THE BYPRODUCTS OF SOLDERING MATERIALS
AND THE POTENTIAL FOR HEALTH IMPACT

By

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A capstone project submitted for Graduation with University Honors

December 10, 2021

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ABSTRACT

The practice of soldering has been demonstrated to exhaust byproduct fumes into the immediate surrounding environment of the solderer, potentially putting them at a risk of inhaling hazardous materials depending on the contents of the fumes. While there has been a shift away from materials demonstrably shown to be harmful, such as lead, cadmium and zinc, there has been little investigation into the currently ubiquitous and “safe” solder material of 96-4 Tin-Silver. For this reason, I believe there are grounds on which to commit to further research, and this study seeks to provide a foundation on which a doubt of the safety of 96-4 Tin-Silver fumes can be established. Particle counts from Tin-Silver have been found to be less than Tin-Lead, though by no means are the particle counts insignificant, the count differences only amounting to a 12.73% drop between Tin-Lead and Tin-Silver. Lead has been known to be hazardous in nearly all forms of human contact, so similarity between Tin-Lead fumes and Tin-Silver fumes is cause for concern. The findings also indicate some similarity in particle size profiles with Tin-Lead. Particle sizes have also been demonstrated to be relatively similar in distribution profile (Tin-Silver being proportional to but less than Tin-lead), though have different lingering qualities over time, warranting investigation. Initial readings of later SMPS scans indicate that Tin-Silver fumes tend to be smaller in size, larger particles making a smaller proportion of the curve as time goes on, meaning that the required ventilation rate for making the fumes safe (if future investigation proves measurable hazard) is another branch of research which this study warrants. Further, questions raised during the analytical stage note other potential sources of hazard in soldering similarly underassessed, such as the true compositions of fluxes in commercially available solders, which in many cases is not disclosed on the packaging.

ACKNOWLEDGEMENTS

I would like to express the highest gratitude for Chen Li, Thomas Eckel, Daniel Gonzales, and Dr. David Cocker, as well as the CE-CERT APL for enabling, assisting, and guiding my research, and thereby for their help in potentially preventing future soldering related loss of human life and health. I must also thank Kristine Parada, Dennis McIver, Lourdes Maldonado, and Dr. Richard Cardullo of the UCR University Honors for their support of my research and guidance through a particularly strange time for research to be conducted in. This research is dedicated to all solderers, past and future, be they tinkerers, artisans or tradespeople, so that they may practice their works and passions without fear of an unknown harm befalling them. I would also like to lend thanks in advance to any particle science and medical researchers who might continue this line of investigation.

TABLE OF CONTENTS

Introduction

It is not often that the average person will question the potential harm produced by objects encountered in their daily lives. Often less attention is paid to the intermediary steps of production and maintenance. Soldering is one such apparently mundane process, an outwardly simple binding method comparatively less hazardous to the user than its usual conceptual counterpart of welding. Unlike brazers and welders, who work with temperatures above 840ºF and thus need insulative gloves, specialized face and eye protection, gripping instruments - be they tongs, wrenches or other aids - and other specialized equipment to safely conduct, soldering merely needs an electrical connection and steady hands (and, of course, a soldering iron). Soldering typically handles temperatures from 600-840ºF and is thus a comparatively low temperature operation. Soldering's applications are also more practically applied by the average person given the proliferation of relatively cheap electronics, and given the general growth of the technology and electronic markets, the amount of soldering done at both the user and manufacturer end can be anticipated to grow. Tinkerers, tradespeople, and manufacturers can, as a result, reasonably be expected to increase in number or in soldering done by each, and with a growth in exposure, one must ask, what is the average solderer being exposed to?

Impetus for Research

The initial interest in this subject was spurred on by curiosity and a certain degree of personal suspicion held towards supposed 'safe practices' in soldering. My grandmother worked on electronics - primarily in the respect of soldering components together - after moving to the United States post-WWII. She was a particularly resilient woman, as evidenced by her leaving her home in Hiroshima, Japan after her apartment was unexpectedly leveled while she was in it, and recovering fully from her injuries aside from some glass lodged in her arms. Despite having perhaps the most justified reason to hold a grudge against the country she moved to, she opted to move on with her life. She was of a strong mental and physical constitution, so her later decline in health came as a surprise. Upon medical examination, this woman who had survived an atomic bombing was suffering irreversible damage from her few years of work as a solderer rather than any latent effects of radiation exposure. This was before lead was widely known to be a toxic material, and was ubiquitous in soldering. It had always been baffling in hindsight that such a minor oversight as to the composition of a medium for binding electronics was enough to ultimately bring down such a strong person. What then gave me the push (and the opportunity) to indulge this interest and research soldering fumes was UCR University Honors recommending me to study outside of my primary field of study - that being Business Administration - within a different personal interest.

Objective of the Research

While it is supposedly now safe - or at least safer - to solder now, it is still a partly combustive process taking place within close proximity to the user. Inhalation of the byproducts of this process is inevitable unless protective equipment or barriers are used. However, the hazard posed by this inhalation risk are dependent on the size, quantity, and other qualities of the airborne particle byproducts. Lead fumes, of example, are a known hazard. While not considered a hazard in the past, it is now a given that it is, but this raises the question: are current ‘safe’ solders actually safe for solderers to be using just because of their lack of lead? To ensure that there are no avoidable missteps in judging the safety of a task in the future, as well as to avoid the resultant possibility for detrimental health effects on those who solder, it is imperative that research be done to assess the potential for this being a hazard now rather than waiting for the consequences to manifest. Therefore, the research will focus on the most ubiquitous form of supposedly safe solder: 96-4 Tin Silver mix.

<u>History of Solder Composition, Fumes, and Harm to Health</u>

<u>Early History of Soldering and Solder Fumes</u>

To understand the depth of the concern, it may be best to start with the hazards posed by past solders which led to the 96-4 Tin-Silver (94% Tin, 4% Silver) mix rising in commonality. Soldering and brazing have existed as far back as the 4th millennium BCE, possibly earlier, in ancient Mesopotamia (Maryon 111). In many instances, the use of soldering was used in making tools, jewelry, art (Figure 1), and later window frames, the intricacies of each developing with time. The solders also changed with time, using bismuth, copper, glue, copper salt, tin, lead, and various other metals

(Figure 1): Cup with a frieze of gazelles

"The projecting heads were made separately, as were the ears and horns, and were fastened invisibly in place by a colloid hard-soldering, a process much practiced in Iran involving glue and copper salt." (The Metropolitan Museum of Art, New York) and alloys. However, due to the qualities of tin and lead - being easy to find and collect, more flexible and malleable than other materials, and having relatively low melting points of roughly 450ºF and 622ºF respectively - solders including one or both of these became ubiquitous. With the development of electronics and the advent of the electric soldering iron, soldering grew further in commonality, being used in pipeworks, tinkerers projects, small machinery, and production lines the world over. Lead has an even longer history independent of soldering, being used at least as far back as the 5th millennium BCE, and since has permeated innumerable craft practices, products and industries. Among the applications in which it had been incorporated were soldering, brazing, and welding, as well as "making pipes and water tanks, power cable coating, ammunition and blasting, glass, plastics, batteries, rubber, metal alloys, dyes, matches, pesticides, automobile fuel, printing letters, binding, [and] dental fillers" (Mohammadyan et al. 31208). However, eventually people began to notice the toxicity of lead, some accounts as old as 2000 BCE, though insofar as the modern worlds understanding of it is concerned, awareness of it began to grow in the 1700s, and even then and didn't really grow in the public conscious until the 1900s, reaching its current zenith in the last third of the 20th century (Needleman 1, 3).

