



Assessment of tobacco heating product THP1.0. Part 2: Product design, operation and thermophysical characterisation



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ABSTRACT

A novel tobacco heating product, THP1.0, that heats tobacco below 245 °C is described. It was designed to eliminate tobacco combustion, while heating tobacco to release nicotine, tobacco volatiles and glycerol to form its aerosol. The stewardship assessment approach behind the THP 1.0 design was based on established toxicological principles. Thermophysical studies were conducted to examine the extent of tobacco thermal conversion during operation. Thermogravimetric analysis of the tobacco material revealed the major thermal behaviour in air and nitrogen up to 900 °C. This, combined with the heating temperature profiling of the heater and tobacco rod, verified that the tobacco was not subject to combustion. The levels of tobacco combustion markers (CO, CO₂, NO and NO_x) in the aerosol of THP1.0 were significantly lower than the levels if there were any significant pyrolysis or combustion. Quantification of other tobacco thermal decomposition and evaporative transfer markers showed that these levels were, on average, reduced by more than 90% in THP1.0 aerosol as compared with cigarette smoke. The physical integrity of the tobacco consumable rod showed no ashing. Taken together, these data establish that the aerosol generated by THP1.0 is produced mainly by evaporation and distillation, and not by combustion or pyrolysis.

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1. Introduction

Cigarette smoking is one of the leading preventable causes of human diseases such as lung cancer, chronic obstructive pulmonary disease and cardiovascular disorders (US DHHS, 2014). Most smoking-related diseases are not caused by nicotine but by toxicants present in the inhaled smoke (Farsalinos and Le Houezec, 2015), many of which form during the combustion and pyrolysis of the tobacco (Baker, 2006).

When a cigarette is lit, the tobacco burns 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). While modifying the way in which a cigarette burns has proved to be technically limited in its effects to significantly reduce the health risks based on current scientific understanding and available technologies (Baker, 2006; McAdam et al., 2012), tobacco-heating products (THPs), where a sample of

tobacco is heated to temperatures sufficient to vaporize 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 (Schorp et al., 2012; Zenzen et al., 2012; Forster et al., 2015; Smith et al., 2016). Furthermore, heating tobacco at temperatures below those found in tobacco burning cigarettes have been shown to reduce the mutagenicity of the smoke condensate (White et al., 2001).

Several ways to deliver aerosol by heating tobacco have been described in both patents and the literature. Studies of first-generation electrically heated cigarettes (EHCs) indicated that approximately two-thirds of aerosol constituents were reduced by at least 50% and many were reduced by more than 90%, as compared with conventional cigarette smoke; however, formaldehyde yields increased (Stabbert et al., 2003). Second-generation EHCs included ammonium magnesium phosphate (AMP) in the cigarette paper to reduce the formation of formaldehyde (Moennikes et al., 2008). Typical smoke exposure-related changes in rat lung were less pronounced after exposure to aerosol from a second-generation EHC with AMP than to aerosol from the first-

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generation EHC or smoke from the conventional reference cigarette, when compared on a particulate matter or nicotine basis (Moennikes et al., 2008).

More recent characterizations of an electrically heated cigarette smoking system (originally EHCSS, now an updated version) found that the aerosol generated by the products was distinctly different from the smoke of a conventional cigarette (Zenzen et al., 2012; Schorp et al., 2012; Smith et al., 2016). With very few exceptions, these electrically heated tobacco products demonstrated a substantial reduction in the toxicological activity of the aerosol versus a conventional cigarette when smoked with comparable puffing intensities or at comparable nicotine yields. Based on an overall weight-of-evidence approach, the authors concluded that the product design could reasonably be expected to reduce the hazard relative to conventional cigarettes, and that smoking using the EHCSS or THS 2.2 would result in substantially reduced exposure to harmful and potentially harmful constituents (HPHCs) (Smith et al., 2016).

Such studies have led to commercially available THPs in some countries, including Eclipse/Revo, Ploom and iQOS. Each of these THPs uses a different heating method characterised by their heater configuration in relation to the tobacco bed or rod (inside vs external to the tobacco bed), the heating profile of the heater (temperature ramp rate, maximum temperature and duration of heating), and last but not least the way in which the tobacco material is specifically processed to work with low to moderate heating temperatures. Thus, it is necessary to understand how tobacco behaves under these different heating methods.

Broadly speaking, tobacco materials undergo four main thermal decomposition processes — dehydration, volatile release, pyrolysis and combustion — as determined by extensive pyrolysis studies conducted to understand the formation of smoke constituents in a burning cigarette in the 1970s and 1980s (summarized in (Baker, 1987)). Temperature changes during puffing were characterised by thermocouples and infrared probes inserted into the end of burning cigarette, and evolved gas concentrations were measured by mass spectrometry. This series of research established that the burning zone of the cigarette, which is oxygen-deficient and hydrogen-rich, comprises two regions: an exothermic combustion zone, and an endothermic pyrolysis/distillation zone. As air is drawn into the cigarette during a puff, O₂ is consumed by the combustion of carbonised tobacco, forming the products CO, CO₂ and H₂O alongside the release of heat that sustains the whole burning process. The temperatures in this combustion region reach as high as 950 °C, and are generated at rates of up to 500 °C/s. Immediately behind is the pyrolysis zone, where the temperatures are lower (200–600 °C) and the O₂ levels are low. Most of the smoke constituents are formed by endothermic processes in this region, and the resulting highly concentrated aerosol is drawn down the cigarette rod to form mainstream smoke during a puff (Baker, 1987).

More recently, pyrolysis experiments under simulated conditions of cigarette burning have been used to investigate mechanistic and kinetic aspects of tobacco combustion (Czégény et al., 2009; Várhegyi et al., 2010), as well as factors that affect the generation of known toxicants/volatiles including temperature, pyrolysis atmosphere and pH (Torikai et al., 2004). Studies have also modelled a burning cigarette using computational fluid dynamic algorithms (Rostami et al., 2003).

Tobacco is a nitrogen-rich plant material: its main components are hemicellulose, cellulose and lignin, while nitrogenous compounds comprise its major characteristic fractions. Thermogravimetric analysis (TGA) coupled with hyphenated detection tools, such as Fourier transform infrared (FTIR) spectroscopy for evolved gases and volatiles has been widely used to examine the thermal

decomposition of the three key biomass components during the pyrolysis of different biomasses (Yang et al., 2006, 2007; Liu et al., 2008, 2013; Lee and Fasina, 2009). The results show that most of the plant material undergoes the following series of thermophysical and thermochemical processes when heated: moisture evolution, hemicellulose decomposition, cellulose decomposition, lignin degradation, and lastly charring. A low-temperature maximum is generally recorded on the derivative of the weight loss curve, indicating the first onset of thermal decomposition, which is usually above 200 °C and below 350 °C.

