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Assessment of tobacco heating product THP1.0. Part 4: Characterisation of indoor air quality and odour

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ABSTRACT

The tobacco heating product THP1.0, which heats but does not burn tobacco, was tested as part of a modified-risk tobacco product assessment framework for its impacts on indoor air quality and residual tobacco smoke odour. THP1.0 heats the tobacco to less than 240 °C ± 5 °C during puffs. An environmentally controlled room was used to simulate ventilation conditions corresponding to residential, office and hospitality environments. An analysis of known tobacco smoke constituents, included CO, CO_2, NO, NO_2, nicotine, glycerol, 3-ethenyl pyridine, sixteen polycyclic aromatic hydrocarbons, eight volatile organic compounds, four carbonyls, four tobacco-specific nitrosamines and total aerosol particulate matter. Significant emissions reductions in comparison to conventional cigarettes were measured for THP1.0. Levels of nicotine, acetaldehyde, formaldehyde and particulate matter emitted from THP1.0 exceeded ambient air measurements, but were more than 90% reduced relative to cigarette smoke emissions within the laboratory conditions defined Residual tobacco smoke odour was assessed by trained sensory panels after exposure of cloth, hair and skin to both mainstream and environmental emissions from the test products. Residual tobacco smoke odour was significantly lower from THP1.0 than from a conventional cigarette. These data show that using THP1.0 has the potential to result in considerably reduced environmental emissions that affect indoor air quality relative to conventional cigarettes.

1. Introduction

Cigarette smoking has been described as one of the leading preventable causes of human diseases, such as cardiovascular disorders, chronic obstructive pulmonary disease and lung cancer (IARC, 1986; US DHHS, 2010; US DHHS, 2014). Scientists widely agree that it is largely the toxicants and not the nicotine found in cigarette smoke that cause smoking-related diseases (Farsalinos and Le Houezec, 2015). When a cigarette is lit, the tobacco burns, and is pyrolysed and vaporised to form smoke containing more than 6500 compounds (Rodgman and Perfetti, 2013), approximately 150 of which are thought to be toxicants (Fowles and Dybing, 2003). As described earlier in this compendium (Forster et al., 2017), tobacco heating products (THPs), where a sample of tobacco is heated to temperatures sufficient to vaporise volatile compounds, including nicotine, into an inhalable aerosol but not high enough to burn the tobacco, have the potential to significantly reduce the levels of combustion-derived toxicants in the generated aerosol as compared to smoke from conventional cigarettes (Forster et al., 2015; Gonzalez-Suarez et al., 2016; Mitova et al., 2016; Ruprecht et al., 2017; Schorp et al., 2012; Smith et al., 2016; Zenzen et al., 2012).

Conventional cigarettes produce two types of smoke: mainstream smoke, which is inhaled directly by consumers and portions of which are exhaled to the environment, and sidestream smoke, which is produced from the lit end of the cigarette that smoulders as the cigarette burns down. Sidestream smoke is formed at lower temperatures than mainstream smoke (600 °C vs. 900 °C) in an oxygen-deficient environment, and cools and is diluted rapidly after leaving the cigarette, forming a condensation aerosol. In general, total sidestream emissions exceed mainstream emissions,

Abbreviations: 3-EP, 3-ethenyl pyridine; EHCSS, electrically heated cigarette smoking system; ETS, environmental tobacco smoke; GC-MS, gas chromatography–mass spectrometry; IAQ, indoor air quality; NGP, next-generation product; PAH, polycyclic aromatic hydrocarbon; PM, particulate matter; RTS, residual tobacco smoke; THP, tobacco heating product; THS, tobacco heating system; TSNA, tobacco-specific nitrosamine; TVOC, total volatile organic compound; VOC, volatile organic compound.

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normally by a factor of 2–3, although subsequent human exposure concentrations are typically lower than those in mainstream smoke because the sidestream smoke is rapidly diluted.

Sidestream smoke can have higher absolute emissions of toxicants, such as ammonia (40–170-fold), particulate matter (PM), nicotine and nitrogen oxides (threefold), volatile organic compounds (VOCs) and carbonyls (onefold to threefold), or lower levels of constituents such as *N*-nitrosamines (0.26–0.55-fold) than mainstream smoke (IARC, 2004; based on smoking to Massachusetts smoking parameters from Borgerding et al., 2000). Sidestream smoke particles are reported to be slightly smaller than mainstream smoke particles (100 nm vs. 180 nm geometric diameter; Guerin et al., 1987). Environmental tobacco smoke (ETS) has been described as a mixture of sidestream smoke and exhaled mainstream smoke, the latter contributing 1–43% of the mixture (Baker and Proctor, 1990).

A series of reviews have summarised potential health risks to non-smokers from exposure to ETS (California EPA, 2005; IARC, 2004; NCI, 1999; US DHHS, 2006; US EPA, 1992). Significant toxicants identified in ETS include the respiratory irritants ammonia, formaldehyde and sulfur dioxide; acrolein and hydrogen cyanide; and nitrogen oxides and phenol (US DHHS, 2016). Around 50 constituents have been identified as or are reasonably anticipated to be human carcinogens, and most of them are present in the particulate phase (IARC, 2004).

According to the US Surgeon General, even brief exposure to ETS can be harmful to health and, on the basis that smoke contains DNA-damaging carcinogens, that there is no risk-free level of exposure (US DHHS, 2006; 2014, 2016). Among adults who have never smoked, ETS is reported to have immediate harmful effects on the heart and blood vessels (US DHHS, 2006; 2014), and these reviews report there is a significant association between ETS exposure and lung cancer, cardiovascular disease, pulmonary function deficits and other diseases, as well as serious respiratory conditions and other adverse health effects in infants and children.

There is also discussion of potential exposure to residual tobacco smoke (RTS) — that is, the tobacco smoke residue from cigarettes and other tobacco products that deposits after smoking and may accumulate on indoor surfaces and furnishings. This residue is reported to contain nicotine and other chemicals, including 3-ethenyl pyridine (3-EP), phenol, cresols, naphthalene, formaldehyde and tobacco-specific nitrosamines (TSNAs) (Matt et al., 2011a, 2016; Singer et al., 2002, 2003).

Although there is evidence that tobacco smoke pollutants persist on indoor surfaces and in house dust, no quantitative studies have assessed their resuspension in the atmosphere.

Like RTS, tobacco odour can persist indoors and on surfaces after smoking has stopped. New residents of former smokers' homes reported tobacco odour in their homes at a median of 33 days after the smokers had moved out (Matt et al., 2011b). Although in the published literature only a few studies have assessed tobacco smoke odour directly (Noguchi et al., 2016), the ratio of odour index to VOC concentration in ETS and RTS is correlated (Noguchi et al., 2016), and many studies have assessed the release of VOCs and semi-VOCs from different clothing fabrics exposed to tobacco smoke emissions (Chien et al., 2011; Ueta et al., 2010; Whelan and Cotte, 2014). Both composition (e.g., natural or synthetic fibres) (Chien et al., 2011; Ueta et al., 2010) and structure (knitted or woven) (Chien et al., 2011) affect the amount and size of compounds that are off-gassed.

Next-generation tobacco and nicotine products (NGPs), such as vapour products and THPs, are likely to produce significantly lower environmental emissions than cigarettes, largely because the tobacco, the source content of the aerosol, is not burnt and/or the product designs should function to prevent sidestream emissions, which are the main contributors to indoor emissions derived from conventional cigarettes. Although the vapour exhaled by consumers of these NGPs has the potential to impact air quality, several studies of indoor air quality (IAQ) have concluded that emissions from electronic cigarette (e-cigarette) aerosols exhaled by consumers are significantly reduced compared to those from conventional cigarettes (Bertholon et al., 2013; Burstyn, 2014; Hess et al., 2016; McAuley et al., 2012; O'Connell et al., 2015a). Limited studies of THPs also support the notion that indoor emissions from these products are significantly lower than those from conventional cigarettes (Mitova et al., 2016; Ruprecht et al., 2017).

Indeed, the potential contribution of NGPs towards tobacco harm reduction, defined by the US Institute of Medicine as "decreasing total morbidity and mortality, without completely eliminating tobacco and nicotine use" (Stratton et al., 2001), can have a considerable impact on reducing the projected health burden of tobacco use. In 2012, the FDA published guidance on assessing the harm reduction potential of a "modified risk tobacco product" through demonstration of reduced toxicant exposure and reduced health risks in comparison to those conferred by conventional cigarette smoking (FDA, 2012). It follows that, given the concerns of public health authorities over the adverse health effects of the exposure to combustible cigarette smoke for non-smokers, substantiating the reduced risk potential of an NGP should include data on the impact of the NGP on air quality in different environments.

The aim of this study was, therefore, to compare, via a simulated indoor exposure model, measured levels of known air quality toxicant markers between THP1.0, which heats but does not burn tobacco, and conventional cigarettes. Tobacco odour intensity was also compared between the two product types by a trained sensory panel. The results demonstrate significantly reduced levels of environmental emissions in respect of measured toxicants and lower tobacco odour intensities associated with aerosol from THP1.0 compared to combustible cigarette smoke, in the test systems employed.

2. Experimental

2.1. Test products

2.1.1. THP1.0

The operation of THP1.0 has been described (Eaton et al., 2017). In brief, the electronically heated THP comprises two main functional parts: an electronic device to host and heat a specially designed tobacco rod (Fig. 1a) and a consumable tobacco rod, consisting of processed tobacco with added glycerol as the main aerosol agent (Fig. 1b).

The electronic heating device contains a rechargeable Li-ion battery (USB rechargeable, 3000 mAh capacity) that supplies the energy to the heating tube when switched on. The heating tube has a heater in two segments that are controlled separately by software, and, thus, the tobacco rod is heated mainly by conduction from its periphery (Fig. 1a). The battery life of the device allows at least 30 repeated uses from a single charge.

The tobacco consumable has a diameter of 5.0 mm, overall length of 82 mm, and a 42-mm tobacco section of (Fig. 1b). The tobacco is a blended Virginia type and is treated by a paper-making reconstitution process (Norman, 1999) to incorporate ~14.5% glycerol (dry-weight basis) into its structure. The diameter of the tobacco rod, which is smaller than an ca. 8 mm conventional kingsize cigarette, allows rapid heat transfer from the peripheral surface to its inner core. The overall dimension of the tobacco section results in a total tobacco weight of approximately 260 mg, as compared with 600–800 mg in a conventional kingsize cigarette.

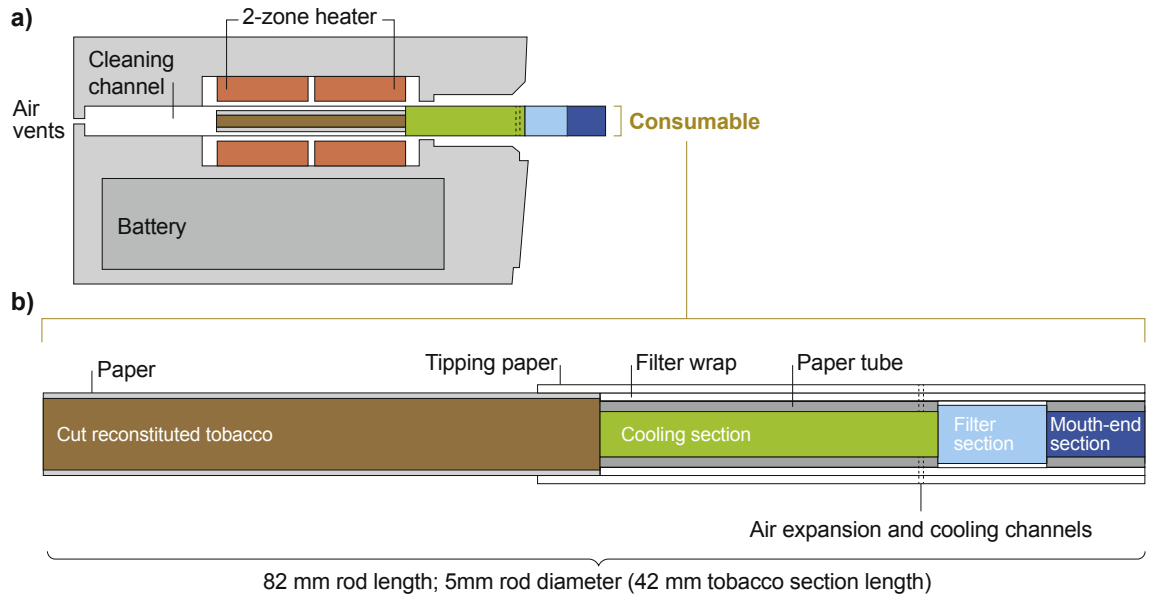

Fig. 1. Schematic drawing of THP1.0. (a) Heating device with a tobacco consumable inserted; (b) physical construction of the tobacco consumable.

During use, a consumable tobacco rod is inserted into the heating tube. On activation of the device by pressing the activation button, the battery-powered heating element reaches approximately 240 °C ± 5 °C. The product is ready for use after approximately 30–40 s. The total heating session is programmed to last an additional 3 min, and the total number of puffs available depends on the frequency and volume of the puffs taken. The device is programmed to shut down at the end of the 3 min, although residual heat will continue to generate aerosol. The consumed tobacco rod can be removed and discarded. The product was developed in accordance with established in-house stewardship protocol for a tobacco product (Costigan and Meredith, 2015).

The THP1.0 devices used in this study were randomly selected from a single batch of commercial devices, sourced from Japan. Prior to all the experiments described in this study, the consumable tobacco rods (a Bright Tobacco Kent Neostick variant, British American Tobacco, London, UK) were tested directly from the pack without conditioning.

2.1.2. Commercial control cigarettes

The IAQ and odour from THP1.0 were compared with those from two commercial cigarettes: a conventional US blend style kingsize cigarette (ISO 'tar' 7 mg) with a conventional cellulose acetate filter (coded as T189, commercially known as Lucky Strike Regular, sourced from Japan); and a conventional kingsize Virginia blend cigarette (ISO 'tar' 9 mg) with a cellulose acetate filter containing activated carbon (coded as D976, commercially known as Du Maurier Silver, sourced from Canada). The 3R4F Kentucky Reference Cigarette (Center for Tobacco Reference Products, University of Kentucky, Lexington, KY, USA), as used for control purposes in other studies of the series, was also used for the odour assessment study. The 3R4F cigarette was deemed unsuitable for the IAQ study because it was not designed for human smoking, only machine smoking.

2.2. IAQ measurements

2.2.1. Study design

The IAQ study was conducted at a testing laboratory accredited by the United Kingdom Accreditation Service for IAQ (VOC and formaldehyde: laboratory number 0578, BRE Ltd, Watford, UK). The study was undertaken in a furnished test office with an adjoining instrument room under three ventilation conditions defined in BS EN 15251 (BSI, 2007): residential II, 1.2 air changes per hour (ACH); office, 2.16 ACH; and hospitality, 7.68 ACH.

