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Analysis of the Elements and Metals in Multiple Generations of Electronic Cigarette Atomizers

Monique Williams[1], **Krassimir N. Bozhilov**[2], **Prue Talbot**[1,*]

[1]Department of Cell Biology and Neuroscience, University of California, Riverside, Riverside, California, USA

[2]Central Facility for Advanced Microscopy and Microanalysis, University of California, Riverside, Riverside, California, USA

Abstract

Background: Since their release in 2004, electronic cigarettes (ECs) and their atomizers have undergone significant evolution.

Objective: The purpose of this study was to evaluate and compare the elemental/metal composition of atomizers in cartomizer and tank style ECs produced over a 5-year period.

Methods: Popular cartomizer and tank models of ECs were dissected and photographed using a stereoscopic microscope and elemental analysis of EC atomizers was done using scanning electron microscopy coupled with energy dispersive x-ray spectroscopy.

Results: Eight elements/metals were found in most products across and within brands purchased at different times. These included chromium, nickel, copper, silver, tin, silicon, aluminum, and zinc. Iron and lead were found in some but not all products, while manganese, cobalt, molybdenum, titanium, and tungsten were only found in a few of the products. The metals used in various components were often similar in cartomizer and tank models. Filaments were usually chromium and nickel (nichrome), although in some newer products, the filament also contained iron, copper, and manganese. The thick wire in earlier products was usually copper coated with silver, while in some newer products, the thick wire was predominantly nickel. In all products, the wick was silica, and sheaths, when present, were fiberglass (silicon, oxygen, calcium, aluminum, magnesium). Wire-to-wire joints were either brazed or clamped with brass (copper and zinc), and air-tube-to-thick wire joints, when present, were usually soldered with tin. Tank style products generally lacked a thick wire and sheaths.

Conclusion: In general, atomizer components in ECs were remarkably similar over time and between brands. Certain elements/metals were consistently found in most models from all generations, and these should be studied carefully to determine if their transfer to aerosols affects user's health and if their accumulation in trash affects the environment.

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*Corresponding author: talbot@ucr.edu.

Author Contributions

Conception and design: MW and PT. Sample preparation and data collection: MW and KNB Data interpretation: MW, KNB and PT. Data analysis and writing of the manuscript: MW and PT, Editing the manuscript: MW, PT and KNB.

Declaration of Interest

None.

Keywords

Electronic cigarettes; e-cigarettes; atomizers; metals; tobacco products

1. Introduction

There are three major classes of electronic cigarettes (ECs), “cig-a-like”, “tank” style and “pod” style. Cig-a-like models were designed to have the look and feel of a conventional cigarette and were the first type to be introduced in China in 2004.[1] The cig-a-likes come in three styles: the classic 3-piece cartridge style, the 2-piece cartomizer/pod, and 1-piece disposable style.[2–4] Tank-style EC were subsequently introduced in 2013 to hold larger volumes of refill fluid.[4,5] These include clearomizers, vape pens, vape MODs, sub-ohm tanks, and rebuildable drippable tanks and are generally equipped with larger batteries and larger fluid reservoirs than cig-a-like models. Pod style EC, which are smaller than tank models and often resemble USB drives, come with small disposable cartridges or pods.

ECs have three basic components: a battery, an atomizer, and a cartridge/tank, which stores e-liquid.[3,6] The atomizer consists of wires, joints between wires, a wick, an air-tube, joints between the air-tube and thick wire, and an insulating sheath.[7] Most EC atomizer components are made of metals, such as nickel, chromium, and copper. Because atomizers heat during aerosol production, there has been concern about the release of metals from the atomizers into aerosols that are inhaled by users. Several studies that have shown that EC aerosols do contain metals as well as other elements [8–15], but their sources are not well understood. Some of the metals in EC aerosols, such as nickel, chromium, and lead, are a health concern and if inhaled for prolonged times could cause diseases, such as cancer.[16] While EC design has changed rapidly in the past 12 years, the evolution of the use of metal components in EC atomizers has not previously been studied.

ECs also present an environmental hazard in that used products are usually disposed of randomly without sufficient knowledge of the components that may leach into the environment following disposal.[17] Given the rapid rise in EC use, the number of EC products entering landfills and other dump sites could become a serious public health problem in the future. We were therefore also interested in analyzing elemental composition of EC atomizers to better understand what long-term effects their disposal may have on the environment.

The purposes of this study were to: (1) identify the elemental/metal composition of the atomizer components in popular cartomizer and tank style ECs and determine how this composition has changed as EC have evolved over a 5 year period, and (2) compare these data to our previously published results on disposable ECs and earlier models of atomizer style EC.

2. Materials and Methods

2.1. ECs selection

This study focuses on second generation cartomizer style ECs that are manufactured by major tobacco companies and products that were popular on the Internet at their time of purchase in 2011 and 2017. Products selected were: BluCig and BluCig Plus (Lorillard Inc., Greensboro, NC), Mark Ten and Mark Ten XL (Altria Group, Inc., Richmond, VA), V2 Cigs (VMR Products LLC., Miami, FL), and Vuse and Vuse Vibe (Reynolds American, Inc., Winston-Salem, NC). Other brands used in the study were Crown 7 Imperial Hydro (Crown Seven Shop, Scottsdale, AZ), GreenSmoke (GreenSmoke LLC, Richmond, VA), Liberty Stix Eagle (Liberty Stix, LLC, Cleveland, OH), NJOY NPRO 2N1 (Sottera Inc., Scottsdale, AZ), Safe Cig (The Safe Cig LLC, Los Angeles, CA), Smoke 51 (Vapor Corp, Miami, FL), Smoking Everywhere Platinum (Smoking Everywhere, Sunrise, FL), and South Beach Smoke (South Beach Java LP, Wood Dale, IL). Upon receipt, all ECs were inventoried and stored at room temperature. All EC cartomizers were tobacco flavored with "high" nicotine concentrations.

These brands were chosen to include products that had received either positive or poor ratings. For example, Smoke 51 was not highly rated on various top EC ranking lists, while BluCig, South Beach Smoke, and V2 Cigs were rated highly by consumers. NJOY NPRO and Liberty Stix Eagle were chosen because we have evaluated their classic models in our prior studies.[18,19] When the study began, SafeCig and Smoking Everywhere Platinum were two of the most popular Internet brands. While they are no longer available from their manufacturers, they can still be purchased from limited third party vendors.