Several studies have specifically examined the thermal decomposition of tobacco by TGA (Wójtowicz et al., 2003; Oja et al., 2006; Barontini et al., 2013a, 2013b). In particular, Barontini et al. (2013a,2013b) developed multivariate deconvolution methodology to obtain quantitative data on key components of interest in gases evolved during TGA-FTIR analysis of tobacco at low heating rates. Analysis of the differential (rate of weight loss) thermogravimetric curves delineated four regions of weight loss: region I (30–120 °C), related to moisture release; regions II (120–250 °C) and III (250–370 °C), related to a two-stage thermal decomposition and evaporation phenomenon; and region IV (370–550 °C), related to a further thermal decomposition (in nitrogen) or to combustion (in air) of the residue obtained from the primary decomposition process Barontini et al. (2013a,2013b). They also obtained emission profiles of seven analytes (CO₂, CO, acetaldehyde, nicotine, phenol, isoprene, water, and glycerol) over the temperature range Barontini et al. (2013b).

Similarly, Liu et al. (2013) determined the composition of evolved volatiles from fast pyrolysis of tobacco stem by pyrolysis coupled with gas chromatography/mass spectrometry (Py-GC/MS) analysis, and investigated the evolution patterns of major products by TGA-FTIR and TGA-MS techniques. Furfural and phenol, generated from the depolymerization of cellulose, were the major products from low-temperature pyrolysis (~400 °C), whereas indene and naphthalene were the major products from high-temperature (~800 °C) pyrolysis. CO, CO₂, phenols, aldehydes, and ketones were released between 167 °C and 500 °C, whereas CO and CO₂ were the main gaseous products at temperatures >500 °C.

Recently, Cozzani et al. (2016) reported the use of two indicators for the detection of tobacco combustion: first, the presence of relevant quantities of NO_x in the aerosol that could not be formed from the decomposition of nitrates present in the original biomass/tobacco; and second, simultaneous evidence of a self-sustaining exothermic process. The latter indicator has been tested by Yan and Fujita (2016), who modelled the way in which tobacco is heated in a solid porous medium with an electrical heater embedded in the axial centre. The outcome of the modelling was a mathematical expression of the self-sustaining exothermic process, defined as $d^2T/dt^2 > 0$ and $dT/dt > 0$ in the range $T > 400$ K for the heated tobacco.

Regarding the design of THPs, it is important to characterise the heating processes within and to establish that little or no combustion takes place. To this end, Forster et al. (2015) used a bench-top tube furnace that heats tobacco between 100 and 200 °C to investigate low-temperature release for selected HPHCs typically associated with tobacco smoke. Among several targeted chemical compounds, seven toxicants (nicotine, CO, acetaldehyde, crotonaldehyde, formaldehyde, NNN and NNK) were quantifiable in the aerosol generated under the ISO machine-smoking protocol, but not at all temperatures examined. In the total aerosol phase collected, water was the largest measured component and seemed to be released mainly by evaporation, whereas between 100 °C and 200 °C, nicotine and some cigarette smoke compounds were released due to evaporative transfer or initial thermal decomposition from the tobacco blend.

Other thermophysical studies are also beginning to provide basic characterisation of how a THP works and may be used to better understand the aerosol formation process (Nordlund and Kuczaj, 2016; Cozzani et al., 2016). For example, thermophysical modelling based on classical nucleation theory has indicated that low-temperature heating (<400 °C), as experienced in a THP, requires the presence of a primer (normally glycerol) to generate a significant amount of aerosol (Nordlund and Kuczaj, 2016). The simulations showed that, when used as intended, glycerol, nicotine and water are evaporated from the tobacco plug in the THP, whereas minor compounds in the gas mixture do not reach supersaturation and therefore cannot generate aerosol droplets (Nordlund and Kuczaj, 2016).

The thermophysical and thermochemical properties of tobacco are fundamental to THP product design. While conventional cigarettes have a relatively uniform physical construction, where pyrolysis and combustion of the tobacco share a high degree of commonality (Baker, 1999, 2006), commercial THPs are constructed to ensure that the tobacco is heated rather than ignited (RJ Reynolds Company, 1988; Gardner, 2000; Patskan and Reininghaus, 2003; Schorp et al., 2012; Smith et al., 2016). Thermal energy transfer (radiative or conductive) assisted by air flow (convective), and the structure of the tobacco each affect the heat and mass transfer in a specific THP design, thereby influencing the possible onset of any smouldering or combustion of the tobacco materials. One early prototype (commercially known as Eclipse) designed by RJ Reynolds contained a carbon fuel section that was lit to heat incoming air that was drawn through a tobacco-containing section to vaporise nicotine and tobacco flavours (RJ Reynolds Company, 1988). Because no products of tobacco combustion were generated, the levels of many of the toxic substances in the smoke were much lower than those in conventional cigarettes (RJ Reynolds Company, 1988; Gardner, 2000); judging by low commercial adoption, however, the initial products were not liked by consumers, who complained difficulty in lighting the fuel cell, and issues with disposal of the spent cigarette (Baker, 2006). Subsequent products that used a handheld device to electrically heat a tobacco rod continued to demonstrate a significant reduction in toxicant emissions in the aerosol (Patskan and Reininghaus, 2003; Schorp et al., 2012), but have also failed commercially, mainly due to the sensory performance of the product.

Despite the challenges, efforts are continuing to design THPs that can meet consumer expectation and at the same time reduce the levels of toxicants in the aerosol emissions. In this context, THP1.0, which has a different heating mechanism (see section 2.1) from those used in other commercial THPs on the market, was launched in Japan in November 2016. In this study, we describe the product design and stewardship principles, in addition to characterizing the thermophysical and thermochemical properties of THP1.0, including its tobacco heating behaviour and the extent of the low-temperature thermal conversion of tobacco.

2. Product design and stewardship

2.1. THP1.0: product design overview

THP1.0 comprises two functional parts: an electronic handheld device with a heating chamber, and a specially designed tobacco rod to be inserted into the heating chamber. The electronic heating device (Fig. 1a) contains a rechargeable Li-ion battery (3000 mAh capacity, with a USB charging port) that supplies the energy to the heating tube when switched on. The heating tube has two heater segments (Fig. 1b), which are separately controlled by the inbuilt software, and thus, the tobacco rod is heated from the periphery.

