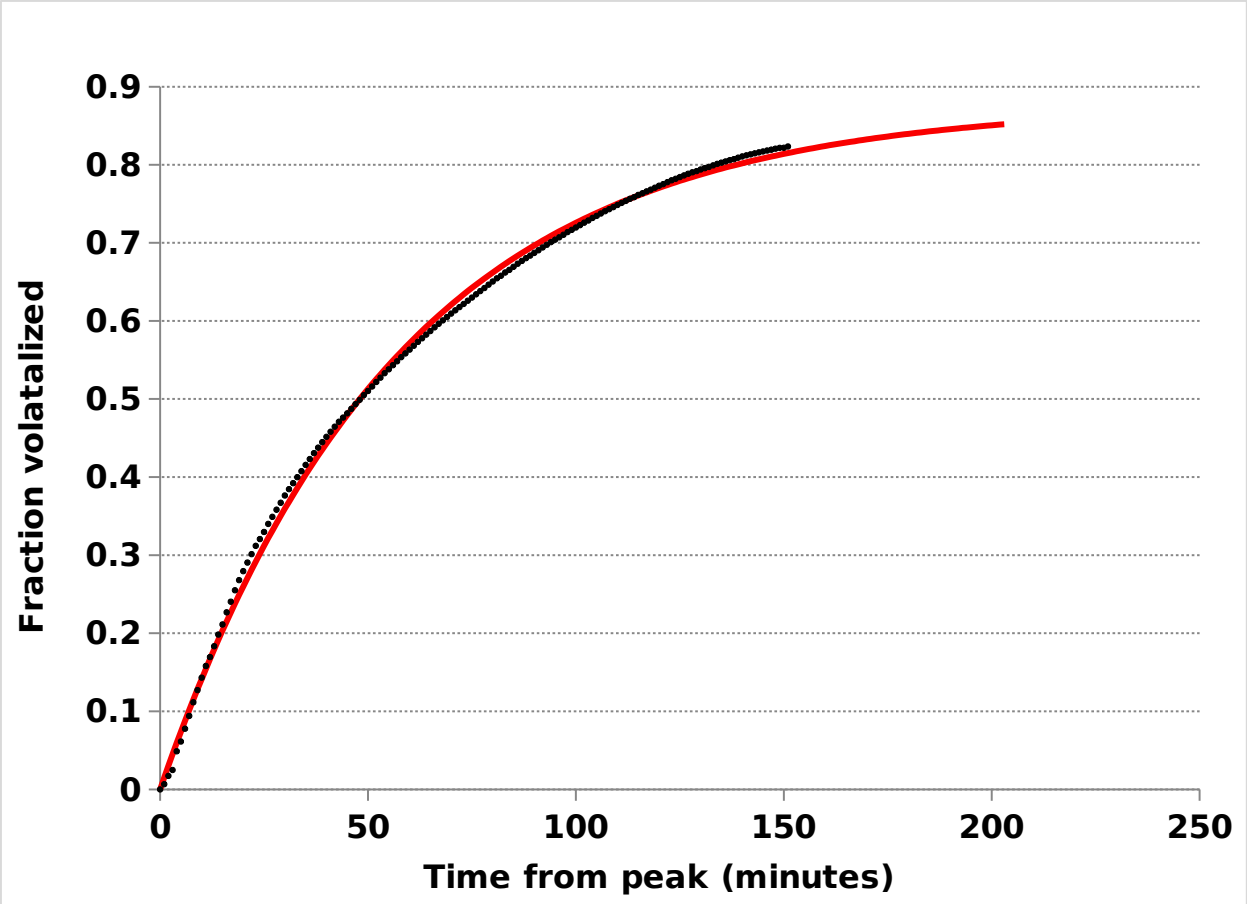

Figure 3. On 9/14/2019, the measured e-cigarette fraction volatilized as a function of time $F(t)$ from a vaping fluid of 35/65 PG/VG was fit using nonlinear estimation to determine the two parameters F_∞ and the characteristic time *tau* (τ) in the equation $F(t) = F_\infty ((1-\exp(-t/\tau))$.

Measured e-cigarette decay rates for the SidePak monitors accelerate over time (Figure 4). The decay rates for the e-cigarettes are extraordinarily large and suggest that evaporation is occurring rapidly during the short residence times of several minutes. The rates are also not constant over time. There is an initial peak followed by a sharp decay, then a rise to a lower peak. We interpret this as the passage of a plume over the monitors, followed by a period of lower concentrations, and then a return to a lower peak as the aerosol becomes better mixed. For the first 1 or 2 minutes after this secondary peak, during which the concentration may drop to 10% or even 1% of the peak, there is one decay rate that can be fitted usually with an R^2 value above 98%. Over the next period of some seconds, the decay rate increases sharply. Finally, it appears to level off at values on the order of 5% or less of the initial values. We interpret the *initial* rates as driven by evaporation, since the observed rate is on the order of 50 h^{-1}, far greater than the rates of deposition + air exchange, which are normally on the order of 0.4 h^{-1} for $PM_{2.5}$ deposition (Özkaynak et al., 1996) and range between 0.1 and 2 h^{-1} for air exchange rates (Chan et al., 2013). The subsequent *increase* in the rates is also related to evaporation, and marks a period of shrinkage of the droplets as noted by Hinds (1999). The rate of evaporation is controlled by the

