Arc Beads from Fires: Can 'Cause' Beads Be Distinguished from 'Victim' Beads by Physical or Chemical Testing?

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ABSTRACT: A wide variety of physical or chemical testing methods have been proposed for differentiating between an electric arc bead that caused a fire, versus one that was caused by the fire itself. The methods all implicitly assume that there *is* some categorical difference between these two types of arc beads. A consideration of the room fire process leads to the conclusion that the thermal or chemical histories in these two cases cannot be claimed to be categorically different. Furthermore, most of the proposed methods only entail subjective, qualitative criteria for distinguishing between beads that did or did not start a fire. Finally, all of the methods have been based on studies where only a small number of specimens were tested; none of the methods have been successfully reproduced in laboratories other than the proponent's, while several have been shown explicitly not to be reproducible. Thus, despite the help to fire investigations that would be possible if a reliable method could be produced, it must be concluded that none of the proposed methods are promising.
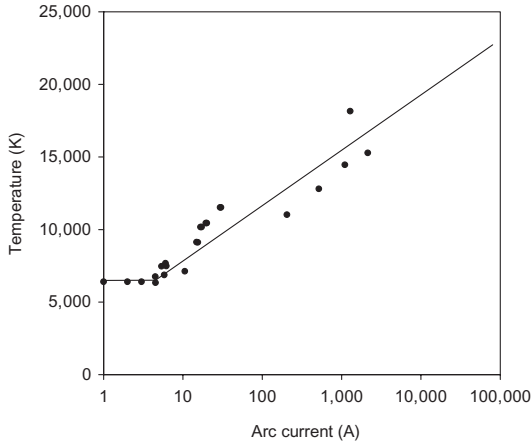
KEY WORDS: arc beads, Auger electron spectroscopy, electric arcs, fire investigation, forensic science, microscopy, Raman spectroscopy.

BACKGROUND

A N ELECTRIC ARC between two current-carrying conductors produces some extremely high temperatures. Figure 1 shows that arcs exhibit temperatures of at least 6000 K, with substantially higher temperatures being found as the arc current increases [1]. If an arc occurs and suitably ignitable fuels are present, a fire may ensue. Since the temperature of an

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Figure 1. *Temperature of an electric arc, as a function of the arc current (points: experimental data [47–49]; solid line: correlation).*

electric arc is greatly in excess of the melting temperature of copper (1085°C) or aluminum (660°C), portions of the conductor may melt in such an event. Upon cooling, the molten material often assumes a roughly-spherical shape (Figures 2, 3) and consequently this resolidified zone is termed an 'arc bead.' The shape, however, does not necessarily have to be spherical (Figure 4). In the investigation of fires, arc beads are frequently encountered because electricity is available in most buildings undergoing a fire and if a fire is sizable, it is likely to burn wiring to the extent that short circuits occur. A single fire may generate a large number of arc beads in this manner, and such beads can be called 'victim' beads. Conversely, if a fire originated because an electric fault produced arcing, the beads from such an event can be called 'cause' beads because they actually correspond to the cause of the fire. It must be pointed out that the definition of a short circuit is [2]: "An abnormal connection (including an arc) of relatively low impedance, whether made accidentally or intentionally, between two points of different potential." Thus, the term in general would include arc tracking without direct metallic contact; however, in the present paper "short-circuiting" is used exclusively to refer to events where metal-to-metal contact is made and, consequently, an arc bead can be created.
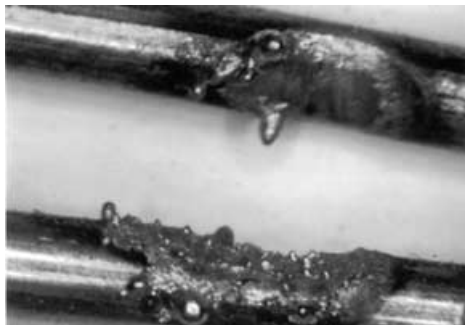
The crystal structure of copper changes with heating. Unless heated to beyond about 300°C, copper wire shows fine longitudinal striations caused by the wire-drawing process [3]. When heated to higher temperatures, fine-grain recrystallization appears, followed by the formation of some large-grain structures as temperatures over about 800°C are attained. Arc beads can be distinguished from fire-melted material by visual or

Figure 2. *Bead created by experimental arcing – cross-section view (Courtesy Yasuaki Hagimoto).*

Figure 3. *'Victim' bead from a real fire (Courtesy Yasuaki Hagimoto).*

Figure 4. *Arc beads with an irregular shape (obtained in laboratory testing by making direct contact between uninsulated conductors carrying 240 VAC) (Courtesy David Reiter).*

microscopic examination. Fire-melted marks are sometimes called 'globules,' as distinguished from 'beads.' Visually, arc beads generally possess a sharp demarcation between a roughly-spherical bead and the cylindrical portion of the wire, while fire-melted wires (Figure 5) do not show a sharp transition between molten/resolidified and virgin material [4]. Shaw [5] proposed that, when examined under a microscope, arc beads