Research done during and since this rise in awareness has indicated quite clearly the hazards involved. Lead has been shown to be a factor in causing all manner of maladies, from kidney damage to nervous system disorders, infertility, and harm to mental faculties (Mohammadyan et al. 31207, 31208). It also has been found to cause a shortening of the telomeres, which leads to cardiovascular issues (Liyun et al. 628). The telomeres protect DNA during the cellular replication process, so their being shortened can lead to dire consequences for the body as a whole, most noticeably in the cardiovascular system, which weakens with age as the telomeres naturally shorten. Telomeres shorten with organic aging due to repeated cellular replication. Because of this, lead can - by impacting this system - essentially have an accelerated aging effect most prominent in critical bodily systems, leading to potential failures and infirmities in those systems, such as heart disease (Liyun et al. 625). When it comes to lead in soldering, some of the findings from a test on are initially at least somewhat reassuring, in that the levels at which production line solderers encounter lead are not beyond established EPA limits. The EPA limit is 1 in 1000 people at an excess lifetime cancer risk (ELCR) in an occupational setting, and subjects in the testing were at an ELCR at a rate of roughly 0.11 per 1000 participant workers (Mohammadyan et al. 31212). While it was found that many of the sample solderers were not at an abnormal or high risk of developing cancer by these EPA set standards, "the risk of non-carcinogenic effects was high among electronics solderers" (Mohammadyan et al. 31213), thereby that the exposure amounts put them at risk of suffering from any number of the aforementioned physiological impairments. It is also noted that as far as international standards were concerned, 75% of the sample solderers were exposed to higher levels of lead in their normal work than is advisable (Mohammadyan et al. 31213). Solder fumes have been found to also create long term lung function reduction, in some studies it has been found that among solderers and their surrounding persons in the workplace, as many as 22% of them suffer some form of lung disease (Arab et al. 64). Many symptoms can manifest at greater frequency in former solderers (Courtney and Merrett 348), indicating the effects may be related to exposure time and a decline in the body's ability to counter the effects from aging. Animal testing on rats using solder fumes has yielded similarly concerning results, as the fumes have been shown to "induce some pathological changes in lung" (Arab et al. 67) with severity changing with exposure time. It would run contrary to the evidence to claim that soldering fumes, notably those containing lead, could be considered safe. Due to the utility of soldering, it could not be reasonably expected to simply fall out of practice, so the solder had to be changed to make it safer. Unfortunately, this has had its own share of health problems.

Attempts to Improve Quality

Zinc was one possible alternative in soldering, and still enjoys use to this day. It already had marginal use in zinc-tin-lead mixtures before, but with the push for lead-free solutions, combinations like zinc-cadmium and zinc-tin-copper alloys grew in prominence. Zinc was a good material for soldering, being like tin and lead in that it was easy to find and collect, and had a relatively low melting point of 600ºF. It has the added benefit of lowering the overall melting point of metals mixed with it in the solder, making other alloys more viable for the purposes of soldering. However, it's position as a 'safe' alternative became compromised when it was discovered that zinc fumes have a tendency to have negative effects on the skin and bronchial passages of solderers, thereby inducing occupational asthma (Conteras and Chan-Yeung 838). Zinc is still used for its properties and low cost, though less prominently than others. Commonly it is sold as either 70/30 Tin-Zinc, Cadmium-Zinc (varying mixes) or as a generic 'lead-free' solder which attempts to hide the composition.

Cadmium was another candidate for the lead-free alternative, again having a fairly low melting point of roughly 610ºF and being relatively cheap, often appearing as a Cadmium-Silver alloy solder. However, cadmium has been shown to have even worse effects on the body than zinc (which also makes the aforementioned mix of Cadmium-Zinc particularly concerning). Even short term exposure to the fumes of Cadmium-Silver solder - of as short as 15 minutes - have produced lethal effects to a solderer over the course of a month, though speculative calculations indicate that an exposure of 10 minutes would also potentially be lethal (Seidal et al.

429, 430). The effect is often not immediate, occurring over time as the cadmium permeates the body and produces pulmonary edema and pneumonitis, which can lead to lethal respiratory insufficiency (Seidal et al. 429-431). In some cases, pulmonary fibrosis can be caused by such cadmium exposures, leading to permanent lung tissue scarring and potentially similarly fatal results. This tends to take longer to manifest, one instance being as far as 17 years after a single exposure - as well as after recovery from the short term respiratory effects - indicating that even after surviving the short term symptoms the solderer is not entirely in the clear (Seidal et al. 430-431). Cadmium has a tendency to damage the renal system to the point that it has trouble flushing it from the body, meaning that even if future exposure is reduced, excessive initial exposure could lead to cadmium remaining a permanent fixture in the body (Mason et al. 556-558). Cadmium is now widely recognized as a toxin, and is even regulated to the point of being banned in some countries. However, it still persists due to some niche use in jewelry production because of its lustrous appearance, though often with careful considerations made to reduce or avoid exposure.

Tin-Copper is a safe alternative to the hazardous lead solders, as well as the now also recognized as hazardous zinc and cadmium solders. The Centers for Disease Control and Prevention (CDC) indicate that "there is little evidence that copper presents a serious industrial hazard, either from acute or chronic poisoning" (Centers for Disease Control and Prevention 1). The CDC has noted that there can be irritations caused by copper fumes, such as that to the upper respiratory system. There can also be a noticeable metallic taste, the inducement of nausea, and the onset of a fever, however these adverse health effects are both minor in severity and only manifest at fume concentrations above 0.4 mg Cu/m^3. There is a consideration of a possible hazard of exceeding an exposure of 100 mg Cu/m^3 primarily due to the "lack of relevant acute toxicity data for workers exposed to concentrations above 100 mg Cu/m^3" (Centers for Disease Control and Prevention 1), as it is a larger than usual exposure amount. The reasons for copper not being the most ubiquitous solder material in lead-free soldering is due to its material qualities, those being a significantly higher melting point relative to other solder materials - that being 1,984°F - and the relative weakness compared to its main competitor, silver. Lead-free solder using copper often utilizes a mixture of 97/3 Tin-Copper because tin is able to lower the melting point, whereas silver - with the slightly lower (but still relatively high) melting point of 1,763°F - requires less tin and can afford a better ratio of 96-4 in its composition. Silver is also a relatively strong bonding material after the solder is melted, with greater mechanical durability than copper, and ironically a better material for binding copper components together in electronics and machinery due to better thermal cycling resistance. For these reasons, as well as a lack of evidence that silver fumes pose a threat to human health, tin-silver has become one of the more common lead-free solders. It is also used more often in jewelry than tin-copper due to a more visually appealing end product. In most categories except for cost - the difference between the two also being negligible in most cases - silver is the preferable option to copper. However, the lack of evidence for silver fumes being hazardous is not as well documented as coppers, and may be more indicative of a lack of depth in research.