During the tests, the following parameters in the test room were measured continuously every 60 s: CO_2, CO, NO_x, ozone (O_3) and PM by size (diameter ≤1, 2.5 and 10 μm [PM_1, $PM_{2.5}$, and PM_{10}] or respirable). In addition, PM_1, $PM_{2.5}$, PM_{10}, NO_x and O_3 were monitored outside the test room building. The following air constituents were sampled continuously over the total 4 h of the test inside the test room: individual and total VOCs; low-molecular-weight carbonyl compounds (formaldehyde, acetaldehyde, acrolein and crotonaldehyde); polycyclic aromatic hydrocarbons (PAHs); nicotine; glycerol; 3-EP; and TSNAs. Particle size, mass and number concentration were also measured continuously every 10 s with an electrical-mobility spectrometer. The species measured were chosen to be representative of known tobacco smoke emissions, but are limited in scope. A more comprehensive review of potential species emitted was conducted as part of the device and consumable materials stewardship process (Eaton et al., 2017) including untargeted emissions scanning and clearly laid out assessment criteria for any chemical species identified. This was supported by subsequent emissions testing (Forster et al., 2017). No additional species were identified from these untargeted and targeted analyses as requirements for IAQ testing.

2.2.2. Participants

The study was approved by an ethics review panel. Adult cigarette smokers (minimum age 22 years; minimum daily cigarette consumption six cigarettes) who had smoked for at least 18 months were recruited by a specialist agency. Prospective participants attended a 2–3 h familiarisation session, and were able to use up to three sticks of the THP after reading a study synopsis, understanding the purpose of the study and providing written informed consent. This process identified a pool of non-rejecters of the THP from which the study participants were selected. Participants were free to leave the study at any time.

Four participants were present in the test room at any time, along with an independent non-smoking moderator.

2.2.3. Test room and monitoring locations

A furnished room was used for the IAQ tests, and an instrument room for monitoring and sample-collection equipment adjacent. PTFE sampling lines passed between the two rooms. Prior to the tests, no smoking or vaping had previously taken place in the test room, which had been maintained under natural ventilation conditions (i.e., no air conditioning or openable windows).

The dimensions of the test office were (l × w × h) 4.20 × 2.95 × 3.05 = 37.8 m^3. A table (1.8 × 0.9 = 1.6 m^2) and 5 chairs were placed in the centre of the room. Air handling apparatus was used to control the ventilation as closely as possible to three different values, as defined in BS EN 15251 (BSI, 2007): residential II, 1.20 air changes per hour ([ACH] 45.4 m^3 h^{-1}); office (2.16 ACH, 81.6 m^3 h^{-1}); and hospitality (7.68 ACH, (290.3 m^3 h^{-1}). The air handling system was a conventional building air-conditioning system with both high-efficiency particulate air and carbon filters on the inlet to remove external contaminants. On each day of testing or when the ventilation condition was changed, the air change rate was measured by using a tracer gas (butane) technique (Walker and White, 1995). Air temperature and relative humidity were monitored throughout the study. The test office, with meeting table installed, is shown in Figs. 2 and 3.

Gaseous samples were drawn from the test room through sampling media at various locations (Table 1) with pumps in the adjacent instrument room. The gaseous samples were collected into tubes or on to cartridges appropriate to the parameter being monitored. To avoid transmission losses down sampling lines, measurements of PM, CO_2 and CO were carried out *in situ* in the test room. Each parameter was determined once per test. Particle size, number and mass measurements, O_3 and NO_x were conducted with the instruments external to the room.

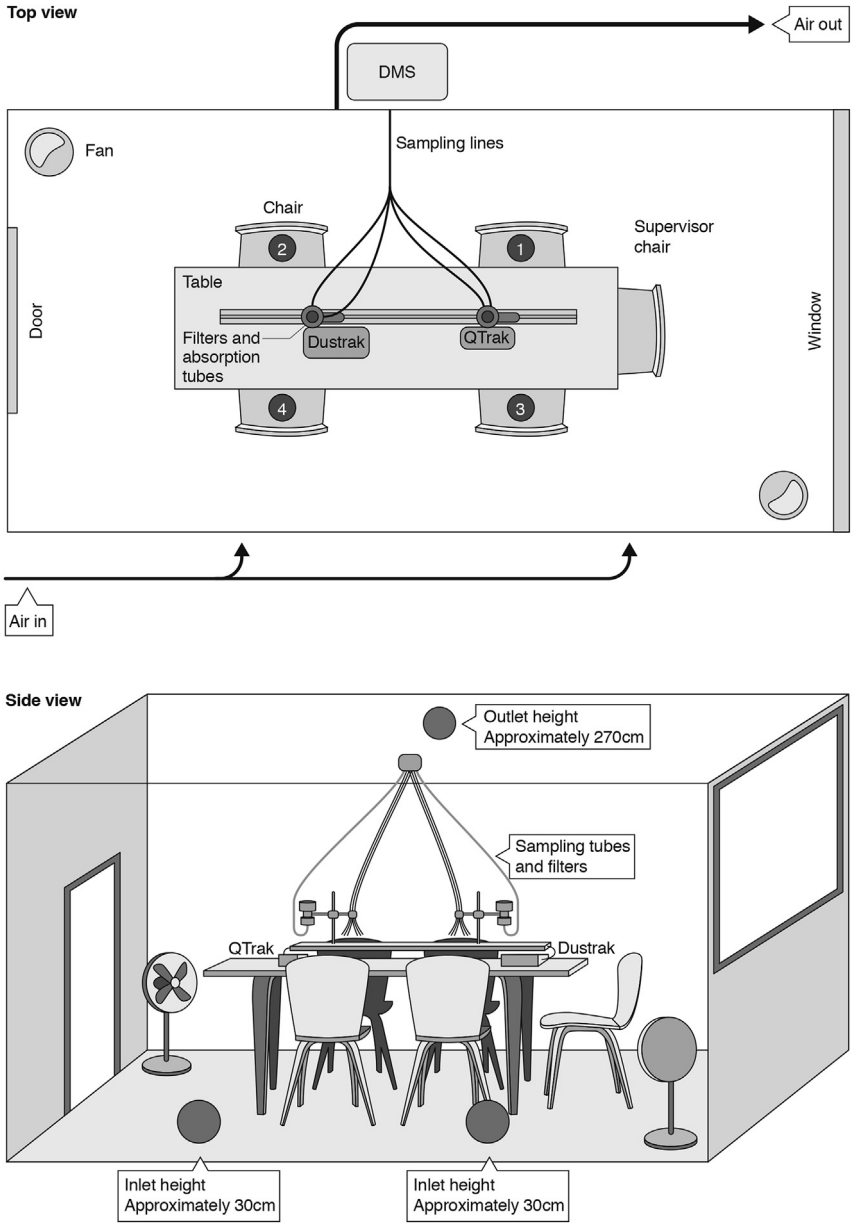

Fig. 2. Top and side views of the test room. DustTrak aerosol monitor and Q-Trak air-quality monitor, TSI Inc., Shoreview, MN, USA. Abbreviation: DMS = differential mobility spectrometer.

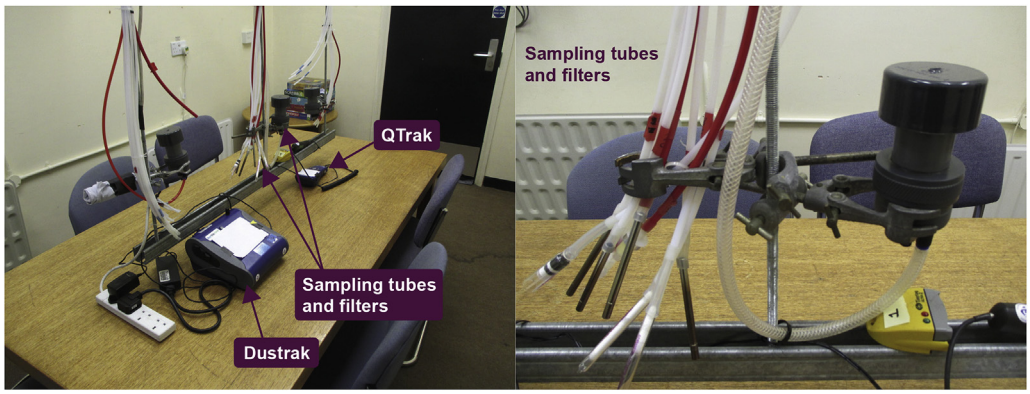

Fig. 3. Location of sampling bar and sampling tubes in the test room. DustTrak aerosol monitor and Q-Trak air-quality monitor, TSI Inc., Shoreview, MN, USA.

Table 1
Sampling locations in the test office.

Sampling location	Height	Position	Air quality parameters monitored
1	Overhead	Line above meeting table	Ozone, NO_x, VOCs, carbonyls, PAHs, nicotine, glycerol, TSNAs
2	Table top	Centre line of meeting table	Particle mass fractions (PM_1, $PM_{2.5}$, PM_{10}), CO, CO_2, temperature, relative humidity
3	Sitting height	Centre of room	Ventilation rate, particle size

Abbreviations: VOCs = volatile organic compounds; PAHs = polycyclic aromatic hydrocarbons; TSNAs = tobacco-specific nitrosamines; PM_1 = particulate matter (diameter ≤1 μm); $PM_{2.5}$ = particulate matter (diameter ≤2.5 μm); PM_{10} = particulate matter (diameter ≤10 μm).

2.2.4. Indoor air constituents

Before all tests, the continuous monitoring equipment used to measure temperature, relative humidity, CO, CO_2, O_3, NO_x and PM was operated within the test office set-up for at least 24 h to allow the equipment to stabilise and equilibrate. For each test, sampling commenced immediately (t = 0 min) and finished at 4 h (t = 240 min).

CO and CO_2 were measured continuously by using a real-time Q-Trak Model 7575 monitor (TSI Inc., Shoreview, MN, USA) with limits of quantification (LOQs) of 1 ppm (1164 μg m^{-3}) and 5 ppm (9690 μg m^{-3}), respectively. O_3 was measured continuously by a Thermo Environmental Systems Ozone Analyser 49C (Thermo Environmental Instruments, Franklin, MA, USA) using a US Environmental Protection Agency (EPA) reference equivalent method (US EPA, 2016). The LOQ for ozone using this analyser was 1 μg m^{-3}. NO and NO_2 were measured continuously using a Thermo Environmental Systems NO_x Analyser model 42C (EPA reference equivalent method), calibrated by use of bottled gas standards. The LOQs of NO and NO_2 were both 1 ppb. NO_x (in μg·m^{-3}) was determined as [NO (ppb) + NO_2 (ppb)] * 1.91 = NO_x.

PM mass fractions (PM_1, $PM_{respirable}$, $PM_{2.5}$ and PM_{10}) were measured continuously every 60 s by a real-time Model 8533 DustTrak monitor (TSI Inc.) with an LOQ for each mass fraction of 1 μg m^{-3}. Particle size distribution was also monitored continuously every 10 s by using a DMS-500 Mk II electrical-mobility spectrometer (Cambustion, Cambridge, UK) in the range 5–1000 nm, with simultaneous measurement of particle mass and particle number concentration. Sampling was conducted at 8.0 L min^{-1} via conductive tubing (length, 5 m; internal diameter, 6 mm), with no particle losses predicted for particle diameters >20 nm. LOQs are dependent on particle size, but number and mass concentrations of 1 particle·cm^{-3} and 0.1 μg m^{-3}, respectively, were readily achievable. For later cigarette smoke samples, gravimetric PM was collected at 1.6 L min onto 37 mm glass fibre filters (pore size, 1.6 μm; Whatman Ltd, Maidstone, UK) as per the UK guideline MDHS 14 (Health & Safety Executive, 2006).

Nicotine and 3-EP were determined by pumped sampling of air at 1.5 L min^{-1} onto an appropriate sorbent resin tube (XAD-4, SKC Ltd, Blandford Forum, Dorset, UK), followed by preparation and analysis according to ASTM D5075 (ASTM, 2017) at an accredited laboratory (Bureau Veritas, MI, USA). The LOQ was 0.2 μg m^{-3} for nicotine and 0.1 μg m^{-3} for 3-EP.

Glycerol was determined by pumped sampling of air onto an appropriate XAD sorbent resin tube (XAD-7, SKC Ltd.), followed by gas chromatography–mass spectrometry (GC-MS) analysis at a laboratory accredited by the United Kingdom Accreditation Service (Scientific Analysis Laboratories (SAL) Ltd, Manchester, UK). The LOQ for glycerol was 10 μg per tube. The maximum sampling volume was 100 l; thus, at a suitable flow rate for 240 min samples, the LOQ of glycerol in air for glycerol was ~100 μg m^{-3}. Later samples used two XAD-7 tubes in series at a flow rate of 1.7 L min^{-1}, giving an LOQ of 43 μg m^{-3}.

To measure airborne VOCs (boiling point, 60–280 °C), pumped sampling of air at 0.025 L min^{-1} onto a Tenax TA adsorbent tube (Markes International Ltd., Llantrisant, UK) was carried out for 240 min. The tubes were then analysed by thermal desorption GC-MS, in accordance with ISO standard method 16000–6:2011 (ISO, 2011a). The concentrations of VOCs and total VOCs (TVOC) were quantified by flame ionization detection as the area of all compounds eluting between and including hexane and hexadecane, quantified as toluene equivalents, and the main compounds were identified by MS. The LOQ for each individual VOC at the sampling volume used was ~ 1–5 μg m^{-3}.

Low-molecular-weight carbonyls (acetaldehyde, acrolein, crotonaldehyde and formaldehyde) were measured by pumped sampling of air at 1.0 L min^{-1} onto 2,4-DNPH cartridges (Waters, UK) over 240 min, followed by high-performance liquid chromatography analysis in accordance with ISO standard method 16000–3 (ISO, 2011b). At the sampling volumes used, the LOQ was 1 μg m^{-3} for formaldehyde, and 2 μg m^{-3} for the other carbonyl compounds.

Sixteen PAHs, corresponding to the US EPA's priority list (acenaphthene, acenaphthylene, anthracene, benzo[a]anthracene, benzo[a]pyrene, benzo[b/k]fluoranthene, benzo[ghi]perylene, chrysene, dibenzo[a,h]anthracene, fluoranthene, fluorene, indeno

[123-cd]pyrene, naphthalene, phenanthrene and pyrene), were determined by pumped sampling of air at 2.3 L min^{-1} on to an appropriate sorbent tube (XAD-2), followed by analysis by GC-MS at Scientific Analysis Laboratories (SAL) Ltd. The LOQ for each PAH was 0.1 μg per tube. The average sampling volume was approximately 0.5 m^3 and, thus, the LOQ in air for each PAH was 0.2 μg m^{-3}. Sampling was conducted only for one pair of residential ventilation samples and for hospitality ventilation.