The battery capacity allows for up to 30 repeated use cycles from a single charge.

The tobacco consumable rod (Fig. 1b) has a diameter of ca. 5.0 mm and overall length of 82 mm, with a 42-mm long tobacco section. A user inserts the tobacco rod into the stainless-steel heating chamber; on pressing the activation button on the device, the heating chamber heats the tobacco rod to less than 250 °C. This is significantly lower than the major pyrolysis and combustion temperature ranges seen in a lit cigarette (typically between 350 and 900 °C) but is sufficient to release nicotine, glycerol (added as the main aerosol agent) and volatile tobacco flavour compounds.

2.1.1. Tobacco consumable rod: tobacco

The tobacco used in THP1.0 consumable is a blended Virginia tobacco, and processed by a paper-style reconstitution process (Norman, 1999). Reconstituted tobacco is typically used in place of cut tobacco leaf for THP because the reconstitution process homogenises the chemical composition of finished material, thereby providing a more consistent aerosol composition and delivery. Reconstitution is also necessary to incorporate a high level of glycerol as the main aerosol agent. In the case of THP1.0, glycerol was added at 14.5 dwt% of the reconstituted tobacco material. Reconstitution incorporates glycerol into the inner structure of the material, which aids subsequent processing of the material. In THP1.0 tobacco consumable rod, 100% reconstituted tobacco material is used. The smaller diameter of the tobacco rod (5 mm) facilitates quicker heat transfer from the peripheral surface into the inner core. The overall mass of the tobacco material is about 260 mg, which is less than the 700–800 mg of tobacco typically contained in a king-size cigarette. Almost all the aerosol produced is emitted through the mouth end.

2.1.2. Tobacco consumable rod: mouthpiece

The mouthpiece of the tobacco consumable rod (Fig. 1b) in THP1.0 is designed to provide a sensorially acceptable aerosol stream in terms of the aerosol amount, aerosol composition, as well as aerosol physical properties (average particle size, particle size distribution and aerosol temperature). In current commercial THP products, a low aerosol filtration mouthpiece is typically adopted to provide sufficient aerosol deliveries (RJ Reynolds Company, 1988; Zenzen et al., 2012; Schorp et al., 2012; Smith et al., 2016). In THP1.0, an elongated paper tube is incorporated with a line of air inlet holes – these are designed to provide the right amount of drawing effort and to encourage the released hot vapour to coagulate and condense into aerosol particles suitable for human inhalation. Under operation, the full length of the tobacco section is heated, with the air inlet holes beneath or in line with the device surface when the end of the tobacco rod reaches the resting position of the heating chamber. This is the optimal position for the satisfactory delivery of aerosol: if the tobacco rod is inserted incompletely, a portion of the tobacco rod will not be heated, leading to a noticeable lack of aerosol. Any accidental or deliberate lip blocking of the air inlet holes would result in a hotter aerosol that is not comfortable for inhalation. A consumer in-use puffing topography study has been conducted, which demonstrated that practically no blocking of the air inlet holes occurs during use (Forster et al., 2015; this series).

2.1.3. Electronic heating device

A two-zone heater is configured in the direction of the tobacco rod (Fig. 1b) of THP1.0 heating device. When the device is activated by the user (by pressing the front button on the device), the two resistive heaters are switched on and managed separately to reach their target temperature program (see later). This separated heating ensures optimal energy usage to deliver a more consistent puff-

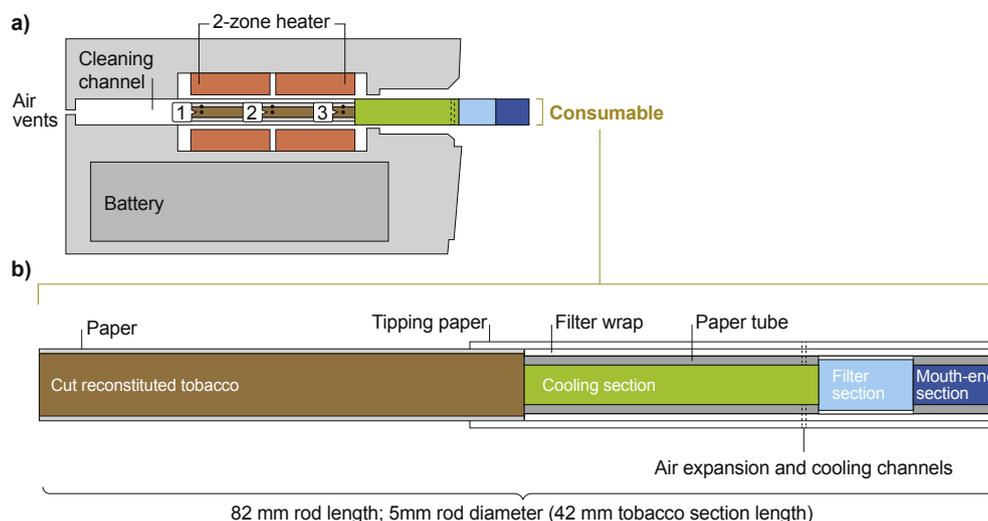


Fig. 1. Schematic drawing of the THP1.0 device with a tobacco consumable inserted (a) and the construction of the consumable (b).

by-puff sensory experience by utilising different portion of the tobacco rod. The maximum temperature of both heaters is set below 240 ± 5 °C. The product reaches operating temperature after approximately 30–40 s, and each heating session lasts for an additional 3 min. The device is then shut down automatically and the consumed tobacco rod can be removed. Air inlets are provided in the device, and together with the tobacco consumable rod design, manage the total draw effort when a user puffs the product. The heating chamber can be opened from the back end by releasing a cover to allow the full interior wall of the heating chamber to be cleaned with a provided brush.

2.2. Product stewardship considerations

Three aspects of product stewardship guide the THP1.0 product development: toxicological assessment of all ingredients and materials used, safety of the device and legal compliance. The stewardship processes are adapted for the different requirements of early prototypes and for final product launch.