Tank style products included four tanks and two RDAs (rebuildable drippable atomizer), which were selected based on their popularity at the time of purchase. Popularity was established by speaking with clerks at a local vape shop near the University of California Riverside campus. The following tanks and RDAs were used: Kangertech Protank (Kangertech, ShenZhen, China), Aspire Nautilus tank (Aspire, ShenZhen, China), Kanger T3S tank (Kangertech, ShenZhen, China), Tsunami 2.4 (Tsunami Vapor Glass, Troy, MI), Smok tank (Shenzhen IVPS Technology Co., Ltd, Shenzhen, China), and Clone RDA. Products were inventoried and stored at room temperature. The four tanks that were purchased in 2014 were not available in 2017. Therefore different products were chosen for the 2017 evaluations.

2.2. Dissections, scanning electron microscopy, and elemental analysis of EC atomizer components

The components of interest (wires, joints between the wires, air tube, wick, and sheath) (Figure 1) were dissected from each atomizing unit and mounted on aluminum pin stubs covered with carbon tape for scanning electron microscopy (SEM) and elemental analysis. [8–10] The morphology and elemental composition of each sample were analyzed using a ThermoFisher Scientific Co. NovaNano SEM 450 equipped with Oxford Instruments NanoAnalysis, Aztec Synergy energy dispersive X-ray spectrometer (EDS) fitted with a X-Max50 50 mm^2 SDD detector with energy resolution of 129 eV at MnKα in the Central

Facility for Advanced Microscopy and Microanalysis at the University of California at Riverside. SEM images were acquired using the secondary electron mode with a dedicated detector at 15 kV. Samples were not coated with conductive film. The distribution of elements in the cartomizers was determined by generating elemental maps using Aztec software.

The EDS system allows detection and analysis of chemical elements with an atomic number of 5 (boron) or higher. The EDS mapping represents a qualitative depiction of the spatial distribution of chemical elements. The detection limit for the EDS method is about 0.1 wt.%. In elemental mapping, distinction between elements is controlled by the ability to separate individual EDS peaks from the background and from each other. Since no interfering overlaps between the characteristic peaks of interest was observed, the only limiting factor was acquiring maps for a long enough time to ensure that the integrated counts for any elemental peak of interest were at least 3 times that of the underlying background. This was achieved by collecting 512 × 512 pixels maps for 5 to 10 mins at an input X-ray signal of 15,000 counts/second or more. For the simplicity of the discussion, we have selected 5 wt % as an arbitrary threshold value. Elements present in concentrations above the 5 % threshold are denoted as major and those below the threshold are minor. Minor elements that were < 1% by weight were analyzed by acquiring EDS spectra from selected points to improve the signal/noise ratio and detectability.

3. Results

3.1 SEM and elemental analysis of the atomizing components in EC

To evaluate the elemental composition of the atomizing units, individual components were dissected and analyzed using SEM and EDS (Figures 2–5, Table 1). An example of an EDS spectrum (Smoke 51 sheath) is shown in Supplemental Figure 1. Oxygen, silicon, aluminum, calcium, magnesium, and sodium are shown with major and minor peaks indicated by red and green arrows, respectively. The relative abundance of each element in each component of the atomizers was categorized as major (red squares Figure 2) or minor (pink squares Figure 2) based on their EDS spectra. The filaments (thin wires) in most brands from all years were made of nickel and chromium, as shown in Figure 2A for all brands and in Figure 3 for BluCig (A-C), BluCig Plus (D-H), V2 Cigs (2012) (I-L), and Tsunami (M-P). However, some differences within and between models and generations were observed. For example, V2 (2012) had iron in the filament (Figure 3I–L), while the later models of V2 (2017) did not (Table 1). In contrast, BluCig (2013) did not have iron in the filament, while the more recent generation, BluCig Plus, had both iron and copper, as well as nickel and chromium (Figure 3 A–H). Unlike any other product we examined, the Clone RDA filament was comprised of chromium, iron, and aluminum (Figure 3 Q–T).

The thick wires, which connected to the filament, in most brands were made of copper coated with silver (Figure 2A, Figure 3 U–W). However, in some brands, the thick wire was nickel (Figure 2A), as shown for Vuse Vibe (Figure 3 X–Y). One brand, Mark10 XL, had a thick wire made of nickel, chromium, and iron (Figure 2A, Figure 3 Z–CC). Thick wires were not present in three of the cartomizers brands (V2 Cig 2012, Vuse 2014, and South

Beach Smoke) and four of the tanks models (Protank, Aspire Nautilus, Clone and Tsunami 2.4) (Table 1).

In previously studied models including disposable brands, tin solder was often used to join the filament to the thick wire [10]; however, none of the models in the current study had tin solder between the filament and thick wire. Instead, wire coiling (Figure 3DD–EE), brass clamps (Figure 3 FF–HH), and brazing (Figure 3 II–KK) were used to join the filament and thick wire. Additional information on the type of joint used in all brands is given in Table 1.

The air-tube was not analyzed in EC models studied previously.[8–10] In this study, the air-tubes in cartomizer style products usually had a brass core made of copper and zinc, which was plated with nickel, and in some cases the plating also included gold, silver, or tin (Figure 2B, Figures 4 A–J; Table 1). However, some brands, such as Mark 10 and V2 Cig (2017), were exceptions in that their air-tubes had a nickel core with silver plating (Figure 4 K–L). In some brands, other elements including lead, manganese, molybdenum, and iron were also present in air-tubes (Table 1). The elements were very similar in the tank model air-tubes and were identical in four of the six brands (Figure 2B). All brands had a brass core with a nickel coating (Figure 4M–R, Table 1). Some brands, such as Kanger T3S, also had an iron, cobalt, or tin coating (Figure 2B, Figure 4M–R). When comparing the older versus the newer models, the air-tube composition changed only in the Mark 10 to Mark 10 XL transition (Figure 2B, Figure 4 K–L and S–V; Table 1). The original air-tube was nickel coated with silver, while in the Mark 10 XL, the air tube was nickel, chromium, and iron.