Four TSNAs, 4-*N*-nitrosonornicotine, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone, *N*-nitrosoanatabine and *N*-nitrosoanabasine, were determined by pumped sampling onto bisulphate-impregnated Cambridge filter pads, followed by analysis by high-performance liquid chromatography-MS at a laboratory accredited by the United Kingdom Accreditation Service (Hall Analytical, Manchester, UK). The LOQ for each TSNA was 0.1 μg per filter. At a flow rate of up to 1.5 L min^{-1}, the LOQ for each TSNA in air was ~0.3 μg m^{-3} for 240 min samples. Sampling was conducted only for one pair of residential ventilation samples and for hospitality ventilation.

In summary, the suite of chemicals measured included the nine identified by the WHO (Burns et al., 2008), as key potential toxicants suggested for mandated lowering and reporting in mainstream cigarette smoke emissions; that is, 1,3-butadiene, acetaldehyde, acrolein, benzo[a]pyrene, benzene, carbon monoxide, formaldehyde, 4-*N*-nitrosonornicotine and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone.

2.2.5. Experimental sequence

THP1.0 and the T189 cigarette were tested in duplicate at all three ventilation conditions; the D976 cigarette was tested only at the lowest 1.2 ACH ventilation (i.e., the highest-concentration condition). Measurements of TSNAs and PAHS were conducted only at the lowest ventilation (highest concentration) conditions. Emission estimates for PAHs and TSNAs relative to PM suggested that these analytes were unlikely to be measurable in the 4 h sampling period, even for cigarette smoke. A gravimetric filter sample was added for later cigarette exposures to resolve differences between reported mass values from the real-time measurement techniques. Gravimetric analysis was not carried out for THP1.0 and the blank air samples because the predicted tare weights from a sample (1–2 μg) were not measurable with suitable precision.

Five test situations, each with a 4 h sampling period, were conducted per week in three stages, corresponding to the three ventilation conditions (Table 2).

Cigarettes were always smoked last in the week to minimise carryover contamination, and the room ventilation continued to operate overnight and at weekends to flush out potential residual contaminants.

A total of 20 test products (residential condition) or 32 test products (office and hospitality conditions) were smoked by the four volunteers moderated in the sequence shown in Table 3. Smokers were asked to take a puff once every 30 s for eight puffs.

All product use was completed while volunteers sat in the chairs provided. At other times, the volunteers were free to leave their chairs, but they were asked to not stand in the direct vicinity of the monitoring equipment in order to keep environmental interference to a minimum. Participants were allowed one 5 min comfort break, if required, and this was noted by the moderator. During breaks they were not allowed to consume any tobacco or vapour products.

2.3. Odour evaluation

2.3.1. Fabric and hair

Cloth or hair samples were installed in the upper part of a compartmented exposure chamber. A cigarette or THP1.0 stick was puffed in the lower compartment allowing any sidestream emissions to be retained and mixed upwards. In this case, in the absence of a human smoker, each mainstream puff was circulated back into the lower chamber, a feature designed to simulate the worst possible “sidestream” emission to the test objects. The lower chamber is shown in Fig. 4 and the upper chamber loaded with hair samples is shown in Fig. 5.

Modified industry smoking machines were used to generate aerosol. Cigarettes and THP1.0 were puffed under the Health Canada Intense regime of a 55 ml bell-shaped puff of 2 s duration every 30 s with 100% ventilation blocking for the commercial control cigarettes, but no ventilation blocking for THP1.0(Eaton et al., 2017).

For the cigarettes T189 and D976, four puffs (fabric) or eight puffs (hair) were taken from each stick, and both the mainstream and sidestream smoke or aerosol generated were fed into the upper exposure chamber. A third test cigarette, the reference cigarette 3R4F (University of Kentucky, Center for Tobacco Reference Products) was also used because this reference product was used to train the odour assessment panel. For THP1.0, eight puffs were taken for both fabric and hair testing. Previous method development and validation had shown that four puffs from a cigarette represented an optimal mid-point level for odour evaluation between cigarettes, and this approach was maintained. In contrast, eight puffs were used from the THP1.0, to represent the full use of the product, and align its use with other testing. Thus, data were tested for significant differences, not for percentage reduction.

Thirty seconds after the last puff, the upper exposure chamber was completely shut off from the lower aerosol generation chamber to allow the aerosol to settle on the test substrate material (fabric or hair) for 60 min.

Sixty minutes after the final puff was taken, the fabric and hair samples were aged in sealed glass jars for a minimum of 30 min before the panellists undertook an assessment of the intensity of cigarette smoke odour.

Volunteers for the odour sensory panel had been previously recruited, selected and trained in accordance with ISO 8586–1 (ISO, 2012), as follows. Initially, to determine the optimum amount of smoke to be assessed by the panellists, a dose–response relationship was derived between the amount of sidestream smoke and the intensity of the sensory perception (irritation and odour). The detection threshold for a “fabric in jar” method was determined by preparing serial dilutions of the reference standard 1-butanol,

Table 2
Test situations and order of testing.

Day of testing	Testing condition
Day 1 morning	Unoccupied room
Day 2 morning	Room occupied by four smokers plus one moderator, but no tobacco products consumed
Day 2 afternoon	THP1.0 used to a moderated schedule by four smokers in presence of one moderator
Day 3 morning	Room occupied by four smokers plus one moderator but no tobacco products consumed
Day 3 afternoon	Cigarettes used to a moderated schedule by four smokers in the presence of one moderator

Abbreviation: THP = tobacco heating product.

Table 3
Product use schedule.

Session time (HH:MM)	Residential (1.20 ACH)		Office (2.16 ACH)		Hospitality (7.68 ACH)	
	Panellists		Panellists		Panellists	
	1 & 3	2 & 4	1 & 3	2 & 4	1 & 3	2 & 4
00:00	1 Stick	–	1 Stick	–	1 Stick	–
00:15	–	1 Stick	–	1 Stick	–	1 Stick
00:30	–	–	1 Stick	–	1 Stick	–
00:45	1 Stick	–	–	1 Stick	–	1 Stick
01:00	–	1 Stick	1 Stick	–	1 Stick	–
01:15	–	–	–	1 Stick	–	1 Stick
01:30	1 Stick	–	1 Stick	–	1 Stick	–
01:45	–	1 Stick	–	1 Stick	–	1 Stick
02:00	–	–	1 Stick	–	1 Stick	–
02:15	1 Stick	–	–	1 Stick	–	1 Stick
02:30	–	1 Stick	1 Stick	–	1 Stick	–
02:45	–	–	–	1 Stick	–	1 Stick
03:00	1 Stick	–	1 Stick	–	1 Stick	–
03:15	–	1 Stick	–	1 Stick	–	1 Stick
03:30	–	–	1 Stick	–	1 Stick	–
03:45	–	–	–	1 Stick	–	1 Stick
04:00	Session ends		Session ends		Session ends	

Abbreviation: ACH = air change per hour.

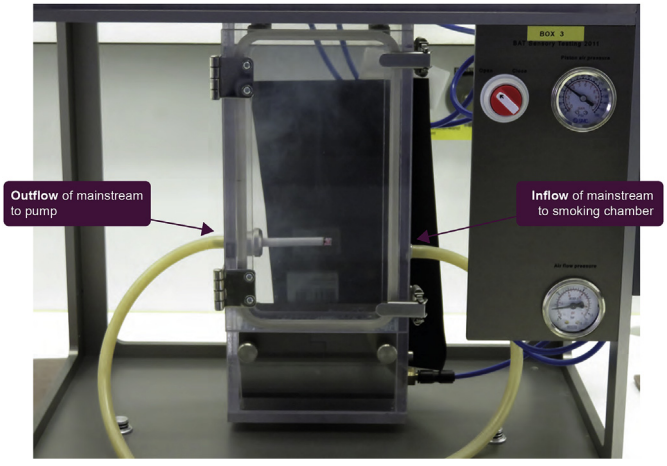

Fig. 4. Smoking chamber with tubes (50 cm) to connect THP1.0 or commercial control cigarette to the smoking machine and let mainstream aerosol back into the aerosol generation chamber.

Fig. 5. Locks of hair arranged in the chamber ready for exposure. Twenty-four locks of washed Asian hair (Banbury Postiche Ltd., Banbury, UK) were spread across the exposure chamber, with eight locks placed equidistant across each of the three shelves in the exposure chamber. Each lock of hair weighed approximately 7 g and was ~26 cm in length.

which the panellists assessed for tobacco odour and nose irritation. The detection threshold was obtained at the 50% chance-corrected probability point. The panellists were then trained to score intensity ratings using ratio scaling (magnitude estimation) and a standardised procedure, with 1-butanol used as a reference (fixed modulus). They were then trained to rate a range of sidestream smoke concentrations (reference cigarette 3R4F). The optimum sidestream concentration to be assessed was identified halfway between detection and terminal threshold.

For this study, 21 of trained panellists calibrated their odour intensity assessment by first smelling a reference jar with the stimulus (fabric or hair) exposed to mainstream and sidestream smoke from the reference cigarette (3R4F), which was given a score of 50. Cigarette smoke/THP aerosol odour intensity was then assessed relative to the reference jar for each stimulus in pairs (D976 and THP1.0; T189 and THP1.0; and T189 and D976) by using magnitude estimation scaling methodology.

2.3.2. Skin odour evaluation

The assessment of cigarette smoke or THP1.0 aerosol odour intensity on skin was conducted on the pre-washed hands of the users of the test products (D976, T189 and THP1.0). A minimum of seven volunteers consumed the test product using one hand only, following a regime of one puff every 30 s for eight puffs. The other hand was kept clean to act as the reference point and given a score of zero. The product was used 15 min before the odour evaluation. A maximum of three panellists from a pool of 30 then assessed the volunteer's hand for residual smoke or aerosol odour intensity in comparison to the clean hand, using a category scale of 0–10, where 0 = no odour and 10 = very high odour intensity. Assessments were conducted in pairs (D976 and THP1.0; T189 and THP1.0; and T189 and D976). Each product evaluation lasted a maximum of 30 min.

2.4. Data analysis

The study data were separated into time- and non-time-related

measurements and treated as follows. For time-related measurements, the data were first split into outdoor data and room data (outdoor data were available only for PM mass fractions and NO_x measures). For CO measurements, the LOD was 1 ppm. For CO only, any values below the LOD were set as half the LOD (i.e. 0.5 ppm). Means were generated based on time-course data for the whole session of 4 h. Descriptive statistics for each product or session at each ventilation rate available were then generated (mean, minimum, maximum, median, standard deviation and sample size).

For non-time-related (chemistry) data, first, cases with a status of "not done" were removed from the analysis. Values below the LOD or LOQ were set as missing and replicates for each product and session were identified. Descriptive statistics for each product or session at each ventilation rate available were then generated (mean, minimum, maximum, median, standard deviation and sample size). The data reported were used to calculate percentage differences between test article 1 (THP1.0) and test article 2 (T189 and D976 commercial cigarettes) as follows:

$$\%Difference(Test\ Article\ 1) = 100 - \left(\frac{Test\ Article\ 1\ Value}{Test\ Article\ 2\ Value} \times 100\right),$$

where each test article value was background-corrected for its same-day baseline value.

3. Results

3.1. IAQ analysis

A summary of the measurement data for the IAQ study are shown in Table 4 for THP1.0 and T189 at the three ventilation conditions. For each analyte, the baseline reported is the level measured before the THP1.0 test. Table 5 shows the equivalent data for only the low ventilation hospitality condition for THP1.0 and the two commercial cigarettes. For statistical analysis, values that were less than the LOD or LOQ were not used.

3.1.1. Temperature and relative humidity

For the occupied room IAQ tests, temperatures within the room ranged from 20.5 °C to 26.4 °C, and relative humidity within the room ranged from 25.1% to 48.8%. Both parameters tended to increase over time with room occupancy, as might be expected (data not shown).

3.1.2. CO_2

As expected, CO_2 concentrations rose owing to respiration of the occupants during occupied room tests. Background CO_2 levels of around 400 ppm increased to mean levels of around 1600–1800 ppm during the occupied phases of the low ventilation tests, with the concentrations peaking at approximately 2500 ppm. At the other extreme of the highest ventilation, background CO_2 levels of around 400 ppm increased to mean levels of around

Table 4
Levels of toxicants in environmental emissions from THP1.0 versus a commercial control cigarette (T189).

Toxicant	Home (1.2 ACH)			Office (2.2 ACH)			Hospitality (7.7 ACH)			% Reduction	Notes
	Baseline	T189	THP1.0	Baseline	T189	THP1.0	Baseline	T189	THP1.0		
VOCs (μg·m^{-3})											
1,3-Butadiene	<5	<5	<5	<5	<5	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
Isoprene	16	197	16	10	226	11	4	86	4	99.5	THP1.0 ≤ baseline
Acrylonitrile	<5	<5	<5	<5	<5	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
Benzene	1	17	1	1	23	1		9	<1		THP1.0 ≤ baseline
Toluene	2	31	3	2	34	2	2	13	2	99.1	THP1.0 ≤ baseline
Propylene glycol	<5	<5	<5	<5	<5	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
Acrylamide	<5	<5	<5	<5	<5	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
TVOC	101	321	49	78	372	70	39	120	21	–	THP1.0 ≤ baseline
TVOC excluding major occupant VOCs	39	286	32	36	347	34	10	93	8	–	THP1.0 ≤ baseline
Carbonyls (μg·m^{-3})											
Formaldehyde	16	36	18	15	48	16	9	23	9	94.8	–
Acetaldehyde	5	100	10	7	140	16	3	42	6	93.7	–
Acrolein	<2	<2	<2	<2	<2	<2	<2	<2	<2	–	THP1.0 & CS ≤ LOD
Crotonaldehyde	<2	<2	<2	<2	<2	<2	<2	<2	<2	–	THP1.0 & CS ≤ LOD
Other (μg·m^{-3})											
Nicotine	2.4	58	0.3	0.6	54	1.4	<0.2	32.5	0.4	98.5	–
3-ethenyl pyridine	<0.1	9	<0.1	<0.1	11	<0.1	<0.1	5	<0.1		THP1.0 ≤ baseline
TSNAs[a] (μg on filter)	<0.1	<0.1	<0.1	–	–	–	–	–	–	–	THP1.0 & CS ≤ LOD
PAHs[b]	<0.2	<0.2	<0.2	–	–	–	–	–	–	–	THP1.0 & CS ≤ LOD
Glycerol	<100	<100	<100	<44	<44	<44	<44	<44	<44	–	THP1.0 & CS ≤ LOD
CO (ppm)	<1	<1	<1	<1	1.5	<1	<1	<1	<1	–	THP1.0 ≤ baseline
NO (ppb)	21	44	4	2	26	2	5	14	3	–	THP1.0 ≤ baseline
NO_2 (ppb)	9	10	8	8	12	8	13	16	12	–	THP1.0 ≤ baseline
NO_X (ppb)	29	54	12	10	38	11	18	29	15	99.0	THP1.0 ≤ baseline
PM_1[c]	9.9	1251	7.1	2.4	1520	10.3	3.8	614	6.5	99.5	–
$PM_{2.5}$[c]	10.2	1251	7.4	2.6	1521	10.7	3.9	614	6.6	99.5	–
PM_{10}[c]	17.8	1257	12.8	5.0	1524	13.8	6.0	616	8.4	99.5	–
$PM_{1.0}$ (mobility)[c]	35	505	6	0.7	661	4.2	1.2	242	3.5	99.3	–
Particle number (cm^{-3})	9.6E+03	2.0E+05	1.0E+04	9.9E+02	2.9E+05	8.5E+03	2.3E+03	1.4E+05	4.7E+03	98.4	–
MMD (nm)	597	231	210	150	225	164	143	218	180	–	–
Gravimetric PM	–	597	–	–	764	–	–	–	–	–	–

[a] TSNAs: 4-*N*-nitrosonornicotine, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone, *N*-nitrosoanatabine and *N*-nitrosoanabasin.
[b] PAHs: acenaphthene, acenaphthylene, anthracene, benzo(a)anthracene, benzo(a)pyrene, benzo(b/k)fluoranthene, benzo(ghi)perylene, chrysene, dibenzo(ah)anthracene, fluoranthene, fluorene, indeno(123-cd)pyrene, naphthalene, phenanthrene, pyrene.
[c] PM_1 mobility values verified as accurate from gravimetric data in separate experiment. Abbreviations: THP = tobacco heating product; ACH = air changes per hour; VOC = volatile organic compounds. CS = cigarettes smoke; LOD = limit of detection; TVOC = total volatile organic compounds; TSNAs = tobacco-specific nitrosamines; PAHs = polycyclic aromatic hydrocarbons; PM = particulate matter; MMD = mass median diameter.