Toxicological assessment of materials and ingredients is carried out by trained toxicologists, and is based on toxicological risk assessment of flavour ingredients and materials proposed to be used in either the prototype and/or final design of THP1.0, some of which are common for the consideration of materials and ingredients used in e-liquids and vapour products (Costigan and Meredith, 2015). The approach excludes classified genotoxicants, carcinogens, reproductive and developmental toxicants and respiratory sensitizers as additives in the tobacco rod. It includes systematic and comprehensive searches of all relevant publications and databases, such as TRACE (BIBRA, 2017), Toxnet (US NLM, 2017a), RTECS (CCOHS, 2017), TSCATS (SRC, 2017), INCHEM (IPCS, 2017), Europa Food Flavouring (EC, 2017), ECHA (ECHA, 2017), EAFUS (FDA, 2017), ChemIDplus (US NLM, 2017b) and eChemportal (OECD, 2017). Where necessary, the information gathered is used to calculate the derived no effect level (DNEL) for local and systemic effects by using published assessment factors. Candidate ingredients are approved if estimated exposure does not exceed the lower DNEL.

Ingredient exposure is estimated via conservative assumptions of transfer of the ingredient to the aerosol emission and of retention by the consumer. It also involves a factor for the number of THP1.0 tobacco rods consumed per day, as measured in a consumer survey. If necessary, the exposure estimate is refined by measurement of targeted substances in the aerosol emission. The process also

includes assessment of potential thermal breakdown at the product's operating temperature. Off-gassing analyses are used to screen ingredients and materials, whereas untargeted and targeted aerosol emission analyses are used to assess the device and consumable combination. Untargeted emission constituents are referenced against the appropriate threshold of toxicological concern (TTC), a measure recommended for chemical risk assessment in many situations (e.g. (SCCS et al., 2012).), and if necessary by a DNEL-based evaluation, as described above. The levels of targeted emission constituents in the aerosol are compared with those in the smoke of a reference cigarette.

Several groups of constituents are examined in the targeted analysis, including "Hoffmann analytes" (Hoffmann and Hoffmann, 1998), compounds identified by regulatory authorities in Europe, the United States and Canada as possible toxicants in tobacco smoke (Health Canada, 1999; Burns et al., 2008; FDA, 2012), and several other substances that might form at the product's operating temperature (e.g. acrylamide and methylglyoxal). The full consideration of toxicant emissions is reported in a separate study in this series (Forster et al., 2015; this series). The group of constituents analysed is also consistent with studies conducted on other commercial THP products (RJ Reynolds Company, 1988; Schaller et al., 2016).

For device safety, failure mode effect analyses (e.g. (ASQ, 2017; ICH, 2005).) are used to guide product and process design through a series of prototypes leading to the approved commercial device. During product development, prototypes are also independently tested against several international safety standards for consumer goods, for example, electromagnetic interference, battery performance and waste disposal. The commercial device has been certified as Safe for Global Market Access. Quality controls are in place to ensure that any safety-related faults are detected and eliminated during commercial production of the tobacco consumables and the heating device. Many national jurisdictions have tobacco control laws relating to ingredients and aerosol yields. THP1.0 complies with all relevant national legislation.

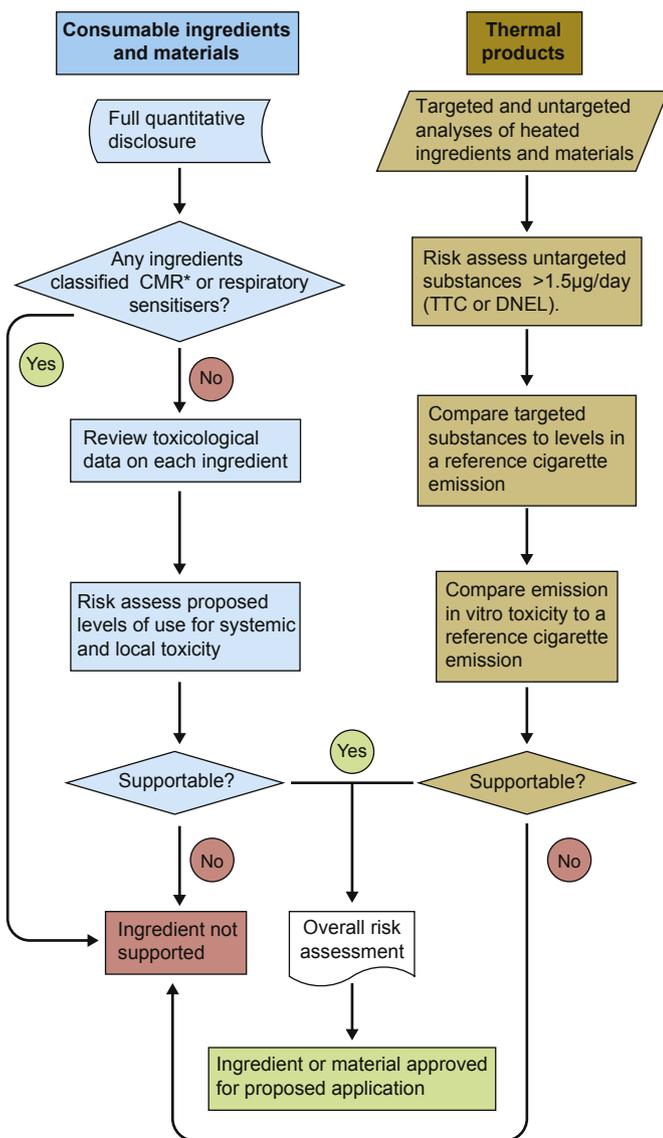
Fig. 2 summarises the overall risk assessment process for ingredients and materials in THP1.0.

3. Experimental

3.1. Study products

All the THP1.0 devices tested in this study were randomly

THP ingredient risk assessment approach



*CMR – carcinogenic, mutagenic, toxic for reproduction

Fig. 2. Ingredient and material risk assessment process.

selected from a single batch of commercial devices. The 3R4F Reference Cigarette (Center for Tobacco Reference Products, University of Kentucky, Lexington, USA), a US-blended king-size cigarette with a cellulose acetate filter and an ISO tar yield of 9.4 mg/cigarette in roughly nine puffs, was used in comparison studies. The blend composition, physical construction, and mainstream smoke toxicant (e.g., HPHC) yields of 3R4F cigarettes have been well characterized (Roemer et al., 2012a; University of Kentucky Tobacco Research and Development Center, 2015). Both the 3R4F cigarettes and the tobacco consumable rods for THP1.0 were conditioned in accordance with ISO protocol 3402 (ISO, 1999) prior to analysis.

3.2. Thermogravimetric analysis (TGA)

A Pyris 1 TGA (PerkinElmer, Seer Green, Bucks, UK) system with Pyris Software version 11.0.2.0468 was used in this study. Approximately 10 g of tobacco and 1.0 g of wrapping paper were

taken from 30 randomly selected manufactured consumable rods. They were cut with a clean shredder equipped with a stainless-steel blade and stored in a clean glass jar until ready for use. Three types of sample were analysed by TGA: the reconstituted tobacco material, the paper wrapper, and the combined tobacco material and wrapping paper in the weight proportion expected based on the total tobacco and paper weights.