rate at which molecules can diffuse away from the droplet. The rate increases because as the particles shrink, it is easier for molecules to escape from the more strongly curved surface (the Kelvin effect). (However, a calculation of the Kelvin effect for 0.1 and 0.4 um droplets suggests that the Kelvin effect alone only accounts for 16% and 6% of the increase in evaporation rate, whereas our observed increases in the rate seem to be larger). Hinds (1999) includes a graph (Figure 13.11, p. 298, 2nd edition) showing a similar shape to our Figure 4 with a gradually increasing rate of shrinkage of the droplets. The graph in Hinds (1999) shows that the time for the droplet diameter to approach zero is given in milliseconds to seconds for water droplets, whereas Table 13.3 (p. 301) shows that the droplet lifetime for larger molecules such as di (2-ethyl-hexyl) phthalate with a diameter of 1 μm is 30,000 s (20 h).

The *final* much slower decay occurs after evaporation is complete and represents the deposition rate of the nonvolatile portion of the aerosol added to the air exchange rate of the room with outdoor air. The overall mean residence time – the reciprocal of the decay rate – was only 1.09 minutes, and the natural logarithm of the concentration decay was curved and not a straight line. The time to return to background is also extremely short (4 minutes).

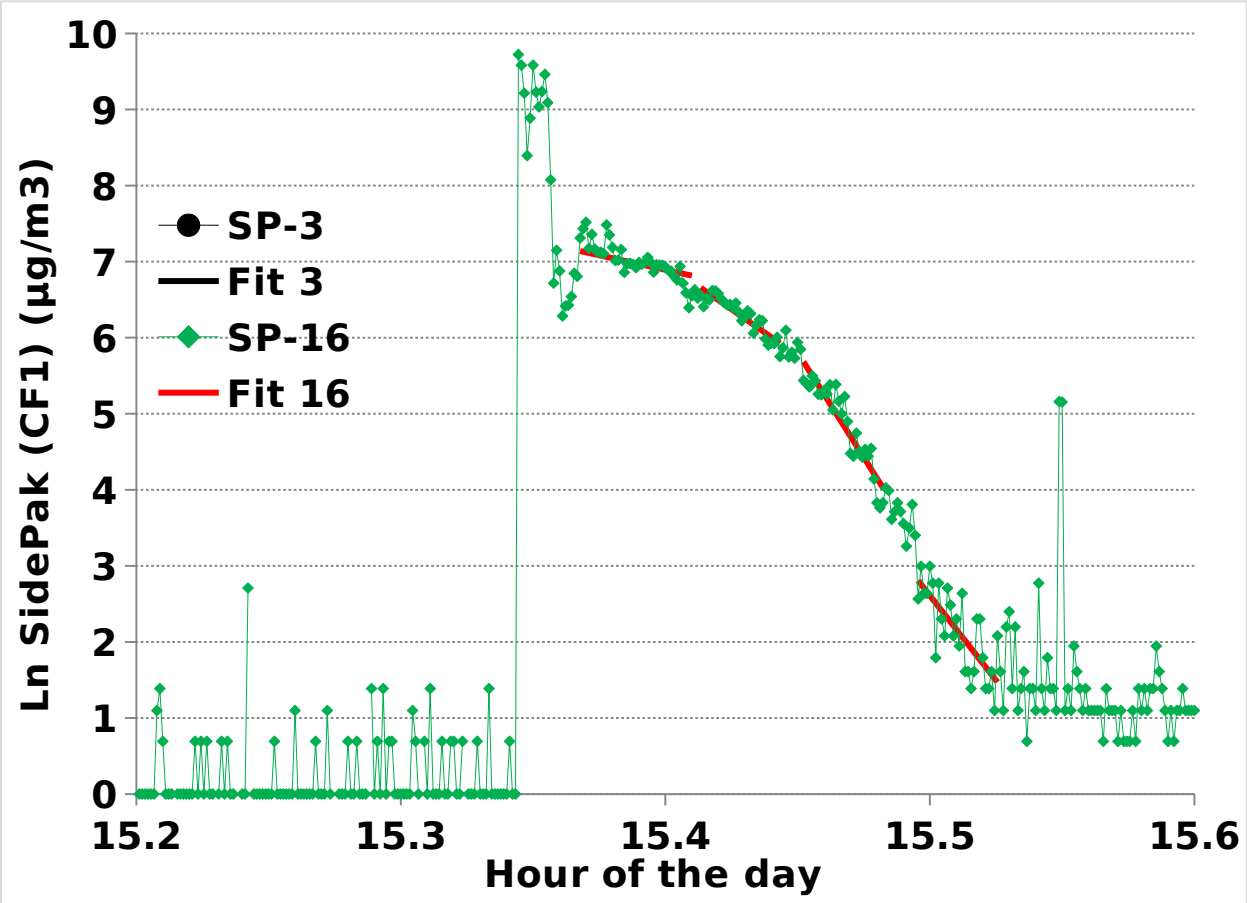

Figure 4. Acceleration of aerosol decay rates attributed to evaporation of e-cigarette aerosol. Data from two collocated SidePaks (4-s averages). The names SP-3 and SP-16 identify the two SidePak monitors used in this experiment.