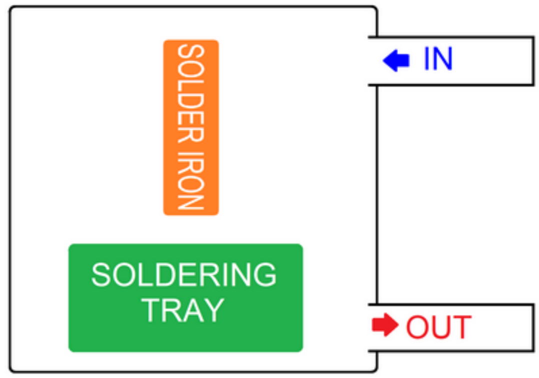
Challenges Relating to Time

As is obligatory for most research attempts made during this specific moment in history, it must be noted that there were significant delays in the research process due to the outbreak of COVID-19 and subsequent lockdowns on facilities which would bring people within potential infectious proximity of other people. In the case of this research project in particular, the delay was entirely front loaded, in that research was not able to begin properly for much of the very limited allotted time. Plans were drawn up for alternatives to be conducted away from a proper laboratory, but put on hold given the constant consideration of a potential reopening of the CE-CERT facility the research was intended to be conducted in. Additionally, it was understood that any research gathered would be overshadowed by the quality, depth and accuracy of future research conducted at a proper facility. Given the quality of the data now collected and the data collection capabilities of the alternative plans, it was clear this inference was accurate. The pandemic also caused secondary issues with the account management systems at UCR, leading to delays in application processing of multiple months. For this reason, once the CE-CERT facility opened, it took an additional several months to properly begin research, as I had to attain proper certifications to gain access to the facility. After this delay, however, the required safety training (Lab Safety and Hazardous Waste Disposal Training) and HIPAA certification delays were a mere week and did relatively little to impede the progress of research.

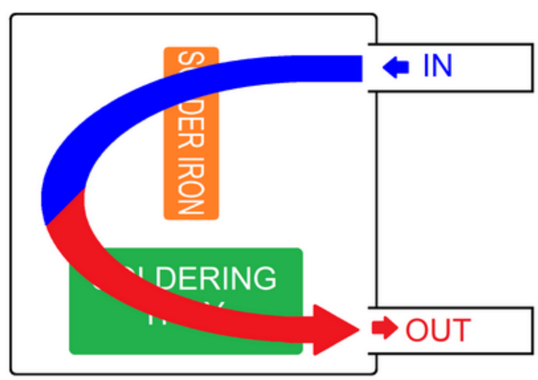
Process and Results

The Measurement Box

The first step in getting measurements of the solder fumes was to select a unit within which to contain and measure the process. The initial plan was to use a large plastic storage box, rubber gloves, sealant, and a commercially available air particle measurement device to create a glove box, ensuring a complete containment of all the fumes, as well as all instruments and the solder itself. Given the massive cost of acquiring an appropriately sized glove box which met the specifications for the task, this was considered a viable alternative. While a cheap glove box may cost $100, one which is heat resistant and comes with proper pipe fittings with which to apply airflow and transfer the fumes to a measurement device would cost significantly more, well into the thousands. However, an alternative solution was proposed by Dr. David Cocker once in-person lab operations resumed: to use a pre-existing 1 cubic foot transparent measurement box, and prevent the introduction of foreign particles by having a positive pressure system within the box (Figure 2). When the door to the box is opened, the positive pressure will ensure that air is flowing out rather than in. While there would be some particle loss, it would not be a significant margin of loss if the process was done quickly enough and the positive pressure was not excessive. There would be an incredibly short time when the door was fully open, as the rest of the time the access point was either closed or would be obstructed by the box operator's hands and instruments, such as the solder material, soldering aid, and soldering iron. To use the box, the operator would ensure a properly cleared environment by using a large amount of clean (particle free) air to flush the box (Figure 3). To establish that the environment was clear, the box would be attached to the measurement device to measure the particle count before the actual test is conducted. The air pressure is then reduced to the set standard positive pressure for this test

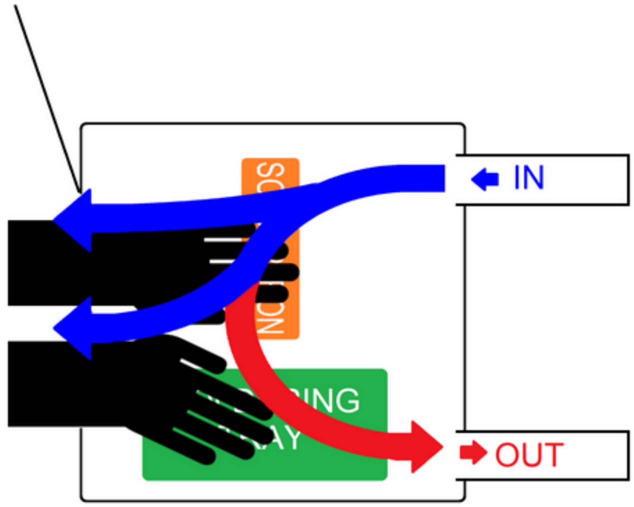


(Figure 2): Box Design



(Figure 3): Clearing Flow

(established as 2 liters per minute of clean air), the door is opened, the soldering done, and the box closed (Figure 4). Once the box is again closed, the fumes contained within would be put through the connected device and the relevant data tabulated until the fumes in the box were exhausted and the unit was once again clear of particles (Figure 3).