For each TGA experiment, between 1.603 and 2.058 mg of the tobacco material or between 1.778 mg and 2.254 mg of the combined tobacco/paper were weighed directly into a platinum crucible. Each sample was heated in both air and nitrogen to distinguish the onset of any oxidation event. The heating programme consisted of an initial ramp at 5 °C per min from ambient to 240 °C, holding for 5 min at 240 °C, and then a further ramping at the same rate to 900 °C. Three replicates per sample were run.

3.3. Device heating chamber and tobacco rod temperature profiling during THP1.0 operation

The heating temperature experienced by the tobacco rod is a key indicator of the potential extent of evaporation and thermal degradation, and was measured by two methods under a machine-puffing condition. In the first, three bare 0.25-mm diameter K-type thermocouples were carefully inserted between the inner surface of the heating chamber and the outer surface of the tobacco rod; the tips of the thermocouples were positioned at three locations along the length of the heating chamber (see Fig. 1). The heating device was activated and the temperature at each location was recorded by using a Model TC-08 datalogger (Omega, Norwalk, CT, USA) sampling at 10 Hz.

In the second method, the temperature inside the consumable tobacco rod was measured by the same thermocouple technique. In this case, a fine needle was used to form a passage through the centre of the tobacco rod, into which a thermocouple was inserted to the required depth (± 1 mm). For these measurements, THP1.0 was machine-puffed using a 55-mL puff volume, 2-s puff duration, and 30-s interval for a total of 8 puffs. For both methods, the temperature profile was measured in triplicate.

3.4. Selected aerosol emission analysis

Aerosol emissions generated by THP1.0 were evaluated from two aspects. First, four marker compounds associated with biomass combustion, carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxide (NO) and oxides of nitrogen (NO_x), were measured. Second, nine toxicants proposed by WHO's TobReg committee for mandatory reduction in cigarette smoke (Burns et al., 2008) were assessed: acetaldehyde, acrolein, benzene, benzo[a]pyrene, 1,3-butadiene, CO, formaldehyde, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK), N-nitrosornicotine (NNN). Because significantly altered levels and relative ratios of these substances give clues to fundamental changes in the thermal history experienced by the tobacco material, the levels in THP1.0 aerosol were compared with those in mainstream 3R4F cigarette smoke.

The quantification of combustion markers and toxicants in aerosol and mainstream 3R4F cigarette smoke was conducted by a single independent laboratory, Labstat International ULC (Kitchener, Ontario, Canada) using validated methods. Aerosol from THP1.0 was generated using the following parameters: puff volume, 55 mL; puff duration, 2 s; puff interval, 30 s; bell-shaped puff profile; the air inlet holes in the mouthpiece of the consumable rod were not blocked. As explained above, this feature is essential to ensure that (1) the heated tobacco vapour from THP1.0 can condense and form an aerosol, and (2) the aerosol temperature is not too hot for human inhalation. Eight puffs were taken per

tobacco stick and five replicates were conducted per analysis. Mainstream smoke from 3R4F was generated using the Health Canada Intense (HCI) smoking regime (Health Canada, 1999) (puff volume, 55 mL; puff duration, 2 s; puff interval, 30 s; bell-shaped puff profile; ventilation blocking 100%). Cigarettes were smoked until the butt mark was reached, and five replicates were conducted per analysis. The number of cigarettes or sticks per sample was analytical method dependent. Analyte levels were reported as mean \pm SD and statistical data analysis was conducted using SAS v9.4 (SAS Institute, Cary, NC, USA).

4. Results and discussion

4.1. Thermogravimetric analysis (TGA) of the tobacco material

To assess whether THP1.0 forms its aerosol mainly by heating and without combusting tobacco material, it is necessary to evaluate the tobacco material's thermal behaviour under a simulated heating programme that can heat to typical cigarette combustion temperatures of around 900 °C (Baker, 2006). To this end, TGA has become a recognised research tool to study the thermophysical behaviour of a wide range of biomass materials, including tobacco (Burton and Childs, 1975) and other types of biomass material (Yang et al., 2006).

Fig. 3 presents the TGA data obtained under air and nitrogen for two sets of materials used in the THP1.0 tobacco consumable: the reconstituted tobacco (Fig. 3a), and the reconstituted tobacco plus its paper wrapper in a mass ratio similar to the manufactured tobacco rod (Fig. 3b). The main reason for comparing behaviour in air and nitrogen was to enable observation of any oxidation and pyrolysis processes known to occur in a burning cigarette. A heating rate of 5 °C/min was used to clearly distinguish the main thermal behaviour regions of the materials because faster heating tends to suppress smaller thermal events (Baker, 1976). An additional 5-min holding time at 240 °C was included to simulate the average heating session experienced by the tobacco inside the THP1.0 device (see later), and a combination of temperature ramping and isothermal holding is typical in THP temperature management.

As Fig. 3 shows, the initial mass loss up to ca. 100 °C was mainly due to water evaporation (Banyasz, 1999) because the tobacco material contained ca. 14% of water. The second mass loss region, between 100 °C and the 240 °C holding temperature, resulted in a further mass loss of ca. 15%. This region may be accounted for by the evaporation of glycerol (14.5% dry mass basis), nicotine and some volatile chemicals from the tobacco. The initial thermal

decomposition of some biopolymers such as sugars and pectins might also contribute to mass loss in this temperature range (Wang et al., 2009). Isothermal holding at 240 °C continued to reduce the mass to a small extent.

Up to approximately 350 °C, the rate of mass loss was not evidently different between samples heated in air or nitrogen. This suggests that no significant oxidation had occurred up to this temperature. In the temperature region above 240 °C, there was a slightly faster rate of mass loss — a behaviour that was observed for all three replicates under both atmospheres and was assumed to represent the initial onset of thermal decomposition of the tobacco materials independent of any oxidation.

The capability of TGA to qualitatively and quantitatively assess the major thermal breakdown behaviour of common biopolymers (e.g., cellulose, hemicellulose, pectin and lignin) is well established (Yang et al., 2006). The three main components of common biomass — hemicellulose, cellulose and lignin — each display a well-defined thermal decomposition region: hemicellulose starts to decompose between 220 and 315 °C, followed by cellulose at temperatures close to 400 °C, and lignin at temperatures above 400 °C. These behaviours are consistent with the faster rate of mass loss or more aerosol generation observed for the THP1.0 tobacco samples once the temperature is above ~200 °C (Fig. 3) and also with the published literature on tobacco (e.g., see (Burton and Childs, 1975; Baker, 1987)).