Figure 5. *Examples of melted copper wire beads caused by exposure to fire without arcing (Courtesy Yasuaki Hagimoto).*

exhibit a much finer, smoother grain structure than do the wires melting due to heating from fire alone. But he was rebutted by Levinson [6], who pointed out that copper melted in the presence of oxygen shows a pattern of pure copper grains interspersed with oxygen-containing material, irrespective of what was the cause of the melting. Singh [7] proposed that, if arcing was involved, there will be a pronounced CuO or Cu_2O grain structure near the end, progressively diminishing away from the end. On the other hand, if the wire was simply fire-exposed without arcing, there will be diverse grain patterns along the length, without a systematic gradient. Takaki [3] conducted more detailed experiments and concluded that arc beads commonly show three regions: (1) a surface layer containing numerous voids, (2) an intermediate layer that did not melt, but did recrystallize, and (3) a deep layer where the material neither melted nor recrystallized (Figure 6). By contrast, fire-melted beads tend to be uniformly recrystallized. Ettling [8] cautioned that no simple rule is likely to cover all cases, but also described a number of other qualitative differences that can help distinguish arcing from simple melting.

   This paper will focus solely on arc beads in copper conductors used in branch-circuit wiring. Arc beads in aluminum wiring commonly do not survive the temperatures of a room fire, while there has been no significant

Figure 6. *Arc bead showing the three metallographic zones (surface, intermediate, deep layers) (Courtesy Akira Takaki).*

research on arc beads in large-diameter wires, such as used in the building service entrance. Wires that are tinned or solder-coated [6] behave differently from solid-copper wires and will also not be considered.

PROPOSED METHODS OF DISTINGUISHING 'CAUSE' FROM 'VICTIM' BEADS

If the melt feature on a conductor is due to arcing and not simply due to melting in a fire, investigators and forensic scientists have explored the notion that the two types of arc beads—'cause' and 'victim' beads—might be distinguished after the fire by some means of physical or chemical testing. If a particular bead could be demonstrated to have been the residue of an arc that caused the fire, this might enable the cause of a fire to be pinpointed which would otherwise be undetermined. Simple visual observation is not sufficient for this purpose, since two Japanese studies [9,10] showed that the following features do not discriminate between 'cause' and 'victim' beads, even when the former were not subjected to the ensuing fire:

- glossiness of the bead
- color of the bead
- shape of the bead
- surface smoothness or roughness
- size of the bead (although the very smallest beads of less than 1 mm tended to be 'cause' beads, while the largest ones of over 3 mm tended to be 'victim' beads).

Consequently, a number of instrumental analysis techniques have been proposed, and these fall into three categories:

 (i) microscopy
 (ii) Raman spectroscopy and X-ray microanalysis
(iii) Auger electron spectroscopy (AES) and secondary ion mass spectrometry (SIMS).

In addition, testing for metal hardness was explored by Takaki [3], but he definitively demonstrated that all copper wires exposed to temperatures over about 250°C showed greatly reduced hardness and this was independent of any details of arcing.

MICROSCOPY METHODS

The simplest proposed methods claim that examination of a bead under a microscope (after preliminary preparation which may include cleaning or etching surfaces, and other techniques for preparing cross-sections) will suffice to make the distinction. The methods that have been suggested for differentiation are:

(1) 'cause' beads have square or rectangular pock marks, while 'victim' beads lack these structures;
(2) 'victim' beads show small surface-deposited particles, while 'cause' beads do not have these;
(3) 'cause' beads have small voids, while 'victim' beads have large ones;
(4) the number of voids or their total cross-sectional area is different in 'cause' beads than in 'victim' beads;
(5) 'cause' beads have a small dendrite-arm spacing, while 'victim' beads have a large spacing;
(6) based on examining long segments of wire and not just beads, if long segments are uniformly recrystallized, the wire suffered gross electrical overheating; this does not directly establish cause/victim status, but may be of help in assessing the sequence of events that transpired.

Method #1 was proposed by Gray et al. [11] in 1983. They presented results from one accidental fire and conducted some (but evidently only a few) experiments in the laboratory on flexible, PVC-insulated cords by passing excessive current through the cord until it shorted out and ignited (producing 'cause' beads) and by heating a cord carrying normal current in a fire until ignition (producing 'victim' beads). They then examined slices cut through the beads under a scanning electron microscope (SEM) and, on the basis of observed features, proposed that 'cause' beads show numerous square or rectangular pock marks, while 'victim' beads show few or none. It was not clear whether the pock marks observed represented impurity inclusions or merely regions of crystallization. No other investigators have reported finding these features, so presumably they were due to some rare combination of circumstances, rather than being a normal characteristic of 'cause' beads.

Method #2 was explored by Erlandsson and Strand [12]. In one set of experiments, they created shorts between copper conductors, then exposed

the wires to a fire fueled by wood and PVC, the latter intended to simulate burning wire insulation. In another set of experiments, they created the short circuit within the fire environment. The 'victim' beads, when examined with SEM, showed a nearly uniform dispersion of small particles of about 2 μm size on the surface of the beads. Supplementary studies showed that particles of this type could also be created when arcing took place in an atmosphere containing pure HCl vapors, generated by evaporating liquid HCl and not by burning PVC. Small surface particles, by contrast, were absent in beads created by arcing of *bare* conductors prior to exposure to a wood/PVC fueled fire. Unfortunately, the latter test condition does not correspond to creation of 'cause' beads. When the authors created true 'cause' beads by shorting together *insulated* wires (by scraping away only small bits of insulation), they found that the bead surfaces contained small particles indistinguishable from those on the 'victim' beads.