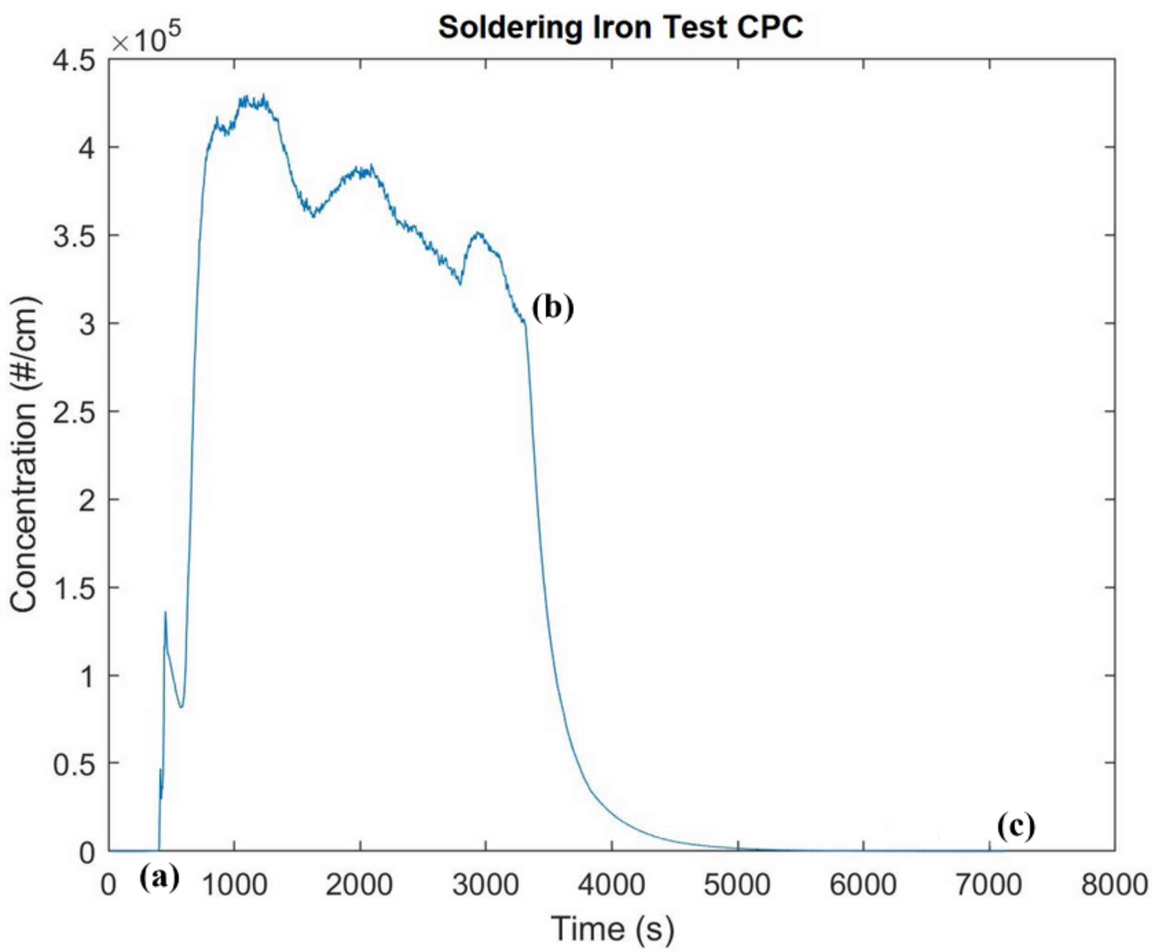


(Figure 4): Positive pressure airflow keeping contaminant particles out during the soldering process.

The CPC

The CPC (Condensed Particle Counter) is a device used to, as the name suggests, count particles. The specific process reads particle concentration in air that is fed to it through a tube at a capped intake flow rate in order to get an accurate reading of the number of particles per cubic centimeter (cm^3). The device has a maximum count of 1.00 x $10^6/cm^3$, or one million particles per cubic centimeter. However, as had been found during the initial soldering test data collection, this limit meant that massive amounts of data was not being counted, as the number of particles far exceeded the countable amount. After several frustrated adjustments of flow amounts, dilution rates, and amount of solder melted in the box yielded minimal improvements, an accidental running of the soldering iron in the box showed there was particle generation. While the soldering iron had been cleaned to about the same level as in average use by solderers in between tests, it was not scrubbed between tests or swapped out to ensure an entirely sanitized soldering iron was being used.

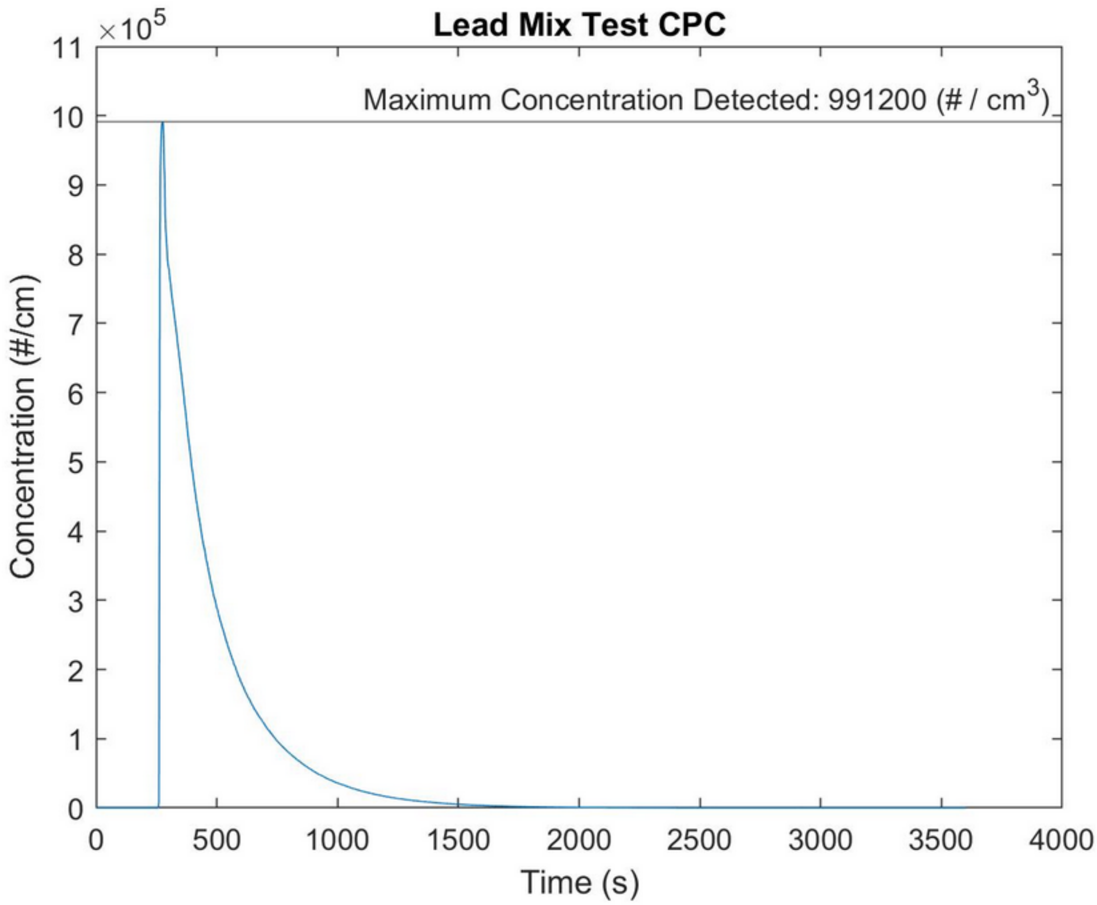
A new test was run on the soldering iron after a normal cleaning procedure, that being scrubbing with a metal brush, washing, and wiping down with a Kimtech Sciences™ Kimwipe (tissue used for removing small particulate matter and liquids without leaving contaminants from the paper), ensuring no foreign particles - aside from solder residue on the iron from the last test which evaded detection and/or removal - were present on the device. The soldering iron was placed in the box with only a stand to keep it from touching the box - itself placed so that it would not be affected by the solder iron. After closing the box and letting it be flushed out for 5 minutes, the iron was turned on, and there was an immediate spike in particles (Figure 5a).



(Figure 5): CPC results for the soldering iron, activated at point **(a)**, deactivated at point **(b)**, and measurement by CPC ending at **(c)**