The Piezobalances also show an acceleration of decay rates over time. However, what they record is the net accumulation of mass on the quartz crystal. This varies according to *two* modes of evaporation—evaporation from the aerosol droplets in the air, and evaporation of the aerosol from the crystal surface. Evaporation from the airborne aerosol results in less mass accumulation on the crystal, and evaporation from the crystal itself adds to this loss. The Piezobalances very quickly reach a point of losing mass faster than they are gaining it. In fact, a substantial portion of experiments (14 of 76, or 18%) returned only one positive value (first minute after the puff) before a run of negative values. Since the Piezobalances are recording two modes of decay and the SidePaks only one, we expect the decay rates to be higher, and the time to return to background shorter, for the Piezobalances (Table 1).

Table 1. Decay rates, peak concentrations, and time to return to background for the Piezobalances and SidePaks in multiple experiments on e-cigarette emissions.

	Decay rates Piezos (h^{-1})	Decay rates SidePaks (h^{-1})	Peak 1-min mass gains Piezos (ng)	Peak 1-min concentrations SidePaks ($\mu g/m^3$)	Time to return to background Piezos (minutes)	Time to return to background SidePaks (minutes)
Valid N	64	78	88	78	76	77
Mean	55.2	39.9	1560	1248	4.0	9.9
Median	52.7	31.6	281	697	3	9
Std.Dev.	34.1	25.6	3540	1405	2.7	5.1
Std.Err.	4.3	2.9	377	159	0.3	0.6

All experiments described above included an e-liquid containing 99.7% VG.

Multiple experiments were also performed on pure PG. We varied the distance from the two Piezobalances and the number of puffs as important variables, and recorded the maximum concentration (or mass accumulation rate), the decay rates, and the calculated volatility fraction (Table S1). These experiments showed that at least 8-16 rapid-fire puffs directed at the Piezobalances were required to reach large mass accumulations rates >1000 ng/min (Table 2). A nonlinear analysis showed that the number of puffs was dominant over the distance variable, with significant coefficients for all three endpoints for the number of puffs and nonsignificant coefficients for all three endpoints for the distance from the Piezobalance.

Table 2. Effect of number of puffs of 100% PG on peak concentration (mass accumulation rate), decay time, and volatility fraction observed for a Piezobalance.

# of puffs	# tests	Distance from S5 Piezo	Peak increased mass accumula	Decay time (minutes)	Volatility fraction

		(m)	tion rate (ng/minute)		
1	2	0.3	114	1	0.16
1.5	1	0.3	211	1	0.62
2	1	0.65	139	1	0.2
4	1	0.65	113	1	0.11
8	1	0.65	1307	4	0.65
12	1	1.2	445	1	0.72
16	7	0.52	2474	6.14	0.49
20	1	0.5	54	1	0.25

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557 This result suggests that 100% PG liquids produce much less aerosol than VG-containing liquids
558 and that evaporation is extraordinarily rapid for PG aerosols, as expected from the ~100-fold
559 higher volatility for PG (Figure S2). A comparison of pure PG results from 16 puffs vs. pure VG
560 results from one puff shows extremely high VG/PG mass ratios (Figure S3).
561

562 **4.2 Marijuana**
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564 A total of 124 marijuana vaping tests were carried out between May 21, 2018 and May 28, 2019.
565 On 122 of those tests, one or both Piezobalances provided estimates of the volatile fraction as a
566 function of decay time (Figure S4). Experiments were varied according to the number of puffs;
567 the heating protocol for the vape pen (Protocol I: low temperature; Protocol II: high
568 temperature); number of fans used; and CBD/THC ratio) (Table S2).
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571

572 Basic statistics for the 124 experiments are provided in Table 3.

Table 3. Basic statistics for the 124 marijuana vaping experiments with decay times for Piezobalances S5 and S6 and averaged source strength and decay rates

	N	Mean	SD	SE	Min	10th %tile	Lower quartile	Upper quartile	Median	90th %tile	Max
Decay time S5 (h)	111	4.4	3.8	0.36	0.50	1.07	1.90	5.67	2.90	10	18
Decay time S6 (h)	85	3.2	3.0	0.33	0.50	1.00	1.55	3.23	2.25	6.5	16
Source strength (mg/puff)	124	3.1	2.3	0.20	0.36	1.00	1.28	4.28	2.38	6.30	9.97
Decay rate (h^{-1})	124	1.6	1.0	0.09	0.33	0.52	0.84	2.12	1.31	2.89	5.03
Air exchange rate (h^{-1})	29	0.13	0.04	0.008	0.06	0.08	0.09	0.15	0.12	0.21	0.23
Tmin (°C)	124	23.0	2.3	0.20	16.4	19.9	21.7	24.6	23.1	25.8	28.5
Tmax (°C)	124	26.2	3.2	0.29	18.4	22.0	23.7	29.1	26.5	29.9	31.6
Delta T (°C)	124	3.1	1.6	0.15	0.24	1.1	1.8	4.3	3.1	5.0	7.6
RH min (%)	115	42.8	4.6	0.43	35.0	37.6	38.5	47.2	42.0	48.9	52.2
RH max (%)	115	47.2	4.1	0.38	40.6	42.2	43.3	50.6	46.8	53.3	55.7
Delta RH (%)	115	4.4	1.9	0.18	1.16	2.1	2.9	5.6	4.1	7.5	9.2