A number of investigators explored voids in the bead as an indicator. Erlandsson and Strand [12] studied the cross-sections of beads created in several different ways. They found that in an air atmosphere, arc beads showed copious voids but beads formed by melting the copper by an overcurrent were without voids. In a reducing atmosphere (within a gas flame), they found that a smaller number, but larger, voids were present, irrespective of whether the bead was created by arcing or simple melting. They also noted that an 'oxide wedge' could be found between the melted and the unmelted material when tests were run in air, but not in a reducing atmosphere. Tokyo Fire Department [13] conducted experiments which showed that, contrary to the findings of Erlandsson and Strand, voids can be created when copper beads are formed in an air atmosphere by an overcurrent melting process. They made beads by fusing wires with overcurrent in air and in atmospheres of N_2 and CO_2. The experiments were conducted in a tube furnace and the ambient temperature was also controlled. Voids were almost always present when beads were formed in air at 1000°C, but almost never when in N_2 or CO_2 at the same temperature.

Method #3 was briefly explored by the Tokyo Fire Department [13]. On the basis of limited testing, they noted that voids in 'cause' beads are smaller than in 'victim' beads. They concluded that the voids in 'cause' beads are also more likely to be near the surface, while those in 'victim' beads deeper inside. They consider that the reason is because 'cause' beads tend to solidify more rapidly and oxygen has a lesser possibility of diffusing further inside while 'victim' beads solidify more slowly and voids near the surface tend to migrate inwards and aggregate into larger voids inside, where the temperature is still high. Their testing was not extensive enough to draw statistical conclusions.
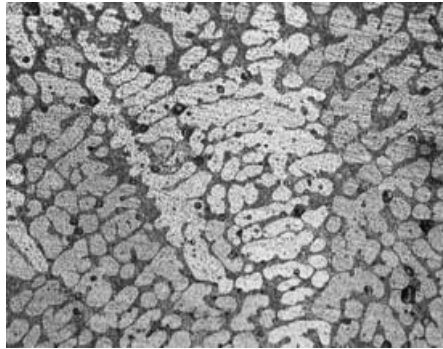
Method #4 was investigated by Ishibashi and Kishida [10], who examined 15 beads from fires where it was known whether the bead was the cause or the victim. They concluded that presence of voids is generally more plentiful in 'cause' beads than in 'victim' beads. Presumably this is because 'cause' beads are more likely to be formed in an oxidizing atmosphere and 'victim' beads in a reducing atmosphere, but differences did not support a firm distinction between the two types of beads. Mitsuhashi [14] created 'cause' beads by making current-limited shorts with a stranded-conductor cord and then placing the beads obtained in an oven heated to 400–1000°C. The 'victim' beads were created by first exposing bare conductors to the oven-heating treatment, then covering them with PVC insulation and producing a current-limited short. Mitsuhashi counted microvoids (0.5–1.0 μm) for each bead in three small areas near the center and found about double the number of voids in 'victim' beads than in 'cause' beads. But he also counted voids in 'cause' beads that were not exposed to any further heating after creation of the bead. In that case, the number of voids was roughly similar to the 'victim' beads. For forensic purposes, the method did not seem promising since, while the average number of voids was different for 'cause' versus 'victim' beads, the distributions were overlapping and a particular concentration of voids could be encountered for either case. Method #4 was also explored by Oba [15] who created 'cause' and 'victim' beads in the laboratory and, in each case, subjected them to various oven-heating regimes afterwards. Typically, 30–45% of the cross-section area comprised voids and this depended on the temperature of heating that was used after formation of the arc bead, but the distributions overlapped greatly and he concluded that void-area percent cannot be used as a tool for discrimination.

Both Methods #3 and #4 were studied by Miyoshi [16,17], who counted large voids and found that they were much more plentiful in 'victim' beads than in 'cause' beads. In his study, the 'victim' beads were created by burning a power cord in a burner flame until shorting occurred. But the 'cause' beads were created by shorting a wire together which was not subsequently placed in a fire; thus, his protocol did not attempt to simulate room-fire effects. Under these conditions, the maximum diameter of the voids in the 'victim' beads was typically 2–3 times larger than in the 'cause' beads. Similarly, the fraction of the total void area occupied by voids of 132 μm or larger diameter was 14% in the 'cause' beads and 72% in the 'victim' beads. Again, however, the actual distributions showed overlap and a particular void distribution could show up in either a 'cause' or a 'victim' bead, albeit with a higher probability in the one than in the other.