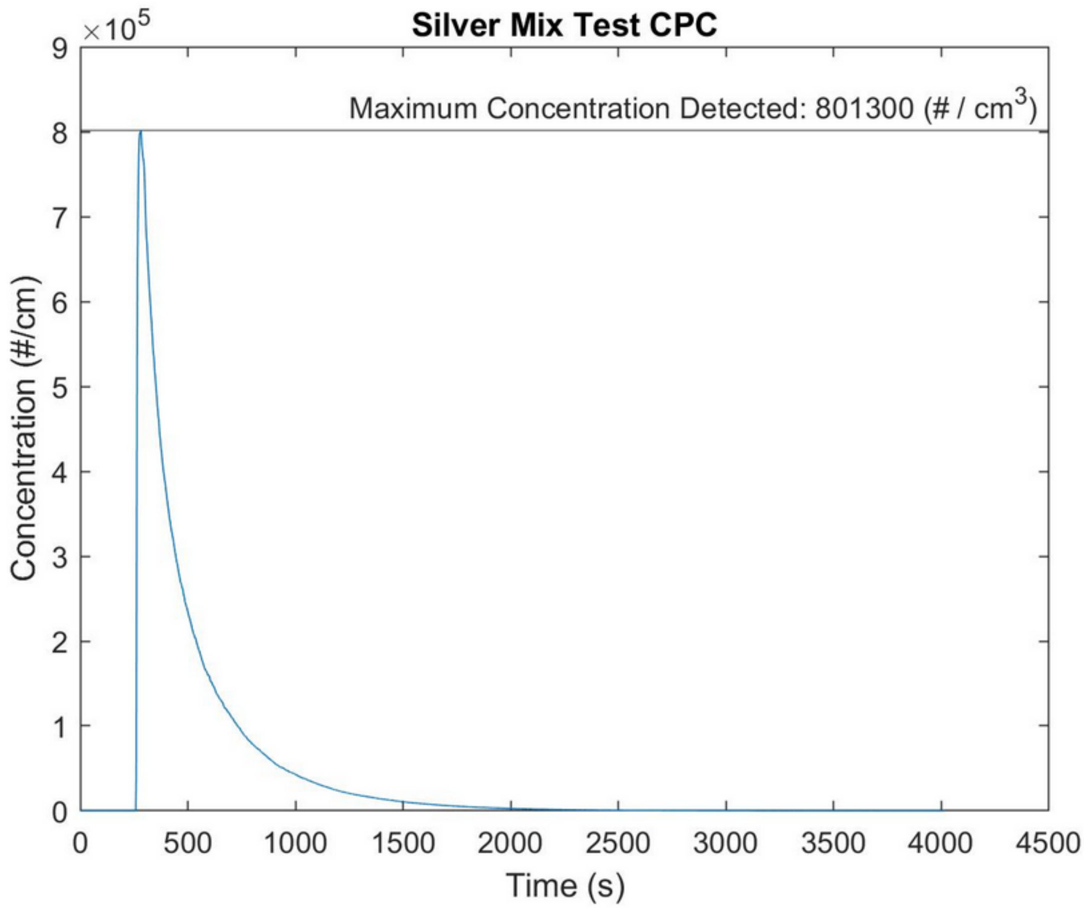
Given the fact that between 1000 seconds and 3000 seconds there is a declining pattern, it was inferred that the soldering iron was burning off whatever was still on it. Despite investigations into the matter, there was no reason which we were able to observe for the strange humps during the soldering iron's burn off period. Once the soldering iron was turned off (Figure 5b), the production of particles ceased, the amount of particles dropping off sharply until the CPC read there were no particles in the box. At that point, the test was ended (Figure 5c). While not directly useful for our data collection aside from being a variable to exclude, it is very useful as far as soldering safety goes, as it is shown that even an iron which appears clean produces a large amount of particles. Since the particle emission may still be hazardous, it is worth it's own study, as it would go beyond the scope of this research.

The next test after the calibration runs was the Tin-Lead solder. In this particular test, 0.2645 grams of 60-40 Tin-Lead solder (one of the most common mixes of lead solder) was melted in the box. The mass was found by cutting a length of solder, weighing it, weighing the soldering iron tip, soldering, weighing the length of solder remaining unused after the test, and the tip after the test, then adding the differences between the before and after masses to find the exact amount melted. This test was the first to be within the CPC's countable range, and it was still quite close to the limit, reaching a particle peak of 991,200/cm^3. The peak is a fairly accurate measure of the total particles produced in a cubic centimeter due to the miniscule amount of time the dilution has to influence the number. An important point to note is that due to the curvature of the line, one might assume that the rate at which the particles are processed slows with time, but the measure used by the CPC is in scientific notation, or exponents centered around powers of 10. The processing rate is likely fairly stable in most cases. In any case, with the findings from this measurement (Figure 6), it is possible to conclude that, after adjusting the mass of the solder against the particles produced, a quarter of a gram of 60-40 Tin-Lead solder produces roughly 936,862/cm^3 particles when soldered. This mass 'standard' is a mostly arbitrary selection to have a comparable measure against the Tin-Silver test, but comes out to be about how much it would take for some quick spot soldering of a few wires would use up.



(Figure 6): The 60-40 Tin-Lead CPC results

The other solder in this series of tests is the 96-4 Tin-Silver mix, and produces a smaller output than the Tin-Lead, though still quite sizable upon first inspection (Figure 7). In this test, 0.2782 grams of solder was melted, producing 801,300/cm3 particles. Adjusted to the quarter of a gram standard previously established, 0.25 grams of 96-4 Tin-Silver solder produces 720,075/cm3 particles when melted, roughly only 77% as much as the Tin-Lead mix.



(Figure 7): The 96-4 Tin-Silver CPC results

CPC Results Aggregated and Compared

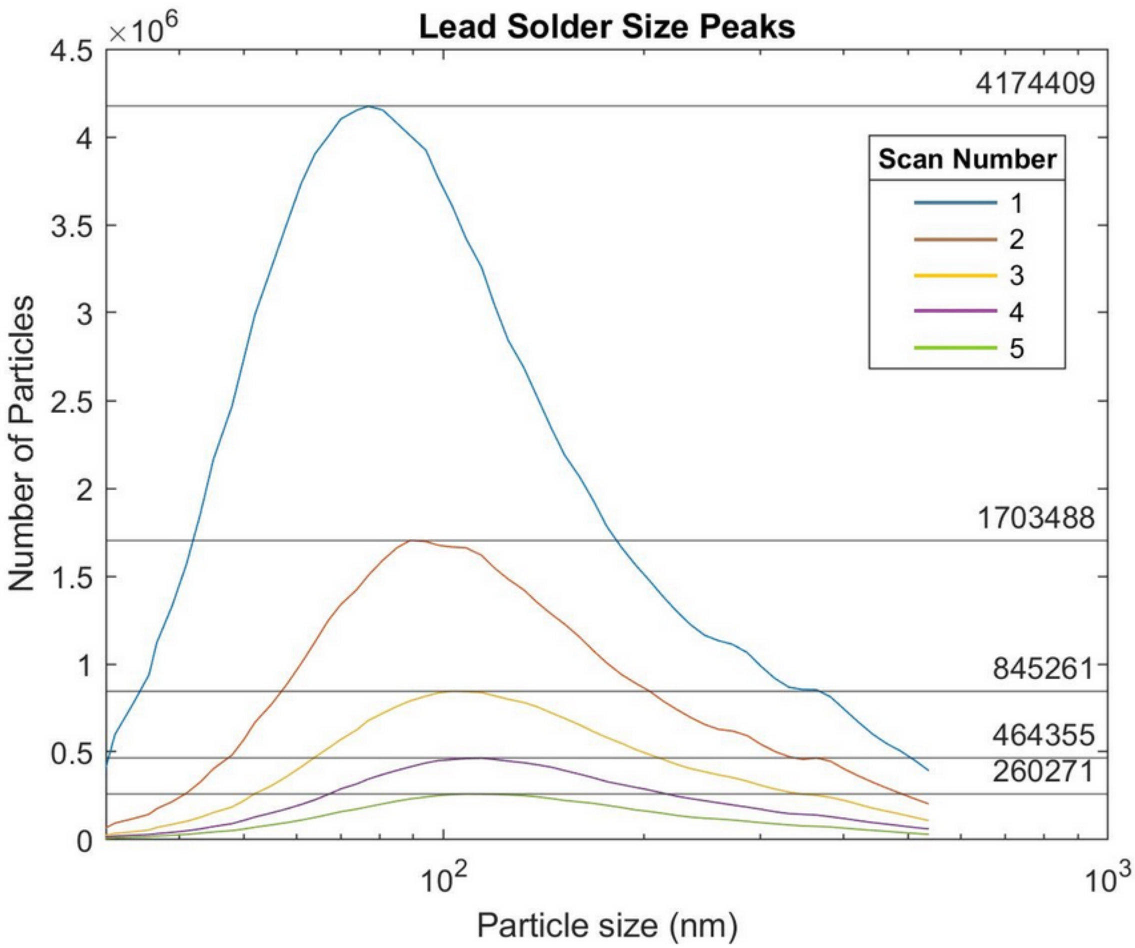
As previously established, the dilution at the peak point is negligible in calculations due to the lack of time there is for dilution to occur. To find the number of particles generated in a box measurement process, the peak number can be converted into the number of particles produced in the box as a whole by multiplying it by the internal capacity of the box in cubic centimeters. To do this, the listed peak number is multiplied by 28316.8 (the number of cubic centimeters in a cubic foot) to yield the total number of particles produced in the 1ft^3 box. This result number is then divided by the mass of solder melted in grams to find the number of particles generated by melting 1 gram of solder.