The measured volatility of the marijuana aerosol depended heavily on the puffing protocol (Table 4). Using the lower-temperature Protocol I, among five tested marijuana cartridges with different CBD/THC ratios (i.e., 2:1, 8:1, and 18:1), the estimates of the volatility fraction of exhaled marijuana aerosol were only 5-7% ($N = 106$) by Piezobalances. However, using the higher-temperature Protocol II ($N = 18$), mass emissions were consistently about 3 times higher than those observed using Protocol I (7.6 mg/puff compared to 2.4 mg/puff). Presumably the increased mass consists of additional compounds with higher boiling points being released. Also, Protocol II resulted in considerably higher volatility fractions compared to Protocol I. However, to observe the full loss of material from the crystal required very long (5-20 h) decay periods. This may be due to the additional compounds being slower to evaporate from the crystal.

Table 4. Volatility fraction for two Piezobalances comparing the high-temperature marijuana vaping Protocol II to the lower-temperature Protocol I.

	N	Mean	Std.Err.	25th	Median	75th	Max
High-temperature Protocol II							
Piezobalance S5	18	0.34	0.037	0.16	0.42	0.44	0.53
Piezobalance S6	8	0.25	0.047	0.19	0.25	0.34	0.46
Lower-temperature Protocol I							

Piezobalance S5	92	0.07	0.012	0	0	0.13	0.47
Piezobalance S6	78	0.05	0.011	0	0	0.06	0.47

Of the various parameters such as CBD/THC ratio, number of fans, air exchange rates, temperature and RH, only RH showed a significant effect in a nonlinear model for the mean volatility fraction (Table 8). Although RH was about 4% higher during the times when Protocol II was being used (46.2 (SD 2.5)% vs. 42.2 (4.1)%), it was not significantly higher as shown by the boxplots in Figure S5. Nonetheless, the higher RH had a small but significant effect in lowering the volatility fraction by about 2.5%. This presumably would be due to the higher atmospheric vapor pressure reducing the aerosol evaporation rate.

Table 5. Effect of ancillary parameters on volatility fraction

	Estimate	Standard error	t-value	p-value	Lower Conf	Upper Conf
protocol	**0.231**	**0.076**	**3.0**	**0.008**	**0.070**	**0.391**
RH	**-0.025**	**0.010**	**-2.5**	**0.023**	**0.046**	**-0.004**
No. of puffs	0.509	0.921	0.6	0.6	-1.43	2.45
decay time	-0.003	0.007	-0.5	0.7	-0.02	0.01
decay rate	-0.195	0.126	-1.5	0.1	-0.46	0.07
Air exchange rate	-0.318	0.448	-0.7	0.5	-1.26	0.63
Temperature	0.009	0.009	1.1	0.3	-0.01	0.03
CBD/THC ratio	323.2	75748	0.0004	0.999	-1597	1598

The volatile fraction for these marijuana experiments was estimated in the same way as shown above for the e-cigarette experiments. That is, the mass accumulation rates were determined minute by minute, and the associated frequency curves showing the total accumulation were plotted. An example is provided in Figures 5 and 6.