From approximately 400 °C onwards, the samples in nitrogen continued to reduce in mass at a steadier rate; in contrast, the samples in air underwent a more rapid mass loss, which was most probably due to the oxidation of cellulose, hemicellulose and lignin at this stage (Wang et al., 2009). For the reconstituted material (Fig. 3a), further oxidation in air from ~425 to 475 °C reduced its mass to below 10%, then followed by a slower weight reduction towards the end of the heating. For the combined mass of the reconstituted tobacco and paper wrapper (Fig. 3b), a similar trend was observed. At the end of the run (~900 °C), the residual masses of the two types of sample were approximately 10% of the total starting mass, and the differences between the samples heated in the 2 atm were small. The tobacco samples heated under the nitrogen atmosphere showed greater variability across replicates.

A key consideration in the effective heating of tobacco is the release of sufficient nicotine from often differently blended tobacco. Moldoveanu and St Charles (2014) measured and modelled the nicotine vapour pressure from the headspace of Burley, Flue-cured and Oriental tobacco stored at 23, 30 and 40 °C, and calculated the relative nicotine activity from these samples as compared

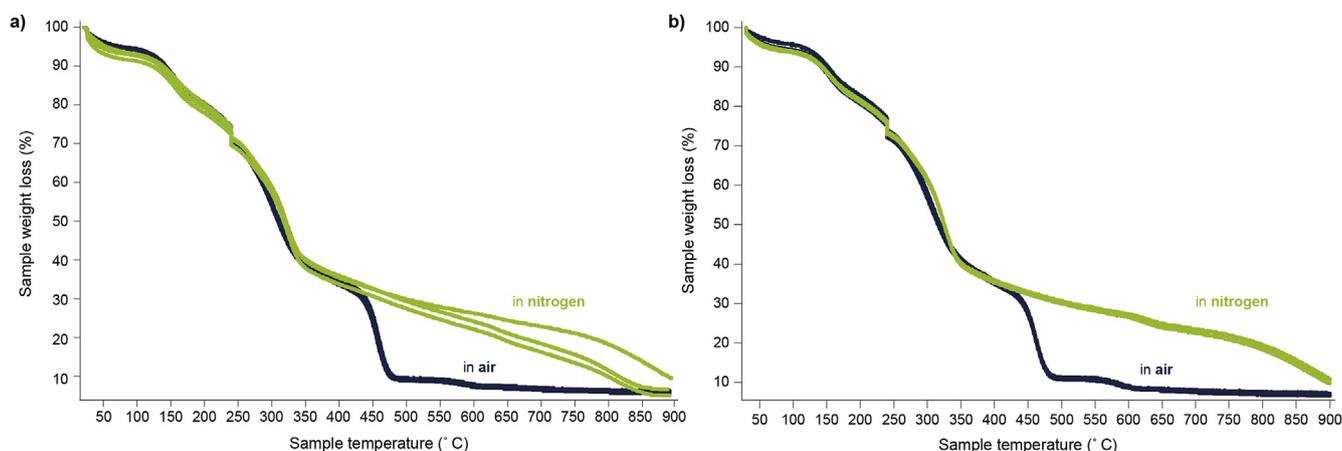


Fig. 3. TGA curves of the reconstituted tobacco material heated in both air and nitrogen. (a) Reconstituted tobacco material alone; (b) reconstituted tobacco material with added paper wrapper.

with pure nicotine. The lack of a trend between the nicotine enthalpy of vaporization from different types and different storage conditions of tobacco (on average, 86.7 kJ/mol, with a relative standard deviation of 6.5%) led the authors to conclude that nicotine vaporisation is an intrinsic property of the nicotine forms present in tobacco rather than a property of tobacco itself.

Taken together, the TGA results confirm that a heating temperature range between ca. 200 and ca. 350 °C — where water, added aerosol agents such as glycerol, nicotine, and tobacco volatiles are formed into vapour (Perfetti et al., 2014; Forster et al., 2015; St. Charles and Moldoveanu, 2016) — provides a usable window for a THP. Heating beyond ~400 °C significantly increases the possibility of oxidative decomposition, and may even induce sustained smouldering and/or flame combustion under certain heat and mass transport conditions.

4.2. THP1.0 heating chamber and tobacco rod temperature profiling

To demonstrate that the heating programme of THP1.0 delivers the intended temperature to its heating chamber throughout a heating cycle, the output from thermocouples at three locations in the heating chamber (Fig. 1b) were recorded with the tobacco rod inserted but the device not puffed to provide a more stable surface temperature reading. The temperature profiles at two of the three locations are shown in Fig. 4.

The unique two-zone heater design in THP1.0 means that an individual software-enabled temperature programme is applied separately to each of the two heaters. This is reflected by the different temperature profiles recorded at the different thermocouple locations: location 1 is closer to the mouth end (i.e., the proximal heater), whereas location 3 is at the other end of the tobacco rod (i.e., the distal heater). As shown in Fig. 4a, the proximal heater temperature increased rapidly to the set maximum of 240 ± 3 °C and stayed relatively constant for up to 150 s. The maximum surface heating rate for the tobacco consumable is therefore around 8 °C/s, which is in stark contrast to the surface heating rate of ca. 500 °C/s for a lit cigarette under puffing (Liu and Woodcock, 2014), and highlights the relatively mild heating condition experienced by the tobacco in THP1.0. The temperature of the distal heater increased more slowly with two step-wise increases. The gradual transfer of heat to the distal portion of the tobacco rod provides a gentle boost to the aerosol being generated from the proximal tobacco rod. During the last 60–80 s of the heating cycle, the proximal heater temperature reduced to ca. 220 °C, while the distal heater temperature was maintained at around 240 ± 3 °C. The overall effect of the two separately heated

zones is more consistent aerosol sensory performance.

To confirm that the heating programme of THP1.0 delivers the intended heating temperature profile during consumer use, the temperature within the consumable tobacco rod was measured at the same locations as in Fig. 4 with the thermocouple sensors inserted inside the tobacco rod itself. In this case, machine-puffing using a 55-mL puff volume and a 30-s puff interval was also applied to assess the dynamic heating of the tobacco rod.