Seki et al. [9] focused on the presence of a dendritic crystal structure (Figure 7) in arc beads. They showed that the general presence or absence of

dendrites in an arc bead cannot be used as a means of identification (Table 1), since it simply reflects the oxygen concentration in the bead. Near-zero O_2 concentration leads to no crystals, as does the eutectic concentration of 0.39 mass%. O_2 concentrations smaller than this produce primary crystals of Cu, while larger concentrations produce primary crystals of Cu_2O. But Seki et al. together with Lee et al. [18], proposed method #5, observing that, if a dendritic crystal structure is created, the spacing between the dendrite arms reflects the ambient temperature at which the bead solidified. In their view, a 'cause' bead will solidify at a near-ambient temperature ($< 400°C$) and therefore have a small dendrite-arm spacing while a 'victim' bead will solidify at a fire-gas temperature ($> 400°C$) and show a large spacing (unless it remelts in the fire). On the other hand, the rate of cooling and the temperature of the environment prior to the formation of the bead were found not to affect the spacing. In support of their thesis, the authors produced experimental curves showing the spacing as a function of ambient temperature at solidification and of oxygen concentration, separately for Cu and Cu_2O dendrites. Based on their photographs, however, assigning a characteristic dendrite arm spacing to a particular bead appears to be a highly subjective determination. The authors performed extensive testing, but the description of their results does not

Figure 7. *A copper wire bead showing a dendritic crystal structure (Courtesy Yasuaki Hagimoto).*

Table 1. Dendritic crystal structure observed by Seki et al. in test arc beads.

Bead	No Dendritic Crystals (%)	Dendritic Cu Crystals (%)	Dendritic Cu₂O Crystals (%)
Cause	57	38	5
Victim	92	8	0

make it clear if categorical classification of results as 'cause' or 'victim' was successful. In any case, the tests were primarily exposures in a small electric furnace and creating 'cause' beads which would then be subjected to a room fire was not undertaken. The method cannot be applied at all if the bead does not exhibit dendritic crystal structures and, as shown in Table 1, most beads do not. The rarity of dendritic structures was recently confirmed by Lewis [19]. Of 29 'victim' beads created in the laboratory, only 3 showed a dendritic structure; of 10 'cause' beads, only 1 did. Furthermore, even the beads that contained dendritic structures exhibited them only over a very small area of the bead, typically about 5%.

Method #6 was proposed by Levinson [6], who noted that if a substantial length of wire exhibits uniform recrystallization, this is most likely due to electrical overcurrent, rather than thermal heating from a fire, since the latter would be unlikely to heat a wire uniformly. Levinson carefully avoided claiming this distinction can be used as a proof of the origin of a fire, however, since the fire itself may have created conditions leading to an overcurrent.

RAMAN SPECTROSCOPY AND X-RAY MICROANALYSIS METHODS

On the basis of a very small number of tests, Tokyo Fire Department [13] noted that carbonaceous material is likely to be found inside 'victim' beads, but not inside 'cause' beads. Masui [20] used X-ray microanalysis to examine for the presence of carbon in arc beads that he created by (a) causing a series-arc[1] failure in a cord; or (b) by first charring the wire insulation with a burner flame, then causing a series-arc. His results were only exploratory, but they did show a negligible amount of carbon in the first type of bead, which would correspond to a 'cause' bead. The analysis showed the second bead to have nearly as high a local concentration of carbon as a pure carbon control sample. The second bead type, however, only partially represents a 'victim' bead in that insulation was charred prior to arcing, but the bead was not subsequently exposed to a fire.

Lee et al. [21,22] carried this idea further by examining the constitution of carbonaceous inclusions. They did not collect any data on what fraction of beads contains carbonaceous inclusions, but rather studied beads that did have these inclusions with Raman spectroscopy to distinguish between amorphous and graphitic carbon. This can be done on the basis of Raman spectra since amorphous carbon shows a broad peak at 1350–$1360\,cm^{-1}$,
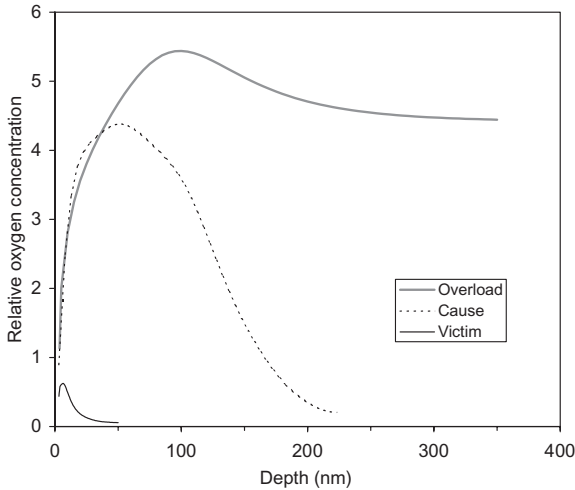
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[1]A series arc involving a pair of conductors is an arc which is in series with the load; it is distinguished from a parallel arc, which takes place in parallel to the load.

while graphitic carbon has a sharp peak at $1580 \, cm^{-1}$. The authors created 'cause' and 'victim' beads in the laboratory and found that 100% of the 'cause' beads always contained amorphous carbon but 27% of 60 samples also contained graphitic carbon. In all of 20 'victim' beads tested, amorphous carbon was detected; in none of them was graphitic carbon detected. The authors then examined 8 beads from actual fires where the status of the bead was established by other means. They were able to find graphitic carbon in 3 of the 5 'cause' beads. The authors hypothesized that the effect occurs because PVC is bodily conveyed into the interior of an arc bead. In their view, graphitic carbon is created inside the bead only if the sequence of creating the 'cause' bead is such that PVC insulation is slowly charred due to an electrical fault before final failure leading to arcing occurs. In a 'victim' bead or in a 'cause' bead where the fault rapidly leads to ignition, time required to form graphitic carbon is not available. 'Cause' beads of the latter type will occur when a large, rapid overcurrent melts the insulation and quickly creates a short circuit. It is not clear how the authors envision that carbon migrates into the copper, since they state that temperatures are only 110–250°C when PVC is being charred. In any case, the method has a rather low probability of identifying a 'cause' bead of only 27–60%.