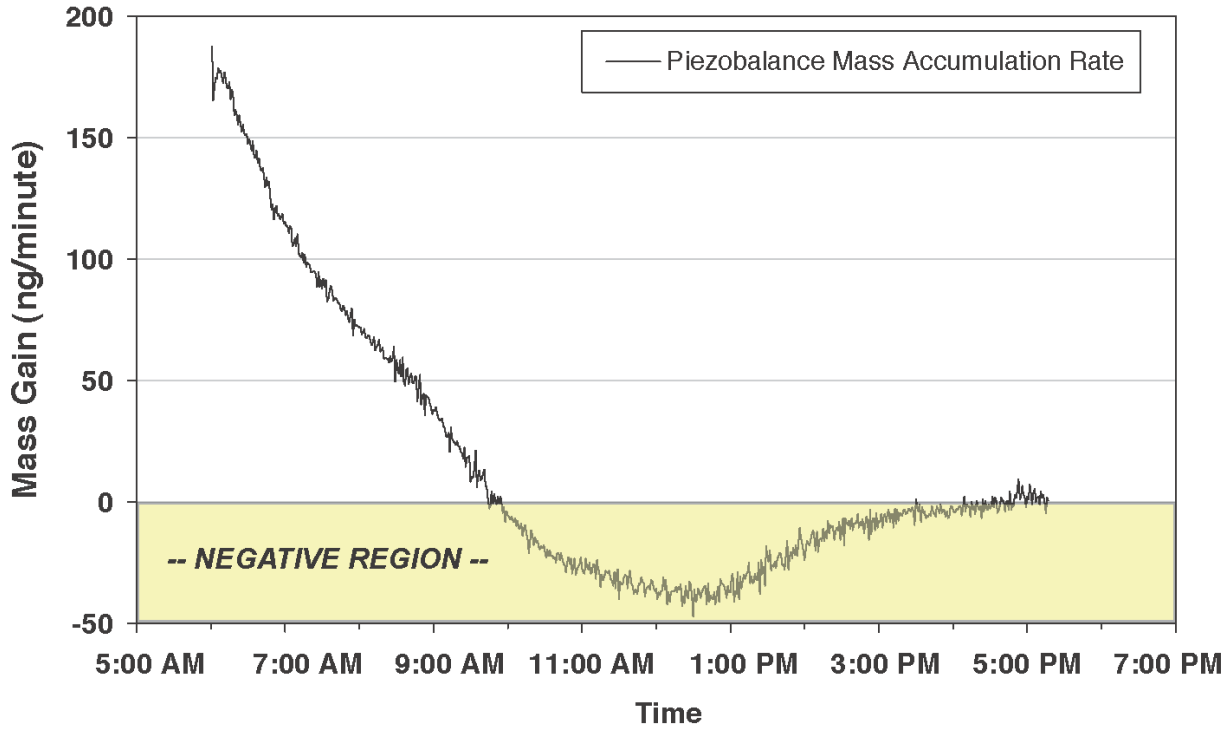

Figure 5. Piezobalance mass accumulation rate in marijuana vaping experiment. On April 28, 2019, the Piezobalance showed a maximum rate of mass accumulation of about 175 ng/ minute, followed by a decline until the mass begins to be lost from the crystal, reaching a peak loss rate of nearly 50 ng/minute before gradually returning to equilibrium about 12 hours later.

Using Method 2 that was illustrated in Figure 2, the volatile fraction for vaping marijuana can be determined directly from Figure 5 by integrating the positive and negative areas under the curve and taking the absolute value of the ratio, which turned out to be 0.43. As before, Method 1 offers an easier way to calculate the volatile fraction directly from the frequency curve (Figure 6). The ratio of the decrease in frequency to its increase provides the volatility fraction.

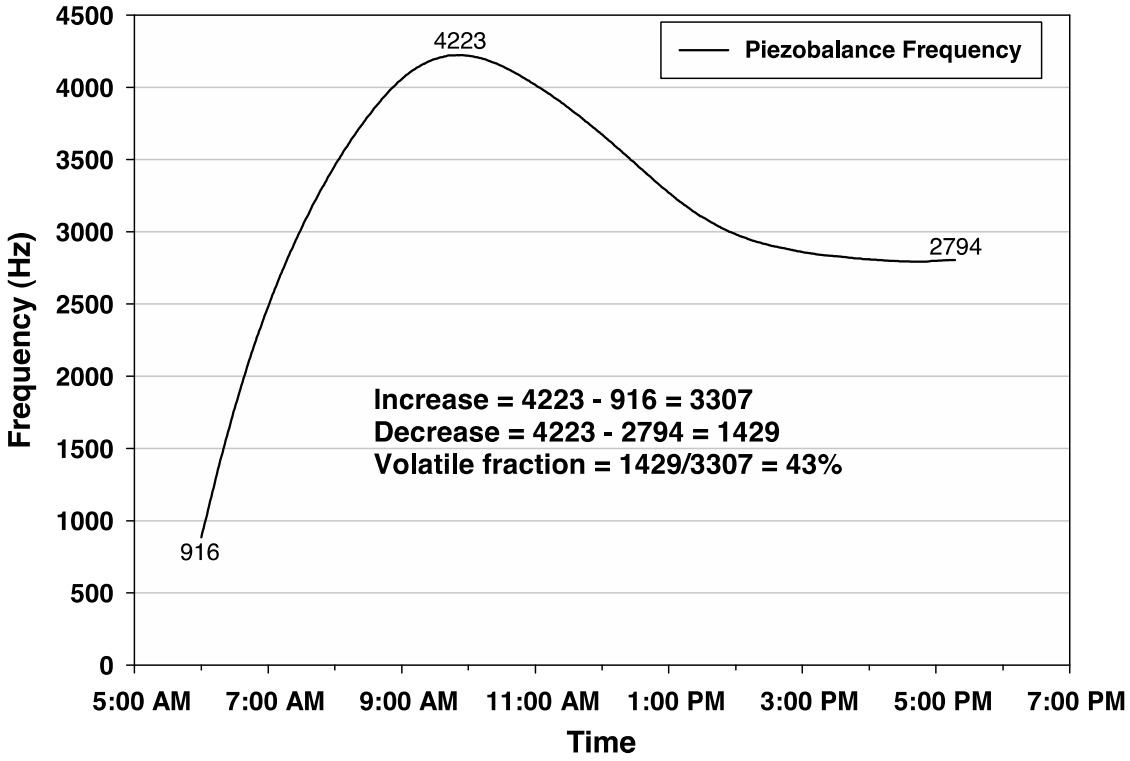

Figure 6. Frequency curve for the same mass concentrations that were shown in Figure 5. Using Method 1, the volatility fraction can be determined directly from the Piezobalance frequency curve in this figure. The increase to the peak frequency and the decrease to the final equilibrium frequency provide the two values needed to determine the volatile fraction of 43%.