Table 5
Levels of toxicants in environmental emissions under residential ventilation conditions (1.2 ACH) from different types of tobacco product.

Toxicant	Baseline	T189	D976	THP1.0	% Reduction	Notes
VOCs ($\mu g \cdot m^{-3}$)						
1,3-Butadiene	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
Isoprene	17	191	255	16	–	THP1.0 ≤ baseline
Acrylonitrile	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
Benzene	1	16	21	1	–	THP1.0 ≤ baseline
Toluene	2	29	32	3	98.9	–
Propylene glycol	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
Acrylamide	<5	<5	<5	<5	–	THP1.0 & CS ≤ LOD
TVOC	174	373	362	49	–	THP1.0 ≤ baseline
TVOC excluding major occupant VOCs	72	298	312	32	–	THP1.0 ≤ baseline
Carbonyls ($\mu g \cdot m^{-3}$)						
Formaldehyde	15.7	33.3	43.0	17.5	91.5	–
Acetaldehyde	8	100	118	10	98.0	–
Acrolein	<2	<2	<2	<2	–	THP1.0 & CS ≤ LOD
Crotonaldehyde	<2	<2	<2	<2	–	THP1.0 & CS ≤ LOD
Other ($\mu g \cdot m^{-3}$)						
Nicotine	1.3	47.0	33.0	0.3	97	–
3-ethenyl pyridine	0.2	9.1	7.8	<0.1	–	THP1.0 ≤ baseline
TSNAs[a] (μg on filter)	<0.1	<0.1	–	<0.1	–	THP1.0 & CS ≤ LOD
PAHs[b]	<0.2	<0.2	–	<0.2	–	THP1.0 & CS ≤ LOD
Glycerol	<44	<44	<44	<44	–	THP1.0 & CS ≤ LOD
CO (ppm)	<1	<1	1.3	<1	–	THP1.0 ≤ baseline
NO (ppb)	12	30	22	4	–	THP1.0 ≤ baseline
NO_2 (ppb)	9	12	11	8	–	THP1.0 ≤ baseline
NO_X (ppb)	20	42	33	12	–	THP1.0 ≤ baseline
PM_1 (light scattering)[c]	10.6	1392	1529	7.1	–	–
$PM_{2.5}$ (light scattering)	10.8	1392	1536	7.4	–	–
PM_{10} (light scattering)	17.0	1398	1541	12.8	–	–
PM_1 (mobility)[c]	23	510	572	6	–	–
Particle number (cm^{-3})	7.4E+03	1.9E+05	2.4E+05	1.0E+04	98.5	–
MMD (nm)	–	234	227	210	–	–
Gravimetric PM	–	597	557	–	–	–

[a] TSNAs: 4-*N*-nitrosonornicotine, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone, *N*-nitrosoanatabine and *N*-nitrosoanabasin.
[b] PAHs: acenaphthene, acenaphthylene, anthracene, benzo(a)anthracene, benzo(a)pyrene, benzo(b/k)fluoranthene, benzo(ghi)perylene, chrysene, dibenzo(ah)anthracene, fluoranthene, fluorene, indeno(123-cd)pyrene, naphthalene, phenanthrene, pyrene.
[c] PM_1 mobility values verified as accurate from gravimetric data in separate experiment. Abbreviations: THP = tobacco heating product; ACH = air changes per hour; VOC = volatile organic compounds. CS = cigarettes smoke; LOD = limit of detection; TVOC = total volatile organic compounds; TSNAs = tobacco-specific nitrosamines; PAHs = polycyclic aromatic hydrocarbons; PM = particulate matter; MMD = mass median diameter.

600–700 ppm during the occupied phases of the tests, with the concentrations peaking at approximately 830 ppm (data not shown).

3.1.3. CO

Significant levels of CO were not detected (all measurements <1 ppm) during any of the tests except for short periods of time (1–4 min) during the cigarette IAQ tests. This finding reflects a general limitation of electrochemical sensors widely used for this measurement, based upon a consensus that exposure levels of <1 ppm are not of physiological or toxicological concern (WHO, 1999). In this case, to calculate mean values for the time-resolved data, data points below the LOD were set at half the LOD, and means were generated based on time-course data for the whole 4 h session. Calculated 4 h mean values that were <1 ppm were reported as below the LOD.

3.1.4. Oxides of nitrogen

In most tests, the concentrations of NO_2 and particularly nitric oxide NO in the room broadly followed those measured outdoors (data not shown), but with a time-lag associated with the ventilation rate of the building and the test room. The exception to this pattern was tests where cigarette smoking took place, during which there was a noticeable increase in the concentrations of NO in the test room.

The lack of CO and NO_x observed during THP1.0 use is consistent with a significantly reduced emission of combustion marker compounds (Eaton et al., 2017).

3.1.5. O_3

Due to the reactivity of O_3 and the carbon filters in the mechanical ventilation system supplying air to the test room, in most tests the indoor concentration of ozone tended to stay in the range 2–10 ppb, despite fluctuations in the outdoor O_3 levels. The ozone analyser used in these tests measured the O_3 concentration via the absorbance of ultraviolet radiation at a wavelength of approximately 274 nm; cigarette smoke contains many chemical compounds, some of which clearly also adsorbed ultraviolet radiation at the same wavelength. This was shown both by the O_3 'measurements' apparently seen during the cigarette smoking tests in both the test room and outdoors (because the common analyser switching between the indoor and outdoor sampling heads remained affected by the cigarette smoke). It was therefore concluded that the elevated O_3 readings obtained in the cigarette IAQ tests should be viewed as unreliable due to smoke interference with the instrument's detection methodology, and these data are not shown.

3.1.6. Volatile organic compounds

BS ISO 16000–6:2011 defines TVOC as the "sum of volatile organic compounds, sampled on Tenax TA®, that elute between and including *n*-hexane and *n*-hexadecane on a non-polar capillary column, detected by flame ionization (TVOC-FID) or MS (TVOC-MS), and quantified by converting the total area of the chromatogram in that analytical window to a nominal mass using the chromatographic response factor for toluene (toluene equivalents)" (ISO, 2011a). It was noted that a number of VOCs were siloxanes and

terpenes, which were identified as originating from the occupants. These compounds were quantified as toluene (toluene equivalent), and the "total occupant (toluene equivalent) VOCs" were subtracted from TVOC to give "total VOCs excluding major occupant VOCs".

In air sampled around THP1.0, TVOC and the following seven VOCs did not exceed levels measured in background room samples: isoprene, benzene and toluene, which were quantifiable; and 1,3-butadiene, acrylonitrile, acrylamide and propylene glycol, which were below the LOD.

At the start of the experiment, the air in the room was relatively clean, having been passed through a filtration system, with a TVOC concentration of less than 5 μg m^{-3}. Over time in the occupied room, the TVOC increased (albeit to a concentration that was about one-quarter of the limit in the UK Building Regulations or the BREEAM Hea 02 limit of 300 μg m^{-3}; BREEAM, 2011). When the occupant VOCs were subtracted from the TVOC value, the increase in TVOC content was more modest. During the IAQ test for THP1.0, TVOC decreased but the "TVOC less occupant VOC" concentration remained at about the same. Thus, it may be reasoned that the use of THP1.0 had little effect on TVOC. In contrast, when cigarettes were smoked there was a marked increase in TVOC to levels to near or slightly exceeding the 300 μg m^{-3} limit. This increase was largely due to elevated levels of isoprene, toluene and benzene.

3.1.7. Carbonyl compounds

Formaldehyde and acetaldehyde levels from use of THP1.0 were greater than background room levels, but significantly lower (>90%) than levels from cigarette use. Neither acrolein nor crotonaldehyde was detected in any of the air samples. At the lowest ventilation level, formaldehyde remained constant at 9–18 μg m^{-3} during background tests and THP1.0 use, and increased to up to 48 μg m^{-3} during cigarette use. The concentration of acetaldehyde varied between 3 and 8 μg m^{-3} during background measurements, and increased to a maximum of 16 μg m^{-3} during THP1.0 use and ~140 μg m^{-3} during cigarette use.

3.1.8. PAHs

The concentrations of 16 PAHs, including benzo[a]pyrene were below the LOD (<0.2 μg m^{-3}) for both the T189 cigarette and THP1.0.

3.1.9. TSNAs

Similarly, the concentrations of the four TSNAs were below the LOD (<0.1 μg) for T189 and THP1.0.

3.1.10. Nicotine, 3-EP and glycerol

Nicotine environmental emissions for THP1.0 were reduced by 97% as compared with those from cigarettes. 3-EP was measured in the air during cigarette use but was below the LOD (<0.1 μg m^{-3}) during THP1.0 use. Glycerol was below the LOD (<44 μg m^{-3}) for both cigarettes and the THP.

3.1.11. Particle mass

Particle mass was measured by both a light-scattering technique (TSI DustTrak, operating range 300–10,000 nm), which splits the aerosol concentration into multiple size bins including PM_1, $PM_{2.5}$, PM_{10}, respirable PM and total mass, and a more sensitive electrical-mobility technique (DMS500, operating range 5–1000 nm), giving effectively PM_1. Aerosol mass concentrations were significantly reduced (>99%) for THP1.0 relative to the commercial cigarettes for both techniques.

However, the two techniques produced different absolute mass values for PM_1: the light-scattering technique gave values that were, on average, 2.5 times greater than those obtained by electrical mobility. A series of separate gravimetric filter analyses were made for cigarette smoke, which supported the accuracy of the electrical-mobility technique as follows:

$$\text{Mobility mass} = 0.89 \times \text{gravimetric mass} \ (R^2 = 0.81)$$

$$\text{Light scattering mass} = 2.30 \times \text{gravimetric mass} \ (R^2 = -11.25)$$

Gravimetric data could not be measured for THP1.0 because the predicted tare weights (<1–2 μg) from a 4 h sample at 1.0 L min^{-1} were too low to measure precisely or accurately by weighing.

An example graph of particle (mobility) mass versus time for baseline measurements for THP1.0 aerosol and T189 cigarette smoke under the office ventilation condition is shown in Fig. 6. Fig. 7 shows a series of time plots for the T189 and D976 cigarettes under the various ventilation conditions. The distinctive repeating saw-tooth pattern suggests that there was good compliance with the volunteer smoking schedule, and good mixing within the room. The consistent build-up and decay also indicates that ventilation

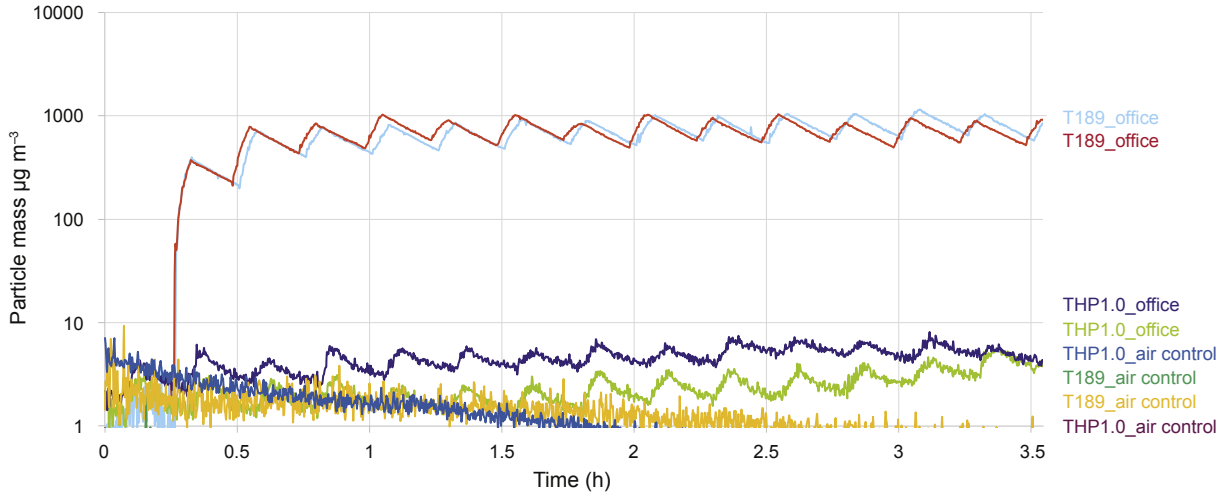

Fig. 6. Logarithmic plot of particle mass data for T189 cigarette smoke, THP1.0 aerosol and baseline data under the office ventilation condition (2.2 ACH). Different colours are used to discriminate between replicates. Abbreviations: THP = tobacco heating product; ACH = air change per hour.