AES, SIMS, AND ESCA METHODS

A number of techniques exist that allow the concentrations of certain elements in a metallic sample to be determined. These include Auger electron spectroscopy (AES), electron spectroscopy for chemical analysis (ESCA), and secondary ion mass spectrometry (SIMS). With any of these, a depth versus concentration profile can be made by progressively etching away portions of the surface and examining a lower layer. Erlandsson and Strand used AES in connection with their experiments discussed above to quantify the chlorine present in the surface particles attached to the bead, but, as mentioned above, the presence of chlorine was found not to be uniquely associated with 'victim' beads and was equally-well found in 'cause' beads, if the 'cause' arcs were created by shorting together insulated, rather than bare, wires.

In 1980, MacCleary and Thaman postulated [23,24] that an arc bead formed without a pre-existing fire ('cause' bead) would be formed in an oxidizing atmosphere, while one that occurred after a fire was already ongoing ('victim' bead) would be formed in a reducing atmosphere. Consequently, they believed that profiles of the oxygen concentration, as a function of depth below the surface of the bead, would enable identification to be made (Figure 8). Their patent [24] envisions that AES, ESCA, or SIMS can be used for this purpose, but their own work used only AES. Because of

Figure 8. *Oxygen concentration profiles shown in the patent by MacCleary and Thaman.*

the limited sensitivity of their technique, they took the derivative of the signal data as the analysis variable and only sought relative magnitudes, not an absolute calibration of oxygen concentration. Figure 8 shows three samples they analyzed. The 'cause' bead was created by short-circuiting two conductors after preheating them for 15 s. The 'victim' bead was created by a small fire which short-circuited an NM cable. The 'overload' bead was created by producing a current-limited overload which heated the cable for some time (unspecified) before the conductor fused and arced. The authors also showed results from four beads taken from real fires where the fire cause was known. Their proposed scheme for identifying beads was to discard the first 5 nm of the surface (since it would likely reflect ambient oxidation of the copper) and to evaluate the remaining portion:

- if the concentration is generally low, the peak is found at 20 nm or less inside the surface, and concentrations beyond the peak become quite small, then this is a 'victim' bead;
- if the concentration is generally high, the peak is found at a depth of 20–200 nm, and the concentration decays slowly at greater depths, then this is a 'cause' bead;
- if the concentration is very high, and oxygen is detected to 2000–4000 nm, then this is a 'cause' bead where arcing was preceded by prolonged overheat.
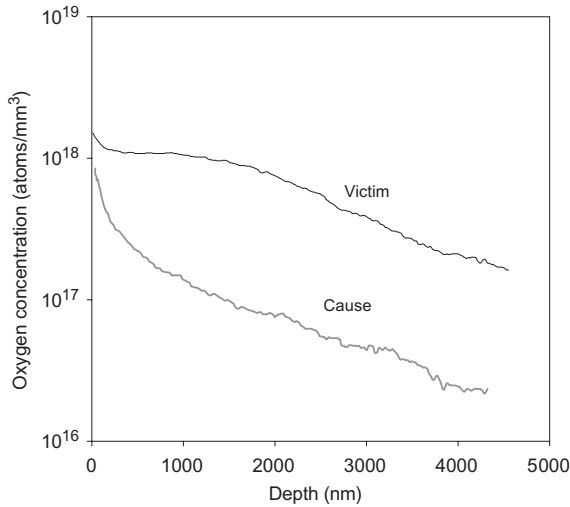
The authors also pointed out that the method cannot be used if a remelt occurred. To detect the latter, they proposed that a bead be cut in half

and an AES scan be made across the diameter. If four, rather than two, peaks are found across the diameter, then a remelt is indicated. Robertsson et al. [25] attempted to validate the MacCleary/Thaman method, but found that the oxygen profiles could not reliably distinguish 'cause' from 'victim' beads.