Beginning on April 25, 2019, an 8-day series of experiments was carried out under Protocol II with a single puff of 2:1 CBD/THC marijuana liquid each day. Six of the 8 experiments were followed sufficiently long (8-18 hours) to determine the final volatility fraction, which averaged close to 47% (SD 5%) (Table S3). This mean volatility fraction of 47% associated with Protocol II is significantly ($p < 0.0001$) greater than the 5-7% values shown under Protocol I. Other experiments at the Redwood City location using Protocol II also found higher source strengths and volatility fractions compared to experiments using Protocol I.

Measured decay rates for both the SidePak and Piezobalance tend to accelerate over time (Figure 7). As a practical matter, we find that the decay rates for most experiments on marijuana vaping remain constant over time for the first hour or two (usually with R^2 values >95%) and then accelerate. Therefore, in referring to "decay rates" it is these relatively constant *initial* rates that are meant. Decay rates observed for marijuana aerosols are far lower than those for e-cigarettes, reflecting the much lower volatility fraction for the marijuana aerosols. These vaping decay rates are strongly affected by the use of table fans (Table 9).

Table 6. Piezobalance decay rates (h^{-1}) as a function of fan configuration.

Piezo decay rate (h^{-1})	N	Mean	Std.Err.	25th	Median	75th	Maximum
fan off	88	1.22	0.07	0.71	1.06	1.65	4.27
1 fan on	29	2.29	0.21	1.34	2.10	3.11	5.03
2 fans on	8	3.05	0.35	2.39	3.04	3.84	4.40

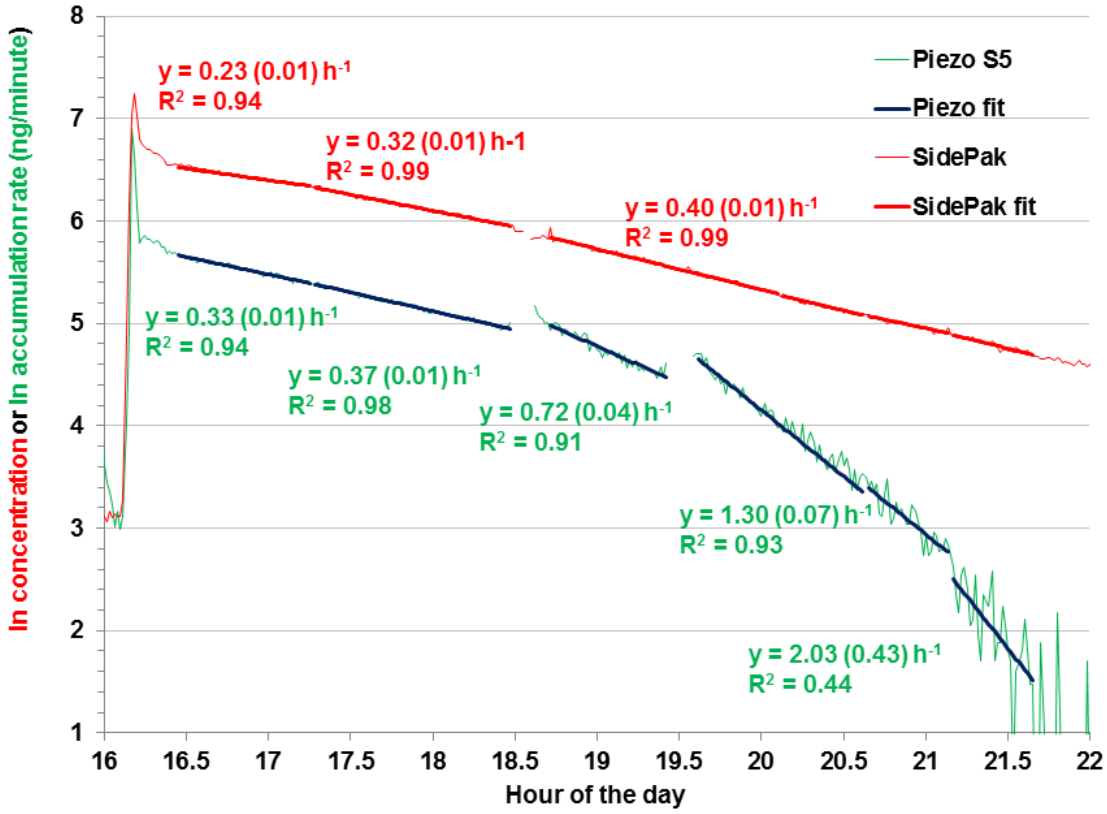

Figure 7. Acceleration of marijuana vapor decay rates due to evaporation. Increased rates measured by SidePak (red) suggest some volatility shown by the airborne aerosol. Increased rates measured by Piezobalance show rapid evaporation from the quartz crystal.