In most cartomizer brands, the thick wire-to-air-tube joint was tin solder (Table 1), as shown for Mark 10 (Figure 4 W–X), and lead was sometimes associated with these solder joints (Table 1). However, in some cases, the wire and air tube were brazed together, as shown for Mark 10 XL (Figures 4 S–V) or were welded together with copper and zinc as in V2 Cig (2017) (Figure 4 Y–BB), which also had lead in its weld. In two cartomizer brands (V2 Cig 2012 and South Beach Smoke) that did not have a thick wire, the filament was wedged between the shell and the air-tube (Table 1). Most tanks did not have thick wires, but in the two that did (Smok and Kanger T3S), the wire and air-tube were brazed together (Table 1). In some products, additional elements (calcium, carbon, chromium, oxygen) were present in the wire-to-air tube joint (Figure 2A). The oxygen and carbon appeared to be part of an organic glue.

In all products, the wick was mainly silicon and oxygen (silica) (Figure 2B and Figure 5 A–B). However, some wicks also contained calcium, aluminum, magnesium, and sodium, characteristic of fiberglass (Figure 2B). The only exception was the Tsunami 2.4, which had an organic wick comprised of carbon and oxygen (Figures 2B and 5 C–E). The sheath, which was only found in the cig-a-like models, was made of fiberglass (silicon, oxygen, magnesium, calcium and aluminum) (Figures 2B and 5 F–J).

4. Discussion

This study compared the element/metal composition of atomizers in cartomizer and tank style EC over a 5-year period. Our previously published data on EC atomizers was included in the comparison (Table 1).[8–10] Across generations, atomizers and styles (cartomizer vs tank) tended to have the same element/metal composition with some variations among brands and years. Eight of the elements/metals were found across brands and within brands purchased at different times. These elements included chromium, nickel, copper, silver, tin, silicon, aluminum, and zinc. Given their widespread use, these dominant elements should be included in future studies on EC elements/metals. Two elements/metals (iron and lead) were found in some but not all products, while manganese, cobalt, molybdenum, titanium, and tungsten were only found in a few of the products. Cartomizers and tank atomizers in the current study had similar element/metal components except that: (1) most tanks did not have a thick wire, (2) there were fewer brass clamps in the tanks, and (3) the tanks did not have silicon sheaths. These differences resulted in a general reduction in the number of atomizer components and elements in the tank style products.

The alloys in the filaments included nichrome (nickel and chromium), elinvar (chromium, iron, nickel), invar (iron, nickel), and kanthal (aluminum, chromium, iron).[20] These alloys were found in filaments across EC generations with nichrome being the most widely used. The thick wires in the cartomizer and disposable models were copper coated with silver, except in the newer cartomizer brands, which had uncoated nickel thick wires, and the tank styles, which generally lacked a thick wire. The thick wire when present was often covered with a layer of plastic/Teflon. While not analyzed in our study, this coating may restrict the release of thick wire elements/metals into aerosols. The elemental composition of the wick (silica) and sheath (fiberglass) were generally similar across the cartomizer and disposable EC products. Joints between the wires in cartomizer and disposable styles usually contained copper and zinc and in the disposables often contained tin. The wire-to-air-tube joint was usually made of tin solder. Air-tubes were comprised mainly of copper and zinc (brass) or nickel. All disposable air-tubes were plastic. The elements/metals in the old vs new purchases did not show any particular change in usage that would indicate manufacturers had altered metal use in atomizer components. When taken together, these data show that some elements/metals in the atomizers of EC are found across products, which will help focus future work on the major elements/metals in EC.

Our data can be compared to EC models sold before 2012.[8,9] In some early cartomizer models, such as SE Platinum, manufacturers used tin solder to stabilize wire-to-wire and wire-to-air-tube joints.[8] While tin solder joints were not present between wires of BluCig, V2 Cigs, Mark Ten or Vuse, they were used to join wires in most disposable brands.[9,10] Tin solder joints were also present between the air-tube and thick wire in most cartomizer and disposable products, but not in those tank models (Smok and Kanger T3S) that had thick wires, in which joining was done by brazing. Prior to the introduction of ECs, solder joints used in manufacturing of consumer products were stabilized by lead. However, the use of lead in solder has been banned since 2006 in China, the site where most ECs are manufactured.[21,22] Nevertheless, five brands (Luxury Lites, Imperial Hookah, V2 Cigs 2017, Liberty Stix Eagle, and Smoke 51) had lead in either the wire-to-wire or wire-to-air-tube solder joint, indicating that some manufacturers are not in compliance with the regulations on lead usage. We previously showed that removing tin solder joints from cartomizer style ECs reduced the amount of tin in the aerosol.[9] In all newer cartomizers, wires were either brazed together or joined by a small brass clamp, which could be the source of the copper and zinc frequently reported in EC aerosols.[11–13] Data in the current study support the idea that manufacturers of cartomizer and tank style EC, but not disposable EC, have moved away from using tin solder joints between the filament and thick wire, and that lead is still found in the solder of some EC products.

The metals found in this study have been identified in EC aerosols [8–13], suggesting their source is at least in part the atomizer. The relative amount of a metal in EC aerosols could be related to its melting point, its abundance in the cartomizer, its proximity to the filament, or faulty workmanship. Tin and lead, which have both been reported in EC aerosol[8–10], have relatively low melting points (232°C for tin, 327°C for lead). Since ECs are capable of heating to or above these temperatures, it is likely that tin and lead enter aerosols from melted solder joints. In our earlier study, Greensmoke had a higher concentration of tin in the first 60 puffs of aerosol than 14 other brands that were examined, due to faulty solder joints in the Greensmoke cartomizers.[9] Other labs have detected tin and lead in the aerosol of tank style EC (0.7–500 μg/L for tin, 0.1–500 μg/L for lead).[13] We did find a tin coating on the air-tubes in most tanks. However, we did not find lead associated with this coating or any other component in the tank style atomizers. It is possible the tin detected in tank aerosols came from the air-tube coating. The sources of the lead in tank aerosol cannot be deduced from our data, perhaps because we studied different products than Olmedo et al (2018). Zinc also has a relatively low melting point (420^{o}C) and was found in most EC atomizers, which are likely the source of the zinc reported in EC aerosols.[8,10,12,13]

Other elements, such as chromium, silver, iron, and nickel, which were commonly found in the wires and air-tubes, have also been detected in EC aerosols.[10,13] These metals have higher melting points than tin, lead, and zinc, which may reduce their transfer to aerosols. We previously found relatively low levels of chromium, iron, and nickel in cartomizer and disposable EC aerosols.[8–10] Even though the filament, which is usually comprised of nickel, chromium, and some brands iron, would be the hottest component in the EC during use, its temperatures may not be high enough to release high levels of chromium, iron and nickel. Silver was not always detected in aerosols or was present in low concentrations [8–10], probably due to its relatively high melting point and/or the Teflon coating that surrounds the thick wire, where it is usually found.