Satoh et al. [26] used AES and SIMS to obtain O, C, and Cl profiles on four specimens: a 'cause' and a 'victim' bead from actual fires and a 'cause' and a 'victim' bead produced in the laboratory. The 'cause' bead was created by short-circuiting a stranded-conductor cord, then exposing it in a burner flame, while the 'victim' bead was produced by placing the cord into a burner flame until it shorted. Depth profiles were obtained by etching the surface down with a cesium ion beam (for the SIMS) or an argon ion beam (for the AES). They plotted both the AES and the SIMS data in a way as to normalize the remaining elements to Cu, which was taken to have a constant depth profile. From these preliminary plots, they concluded that the primary feature of a 'cause' bead is an oxygen profile that rises to a peak at about 1000 nm beneath the surface, and only then proceeds to fall. By contrast, 'victim' beads showed O, C, and Cl concentrations that were all similarly-shaped decay curves, without any appreciable rising portion. By comparing AES and SIMS results, they observed that AES is much less sensitive and incapable of good resolution deeper than about 1000 nm; thus they concluded that SIMS is the preferred technique. In a later study [27], they used only SIMS to examine 10 beads recovered from fires where the cause/victim identity of the beads was known (Figure 9). The fires however were all small and none had reached the fully-involved room stage. One of the beads was so heavily surface-damaged that it was considered not appropriate for analysis. Of the remaining 9 beads, all were correctly classified by adopting the following rule:

- if the (absolute) oxygen concentration at the 3000 nm depth is $< 10^{17}$ atoms/mm^3, then it is a 'cause' bead;
- if the concentration is $> 10^{17}$ atoms/mm^3, then it is a 'victim' bead.

They cautioned, however, that the results must only be viewed as preliminary. They hypothesized that the distinction arises because the environment temperature is high when a 'victim' bead is formed and this allows a greater amount of oxygen to diffuse into a piece of copper that has been preheated. It must be noted that this is the exact opposite of the MacCleary/Thaman classification, where low—not high—oxygen concentration denote a 'victim' bead, although Satoh et al. analyzed concentrations at much greater depths into the bead, while the MacCleary/Thaman technique had sufficient sensitivity to characterize only a shallower region.
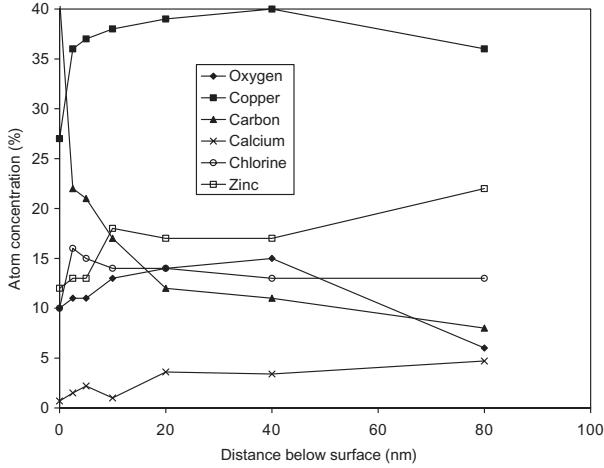
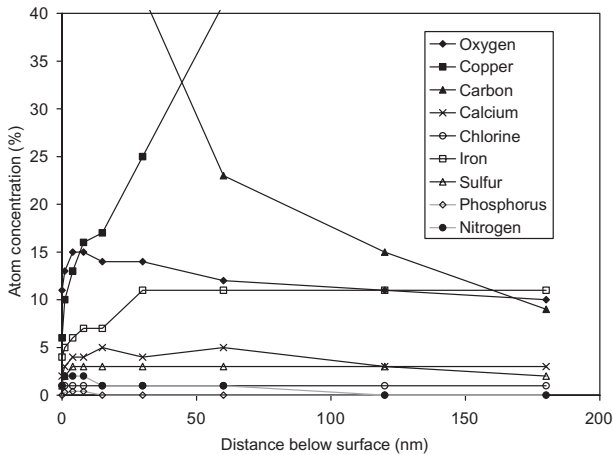**Figure 9.** *Oxygen concentration profiles, as measured by Satoh et al.*

Satoh et al. [28] continued the research with 65 additional samples from real fires and then found that there was only a 39% agreement between their proposed technique and the conclusion from that particular fire investigation.

MacCleary and Thaman did not pursue further the ideas of their patent, but since 1989, a method has been promoted by Anderson [29] that is an extension of the MacCleary/Thaman idea. Anderson noted that ambient air contains significant amounts only of oxygen and nitrogen. If an arc occurs between two wires in ambient air, then only oxygen can dissolve into the bead while the bead is in its molten state (nitrogen does not dissolve into copper). However, if the arc occurs in an atmosphere where there is an ongoing fire, then a number of other atoms will be found in the atmosphere; these will also dissolve in the bead. Apart from oxygen, Anderson used carbon, chlorine, sulfur, calcium, zinc, iron, phosphorus, and chromium atom profiles. He did not propose any quantitative criteria for distinguishing between 'cause' and 'victim' beads, relying instead on a subjective evaluation, with apparently some emphasis placed on the carbon profile. Thus, a sizable concentration of carbon would indicate a 'victim' bead, while a lack thereof would suggest a 'cause' bead. Figure 10 shows a bead presented by Anderson [36] as a 'cause' bead, while Figure 11 shows a 'victim' bead.

The basic notion, however, that nonoxygen atoms will become available for incorporation only into 'victim' beads lacks foundation. In most practical cases, wires are insulated by a polymeric material, typically PVC.

Figure 10. A 'cause' bead, Anderson's case 1 (plots of data originally presented by Anderson in tabular form).

Figure 11. A 'victim' bead, Anderson's case 3 (plots of data originally presented by Anderson in tabular form).