Fig. 5a shows that the temperature of the proximal tobacco section increased quite quickly as heat was applied (Fig. 4a). However, this rapid increase was momentarily arrested at around 100 °C by the evaporation of water contained in the tobacco rod. The first puff taken at ca. 50 s seemed to withdraw much of the water vapour and subsequently the temperature increased quickly to above 200 °C. Each puff led to a significant decrease in temperature with slower temperature recovery but this effect reduced for the later puffs. From ca. 100 s onwards, the proximal tobacco section reached a temperature >200 °C and remained broadly at this temperature for the remainder of the heating cycle. For the distal section of the tobacco rod (Fig. 5b), the lower heating rate (Fig. 4b) resulted in a longer plateau at a temperature of ca. 100 °C. In contrast to the proximal section, the distal tobacco section temperature exceeded 200 °C for only the last four puffs.

The maximum temperature experienced by both sections of the tobacco rod was less than the maximum heater temperature. There was no evidence of self-sustained energy release (or autorun-off) and puffing reduced tobacco rod temperature significantly rather than causing the temperature increase that is observed in a lit cigarette.

4.3. Analysis of combustion markers

Under the controlled heating programme of THP1.0, the tobacco rod should avoid the onset of major pyrolysis and combustion should be eliminated. Nevertheless, a small degree of tobacco thermal decomposition may still occur and contribute to the aerosol that forms. This is because the thermal decomposition of biomass materials is a gradual process up to approximately 400 °C (e.g., see Fig. 3), and evaporation and devolatilisation can occur at low temperatures.

In terms of THP design, it is important to ensure the heating programme that is applied does not lead to self-sustained pyrolysis, as in a lit cigarette. Therefore, to assess the actual degree of thermal decomposition experienced by the tobacco rod inside THP1.0, four chemical markers of biomass combustion were measured in the aerosol emitted from THP1.0, machine-puffed using a 55-mL puff

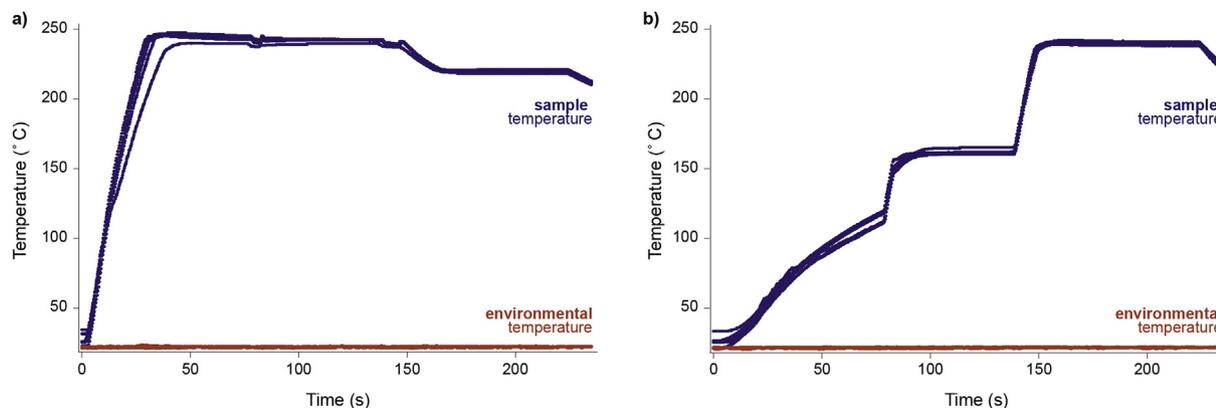


Fig. 4. Thermocouple temperature profiles at two locations inside the heating chamber without puffing. (a) Location 1; (b) Location 3. The flat green lines mark the laboratory ambient temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

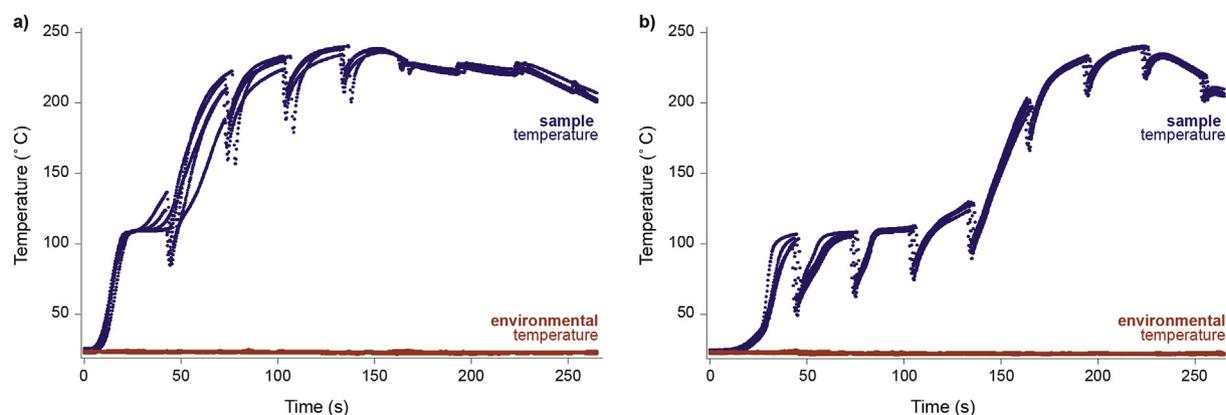


Fig. 5. Thermocouple temperature profiles at two locations inside the tobacco rod with puffing. (a) Location 1; (b) Location 3.

volume and a 30-s puff interval.

CO and CO₂ were measured as markers of the onset of major thermal decomposition, as supported by previous tobacco pyrolysis studies (e.g., see (Baker, 1987)). NO and NO_x were also measured to assess the thermal breakdown of nitrogenous compounds, which represent a wide range of tobacco-specific organic constituents (Baker, 1999). The levels of these four marker compounds in THP1.0 aerosol were measured and compared to those in the aerosol from two self-sustained tobacco pyrolysis/combustion systems: the consumable tobacco rod used in THP1.0 ignited and smoked as for a cigarette, and the 3R4F reference cigarette. Both comparators were machine-smoked under the same puffing parameters (Table 1). It should be emphasized that the tobacco rod in THP1.0 was not designed to be smoked in a conventional way: the 100% reconstituted material and much higher glycerol content (14.5%) of the consumable do not produce a smoking experience that is sensorially comparable to that of a conventional cigarette. The purpose of this test was to compare the abundances of chemical markers of combustion.