Some elements (e.g., arsenic, selenium, cadmium, and boron) have been detected in EC aerosols, but were not in the atomizer components in our current or prior studies.[8,10,13] These elements could have been introduced during the manufacturing process or from components other than those in the atomizing units, such as the battery, mouthpiece, air, e-fluid, or refill fluids (tanks). Other labs have reported elements/metals in e-fluid of cartomizer style EC before use.[12,13,23,24] Additionally, they could have been in the atomizing units at concentrations not detected by SEM/EDS. Analysis of metals in EC aerosols has generally been done using ICP-OES or ICP-MS, which both have lower detection limit compared to SEM/EDS.

Cigarette butts are the most tossed piece of trash accounting for 38% of the world wide liter.[25,26] The rapid surge in EC sales will add to this liter. While cigarettes have plastic filters that will degrade in about 12 years, the metal components in EC may take longer to degrade, during which time metals that are potentially harmful, such as nickel, chromium and lead, will leach into the environment and could be harmful to plants and animals, including humans. [27,28] Currently, there are 10.8 million EC users in the U.S. which make up ~43% of EC users worldwide, and this number is growing exponentially.[29,30] The impact of disposal of EC atomizers on the environment has not received much attention. While there are guidelines in many countries for the disposal of battery products and in some instances guidelines also exist for nicotine disposal[31], there are currently no guidelines or regulations for the disposal of atomizing units, which are often separable from the battery. Data from our study could help environmental agencies focus on those elements/metals that are most likely to be components of ECs and therefore likely to appear in the environment and in leachates.

Elements identified in atomizers can have adverse health effects. For example, chromium, lead, and nickel are known carcinogens.[32] Also, lead, which is not permitted in solder in China where most ECs are made [22], can cause vomiting, diarrhea, body and stomach pain, and long term exposure can lead to lung fibrosis, as well as cardiovascular and kidney disease.[33] Exposure to chromium and nickel can result in lung, nasal, and pancreatic cancer, oxidative stress, shortness of breath, wheezing, and abdominal pain.[33,34] Additional information on the potential health effects of the metals in EC can be found in several recent reviews.[33–37]

The ability to map individual components and identify multiple elements in each atomizer structure.is a major advantage of SEM/EDS technology. This method also gives information on the relative abundance of each element. While we have examined many different EC products, there are numerous models that were not examined, which could contain additional elements. Also, the SEM/EDS technology may not have been sensitive enough to detect elements that were present in low concentrations. Therefore our data may not include all elements present in EC atomizers.

5. Conclusions

This and our prior studies provide foundational data that identify specific elements/metals in EC atomizer components, compare their frequency of use in EC atomizers, examine their use in different models of ECs, and examine how this use has changed over a 5-year time span. Many of the elements/metals that have been identified in EC atomizers have been detected in EC aerosols, and likely originated in the atomizers. The data further suggest areas for improvement of metal usage in EC that may reduce risk to users and minimize transfer of harmful metals from atomizers to environmental leachates. These data should help focus future attention on those metals that are generally found in all types of EC products, are most frequently used, are the best candidates for future health-related risk assessments, and are most likely to enter the environment following EC disposal.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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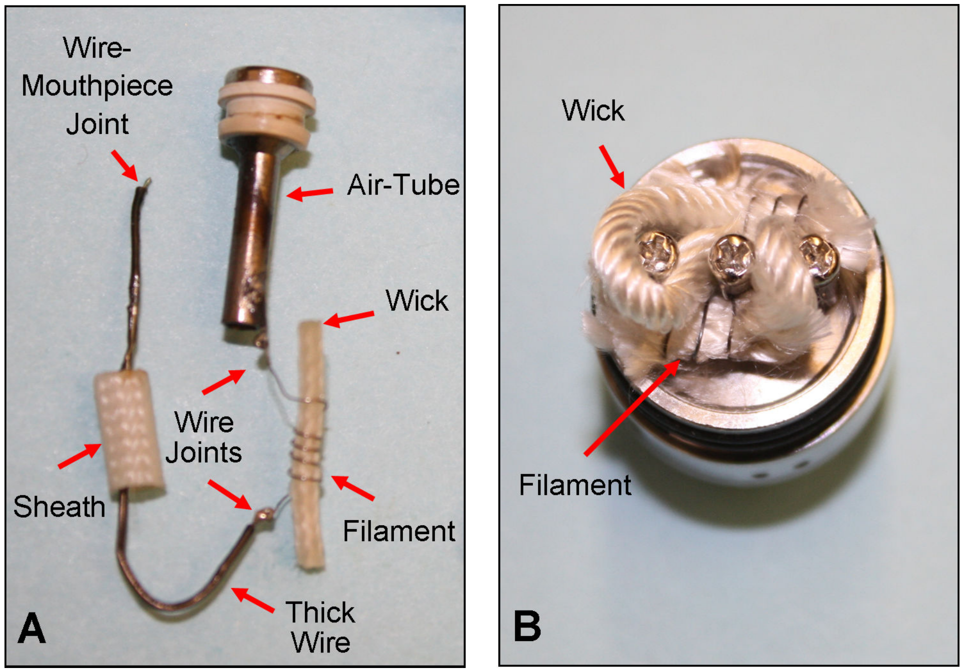

Figure 1: Examples of atomizing units from a cartomizer (A) and tank (B) style EC.
(A) An atomizer from a cartomizer EC purchased in 2011. (B) The atomizer from a RDA tank style EC purchased in 2014. Individual components are labeled in each figure.