The polymer is in contact with the conductor and may be vaporized regardless of whether the arc bead was the first event of the fire, or if it occurred much later in the fire. Thus, it is not clear why a more copious presence of carbon or chlorine atoms would suggest a 'victim' bead. Similarly calcium carbonate is a common filler for plastics used in electrical wiring, so calcium may also be anticipated from either destruction

of wire insulation as part of the initial arcing or from events much later in the fire.

One of the pivotal assumptions of the MacCleary/Thaman/Anderson theory is that the elemental profiles are frozen into the bead once the bead has cooled. Consequently, it is considered that once the arcing has stopped, further exposure to the fire atmosphere will not affect distribution of elements to be found within the bead (except possibly at the very surface, which is to be removed and discarded in their testing procedure). The principle is that the solubility of gases is much greater in liquid copper than in solid copper and, thus, the gases will be trapped after the bead solidifies and this distribution will be frozen in place and available for later study. Howitt [30] argued against this, but the basic concept that a substantial amount of oxygen can be dissolved in molten copper is correct [31,32]. Some gases can enter into copper while it is hot but not molten, however. This is the reason that stranded copper wires recovered from fire scenes often crumble to bits in the process of examination—the material has turned into copper oxide and no longer has mechanical strength. Howitt also conducted tests [33], but using energy-dispersive X-ray spectrometry (EDS), instead of AES. He was criticized by a laboratory offering AES services [34] for using a technique that is much less sensitive, but this does not seem germane, since his results showed adequate sensitivity. More problematic is the fact that a depth profile was not established, only a concentration within a relatively thick subsurface layer. Howitt analyzed 13 samples obtained under various combustion and no-combustion conditions and noted that no systematic differences in C or O concentrations could be found that would be attributed to the presence of a pre-arc fire.

The use of Anderson's method for forensic purposes would require a quantitative protocol for analysis, specifically, concerning how the depth profile should be considered. Argon-ion sputtering is used in the Anderson method to remove the outer layer ("environmental cap" in his terminology). In his scheme, the cap comprises all the layers until a region is reached which has at least 60% copper. Consequently, the disregarded environmental cap is stated in his reports as having widely-varying thicknesses: 2.5 nm [38], 5 nm [35], 5–10 nm [36], or 5–20 nm [37]. But once the "environmental cap" has been removed, Anderson relies solely on a qualitative judgment that a 'victim' bead shows a profile where C, Cl, and Ca atoms are abundant to a greater subsurface distance than in a 'cause' bead [38]; he does not appear to have been able to establish any quantitative criteria for making this distinction.

Béland [39] pointed out that there is a significant statistical problem with the method even in a single laboratory: tests conducted on different portions

of the same bead give substantially different results. An AES spectrometer can be operated in a raster-scan mode to characterize surface areas; however, no statistical technique has been demonstrated for obtaining characteristic averages in this way. He also pointed out [40] that Anderson's published work did not include even elementary descriptions of the tests performed, such as the exposure times for the specimens. Anderson claimed [37] that, in a fire litigation case, he was able to correctly distinguish 'cause' from 'victim' beads but Béland [40] argued that this was not done 'blind.'

Ettling [41] examined Anderson's data [29] and found numerous problems and inconsistencies. In his view, the basic problem is that in real fires—as opposed to Anderson's laboratory tests—a bead will most likely remain in a fire environment for an extended time, regardless of whether it is a 'cause' or a 'victim' bead. Thus, laboratory studies where a bead is created and then quickly removed from a fire environment do not present relevant information. Ettling also noted that in Anderson's study, the oxygen content of a bead formed in air was higher than for a bead formed in oxygen. No explanation was given by Anderson in his paper [29] for this (nor did Anderson provide any description in his paper of specimen preparation or exposure procedures). Another questionable result was a bead from a 'victim' arc occurring near a gypsum wallboard which showed high amounts of sulfur. Electric arcs in branch circuit wiring do not normally vaporize gypsum wallboard, and there is negligible calcium sulfate liberated even as hydration water is lost during a postflashover stage of fire. Thus, Ettling concluded that presence of sulfur is likely to indicate contamination to a hot bead, rather than being a useful tool for unraveling the early history of the fire.

Ettling also analyzed Anderson's later paper [36] where he presented AES results on beads recovered from three fires. In one case (Figure 10), the very deepest layer tested, 80 nm, showed zinc to be about 2/3 as plentiful as copper. Ettling points out that, at high temperatures, zinc oxidizes in air so readily that only zinc oxide should be available in the air, and the latter is unlikely to migrate into the bead. Thus, he concluded that this large amount of zinc came from a gross surface contamination of the bead. In another of Anderson's example cases (Figure 11), a power cord bead was examined from a failed electrical cooking pot. For layers below the "environmental cap," copper was the most abundant element, with iron being next. Anderson claims the iron came from the failed element, but this would require that both the cord and the element be arcing at the same time, and that a huge fraction of the iron end up in the bead. Equally problematic is that if the iron came from the heating element, no chromium or nickel (from the resistance wire itself) was recovered.