The levels of all four markers were significantly lower in the THP1.0 aerosol than in the mainstream smoke from 3R4F or the combusted THP1.0 tobacco rod (Table 1). These findings demonstrate that thermal decomposition of the THP1.0 consumable is significantly less than would occur during pyrolysis and far less than for combustion.

4.4. Analysis of tobacco smoke toxicants

Owing to their significance in cigarette smoke, several toxicants have been widely studied in relation to their routes of formation in smoke and their connection to leaf precursors (Hoffmann and Hoffmann, 1997; Baker, 2006; Piadé et al., 2013). Nine toxicants proposed by the WHO study group on tobacco product regulation for reduction in cigarette smoke (Burns et al., 2008) were analysed in THP1.0 aerosol and 3R4F mainstream smoke to gain further insight into the degree of thermal decomposition of tobacco under

different heating conditions (Table 2) (Forster et al., 2017).

Table 2 compares the levels of the nine toxicants measured in THP1.0 aerosol and 3R4F mainstream smoke. In addition to the significantly lower CO level, as discussed in Section 3.3, the levels of acetaldehyde and formaldehyde, which have been linked to the decomposition of sugars that are naturally present in the tobacco leaf or added as casing agents (Várhegyi et al., 2010; Roemer et al., 2012b), were considerably lower in THP1.0 aerosol than in 3R4F smoke. The significantly lower content in THP1.0 aerosol indicated the reduced thermal decomposition of this class of tobacco leaf constituent under the heating condition of THP1.0.

Acrolein, benzene and 1,3-butadiene are low-molecular weight volatile organic compounds with multiple formation routes, but are typically formed by the pyrolysis and incomplete combustion of tobacco cell-wall constituents (Piadé et al., 2013). Their levels were typically below or close to the limit of detection in THP1.0 aerosol, which suggests that the operating temperature and duration for THP1.0 result in their negligible formation.

The remaining three toxicants, benzo[a]pyrene and the two tobacco-specific nitrosamines (NNN and NNK) are condensed phase substances and are largely associated with the particulate matter of cigarette smoke. All three constituents are present in conventionally cured and processed tobacco leaf; benzo[a]pyrene, a polycyclic aromatic hydrocarbon, can also form as the result of incomplete combustion of organic materials at temperatures between 300 °C and 600 °C. Pyrosynthesis of NNN and NNK in a lit cigarette is thought to involve nitrosation reactions occurring above 240 °C (Rodgman and Green, 2014; Moldoveanu and Borgerding, 2014). Their levels were significantly lower in THP1.0 aerosol than in 3R4F mainstream smoke, which was consistent with their formation mechanisms as discussed above.

4.5. Physical integrity of the THP1.0 tobacco rod post heating

The tobacco rod used in THP1.0 was designed to maintain its physical integrity after use so that it is easily withdrawn from the

Table 1

Mean (\pm SD) levels of four combustion markers in THP1.0 aerosol and 3R4F mainstream smoke.

Marker(per stick)	THP1.0 (8 puffs/per stick)	THP1.0—"smoked" (5.1 puffs/per stick)	3R4F (10.3 puffs/per stick)
CO, mg	N.Q. ^a (<0.233)	14.4 (\pm 0.4)	32.0 (\pm 0.9)
CO ₂ , mg	2.35 (\pm 0.14)	29.6 (\pm 1.0)	85.1 (\pm 4.0)
NO, μ g	10.1 (\pm 0.4)	75.3 (\pm 3.9)	496 (\pm 16)
NO _x , μ g	12.0 (\pm 0.4)	90.0 (\pm 5.1)	553 (\pm 16)

^a N.Q.: not quantifiable.

Table 2
Levels of TobReg 9 toxicants in THP1.0 aerosol versus 3R4F mainstream smoke and proposed key mechanisms of formation.

TobReg 9 analytes	THP1.0		3R4F	
	Mean (\pm SD) emission per stick	Formation mechanism	Mean (\pm SD) emission per stick	Formation mechanism
Acetaldehyde, μ g	111 (\pm 8)	Initial degradation of carbohydrates	2200 (\pm 103)	Decomposition of carbohydrates by pyrolysis
Acrolein, μ g	2.22 (\pm 0.52)	Same as above with glycerol breakdown	157 (\pm 9)	Decomposition of carbohydrates and leaf polymers and glycerol if added
Benzo(a)pyrene, ng	N.Q. ^a (<0.354)	Not quantified	12.9 (\pm 1.3)	Decomposition of leaf terpenoids and transfer of contaminants
Benzene, μ g	N.Q. (<0.056)	Not quantified	78.6 (\pm 4.6)	Decomposition of leaf polymers with C6-ring moieties, above 300 °C
1,3-Butadiene, μ g	BDL ^b (<0.029)	Not detected	108 (\pm 4)	Similar mechanisms as benzene with thermal cracking involving tobacco char
CO, mg	N.Q. (<0.223)	Significantly reduced	32.0 (\pm 0.9)	Combustion of tobacco, pyrolysis and char reaction
Formaldehyde, μ g	3.29 (\pm 0.30)	Initial decomposition of sugars	54.1 (\pm 6.0)	Decomposition of sugars and cellulose
NNN, ng	24.7 (\pm 2.5)	Thermal transfer	263 (\pm 12)	Transfer and pyrosynthesis
NNK, ng	6.6 (\pm 0.86)	Thermal transfer	281 (\pm 16)	Transfer and pyrosynthesis ^c

^a N.Q.: not quantifiable.

^b BDL: below detection limit.

^c Lipowicz and Seeman, 2017.

heating chamber. The appearance of the used tobacco rod was brown, partially discoloured by the heating and partially by condensation from inside the chamber; however, the paper wrapper showed little sign of breakage and no tobacco ash was visible (not shown).

5. Conclusion

A multi-step approach was applied to evaluate the thermo-physical and thermochemical properties of a novel tobacco heating product, THP1.0, including assessment of potential thermal decomposition of the tobacco consumable rod. Thermogravimetric examination of the tobacco and paper in oxygen-containing and nitrogen atmospheres demonstrated that no major thermal decomposition or combustion event occurred in these materials at temperatures below 300 °C. The temperature of the tobacco rod surface and inner core were monitored and the data confirmed that the tobacco in the proximal and distal zones did not exceed 250 °C. Measurement of chemical markers of combustion and selected toxicants indicated very low thermal decomposition of the tobacco. Overall the results of the study indicate that for THP1.0 the primary mechanisms of aerosol formation are distillation and evaporation and that there is very little or no combustion. The authors propose this multi-step characterisation method be considered for assessing any new or novel THP.

Conflicts of interests statement

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