4.3 Comparison of e-cigarettes and marijuana exposures

We have found that both e-cigarettes and marijuana vaping produce aerosols showing strong concentration peaks accompanied by some volatility. However, the differences in resulting exposures are large on a per-puff basis. Figure 8 shows that the peak concentrations observed from e-cigarettes disappear in minutes, whereas the exposure from marijuana vaping can last for up to 8 hours. Secondhand exposures (concentration × time) in this example were 152 μg/m^3-h for the marijuana aerosol (3 puffs) and 77 μg/m^3-h for the e-cigarettes (12 puffs), or about a factor of 8 on a per-puff basis.

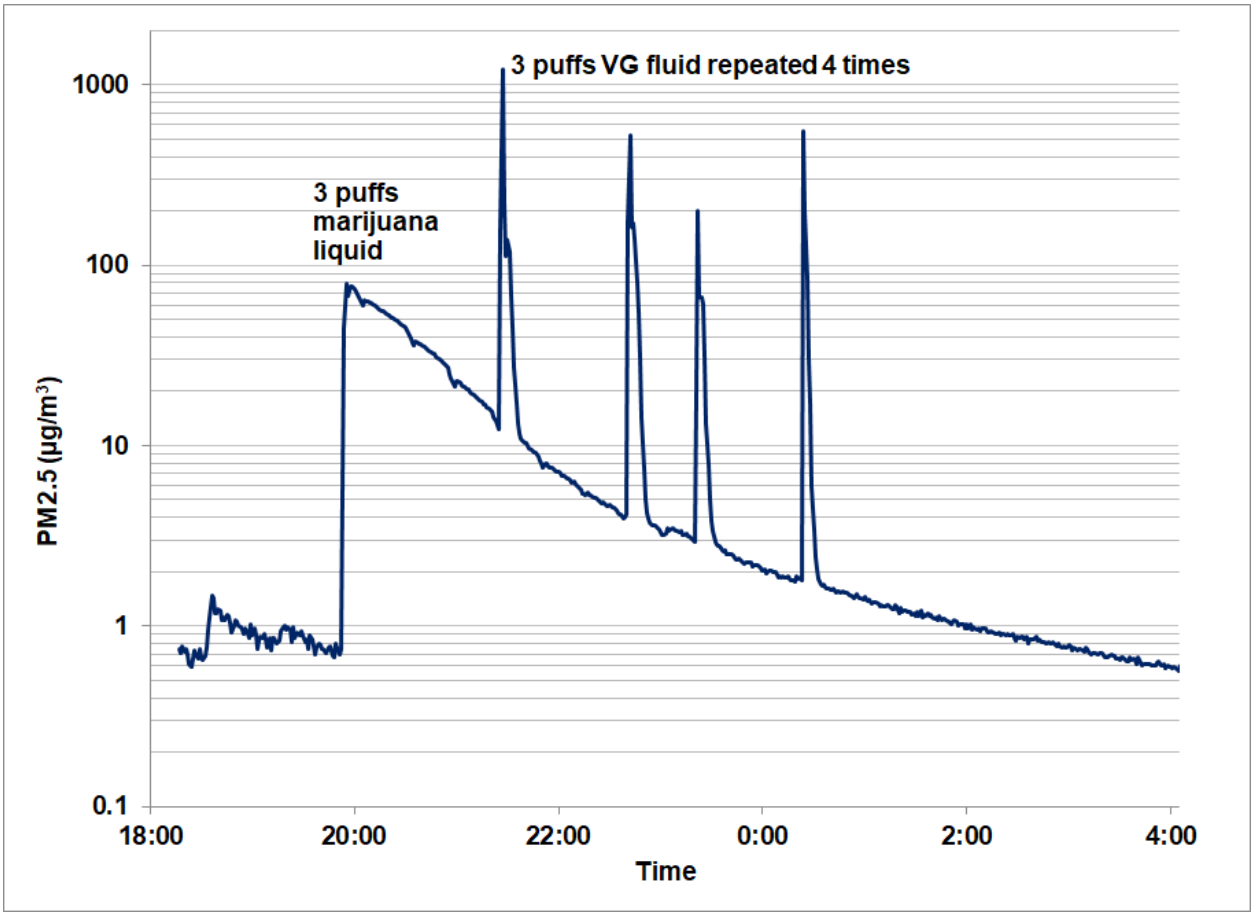

Figure 8. Time to return to room background for e-cigarette aerosol compared to marijuana aerosol. Following 3 puffs of marijuana liquid, on four separate occasions there was an additional set of 3 puffs of a 99.7% pure VG e-liquid. A single instrument (the SidePak) recorded the concentration.