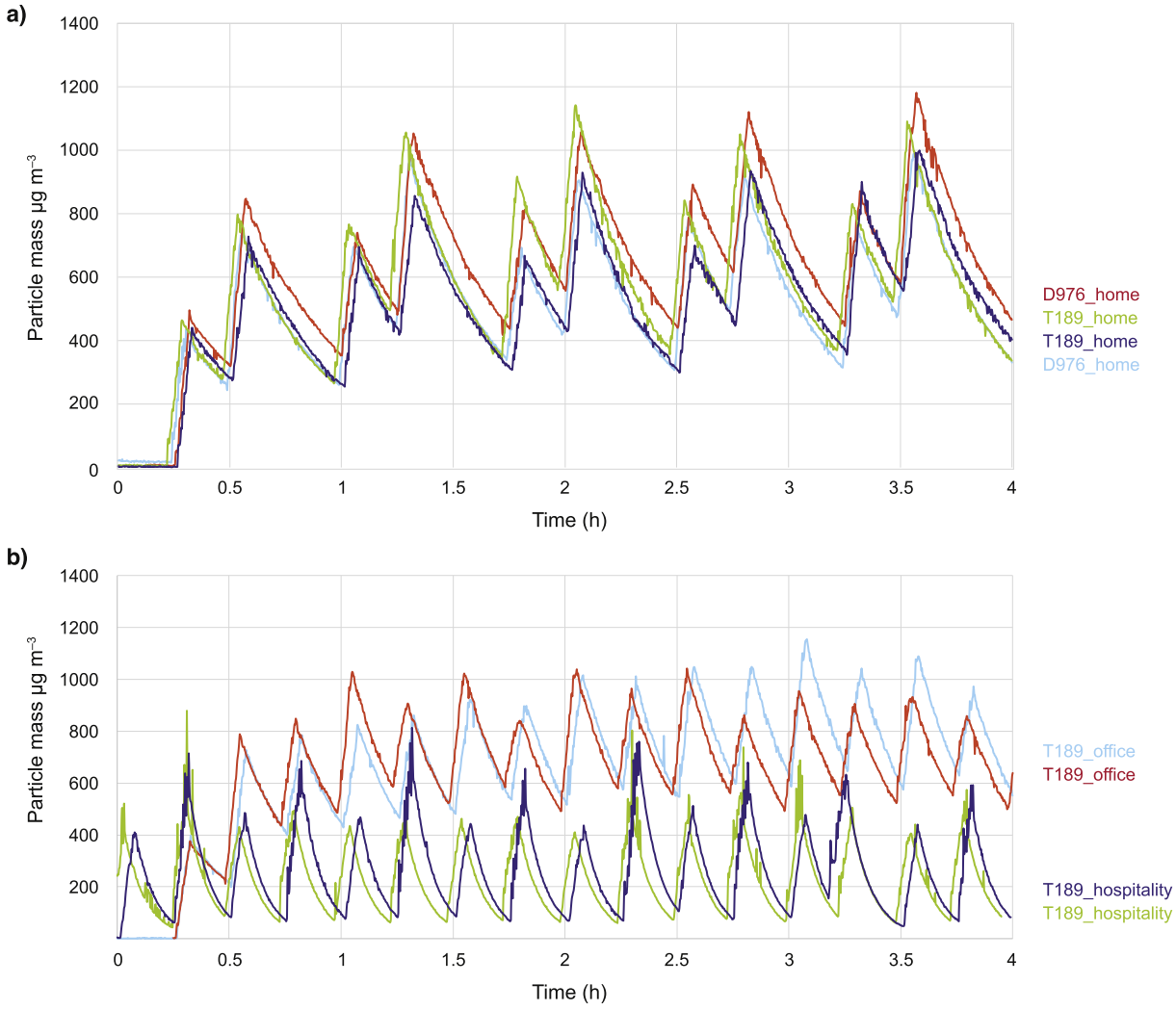

Fig. 7. Plot of cigarette smoke particle mass under the three different environmental conditions. (a) Cigarettes T189 and D976: 20 cigarettes smoked at 1.2 ACH. (b) Cigarette T189: 32 cigarettes smoked at 2.2 and 7.7 ACH. Different colours are used to discriminate between replicates. Abbreviation: ACH = air changes per hour.

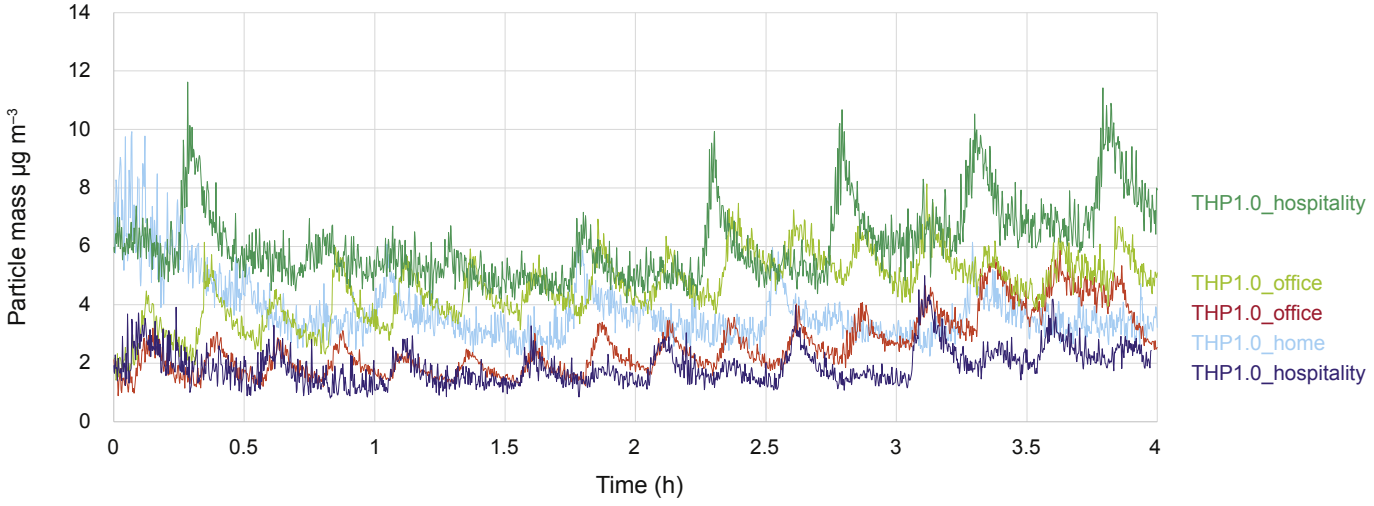

Fig. 8. Plot of uncorrected particle mass versus time for five THP1.0 IAQ tests at differing ventilation rates. Morning background averages ranged from 0.1 to 2.2 µg m^{-3} under the office and hospitality ventilation conditions. Particle generation from THP1.0 was consistent with the volunteer usage schedules, but significantly (99%) lower than that from cigarette smoke. Different colours are used to discriminate between replicates. Abbreviation: THP = tobacco heating product.

rates were consistent throughout the experiment.

Fig. 8 plots PM versus time for five THP1.0 IAQ tests in the context of baseline measurements. It can be observed that the mass concentrations lie in the same order of background levels, and do not exceed recommended indoor and outdoor air guidelines.

3.1.12. Particle number concentration

Particle number emissions were reduced by 98% for THP1.0 relative to cigarette smoke. An example graph of particle number concentration versus time is shown in Fig. 9 for background measurements, THP1.0 aerosol and T189 cigarette smoke under the home ventilation condition (1.2 ACH). The logarithmic scale in Fig. 9 illustrates the pattern of THP1.0 emissions; the activity can be observed but is two orders of magnitude lower than the activity from cigarette smoke.

3.1.13. Particle size

Mass median diameter data indicated that the THP1.0 aerosol and cigarette smoke produced similarly sized particles, typically in the 150–250 nm range (i.e., respirable). This is consistent with formation of a condensation aerosol and, in the case of cigarette smoke, is consistent with literature values for sidestream smoke. The diameter tended to decrease at higher ventilation (and hence higher dilution) rates. An example graph of particle size versus time is shown in Fig. 10 for THP1.0 and T189 cigarette smoke under the home ventilation condition. The data show that the particle diameter tended to increase slowly during periods when the concentration was decreasing, in other words, when there was no smoking activity current in the room. This is consistent with aerosol accumulation processes (collisions): as fresh aerosol is generated, the smaller primary droplets reduce the median diameter.

Overall, these particle metrics indicate that aerosol is generated when THP1.0 is used, but the aerosol is of the order of baseline concentrations within the room, and significantly lower than cigarette smoke emissions. It is not possible to discriminate from this study design whether the aerosol from THP1.0 is a direct emission from the tobacco rod or aerosol exhaled by the product user, although the latter is deemed to be more likely.

3.2. Comparison of odour between conventional cigarettes and THP1.0

In the first test, 21 panellists trained in odour assessment assessed fabric or hair samples exposed to either mainstream plus sidestream smoke from conventional cigarettes or aerosol from THP1.0, relative to the odour from a reference cigarette (3R4F), which was given a score of 50.

In the second test, the odour on the exposed hand of the product user was scored on a scale from 0 to 10 relative to their clean hand, which had not handled the product (Table 6 and Figs. 11 and 12).

In all cases (i.e., fabric, hair and skin), the residual tobacco smoke odour was significantly less for THP1.0 than for the conventional cigarettes. The test scores for the two cigarettes did not differ significantly for Fabric and Hair, but were significantly different for Skin.

4. Discussion

4.1. IAQ: environmental emissions

4.1.1. Chemistry

The chemical species chosen for measurement in this work reflect a combination of known tobacco smoke emissions, including those reported previously for environmental exposure, and key compounds of toxicological interest (Burns et al., 2008). The selected analytes are supported by the present results for cigarette smoke exposure, where increases over baseline were observed and levels were at or above those previously reported in field

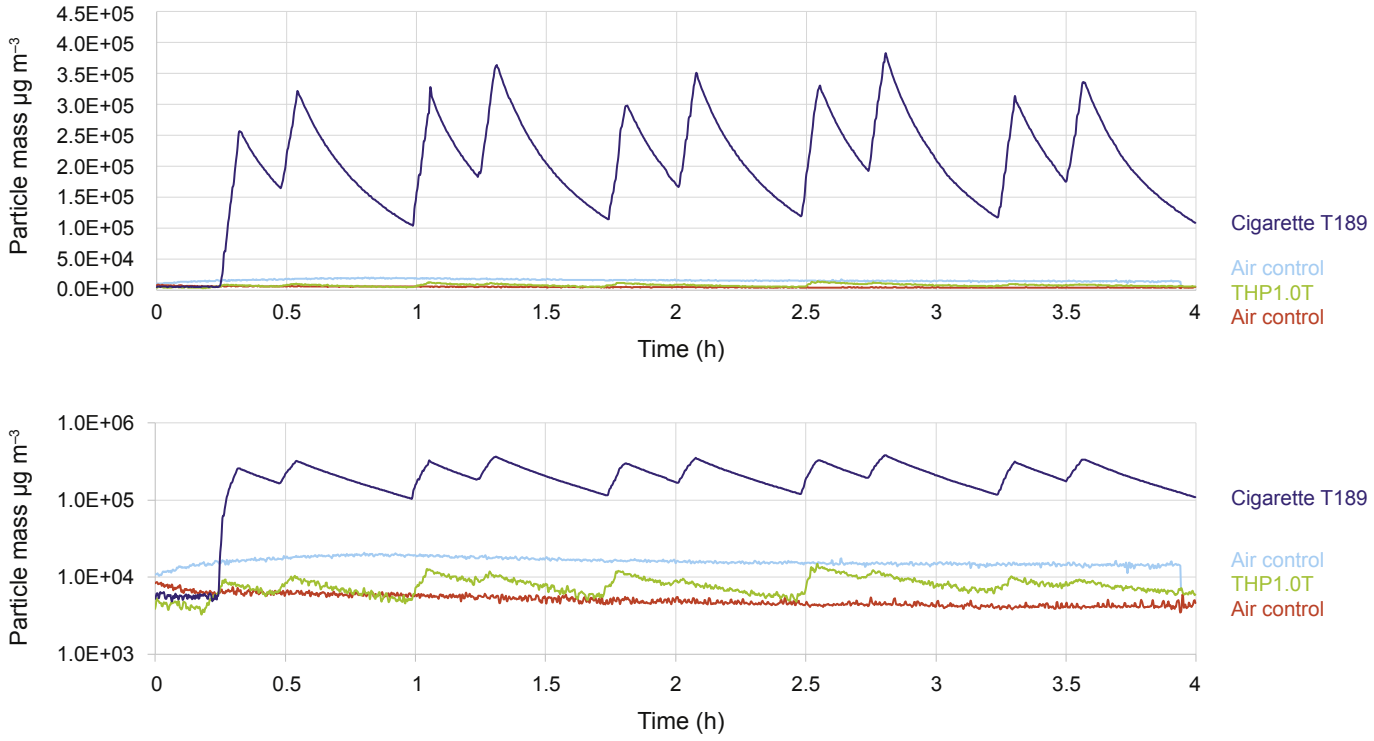

Fig. 9. Plot of particle number concentration (linear and logarithmic) with time for air control baseline, THP1.0 and T189 cigarette smoke at 1.2 ACH. Abbreviations: THP = tobacco heating product; ACH = air change per hour.

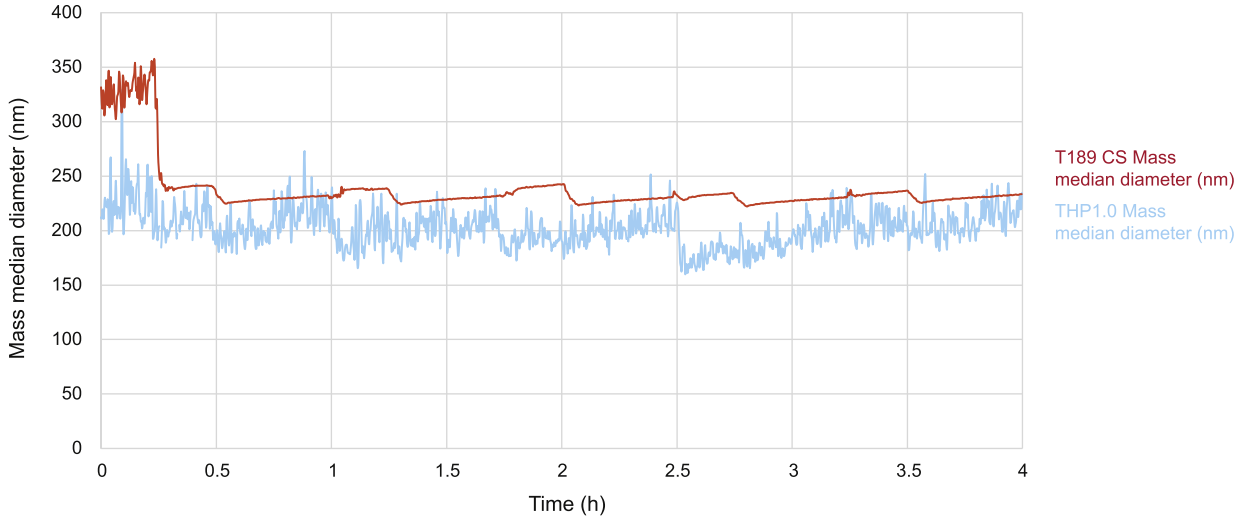

Fig. 10. Particle mass median diameter versus time for THP1.0 and T189 cigarette smoke at 1.2 ACH; THP1.0T data are noisier due to significantly lower particle concentration. Abbreviations: THP = tobacco heating product; ACH = air change per hour; CS = cigarette smoke.