This was done for all of the relevant CPC tests run on both solder samples, and the results for Tin-Silver were, on average, 9.03E+10 (90,276,386,740.69) particles per gram of solder melted, with an average standard deviation of 9.68%. The Tin-Lead samples taken - excluding the initial tests with excessive (well beyond countable by the CPC) particle numbers - yielded 1.03E+11 (103,443,633,101.87) particles generated per gram of solder melted, with an average standard deviation of 5.6%. Comparing these two particle totals, Tin-Silver comes out closer to the results of Tin-Lead than previously anticipated, being only 12.73% lower in count. To gain a better understanding of this, the size composition of the fumes would have to be investigated.

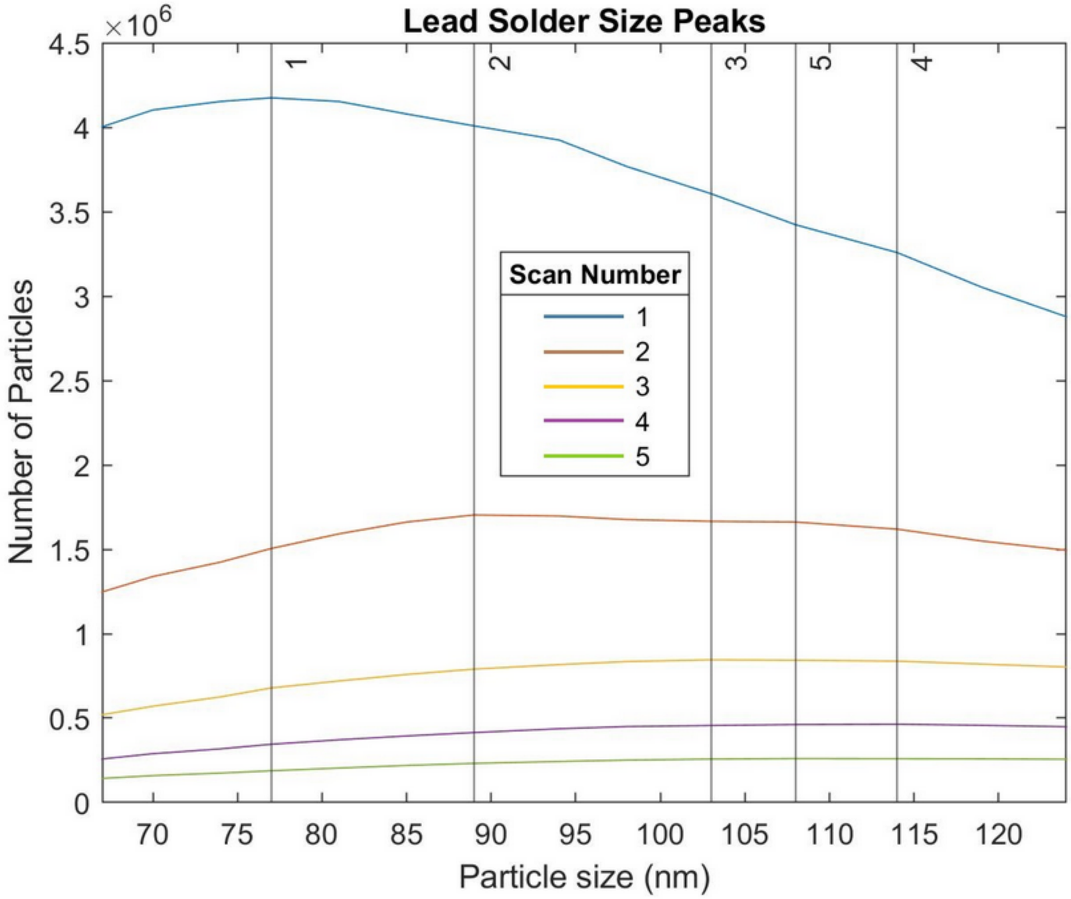
The SMPS

The Scanning Mobility Particle Sizer (SMPS), which scans for both particle size and number to create an accurate model of the size distribution of particles, was the next step in researching the solder particles. While particles are counted, it is not the device's primary purpose. Getting the size distribution of the fumes would allow for a better understanding of the proportions of particle sizes produced, and a better idea of the comparability of the size profiles might give some insight into the possibility of hazard. While dissimilarity would not necessarily rule out hazard and under certain conditions might be grounds for concern, some form of similarity would certainly be grounds for concern. These results are shown in scans, which are subsequent runs on the particles in the box and thus have declining numbers. This helps to provide an understanding of which sizes of fume particles tend to linger longest in the environment.

Starting with the Tin-Lead readings (Figure 8), the results indicate that the largest number of particles are smaller than 10^2 (100) nanometers. The peak indicates that these are around 77 nanometers in size. However, after successive scans, the peak shifts beyond the 10^2 line (Figure 8) and has the fourth scan (which shall be considered the 'last' for comparative purposes with Tin-Silver) at 114 nanometers. This indicates that the larger particles produced by Tin-Lead linger longer than the smaller ones.