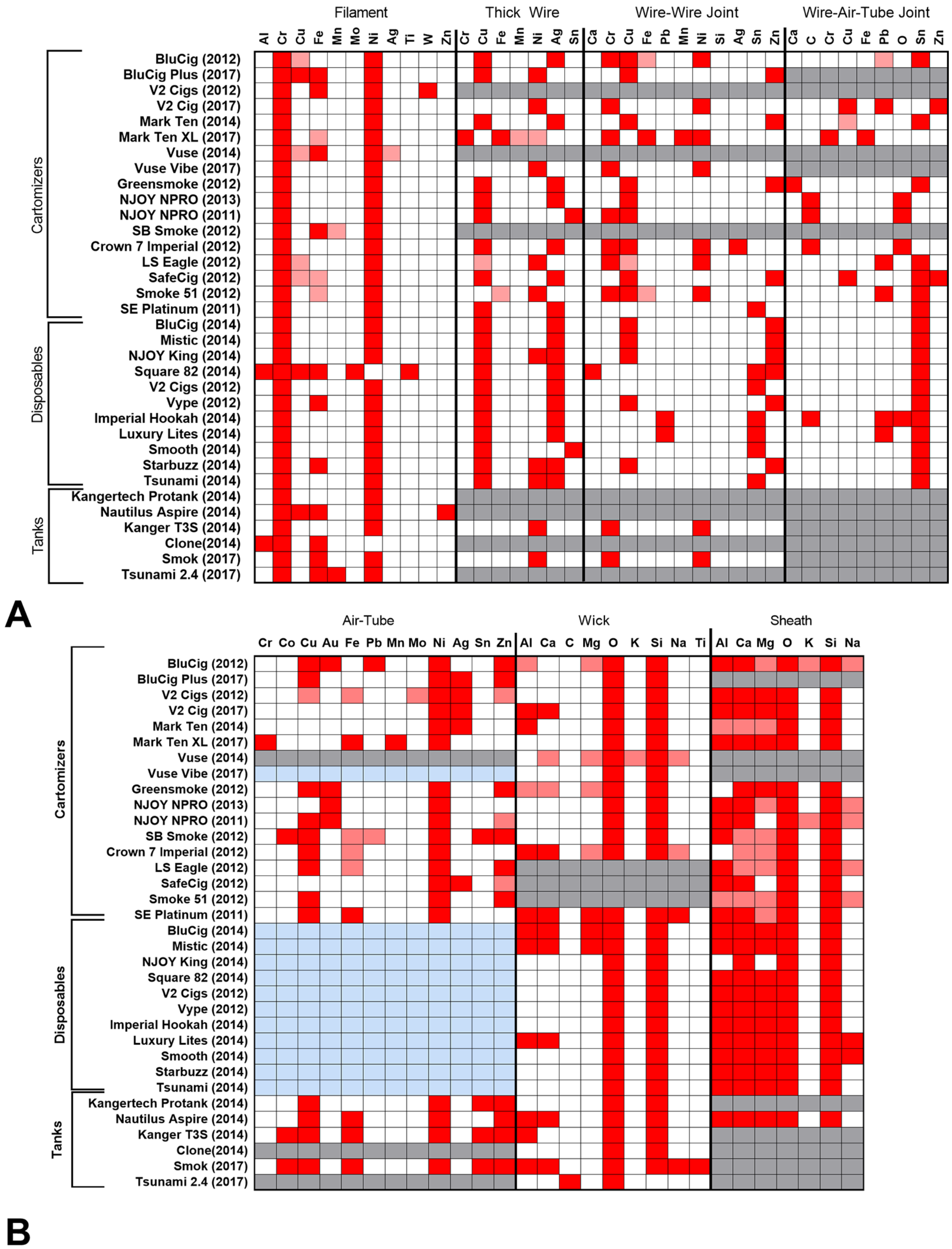

Figure 2: Heat map showing the elements/metals in each component in each product.

Dark red squares indicate the element was a major peak in the EDS spectrum. Pink squares indicate elements were minor peaks in spectra. Dark gray squares indicate the component was not present. Light blue squares indicate components that were made of plastic and not analyzed.