Table 6
Intensity scores for tobacco odour on fabric, hair and skin for THP1.0 and cigarettes T189 and D976.

Test number	Stimulus	Product code	Number of panellists	Odour score		*P* value (*t*-test)
				Mean	SD	
1[a]	Fabric	D976	21	54.5	13.3	<0.0001
		THP1.0	21	3.3	4.3	
2[a]	Fabric	T189	21	47.3	9.8	<0.0001
		THP1.0	21	7.9	7.4	
3[a]	Fabric	D976	21	42.6	15.6	0.4907
		T189	21	41.9	18.7	
4[a]	Hair	D976	21	50.0	8.4	<0.0001
		THP1.0	21	9.1	14.9	
5[a]	Hair	T189	21	48.8	7.7	<0.0001
		THP1.0	21	9.3	9.6	
6[a]	Hair	D976	21	41.2	18.4	0.4958
		T189	21	42.1	14.1	
7[b]	Skin	D976	26	4.9	2.0	<0.0001
		THP1.0	26	0.7	1.3	
8[b]	Skin	T189	20	6.3	2.1	<0.0001
		THP1.0	20	1.4	1.9	
9[b]	Skin	D976	26	6.0	2.2	0.0002
		T189	26	4.2	2.5	

[a] Paired *t*-test was performed on geometric means of the log-transformed data (scale 0–100).
[b] Paired *t*-test on untransformed data scale 0 to 10. Abbreviation: THP = tobacco heating product.

environmental studies for most of the measured species. We note that glycerol, PAHs and TSNAs were not detected for either THP1.0 or the cigarettes, reflecting limitations in the capacities of the sampling media used.

For most species measured, data for THP1.0 were below the LOD or not significantly different from baseline levels. The exceptions were nicotine, formaldehyde, acetaldehyde, particle mass and particle number, which were raised above baseline values. However, the levels of these analytes were significantly less for THP1.0 than for the commercial control cigarettes. It is recognised however, that detection and quantification of several the chosen species were limited by the LOD of the analytical methods, the capacity of the sample media, and a practical limitation on volunteer exposure times and exposure levels. Estimated reductions may require validation of new analytical methods, although magnitude estimates may also, in part, be gauged from relative mainstream emissions data (Forster et al., 2017).

Although multiple IAQ studies have been conducted on e-cigarettes (e.g., as reviewed by Hess et al., 2016), there are very few IAQ data for THPs. This, in part reflects, the fewer THP products that are commercially available and their more recent emergence into (so far) limited markets. The most comprehensive study is that reported by Mitova et al. (2016), following a validation paper by Mottier et al. (2016), who carried out similar sampling under multiple ventilation conditions for tobacco heating system 2.2 (THS2.2) versus a cigarette. In this case, THS2.2 is designed to work differently from THP1.0 and the tobacco rod is heated to a different temperature profile, not exceeding 350 °C (Smith et al., 2016). The result from this study shows that only acetaldehyde and nicotine were observed above baseline levels during THS2.2 use, at levels of up to 5.1 μg m^{-3} for acetaldehyde and up to 1.81 μg m^{-3} for nicotine, representing a reduction versus cigarette smoke of more than 90%. In comparison, baseline-corrected values for THP1.0 in the present study were up to 0.8 μg m^{-3} for nicotine and up to 9 μg m^{-3} for acetaldehyde, although more products were used in the current study. Cigarette smoke data were comparable across exposures, but

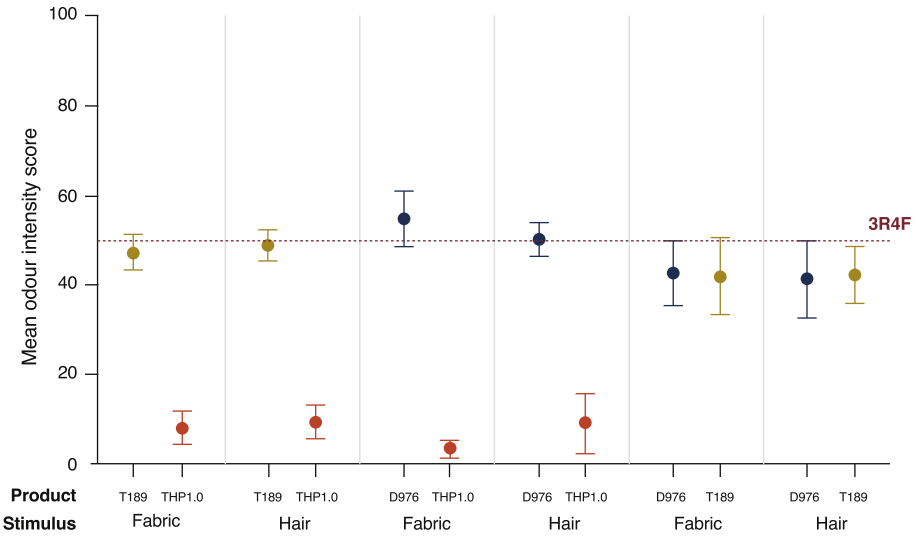

Fig. 11. Intensity scores for tobacco odour on fabric and hair for THP1.0 and cigarettes T189 and D976 relative to a 3R4F reference cigarette, assigned a score of 50. Abbreviation: THP = tobacco heating product.

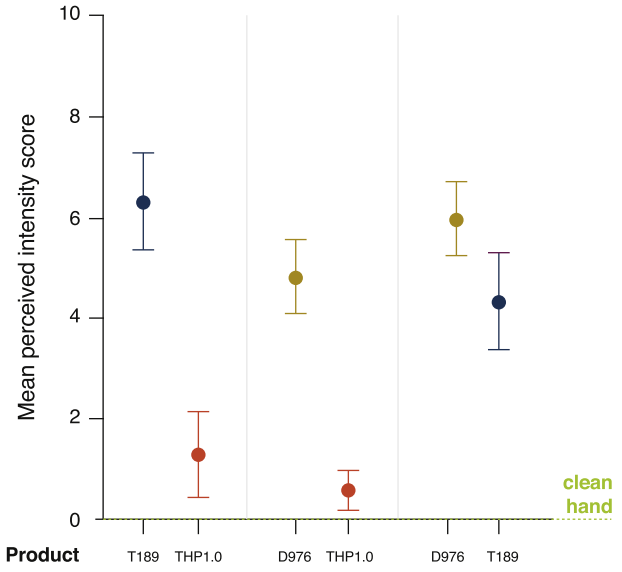

Fig. 12. Intensity scores for tobacco odour on skin for THP1.0 and cigarettes T189 and D976 relative to the clean hand of the product user, assigned a score of 0. Abbreviation: THP = tobacco heating product.

were generally around twice as high in the present study (five or eight products per hour smoked) as in Mitova et al.'s (2016) study (three or four products per hour smoked). Measurements of particle mass by Mitova et al. were below an LOD of 14.7 μg m^{-3}, which is consistent with our PM_1 mobility values of ≤5 μg m^{-3} obtained with a measurement technique that was significantly more sensitive.

Tricker et al. (2009) compared IAQ between aerosol from an electrically heated cigarette smoking system (EHCSS) and smoke from a conventional cigarette, using similar markers across multiple ventilation environments. They found that 24 of 29 smoke constituents were reduced by more than 90% for the EHCSS and the other five by 80%–90% (average 94% ± 4%); for example, PM, nicotine and acetaldehyde were reduced by 90%, 97% and 93%, respectively. Frost-Pineda et al. (2008) also reported ETS data for the EHCSS, but less comprehensively than Tricker et al. (2009).

More recently, Protano et al. (2016) measured particle size and number emissions in the 5.6–560 nm range for the iQOS™ THS (the commercial name for a variant of THS2.2) versus a conventional cigarette and modelled particle deposition in the lung. No absolute concentration data were reported, but particle concentrations were noted to be fourfold higher for the cigarette than for the THS, with the cigarette particles persisting longer in the atmosphere after cessation of smoking. The rapid loss of heated tobacco particles was ascribed to rapid accumulation, which would expand the particles beyond the 560 nm measurement range, but it seems equally likely to be due to evaporative losses, because Mitova et al. (2016) describe the mainstream output of the similar THS2.2 product as being 76% water, 10% glycerol and 3% nicotine.

A very limited single-spectrum qualitative study by O'Connell et al. (2015b) that used proton transfer reaction MS suggested that sidestream VOC emissions from THS were more complex than those from an e-cigarette or a Nicorette™ Inhalator (Johnson & Johnson, New Brunswick, NJ, USA), but less complex than sidestream cigarette smoke. In contrast to the studies of Mitova et al. (2016) and Ruprecht et al. (2017), however, no quantification was carried out.

Ruprecht et al. (2017) conducted a wider analytical study on THS versus a conventional cigarette in which two or three volunteers smoked six products per hour in a 48 m^3 room under 1.54 ACH. They concluded that, where detectable, emissions from THS were significantly less than those from the cigarette. In their study, emissions were newly detected for black carbon and certain metals, plus a series of *n*-alkanes, organic acids and levoglucosan. Previously reported markers included particle mass (>99% reduction), particle number (>76% reduction), formaldehyde (93% reduction), acetaldehyde (>94% reduction) and acrolein (>97% reduction).

In summary, the limited published data regarding environmental emissions and effects on IAQ for THPs are in general agreement: there is no evidence of combustion by-products, such as CO or NO_x. There is evidence for the generation of some distilled and thermal degradation products, as well as for aerosol droplet formation, but these are significantly reduced as compared with conventional cigarette smoke. Most tobacco smoke toxicants of those measured are detected at baseline levels or are below the LOD of the experimental systems reported.

To understand how chamber studies may relate to real-life field

conditions, it is useful to look at published values for particle mass and nicotine exposures from tobacco smoking. Very few data have been reported recently, which may be a consequence of the indoor smoking restrictions that have emerged in many jurisdictions, with a consequent fall in survey work. A reasonably comprehensive overview of published data sets was carried out in 2000 by Jenkins et al. (2000), who noted that the data should be approached with caution due to the use of multiple techniques with different sensitivities and LODs. In general, however, most studies in home, work and hospitality environments report averages of <100 μg m^{-3} PM and <10 μg m^{-3} nicotine, although more extreme values of up to 1000 μg m^{-3} PM have been reported.

More recently, Health Canada (2016) reported average indoor $PM_{2.5}$ concentrations of 15 μg m^{-3} in non-smoking homes versus 35 μg m^{-3} in homes with smokers. At the other extreme, in a study of 28 German hospitality venues where smoking was permitted, Bolte et al. (2008) found median levels of nicotine of 15 μg m^{-3} in restaurants, 31 μg m^{-3} in pubs, and 193 μg.m^{-3} in discotheques; median levels of 3-EP ranging from 3 to 24 μg.m^{-3}; median levels of benzene of 8–20 μg.m^{-3}; and median levels of the sum of 16 PAHs (in accordance with the US EPA) of 215–375 ng m^{-3}. Median $PM_{2.5}$ mass concentration (gravimetric) ranged from 178 to 808 μg m^{-3}, and particle number concentration from 120,000 to 210,000 particles per cm^3.

Thus, at up to 764 μg m^{-3} (gravimetric) PM and 54 μg m^{-3} nicotine, the measured levels for cigarette smoke exposure in the present IAQ study suggest exposures at the more intense end of the spectrum.

Formaldehyde and acetaldehyde were also noted to have slightly increased over baseline levels in this experiment, with formaldehyde being of greater toxicological concern. It is noted that both the baseline values and increments for formaldehyde lie within a wide range of reported literature data for indoor and outdoor exposure, arising from multiple sources of exposure, particularly in the indoor environment (Salthammer, 2013; Salthammer et al., 2010).

The real-time particle mass and number data from the mobility spectrometer at 10 s resolution with high sensitivity offer useful insight. The observed saw-tooth pattern of build-up and decay for cigarette smoke (Figs. 6 and 7) was highly consistent, suggesting both good mixing in the room and good volunteer compliance with the required smoking patterns. The high sensitivity also demonstrated that there was a similar aerosol production and decay pattern for THP1.0, albeit at two orders of magnitude lower than the cigarette smoke.

There are observed anomalies with the light-scattering data from the TSI DustTrak instrument. In general, $PM_{1.0} = PM_{2.5} = PM_{10.}$, suggesting all the aerosol is sub-micron; this is consistent with condensation aerosols and in agreement with the mass median diameter measurements of <300 nm. However, the light-scattering and electrical-mobility techniques differed for absolute mass values at PM_1: the light-scattering technique yielded values that were, on average, 2.5 times higher than those of the electrical-mobility measurements. As noted previously, separate gravimetric filter analyses for cigarette smoke, supported the accuracy of the electrical mobility technique.

This is a recognised phenomenon of the two techniques: the scatter intensity of an aerosol falls off rapidly at aerosol diameters less than the wavelength of light, and, ideally, calibrations of the light-scattering technique versus a gravimetric filter are desirable for controlled chamber studies. This may be less effective for uncontrolled field studies in real domestic, office and hospitality environments, where multiple particle sizes might be encountered and a calibration factor applied to correct one end of the size spectrum could influence the recording of other sizes.

Field studies conducted by Jenkins et al. (2004) indicated that the TSI DustTrak units might over-report actual PM concentrations by a factor of 2.6–3.1, depending on whether the sampling is conducted in the non-smoking or smoking section of the test locations.

In the present study, the particle diameters reported for cigarette smoke and the THP1.0 aerosol were <300 nm mass median diameter with geometric standard deviation in the range 2.2–2.5. Count median diameters were approximately 110 nm and 60 nm for the T189 cigarette and THP1.0, respectively; the cigarette smoke data are consistent with previously reported data (e.g., Guerin et al., 1987).

4.1.2. Air quality standards

A significant driver in the development of new categories of nicotine delivery systems by inhalation is the potential for harm reduction. This has been recognised in part for vapour products (McNeill et al., 2015; RCP, 2016), although others remain more cautious (Fernández et al., 2016). For cigarette smoke, environmental exposure has been identified by various regulatory authorities as a public health concern. For example, in 2006, the California EPA Air Resources Board identified ETS as a toxic air contaminant, and concluded that, owing to carcinogens being present, there was no acceptable air quality limit (US EPA, 1992; California Air Resources Board, 2006).