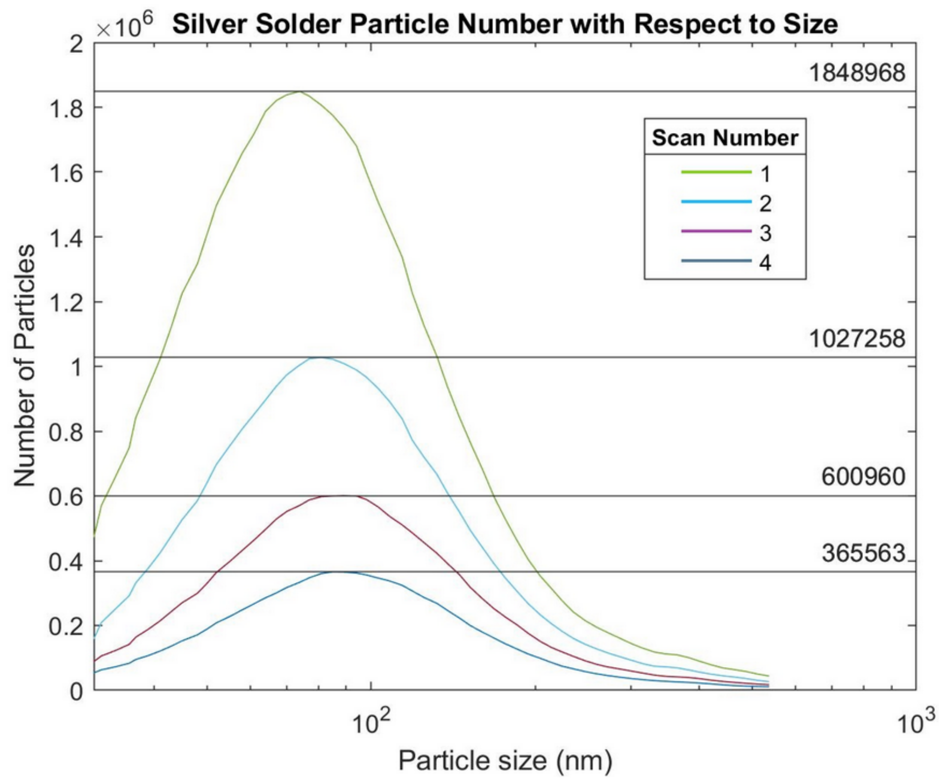


(Figure 8): 60-40 Tin-Lead SMPS Measurements and Peaks

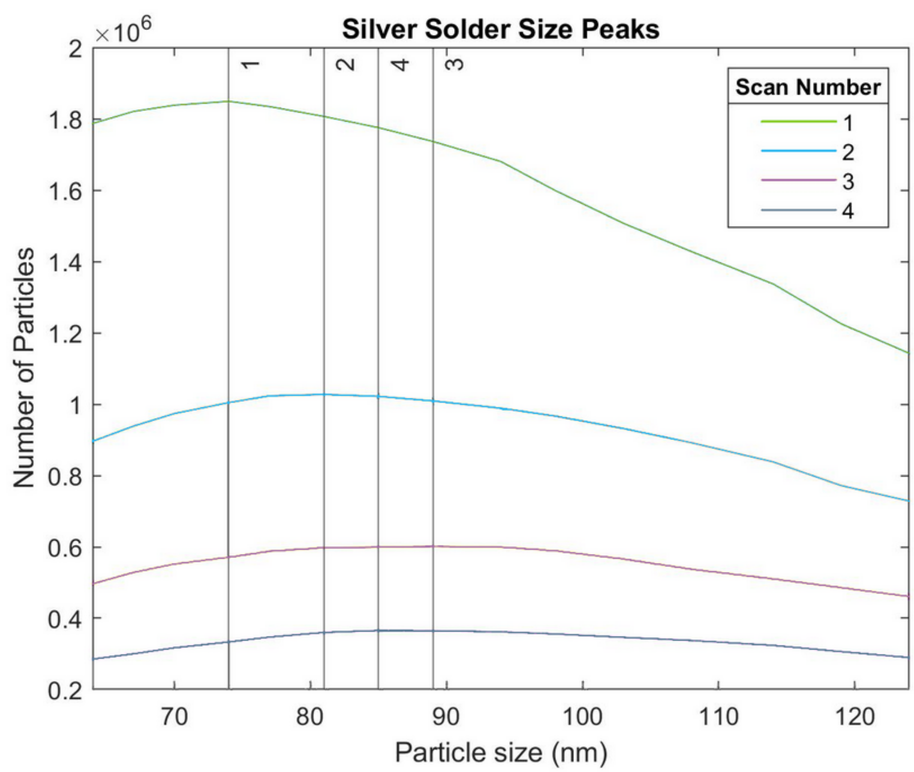


(Figure 9): Closer look at the 60-40 Tin-Lead SMPS peaks

The Tin-Silver tests have readings which appear to be outwardly similar (Figure 10). The initial scan shows the grand majority of particles produced are below 10^2 nanometers. The first peak for Tin-Silver being at 74 nanometers (Figure 11), quite close to Tin-Lead's 77 nanometer initial peak. Perhaps most notable about this is the fact that none of the peaks, even in successive runs, exceed 90 nanometers (Figure 11), let alone 10^2 nanometers. The final peak is at 85 nanometers, in stark contrast with Tin-Lead's final peak (4th Scan) of 114 nanometers. This means that the Tin-Silver large particles linger at a similar rate to their smaller particles, more evenly than those of Tin-Lead.



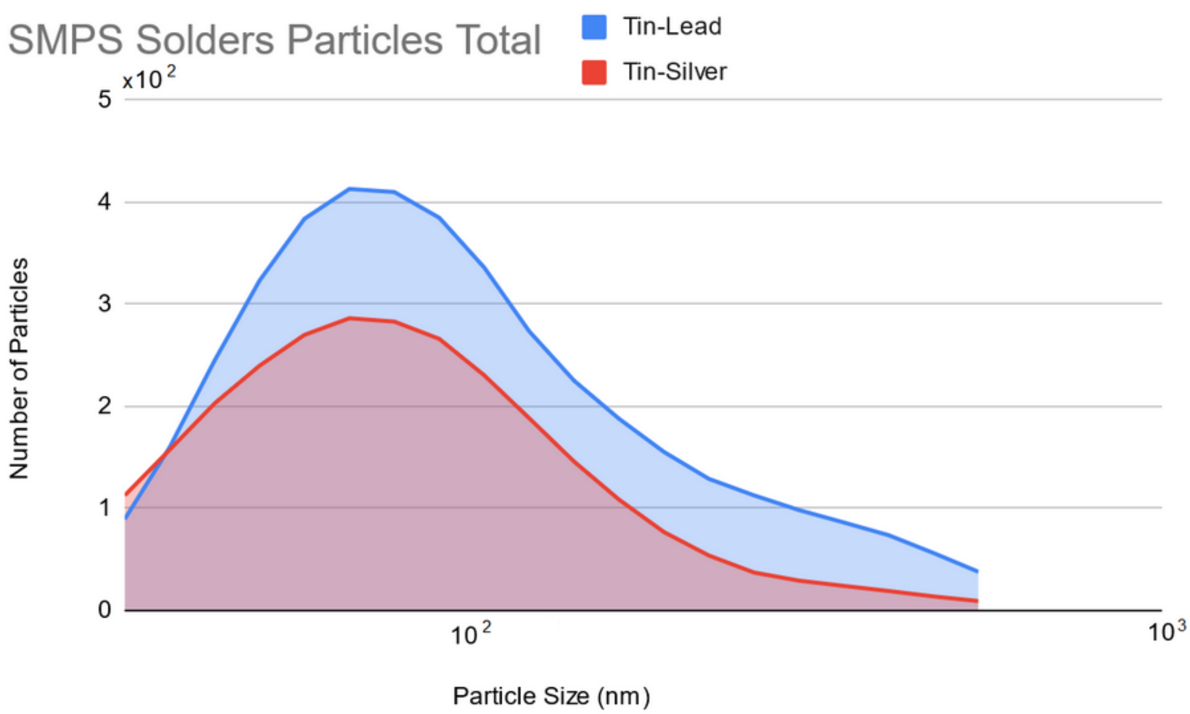
(Figure 10): 96-4 Tin-Silver SMPS Measurements and Peaks