4.4 Limitations of the Study

Because the e-cigarette aerosol evaporates so rapidly, the normal approach of collecting material and weighing it in a collocated gravimetric device cannot be used. We have therefore not been able to determine the density of the e-cigarette aerosol, and therefore the readings of the Piezobalance are only within some unknown calibration factor of the actual concentration. The Piezobalance is factory calibrated using welding particles, and the density of these is not known. However, multiple studies have indicated that the Piezobalance is a good estimator (within ±15%) of tobacco smoke particle concentrations (Repace and Lowrey. 1980; Ott et al., 1996). For example, Fairchild et al., (1980) compared two Piezobalances to gravimetric measurements of 8 aerosol sources, including coal dust, silica dust, arc-welding fumes, polydisperse phthalate, etc. High R^2 values of 83-93% were obtained for 1-minute, 15-minute, 1-hour and daily samples, although positive biases were observed. Earlier Sem et al., (1977) compared the Piezobalance to gravimetric measures of several aerosols and found agreement within 10% for all tested aerosols except for environmental tobacco smoke (15%). Ingebrigtsen et al., (1988) found general

agreement between the Piezobalance and gravimetric measurements of ETS, provided careful flow checks were made to adjust the calibration of individual instruments.

Our study of e-cigarettes is also limited to estimating room concentrations produced by a single person. With the high observed rate of evaporation, it is not possible for a single vaper to bring the room air to a stable well-mixed concentration; however, for multiple vapers in one room, it might be possible to attain a well-mixed condition, and in that case, there might be a slower rate of decay when the vaping ceases. This case of multiple vapers may be of interest for future research.

5.1 Discussion

Our study employed optical monitors to detect aerosol volatility, as measured by the increase in the decay rate over time. We also used the Piezobalance to measure the combined losses due to aerosol volatility and evaporation from the crystal surface. To our knowledge, this is the first study to present a method for using the Piezobalance to estimate the volatility of an aerosol mixture.

A primary finding of this investigation is the extreme rapidity with which the e-cigarette aerosols return to background, ranging between just 1-10 minutes. A second finding is the large fraction of the pure (99.7%) VG aerosol that is subject to evaporation, averaging 88%.
These two findings indicate that e-cigarette exposures will be brief following a puff and will quickly fall to the background concentration. The experimental rooms were quite small, the air exchange rates were very low ($< 0.4\ h^{-1}$), and therefore the concentrations measured here are likely to be near the maximum concentrations observed in most homes. An average-size home will be 5-10 times the volume of these rooms and thus house-wide exposures will be 5-10 times lower than the values reported here. The rapidity with which the aerosol disappears will ensure that good mixing will not occur throughout the home, meaning that persons a few meters away from the vaper will be exposed to aerosol concentrations for a very short time. For 100% PG, the aerosol concentrations will be negligible for persons at a distance >0.65 m.

These findings for e-cigarettes are very different from the results reported here for marijuana vaping. Exhaled marijuana aerosols remain elevated in the home for hours as opposed to about 6-8 minutes. Secondhand exposure to marijuana aerosol was both substantial and long-lasting, with mean $PM_{2.5}$ concentrations during the nine hours after one or several puffs about 10 times the background level. For most tests using Protocol I (Low to moderate temperatures), volatility was low at around 5-7%. However, for Protocol II (higher temperatures), the volatility was much higher at 36-45%. Because of the long residence times and relatively high $PM_{2.5}$ concentrations caused by marijuana vaping, future research should include studies of air pollution from marijuana vaping indoors.

6.1 Conclusions

This paper shows that a monitor designed to measure and record mass accumulation on a minute-by-minute basis can be used to estimate the volatility of the aerosols produced by vaping. For e-

cigarettes, a major portion (88%; CI 77-99%) evaporates within a few minutes. For marijuana liquids, the major portion lasts for hours. Volatility of the marijuana liquids appears to depend on peak temperature liquid reached during the heating process; low temperatures (Protocol I) showed low (5-7%) volatility and high temperatures (Protocol II) showed higher (25-34%) volatility. This new methodology for measuring the rate of change of the mass collected on a surface on a minute-by-minute basis could enhance our understanding of aerosol dynamics including volatility.

7.1 Conflicts of interest

The authors declare no conflicts of interest.

8.1 Funding Source

This study was supported in part by a grant awarded to Stanford University to study secondhand exposure to marijuana: Agreement #28IR-0062 sponsored by the University of California Office of the President; Tobacco Related-Disease Research Program (TRDRP).

8.1.1 Ethical considerations

As part of that grant, the Stanford Institutional Review Board (IRB) gave approval to the authors to carry out human experimentation. Since no human subjects were recruited for the experiments presented in this paper, telephone contact was made with a member of the IRB to obtain his opinion on whether IRB coverage of the authors was needed by the IRB. His advice was that IRB review is not required if the researchers doing the study are the only human subjects. Finally, the emissions of every experiment were produced by a subset of the authors, who were experienced in inhaling both nicotine and marijuana smoke, and no persons were present in the room during the air pollutant decay periods. No other individuals participated in the smoking or vaping activities, nor were any persons other than the authors exposed to the aerosols produced.

8.1.2 Role of funding source

The funding source had no involvement in the study design, collection, analysis, or interpretation of data, writing or editing of the report, or the decision to seek publication.

9.1 CRediT authorship contribution statement

Lance Wallace: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **Wayne Ott:** Methodology, Software, Validation, Investigation, Formal analysis, Writing - review & editing. **Tongke Zhao:** Methodology, Validation, Investigation, Formal analysis, Writing - review & editing. **Kai-Chung Cheng:** Methodology, Validation, Investigation, Formal analysis, Writing - review & editing, Project administration. **Lynn Hildemann:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

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