There has also been an increasing awareness of the potential impact of air pollution on public health (WHO, 2005; WHO, 2016), particularly from other combustion sources, and there are significant ongoing activities to reduce emissions and improve air quality through increasingly rigorous air quality standards.

Although humans in developed countries spend more than 90% of their time indoors, IAQ standards are relatively sparse and fragmented. The most comprehensive standards are those for industrial workplaces, but these are set at relatively high levels and are not generally deemed as appropriate for environmental exposures for the wider population.

For example, the UK Health & Safety Executive sets occupational exposure limits for many relevant compounds such as propylene glycol (474,000 μg m^{-3}), glycerol (10,000 μg m^{-3}), nicotine (500 μg m^{-3}), formaldehyde (2500 μg m^{-3}), acetaldehyde (37,000 μg m^{-3}), acrolein (230 μg m^{-3}), Total VOC (300 μg m^{-3}), acrylamide (300 μg m^{-3}), acrylonitrile (4400 μg m^{-3}), benzene (3250 μg m^{-3}), 1,3–butadiene (22,000 μg m^{-3}), CO_2 (9,150,000 μg m^{-3}), CO (35,000 μg m^{-3}), nitrous oxide (183,000 μg m^{-3}), toluene (191,000 μg m^{-3}), and PAH (200 μg m^{-3}) (Health & Safety Executive, 2011) but, as noted above, these are not necessarily appropriate for the general population. In Japan, the Japan Society for Occupational Health (2016) recommends the Occupational Exposure Limits as reference values for preventing adverse health effects on workers, including those caused by occupational exposure to chemical substances. Relevant species include acetaldehyde (90,000 μg m^{-3}) and formaldehyde (120 μg m^{-3}).

The World Health Organization (2010) has published guidelines for indoor air for benzene (no safe level), CO (8 h exposure, 10,000 μg m^{-3}; 24-h exposure, 7000 μg m^{-3}), formaldehyde (30–min exposure, 100 μg m^{-3}; rounded down from the no adverse effect level of 600 μg m^{-3} divided by 5 to avoid sensory irritation), naphthalene (10 μg m^{-3} annual average), NO_2 (1 h average, 200 μg m^{-3}) and PAHs (no safe level).

An earlier EU Index project ascribed high priority to CO (8 h exposure, 10,000 μg m^{-3}), NO_2, (<40 μg m^{-3} annual average) and naphthalene (10 μg m^{-3}) (European Commission, 2005); however, it questioned whether the NO_2 limit could be achieved due to high outputs from gas appliances. Benzene was ascribed no safe level, but the study measured a median concentration of 4.2 ± 3.2 μg m^{-3}

with a 90th percentile of 11.5 ± 11.1 μg m^{-3} and believed that a limit of 10 μg m^{-3} might be achievable. Similarly, concern was expressed for formaldehyde exposures of >1 μg m^{-3}, while recognising median and 90th percentile exposures of 26 ± 6 μg m^{-3} and 59 ± 7 μg m^{-3}, respectively. Secondary priorities were recommended for acetaldehyde (200 μg m^{-3}) and toluene (300 μg m^{-3}).

Although designed primarily for testing VOC emissions from indoor sources, the California Department of Public Health (2017) produced a standard test method using environmental chambers. This laid out guidelines for chemicals including acetaldehyde (70 μg m^{-3}), benzene (1·5 μg m^{-3}), formaldehyde (9 μg m^{-3}), naphthalene (4·5 μg m^{-3}) and toluene (150 μg m^{-3}).

Health Canada (2016) issued a series of residential IAQ guidelines with recommended exposure limits incorporating long-term exposure limits for health problems that can occur from continuous or repeated exposure over several months or years, and short-term exposure limits, for health problems that can occur immediately after a brief exposure. Relevant species included benzene (keep indoor levels of benzene as low as possible), CO (24 h exposure, 11,500 μg m^{-3}; 1 h exposure, 28,600 μg m^{-3}), formaldehyde (8 h exposure, 50 μg m^{-3}; 1 h exposure, 123 μg m^{-3}), $PM_{2.5}$ (keep indoor levels of $PM_{2.5}$ as low as possible, use a stovetop fan [that exhausts outdoors] while cooking, and do not allow smoking indoors), naphthalene (24 h exposure, 10 μg m^{-3}), NO_2 (24 h exposure, 20 μg m^{-3}; 1 h exposure, 170 μg m^{-3}), O_3 (8 h exposure, 40 μg m^{-3}) and toluene (24 h exposure, 2300 μg m^{-3}; 8 h exposure, 15,000 μg m^{-3}). It was noted for $PM_{2.5}$ that averages were <15 μg m^{-3} in homes without smokers and <35 μg m^{-3} in homes with smokers (Health Canada, 2016).

Some guidance can be found from outdoor air quality standards. The US EPA (2015) recommends an annual $PM_{2.5}$ standard of 12 μg m^{-3} and an annual NO_2 standard of 57 μg m^{-3}. The World Health Organization (2016) recommends an annual $PM_{2.5}$ standard of 10 μg m^{-3}, a 24 h $PM_{2.5}$ standard of 25 μg m^{-3}, an annual NO_2 standard of 57 μg m^{-3} and a 1 h NO_2 standard of 200 μg m^{-3}. The European Union recommends annual outdoor air standards for $PM_{2.5}$ (25 μg m^{-3}), NO_2 (40 μg m^{-3}) and benzene (5 μg m^{-3}) (European Commission, 2005). The Ministry of the Environment, Government of Japan (2014) suggests outdoor air standards for $PM_{2.5}$ (15 μg m^{-3} annual; 35 μg m^{-3} daily), NO_2 (76–115 μg.m^{-3}) and benzene (3 μg m^{-3}). It can be observed that there is an increasing degree of consensus across the various recommended limits.

It is notable in the context of the present study that the short-term concentrations of toxicants from intense cigarette smoke exposures exceeded some of the long-term exposure limits, for example, for VOCs, benzene, formaldehyde and $PM_{2.5}$. By contrast, the short-term concentrations of all measured THP1.0 emissions were within the long-term exposure limits.

4.2. Odour

In all test substrate materials – namely fabric, hair and skin – the residual tobacco smoke odour was found to be significantly less for THP1.0 than for the test cigarettes. The test scores of the two cigarettes did not differ significantly between fabric and hair, but were significantly different for skin. It should be noted that the nature of the exposure was different in the two sets of experiments. For skin exposure, the smoker used the cigarette or THP1.0 in one hand, which would thus be exposed to sidestream aerosol from the inter-puff phase and to exhaled mainstream aerosol, albeit briefly. Lower scores might be expected for THP1.0 because it does not combust the tobacco (Eaton et al., 2017) and, effectively, does not smoulder between puffs. The mainstream chemistry of THP1.0 is also significantly less complex than that of cigarette smoke (Forster et al., 2017); it has a significantly reduced vapour phase, which tends to be responsible for much of the irritation attributed to cigarette smoke sidestream emissions. Notably, there was a significant difference in the skin test scores of the two cigarettes, and the order of intensity was reversed from that observed when they were pair-tested versus the THP. It is possible that the chemical composition of the smoke from the two cigarettes differed because T189 contained US blend-style tobacco and D976 Virginia-style tobacco.

For the studies of residual odour on fabric and hair, the smoke aerosol was generated by machine and the substrate samples were exposed to the combined mainstream and sidestream aerosol; in real life, much of the mainstream smoke is retained by the smoker, especially the lower-molecular-weight vapour-phase compounds, of which typically 90–95% are retained (Baker and Dixon, 2006; Feng et al., 2007; Moldoveanu and St. Charles, 2007; St. Charles et al., 2013). Again, the lower scores for residual odour for THP1.0 might be expected owing to the lack of combustion, inter-puff smoulder and significantly reduced mainstream aerosol emissions (Eaton et al., 2017; Forster et al., 2017).

Measurement of residual odour in the room used for IAQ studies was considered, but deemed impractical on both logistic and scientific grounds. Experimentally, this would have required a further independent group of volunteers because the group within the room might be habituated to any residual odour. On scientific grounds, it is unlikely that the room would have reached an equilibrium with respect to deposited smoke (Piadé et al., 1999) or washout of second-hand smoke.

5. Conclusions

In summary, THP1.0 has a significantly lower impact on IAQ than conventional combustible cigarettes, driven by a significantly lower emissions profile of both aerosol particles and chemical emissions in respect of the toxicants measured.

In the chamber study, particle and chemical emissions were observed at low levels, with particle metrics of mass and number >98–99% lower than cigarette smoke. Particle diameters were similar for THP1.0 aerosol and cigarette smoke. For THP1.0, most test analytes were below detectable levels or did not exceed baseline levels. For those that were measurable – namely, nicotine, acetaldehyde and formaldehyde – the levels were typically >90% lower than those from cigarette smoke. These data are consistent with other THPs. Environmental emissions from THP1.0 would conform to published IAQ guidelines, such as those from the World Health Organization (2010) and, for particles, would conform to target the World Health Organization (2016) outdoor air annual mean limits of 10 μg m^{-3} $PM_{2.5}$.

In conclusion, this study found that THP1.0 had significantly less impact on IAQ, and that the emissions from THP1.0 are significantly less odorous than those from conventional cigarettes and their emissions.

Conflict of interests

All authors are employed by British American Tobacco.

Transparency document

Transparency document related to this article can be found online at https://doi.org/10.1016/j.yrtph.2017.09.017.

References

ASTM, 2017. Standard Test Method for Nicotine and 3-Ethenylpyridine in Indoor Air.