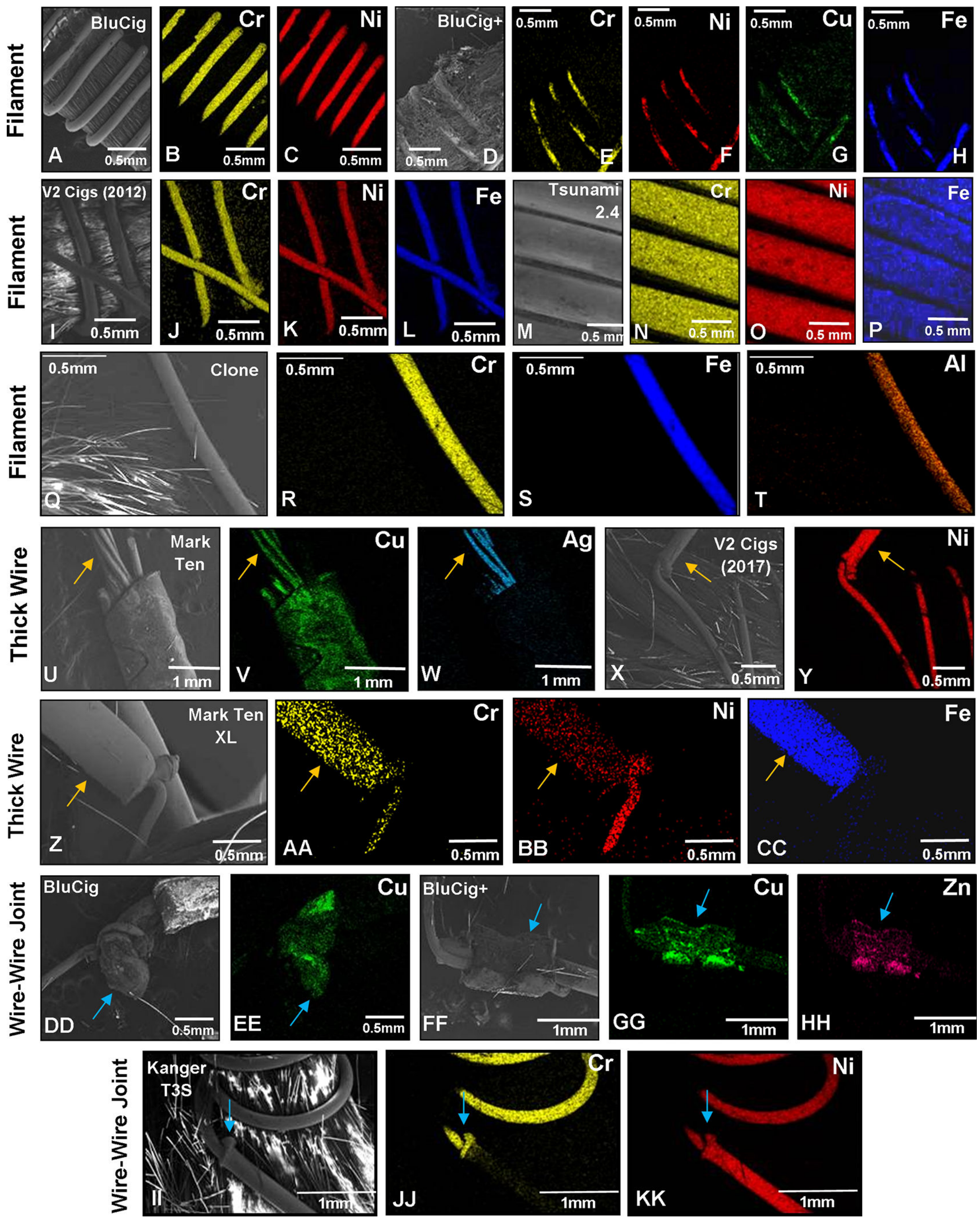

Figure 3: SEM images and EDS elemental maps of the filament, thick wire and wire-to-wire joint in EC.

(A) The filament in the BluCig atomizer was chromium (B) and nickel (C). (D) The filament in the BluCig Plus atomizer was of chromium (E), nickel (F), copper (G), and iron (H). (I) The filament in the V2 Cigs 2012 atomizer was chromium (J), nickel (K), and iron (L). (M) The filament in the Tsunami 2.4 atomizer was chromium (N), nickel (O), and iron (P). (Q) The filament in the Clone atomizer was chromium (R), iron (S), and aluminum (T). (U) The thick wire in the Mark Ten atomizer was copper (V) and silver (W). (X) The thick wire in a V2 Cigs 2017 atomizer was nickel (Y). (Z) The thick wire in the Mark Ten XL atomizer was chromium (AA), nickel (BB), and iron (CC). (DD) The filament-to-thick wire joint in the BluCig atomizer was copper (EE). (FF) The filament-to-thick wire joint in the BluCig Plus atomizer was copper (GG) and zinc (HH). (II) The filament-to-thick wire joint in the Kanger T3S atomizer was chromium (JJ) and nickel (KK). Orange arrow = thick wire, blue arrow = filament to thick wire joint.

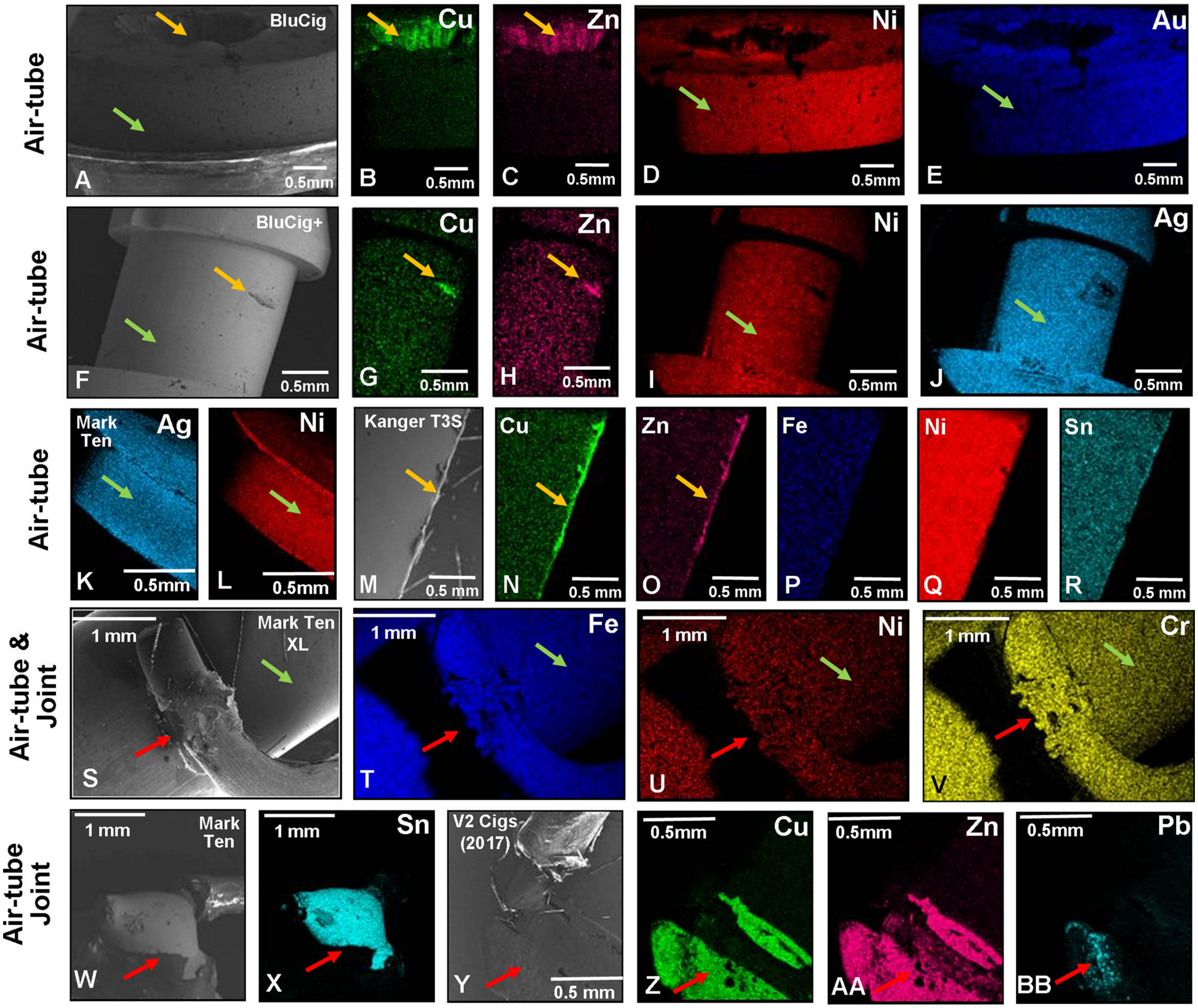

Figure 4: SEM images and EDS elemental map of the air-tube and wire-to-air-tube joint.
(A) The air-tube in the BluCig atomizer was copper (B), zinc (C), nickel (D), and gold (E). (F) The air-tube in the BluCig Plus atomizer was copper (G), zinc (H), nickel (I), and silver (J). The air-tube in the Mark Ten atomizer was silver (K) and nickel (L). (M) The air-tube/shell in Kanger T3S atomizer was copper (N), zinc (O), iron (P), nickel (Q), and tin (R). (S) The thick wire-to air-tube joint in the Mark Ten XL atomizer was iron (T), nickel (U), and chromium (V). (W) The thick wire-to-air-tube joint in the Mark Ten atomizer was tin (X). (Y) The thick wire-to-air-tube joint in the V2 Cigs 2017 atomizer was copper (Z), zinc (AA), and lead (BB). Orange arrow = core of the air-tube, green arrow = outer coating of the air-tube, red arrow = thick wire to air-tube joint.