(Figure 11): Closer look at the 96-4 Tin-Silver SMPS peaks

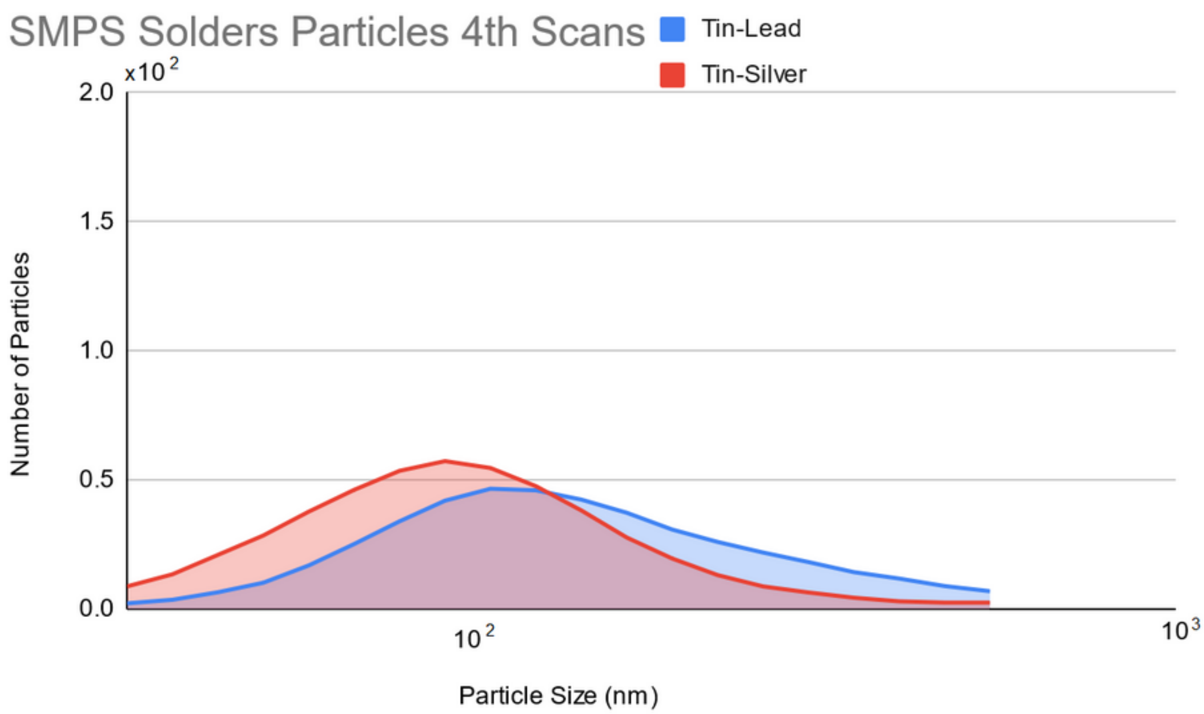
SMPS Results Aggregated and Compared

The results from the SMPS tests' first scans indicate, like in the CPC tests, that more particles are initially produced. However, the SPMS is not primarily a particle counter, and as can be seen on the totals table, which focuses on the maximums from the 1st scans (Figure 12), the Tin-Silver curve starts at a higher point than the lead with a lesser slope, indicating that what makes the difference between the two figures so large - a 45% difference - is particles smaller than could be detected. This in consideration, the important component of the comparative is to show the initial closeness of the majority of particle sizes, as well as the initial similarity in curve profile. While there are less particles, there is proportionality aside from the possible smaller particles from Tin-Silver to the left.



(Figure 12): Comparative graph of 96-4 Tin-Silver and 60-40 Tin-Lead SMPS Measurements

The 4th scan runs (considered the ‘final’ counted runs), in their comparison, show a much different picture (Figure 13). The Tin-Silver peak filtered out more slowly, to the point that the 4th scan Tin-Lead peak shrunk faster. However, the Tin-Lead particles which did linger tended to be larger, as was the conclusion drawn earlier, though now more clearly illustrated.



(Figure 13): Comparative Graph of Tin-Silver and Tin-Lead SMPS 4th Scan Measurements

<u>Conclusions</u>

Given the disparity of particle counts between Tin-Silver and Tin-Lead, as well as the differing size distributions, it may be tempting to say that silver is the de-facto safe option. However, the amount of exposure for different materials to constitute a hazard for human inhalation varies by the material. To refer back to the lead-free alternative materials, copper fumes could be inhaled at amounts greater than general use would normally make and still not pose a long term health threat, meanwhile cadmium fumes can prove capable of generating life threatening effects after one short exposure (and some time lingering in the body). That being said, there are still a considerable number of particles being produced in the soldering processes using Tin-Silver, and while a smaller proportion of them are as large as those produced by Tin-Lead, there are still large particles being produced. This alone is grounds for further investigation. This line of research would naturally lead to exposure testing in designed experiments on live animal subjects or population studies of existing solderers using Tin-Silver solders. Once an established level of hazard is established - and if there is indeed a hazard - a SIFT-MS (Selected Ion Flow Tube and Mass Spectrometer) test would be useful in determining volatility of the fume particles and thus in finding out the amount of ventilation needed in a workspace to reduce the exposure the solder will experience to safer levels.

Another avenue of research would be the composition of the fumes to determine if it is really one source of hazard. One point which had not been considered until the end of research, in a meeting with Dr. Cocker and the graduate students who oversaw, guided and helped design the experiments, when it was asked: what is the boiling point of all these solder materials? While the melting point is clearly met, as evidenced by numerous past uses by others and the observed uses from testing, the boiling point - at which a material vaporizes (other than by evaporation) - was clearly not reached. Tin boils at 4,716°F, lead boils at 3,180°F, and silver boils at 3,924°F, all well above the 600ºF-840ºF range soldering operates at. The question posed in the meeting was this: If the boiling point is so far away, then how was such a small amount of melted material producing so many particles? While it is feasible that *some* of the material was vaporizing as a result of a lowered boiling point caused by the solder alloy composition, we could not be sure it was not a flux acting as a loose variable. Upon checking, both solders contained flux. The next step in pursuing an answer to this would be to use an APM (Aerosol Particle Mass) density analyzer, which could differentiate the different components of the fumes. By doing this, it would likely be possible to determine if the particles were metallic, synthetic or organic in origin.

Another point to consider is the composition of solder flux. Flux acts to prevent and remove oxidation during soldering, keeping solder points strong as well as removing impurities from the surfaces being connected. Many solders now come with the flux integrated into the solder, however, in many cases the type of flux is not disclosed. What is particularly concerning about this - aside from how this makes testing more difficult - is that fluxes with colophony can cause dermatitis and respiratory issues (Arab et al. 66). Colophony, also called rosin, is condensed and processed resin, often taken from plants (primarily conifers) though sometimes made synthetically, from chlorinated paraffins or various hydrocarbon combinations. The different compositions can each have their own health hazards, some even containing zinc chloride and ammonium chloride, which have been shown to cause occupational asthma when inhaled as a fume (Conteras and Chan-Yeung 838). Research already exists on the hazards of many different flux materials, yet despite the known hazard, the labeling on many solders only discloses as much as there being the presence of flux, and sometimes the amount relative to the rest of the solder mixture. Large scale testing from different sources, especially the most commonly used sources, to determine the composition of the flux and thus its safety.

With these options in consideration, the findings of the research were successful in finding meaningful grounds to doubt the safety of Tin-Silver solder, as well as grounds to investigate possible sources of hazard within the material.

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