D5075–01(2017)e1. http://www.astm.org/cgi-bin/resolver.cgi?D5075-01(2017)e1 (accessed April 25, 2017).
Baker, R.R., Dixon, M., 2006. The retention of tobacco smoke constituents in the human respiratory tract. Inhal. Toxicol. 18, 255–294.
Baker, R.R., Proctor, C.J., 1990. The origins and properties of environmental tobacco smoke. Environ. Int. 16, 231–245.
Bertholon, J.-F., Becquemin, M.H., Roy, M., Dautzenberg, B., 2013. Comparaison de l'aérosol de la cigarette électronique à celui des cigarettes ordinaires et de la chicha. Rev. Des. Mal. Respir. 30, 752–757.
Bolte, G., Heitmann, D., Kiranoglu, M., Schierl, R., Diemer, J., Koerner, W., Fromme, H., 2008. Exposure to environmental tobacco smoke in German restaurants pubs and discotheques. J. Expo. Sci. Environ. Epidemiol. 18, 262–271.
Borgerding, M.F., Bodnar, J.A., Wingate, D.E., 2000. The 1999 Massachusetts Benchmark Study. Final Report. Department of Health, Massachusetts. http://legacy.library.ucsf.edu/tid/yek21c00 (accessed April 26, 2017).
BREEAM, 2011. Hea02 indoor air quality. In: BREEAM New Construction Non-domestic Buildings Technical Manual SD5073 – 5.0:2011. https://www.breeam.com/BREEAM2011SchemeDocument/Content/05_health/hea02.htm (accessed April 25, 2017).
British Standards Institute (BSI), 2007. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. BS EN 15251:2007. BSI, London, UK.
Burns, D.M., Dybing, E., Gray, N., Hecht, S., Anderson, C., Sanner, T., O'Connor, R., Djordjevic, M., Dresler, C., Hainaut, P., Jarvis, M., Opperhuizen, A., Straif, K., 2008. Mandated lowering of toxicants in cigarette smoke: a description of the World Health Organization TobReg proposal. Tob. Control 17, 132–141.
Burstyn, I., 2014. Peering through the mist: systematic review of what the chemistry of contaminants in electronic cigarettes tells us about health risks. BMC Public Health 14, 18.
California Air Resources Board, 2006. Proposed Identification of environmental tobacco smoke as a toxic air contaminant. https://www.arb.ca.gov/regact/ets2006/app3partb.pdf (accessed April 27, 2017).
California Department of Public Health, 2017. Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environmental Chambers. Version 1.2 : Emission testing method for California Specification 01350. Indoor Air Quality Section Environmental Health Laboratory Branch Division of Environmental and Occupational Disease Control, California Department of Public Health.
Chien, Y.-H., Chang, C.-P., Liu, Z.-Z., 2011. Volatile organics off-gassed among tobacco-exposed clothing fabrics. J. Hazard. Mat. 193, 139–148.
Costigan, S., Meredith, C., 2015. An approach to ingredient screening and toxicological risk assessment of flavours in e-liquids. Regul. Toxicol. Pharmacol. 72, 361–369.
Eaton, D., Jakaj, B., Forster, M., Nicol, J., Mavropoulou, E., Scott, J.K., Liu, C., McAdam, K.G., Murphy, J., Proctor, C.J., 2017. Assessment of tobacco heating product THP1.0. Part 2: product design, operation and thermophysical characterisation. Regul. Toxicol. Pharmacol. (in this issue).
California Environmental Protection Agency (EPA), 2005. Office of Environmental Health Hazard Assessment. Proposed Identification of Environmental Tobacco Smoke as a Toxic Air Contaminant: Part B Health Effects. State of California Air Resources Board. https://www.arb.ca.gov/regact/ets2006/app3exe.pdf (accessed April 26, 2017).
European Commission Joint Research Centre, 2005. The INDEX Project – Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/index-project-critical-appraisal-setting-and-implementation-indoor-exposure-limits-eu (accessed April 27, 2017).
Farsalinos, K.E., Le Houezec, J., 2015. Regulation in the face of uncertainty: the evidence on electronic nicotine delivery systems (e-cigarettes). Risk Manag. Healthc. Policy 8, 157–167.
FDA, 2012. Guidance for industry modified risk tobacco product applications. Draft guidance. http://www.fda.gov/downloads/TobaccoProducts/GuidanceComplianceRegulatoryInformation/UCM297751.pdf (accessed April 26, 2017).
Feng, S., Plunkett, S.E., Lam, K., Kapur, S., Muhammad, R., Jin, Y., Zimmermann, M., Mendes, P., Kinser, R., Roethig, H.J., 2007. A new method for estimating the retention of selected smoke constituents in the respiratory tract of smokers during cigarette smoking. Inhal. Toxicol. 19, 169–179.
Fernández, E., Fu, M., Martínez-Sánchez, J.M., 2016. Exposure to Aerosols from Smoking-proxy Electronic Inhaling Systems: a Systematic Review. World Health Organisation, Barcelona, Spain. http://www.who.int/tobacco/industry/product_regulation/BackgroundPapersENDS1_4november.pdf (accessed April 26, 2017).
Forster, M., Liu, C., Duke, M.G., McAdam, K.G., Proctor, C.J., 2015. An experimental method to study emissions from heated tobacco between 100 to 200°C. Chem. Cent. J. 9, 20.
Forster, M., Mariner, D., Wright, C., Fiebelkorn, S., Yurteri, C., Liu, C., McAdam, K.G., Proctor, C.J., 2017. Assessment of tobacco heating product THP1.0. Part 3: comprehensive chemical characterisation - harmful and potentially harmful aerosol emissions. Regul. Toxicol. Pharmacol. (in this issue).
Fowles, J., Dybing, E., 2003. Application of toxicological risk assessment principles to the chemical constituents of cigarette smoke. Tob. Control 12, 424–430.
Frost-Pineda, K., Zedler, B.K., Liang, Q., Roethig, H.J., 2008. Environmental tobacco smoke (ETS) evaluation of a third-generation electrically heated cigarette smoking system (EHCSS). Regul. Toxicol. Pharmacol. 52, 118–121.
Gonzalez-Suarez, I., Martin, F., Marescotti, D., Guedj, E., Acali, S., Johne, S., Dulize, R., Baumer, K., Peric, D., Goedertier, D., Frentzel, S., Ivanov, N.V., Mathis, C., Hoeng, J., Peitsch, M.C., 2016. In vitro systems toxicology assessment of a candidate modified risk tobacco product shows reduced toxicity compared to that of conventional cigarette. Chem. Res. Toxicol. 29, 3–18.
Guerin, M.R., Higgins, C.E., Jenkins, R.A., 1987. Measuring environmental emissions from tobacco combustion: sidestream cigarette smoke literature review. Atmos. Environ. 21, 406–408.
Health & Safety Executive, 2006. MDHS14/4 General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols. http://www.hse.gov.uk/pubns/mdhs/pdfs/mdhs14-4.pdf (accessed April 27, 2017).
Health & Safety Executive, 2011. EH40/2005 workplace exposure limits. http://www.hse.gov.uk/pubns/books/eh40.htm (accessed April 27, 2017).
Health Canada, 2016. Residential indoor air quality guidelines. https://www.canada.ca/en/health-canada/services/air-quality/residential-indoor-air-quality-guidelines.html#a2 (accessed April 25, 2017).
Hess, I.M., Lachireddy, K., Capon, A., 2016. A systematic review of the health risks from passive exposure to electronic cigarette vapour. Public Health Res. Pract. 26, 2621617.
IARC, 1986. Tobacco Smoking. IARC Monographs on the Evaluation of Carcinogenic Risk of Chemicals to Humans, vol. 38. IARC, Lyon, France.
IARC, 2004. Tobacco Smoke and Involuntary Smoking. IARC Monographs on the Evaluation of Carcinogenic Risk of Chemicals to Humans, vol. 83. IARC, Lyon, France.
ISO, 2011a. Indoor Air — Part 6: Determination of Volatile Organic Compounds in Indoor and Test Chamber Air by Active Sampling on Tenax TA Sorbent, Thermal Desorption and Gas Chromatography Using MS/FID). ISO 16000-6. ISO, Geneva, 2011.
ISO, 2011b. Indoor Air — Part 3: Determination of Formaldehyde and Other Carbonyl Compounds in Indoor Air and Test Chamber Air — Active Sampling Method. ISO 16000-3. ISO, Geneva, 2011.
ISO, 2012. Sensory Analysis — General Guidance for the Selection, Training and Monitoring of Selected Assessors and Expert Sensory Assessors. ISO 8586, vol. 2012. ISO, Geneva.
Japan Society for Occupational Health, May 25, 2016. Recommendation of occupational exposure limits (2016–2017). J. Occup. Health 58, 489–518.
Jenkins, R.A., Guerin, M.R., Tomkins, B.A., 2000. The Chemistry of Environmental Tobacco Smoke: Composition and Measurement, second ed. CRC Press, Oxford, UK.
Jenkins, R.A., Ilgner, R.H., Tomkins, B.A., Peters, D.W., 2004. Development and application of protocols for the determination of response of real-time particle monitors to common indoor aerosols. J. Air Waste Manage. Assoc. 54, 229–241.
Matt, G.E., Quintana, P.J., Destaillats, H., Gundel, L.A., Sleiman, M., Singer, B.C., Jacob, P., Benowitz, N., Winickoff, J.P., Rehan, V., Talbot, P., Schick, S., Samet, J., Wang, Y., Hang, B., Martins-Green, M., Pankow, J.F., Hovell, M.F., 2011a. Thirdhand tobacco smoke: emerging evidence and arguments for a multidisciplinary research agenda. Environ. Health Perspect. 119, 1218–1226.
Matt, G.E., Quintana, P.J., Zakarian, J.M., Fortmann, A.L., Chatfield, D.A., Hoh, E., Uribe, A.M., Hovell, M.F., 2011b. When smokers move out and non-smokers move in: residential thirdhand smoke pollution and exposure. Tob. Control 20, e1.
Matt, G.E., Quintana, P.J., Zakarian, J.M., Hoh, E., Hovell, M.F., Mahabee-Gittens, M., Watanabe, K., Datuin, K., Vue, C., Chatfield, D.A., 2016. When smokers quit: exposure to nicotine and carcinogens persists from thirdhand smoke pollution. Tob. Control. https://doi.org/10.1136/tobaccocontrol-2016-053119.
McAuley, T.R., Hopke, P.K., Zhao, J., Babaian, S., 2012. Comparison of the effects of e-cigarette vapor and cigarette smoke on indoor air quality. Inhal. Toxicol. 24, 850–857.
McNeill, A., Brose, L.S., Calder, R., Hitchman, S.C., Hajek, P., McRobbie, H., 2015. E-cigarettes: an evidence update A report commissioned by Public Health England. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/457102/Ecigarettes_an_evidence_update_A_report_commissioned_by_Public_Health_England_FINAL.pdf. Accessed April 25, 2017.
Ministry of the Environment, Government of Japan 2014. http://www.sea.gob.cl/sites/default/files/migration_files/Normas_secundarias/Anexo_documental/Jap%C3%B3n/Aire/JA-AI-02-EQS.pdf (accessed 7 August 2017).
Mitova, M.I., Campelos, P.B., Goujon-Ginglinger, C.G., Maeder, S., Mottier, N., Rouget, E.G., Tharin, M., Tricker, A.R., 2016. Comparison of the impact of the Tobacco Heating System 2.2 and a cigarette on indoor air quality. Regul. Toxicol. Pharmacol. 80, 91–101.
Moldoveanu, S.C., St Charles, F.K., 2007. Differences in the chemical composition of the particulate phase of inhaled and exhaled cigarette mainstream smoke. Beitr Tab. Int. 22, 290–302.
Mottier, N., Tharin, M., Cluse, C., Crudo, J.R., Lueso, M.G., Goujon-Ginglinger, C.G., Jaquier, A., Mitova, M.I., Rouget, E.G., Schaller, M., Solioz, J., 2016. Validation of selected analytical methods using accuracy profiles to assess the impact of a Tobacco Heating System on indoor air quality. Talanta 158, 165–178.
National Cancer Institute (NCI), 1999. Health Effects of Exposure to Environmental Tobacco Smoke. National Cancer Institute; Smoking and Tobacco Control Monograph 10, Bethesda, MD, USA.
Noguchi, M., Tanaka, S., Watanabe, K., Yamasaki, A., 2016. Correlation between odor concentration and volatile organic compounds (VOC) composition of environmental tobacco smoke (ETS). Int. J. Environ. Res. Public Health 13 (10), E994.
Norman, A., 1999. Cigarette design and materials. In: Davis, D.L., Nielsen, M.T. (Eds.), Tobacco: Production, Chemistry and Technology. Blackwell Science, Oxford, UK.

O'Connell, G., Colard, S., Cahours, X., Pritchard, J.D., 2015a. An assessment of indoor air quality before, during and after unrestricted use of e-cigarettes in a small room. Int. J. Environ. Res. Public Health 12, 4889–4907.
O'Connell, G., Wilkinson, P., Burseg, K.M.M., Stotesbury, S.J., Pritchard, J.D., 2015b. Heated tobacco products create side-stream emissions: implications for regulation. J. Environ. Anal. Chem. 2, 163.
Piadé, J.J., D'André, S., Sanders, E.B., 1999. Sorption phenomena of nicotine and ethenylpyridine vapors on different materials in a test chamber. Environ. Sci. Technol. 33, 2046–2052.
Protano, C., Manigrasso, M., Avino, P., Sernia, S., Vitali, M., 2016. Second-hand smoke exposure generated by new electronic devices (IQOS® and e-cigs) and traditional cigarettes: submicron particle behaviour in human respiratory system. Ann. Ig. 28, 109–112.
Royal College of Physicians (RCP), 2016. Nicotine without Smoke: Tobacco Harm Reduction. RCP, London, UK. https://www.rcplondon.ac.uk/myrcp (accessed April 27, 2017).
Rodgman, A., Perfetti, T.A., 2013. The Chemical Components of Tobacco and Tobacco Smoke, second ed. CRC Press, Boca Raton.
Ruprecht, A.A., De Marco, C., Saffari, A., Pozzi, P., Mazza, R., Veronese, C., Angellotti, G., Munarini, E., Ogliari, A.C., Westerdahl, D., Hasheminassab, S., Shafer, M.M., Schauer, J.J., Repace, J., Sioutas, C., Boffi, R., 2017. Environmental pollution and emission factors of electronic cigarettes, heat-not-burn tobacco products and conventional cigarettes. Aerosol Sci. Technol. 51, 674–684.
Salthammer, T., 2013. Formaldehyde in the ambient atmosphere: from an indoor pollutant to an outdoor pollutant? Angew. Chem. Int. Ed. 2013, 3320–3327.
Salthammer, T., Mentese, S., Marutzky, R., 2010. Formaldehyde in the indoor environment. Chem. Rev. 110, 2536–2572.
Schorp, M.K., Tricker, A.R., Dempsey, R., 2012. Reduced exposure evaluation of an electrically heated cigarette smoking system. Part 1: non-clinical and clinical insights. Regul. Toxicol. Pharmacol. 64, S1–S10.
Singer, B.C., Hodgson, A.T., Guevarra, K.S., Hawley, E.L., Nazaroff, W.W., 2002. Gas-phase organics in environmental tobacco smoke. 1. Effects of smoking rate, ventilation, and furnishing level on emission factors. Environ. Sci. Technol. 36 (5), 846–853.
Singer, B.C., Hodgson, A.T., Nazaroff, W.W., 2003. Gas-phase organics in environmental tobacco smoke: 2. Exposure-relevant emission factors and indirect exposures from habitual smoking. Atmos. Environ. 37, 5551–5561.
Smith, M.R., Clark, B., Lüdicke, F., Schaller, J.-P., Vanscheeuwijck, P., Hoeng, J., Peitsch, M.C., 2016. Evaluation of the tobacco heating system 2.2. Part 1: description of the system and the scientific assessment program. Regul. Toxicol. Pharmacol. 81 (Suppl. 2), S17–S26.
St Charles, K., McAughey, J., Shepperd, C., 2013. Methodologies for the quantitative estimation of toxicant dose to cigarette smokers using physical, chemical and bioanalytical data. Inhal. Toxicol. 25, 383–397.
Stratton, K., Shetty, P., Wallace, R., Bondurant, S. (Eds.), 2001. Clearing the Smoke: Assessing the Science Base for Tobacco Harm Reduction. National Academies Press, Washington DC, USA.
Tricker, A.R., Schorp, M.K., Urban, H.G., Leyden, D., Hagerdorn, H.W., Engl, J., Urban, M., Riedel, K., Gilch, G., Janket, D., Scherer, G., 2009. Comparison of environmental tobacco smoke (ETS) concentrations generated by an electronically heated cigarette smoking system and a conventional cigarette. Inhal. Toxicol. 21, 62–77.
Ueta, I., Saito, Y., Teraoka, K., Miura, T., Jinno, K., 2010. Determination of volatile organic compounds for a systematic evaluation of third-hand smoking. Anal. Sci. 26, 569–574.
US DHHS, 2006. The Health Consequences of Involuntary Exposure to Tobacco Smoke. A report of the Surgeon General. Centers for Disease Control and Prevention, Atlanta, USA.
US DHHS, 2010. How Tobacco Smoke Causes Disease: the Biology and Behavioral Basis for Smoking-attributable Disease. A Report of the Surgeon General. Centers for Disease Control and Prevention, Atlanta, GA, USA.
US DHHS, 2014. The Health Consequences of Smoking: 50 Years of Progress. A Report of the Surgeon General. Centers for Disease Control and Prevention, Atlanta, GA, USA. Printed with corrections, January 2014.
US DHHS, 2016. Tobacco-related Exposures, 14th Report on Carcinogens. National Toxicology Program. http://ntp.niehs.nih.gov/ntp/roc/content/profiles/tobaccorelatedexposures.pdf#search=tobacco%20smoke (accessed April 25, 2017).
US EPA, 1992. Respiratory Health Effects of Passive Smoking (Also Known as Exposure to Secondhand Smoke or Environmental Tobacco Smoke—ETS). EPA/600/6–90/006F. Office of Health and Environmental Assessment, Office of Research and Development, US Environmental Protection Agency, Washington, DC, USA.
US EPA, 2016. List of designated reference and equivalent methods. https://www3.epa.gov/ttnamti1/files/ambient/criteria/AMTIC%20List%20Dec%202016-2.pdf (accessed April 25, 2017).
US EPA, 2015. Reviewing National Ambient Air Quality Standards (NAAQS): Scientific and Technical Information. https://www.epa.gov/criteria-air-pollutants/naaqs-table (accessed April 25, 2017).
Walker, R., White, M., 1995. The Passive Gas Tracer Method for Monitoring Ventilation Rates in Buildings. BRE Information Paper IP 13/95. September 1995. BRE, Garston, Watford, Herts, UK.
Whelan, V., Cotte, V., 2014. GC-MS Measurement of the Headspace of Sidestream Smoke Deposited on Fabric, 14th Weurman Flavour Symposium. Oxford, UK. September 15–19, 2014.
WHO, 1999. Carbon Monoxide. Environmental Health Criteria 213. International Programme on Chemical Safety.
WHO, 2005. Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf (accessed April 27, 2017).
WHO, 2010. Guidelines for indoor air quality: selected pollutants. http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf (accessed April 27, 2017).
WHO, 2016. WHO expert consultation: available evidence for the future update of the WHO global air quality guidelines (AQGs). http://www.euro.who.int/__data/assets/pdf_file/0013/301720/Evidence-future-update-AQGs-mtg-report-Bonn-sept-oct-15.pdf (accessed April 27, 2017).
Zenzen, V., Diekmann, J., Gerstenberg, B., Weber, S., Wittke, S., Schorp, M.K., 2012. Reduced exposure evaluation of an electrically heated cigarette smoking system. Part 2: smoke chemistry and in vitro toxicological evaluation using smoking regimes reflecting human puffing behaviour. Regul. Toxicol. Pharmacol. 64, S11–S14.