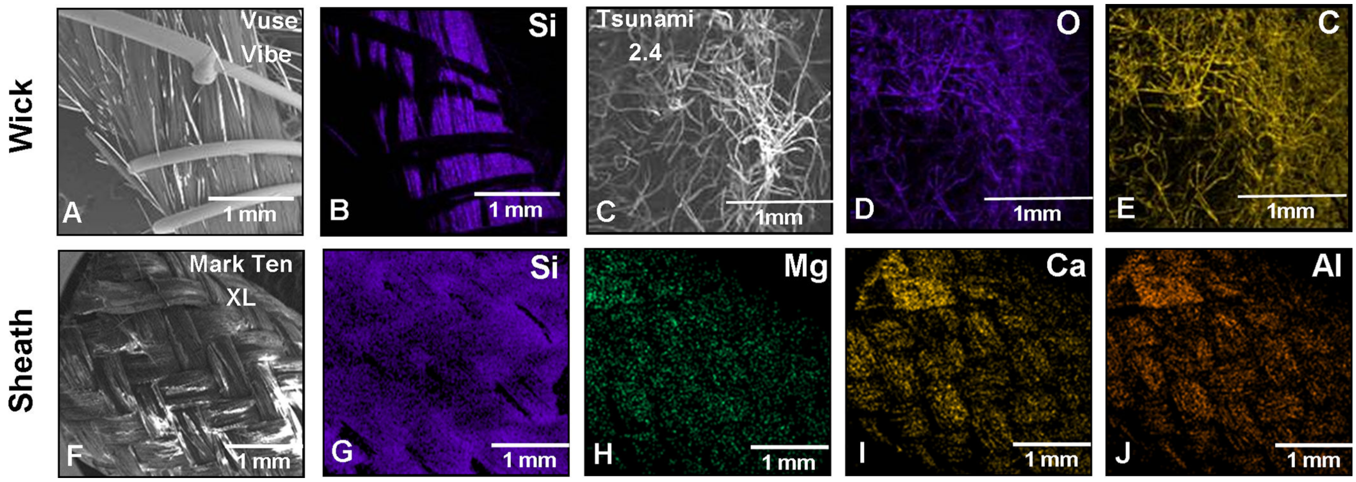

Figure 5: SEM images and EDS elemental map of the wick and sheath.

(A) The wick in the Vuse Vibe atomizer was silicon (B) and oxygen (not shown). (C)The wick in the Tsunami 2.4 atomizer was oxygen (D) and carbon (E). (F) The sheath in the Mark Ten XL atomizer was silicon (G), oxygen (not shown), magnesium (H), calcium (I), and aluminum (J). For Tsunami 2.4 wick, the oxygen and silicon are the same color.

Table 1:

Summary of elemental analysis of cartomizer, disposable, and tank style EC atomizer unit components

Brand	Filament	Thick Wire	Wire to Wire Joint	Wire to Air-Tube Joint	Air-tube	Wick	Sheath	Miscellaneous Components
BluCig	Nickel, chromium (minor: copper)	Copper, silver coating	Nickel, chromium, copper, (minor: iron) coiled joint	Tin solder (minor levels: lead)	Outer - nickel, gold; inner - copper, zinc, lead	Silicon, oxygen (minor: aluminum, magnesium)	Oxygen, silicon, calcium, aluminum, (minor: magnesium, potassium, sodium)	
BluCig Plus	Nickel, chromium, iron, copper	Copper, nickel plated	Copper, zinc clamp	None	Copper, zinc core and nickel-silver plated	Silicon, oxygen	None	Battery interface: Copper, zinc (minor lead), nickel-silver plated
V2 Cigs ’12	Chromium, nickel, iron, tungsten	None	None	None	Nickel, silver – (minor: copper, zinc, iron, molybdenum)	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	Adhesive: Silicon, oxygen, aluminum, titanium, calcium
V2 Cig ’17	Nickel, chromium	Nickel	Welded chromium, nickel	Welded Copper, zinc, and lead solder	Nickel, silver	Silicon, oxygen, (minor: calcium, aluminum)	Silicon, oxygen, aluminum, magnesium, calcium	
Mark Ten	Nickel, chromium	Copper, silver coated	Copper, zinc clamp	Tin (minor: copper) solder	Nickel, silver	Silicon, oxygen, (minor: aluminum)	Silicon, Oxygen (minor: calcium, aluminum, magnesium)	2nd Air-tube: Silicon, oxygen
Mark Ten XL	Nickel, chromium, (minor: iron)	Iron, chromium, (minor: manganese, nickel)	Brazed Iron, chromium, manganese, nickel	Iron, chromium welding	Iron, chromium, manganese, nickel	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	
Vuse	Nickel, iron, chromium (minor: copper, silver)	None	None	Wire to metal holder:	None	Silicon, oxygen (minor: sodium, calcium, potassium, magnesium)	None	Chip: silver, aluminum, oxygen, iron
Vuse Vibe	Nickel, chromium	Nickel	Brazed, Nickel, chromium	None: Wedge between the gasket	Plastic	Silicon, oxygen	None	
Greensmoke	Nickel, chromium[b]	Copper, silver coated[b]	Copper, zinc, nickel Clamp[b]	Tin and calcium solder[b]	nickel, gold, copper, zinc	Silicon, oxygen (minor: calcium, aluminum, magnesium)	Silicon, oxygen, magnesium, calcium	Gasket: carbon, oxygen, calcium, silicon, (minor: sodium, barium, magnesium, aluminum). Tin particles

Brand	Filament	Thick Wire	Wire to Wire Joint	Wire to Air-Tube Joint	Air-tube	Wick	Sheath	Miscellaneous Components
NJOY NPRO '13	Nickel, chromium[b]	Copper, silver coated[b]	Copper, zinc clamp[b]	Organic glue[b]	Nickel, gold plated	Silicon, oxygen	Oxygen, silicon, calcium, aluminum. (minor: sodium, magnesium)	
NJOY NPRO '11	Nickel chromium[b]	Copper, tin coated[b]	Chromium, copper braze[b]	Organic glue[b]	Nickel, copper, gold plated (minor: zinc)	Silicon, oxygen	Silicon, oxygen, calcium, aluminum (minor: sodium, potassium)	
SB Smoke	Iron, nickel, chromium (minor: manganese)	None	None	None	Nickel, zinc, copper, cobalt, (minor: iron), coated with Tin (minor: lead)	Silicon, oxygen	Silicon, oxygen, aluminum (minor: calcium, magnesium)	
Crown 7 Imperial	Nickel, chromium	Copper, silver coated	Nickel, chromium, copper, silver coated hooked and coiled joint	Organic glue	Nickel, copper (minor: Iron)	Silicon, oxygen, calcium, aluminum (minor: sodium, magnesium)	Silicon, oxygen (minor: calcium, magnesium)	
LS Eagle	Nickel, chromium (minor: copper)	Nickel (minor: copper)	Nickel, chromium (minor: copper) hooked joint	Lead and tin solder	Nickel, zinc, copper, (minor: iron)	None	Silicon, oxygen, aluminum (minor: calcium, magnesium, sodium)	
SafeCig	Chromium, nickel, (minor: iron, copper)	Copper, silver coat	Copper, zinc clamp	Copper, zinc with tin solder	Nickel, silver (minor: zinc)	None	Silicon, oxygen, aluminum, calcium	
Smoke 51	Nickel, chromium (minor: iron)	Nickel (minor: iron)	Nickel, chromium, copper, (minor: iron) hooked joint	Lead and tin solder	nickel, zinc, copper	None	Silicon, oxygen (minor: aluminum, calcium, magnesium, sodium)	Gasket: Silicon, oxygen
SE Platinum	Nickel, chromium[a,b]	Copper, silver coat[a,b]	Tin solder[a,b]	Tin solder[a,b]	Nickel, copper, iron[a]	silicon, oxygen, aluminum, calcium, magnesium, sodium[a]	Silicon, oxygen, aluminum, calcium (minor: magnesium)	Gasket: silicon, titanium, oxygen Mouthpiece: Iron chromium, manganese[a]
BluCig[c]	Nickel, chromium	Copper, silver coated	Copper, zinc clamp	Tin solder	Plastic	1st wick: Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	2nd wick: Silicon, oxygen, aluminum, magnesium, calcium
Mistic[b,c]	Nickel, chromium[b]	Copper, silver coated[b]	Copper, zinc clamp[b]	Tin solder[b]	Plastic	Silicon, oxygen, aluminum,	Silicon, oxygen, aluminum,	

Brand	Filament	Thick Wire	Wire to Wire Joint	Wire to Air-Tube Joint	Air-tube	Wick	Sheath	Miscellaneous Components
						magnesium, calcium	magnesium, calcium	
NJOY King[c]	Nickel, chromium	Copper, nickel, silver coated	Copper, zinc clamp	Tin solder	Plastic	Silicon, oxygen	Silicon, oxygen, calcium	
Square 82[c]	Chromium, copper, aluminum, titanium, molybdenum, iron	Copper, silver coated	Tin, calcium solder	Tin solder	Plastic	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	
V2 Cigs[c]	Nickel, chromium	Copper, silver coated	Tin solder	Tin solder	Plastic	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	
Vype[c]	Nickel, chromium, iron	Copper, silver coated	Copper, zinc clamp	Tin solder	Plastic	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	
Imperial Hookah[c]	Nickel, chromium	Copper, silver coated	Tin, lead solder	Tin, lead solder and organic glue	Plastic	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	
Luxury Lites[c]	Nickel, chromium	Copper, silver coated	Tin, lead solder	Tin, lead solder	Plastic	Silicon, oxygen, aluminum, calcium	Silicon, oxygen, aluminum, magnesium, calcium, sodium	
Smooth[c]	Nickel, chromium	Copper, silver coated	Tin solder	Tin solder	Plastic	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium, sodium	
Starbuzz[c]	Nickel, chromium iron	Copper, nickel, silver coated	Copper, zinc clamp	Tin solder	Plastic	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	
Tsunami[c]	Nickel, chromium	Copper, nickel, silver coated	Tin solder	Tin solder	Plastic	Silicon, oxygen	Silicon, oxygen, aluminum, magnesium, calcium	
Kangertech Protank	Nickel, chromium	None	None	None: Wedged between silicon gaskets	Copper, zinc, nickel-tin plated	Silicon, oxygen	None	Shell: Nickel, tin, copper, zinc, cobalt
Nautilus Aspire	Nickel, iron, copper, zinc, chromium	None	None	None: Wedged between silicon gaskets	Copper-zinc core, iron, nickel plating	Silicon, oxygen, calcium, aluminum	None	Sheath: silicon, oxygen, magnesium, aluminum, calcium. Gasket: silicon,

Brand	Filament	Thick Wire	Wire to Wire Joint	Wire to Air-Tube Joint	Air-tube	Wick	Sheath	Miscellaneous Components
								oxygen, aluminum
Kanger T3S	Nickel, chromium	Nickel	Welded: Nickel, chromium	None: Wedged between silicon gaskets	Nickel, tin, cobalt, copper, iron, zinc	All Wicks: Silicon, oxygen, aluminum	None	Shell: Nickel, tin, copper, zinc, cobalt
Clone	Chromium, iron, aluminum coated with organic material	None	None: Screwed	None: Screwed	None: whole piece	Silicon, oxygen, coated with organic material and Iron	None	
Smok	Nickel, chromium, iron	Nickel	Welded: Nickel, chromium, coated with silicon, oxygen, aluminum, (minor: manganese, Titanium)	None: Wedged between silicon gaskets	Nickel, tin, cobalt, copper, iron, zinc	Silicon, oxygen, aluminum, calcium, sodium, titanium	None	Mesh Ring: Iron, chromium, nickel, manganese, copper
Tsunami 2.4	Nickel, chromium, iron manganese	None	None: Screwed	None: Screwed	None: whole piece	Carbon, oxygen	None	

[a]Data presented in Williams et al 2013 PlosOne.

[b]Data presented in Williams et al 2015 PlosOne

[c]Data in these rows were presented in Williams et al 2017 PlosOne