Henderson et al. [42] attempted a direct validation of Anderson's theory by preparing specimens under two conditions. The 'cause' beads were prepared by shorting together 18 AWG stranded copper wire in air; the 'victim' beads by placing the insulated, energized wire in a fire and waiting until an arc occurred. They found that the carbon profiles overlapped, and that there was no way to unambiguously differentiate between the two sets of results. Béland ran a similar set of experiments [39] and obtained the same conclusion in comparing the chlorine profiles of 'cause' and 'victim' beads.

Reese [43] pointed out that in dwellings, when a fire originates in branch circuit wiring and a bead is found, the event commonly involves arcing-through-char, not a simple metal-to-metal short. The latter would be likely to cause rapid tripping of the circuit breaker and would only rarely start a fire. Thus, while wire beads can be created readily in the laboratory by simply shorting two bare conductors against each other, this type of event is not common in accidental fires. If a fire originates from an electrical fault where charring occurred first, followed by shorting, then the AES test result will presumably be a false negative, since it will be formed in an environment containing reaction products from the charring of wire insulation. Fitz [44] pointed out a more fundamental logical concern with the AES scheme. In addition to arcing-through-char, a short circuit can happen due to radiant heat flux falling onto a thermoplastic cable or cord from an ongoing fire. When the insulation softens sufficiently for the conductors to make contact and produce a short circuit, there will not be any combustion or combustion products in the vicinity of this arc. This effect particularly may occur inside appliances, in engine compartments, or in wall cavities subjected to external heating. Thus, a positive AES result ("this bead was the cause of the fire") will be reported, despite the fact that the bead was the victim and not the cause.

For a laboratory technique that has been offered for forensic purposes, it is also a serious concern that the basic details of the phenomenon being utilized have not been studied scientifically. The elements identified in an AES spectrum must originally start out as atoms or molecules somewhere else. Through processes of transport and reaction, they end up embedded in the bead, but the chemical history that takes them there has not even been conjectured. Likewise, after they have entered the bead, no theory has been offered to provide a quantitative understanding of the depth profiles and of the lateral concentration variations in the bead.

Only one published study could be found supportive of Anderson's claims. Metson and Hobbis [45] performed an AES analysis on a single bead removed from the wall cavity of a fire scene, but suggested that reference to Anderson's work suffices to establish validity of results.

DISCUSSION

Most of the proposed methods have been pure empiricisms, without any theoretical basis. Obviously, these could only be validated by a preponderance of empirical data. But some others refer to a theoretical principle, even though an actual quantitative theory has not been offered by any researcher. The relevant principles must necessarily be based on some hypothesis that the chemical or the thermal histories of 'cause' and 'victim' beads form nonoverlapping populations. Concerning chemical histories, there have been only two hypotheses: (1) 'Cause' and 'victim' beads are uniquely associated with oxidizing and reduction atmospheres, respectively. In turn, the oxygen content of the bead will uniquely reflect this. But as Robertsson et al. [25] observed: ''The oxygen content in the surface layer of a melt bead does not only depend on the type of damage but also on the thermal pre- and post-history of the electrical damage.'' In other words, once a bead is created—either a 'cause' or a 'victim' bead—it may remain for a long time in atmospheres that range from oxidizing (good supply of oxygen), to reducing (buried in oxygen-depleted, glowing or smoldering rubble). (2) The atmosphere surrounding a 'victim' bead will contain material that originated from decomposing solids nearby, while that around a 'cause' bead will not. Adequate amounts of this material (carbon, etc.) will then be found in the bead. This hypothesis is refuted, however, when it is considered that 'cause' arcs can and do occur in environments where the insulation already has been substantially degraded. Conversely, a short-circuit can occur during a fire due to molten wire insulation in a protected environment where there are no local combustion products and a minimum of pyrolysis products.

Thermal histories of arc beads can be diverse, but it is hard to envision any aspects that innately separate 'cause' from 'victim' beads. The temperature of an arc itself is vastly higher than the temperature of flames, but this is no help in making a distinction, since both arc temperatures and flame temperatures will have been attained at some time for beads of both types. Any bead can be expected to remain in a fire for a long time after it was formed—or a short time. An extended period of very high conductor temperatures, due to gross overload, may also precede the formation of an arc, irrespective of whether it is a 'cause' or a 'victim' arc. Remelting of an arc bead, of course, is universally agreed to eliminate any chance of deducing its prior history. One research group proposed that 'cause' beads, once formed, are likely to solidify at fairly low temperatures, while 'victim' beads will solidify at high temperatures. This presumes that fire heating will not be rapid, once a 'cause' bead initiates a fire. The hypothesis is questionable and, in any case, has not been experimentally examined apart from the authors' work.

Most of the techniques described in the literature have clearly been identified by their authors as being exploratory, initial investigations and not as finalized, validated methods. The one exception is Anderson's method, which he has claimed is sufficiently developed to be suitable for forensic purposes [29]. But evidence does not support the idea that this method is indeed ready for such usage. The main problems with the method are: (1) apart from the knowledge that oxygen and some other elements can dissolve into molten copper, there has been no chemical or metallurgical study that examines the details of the process and establishes a theoretical basis for concentration distributions to be expected in the solidified bead; (2) no quantitative criteria for distinguishing 'cause' from 'victim' beads have been developed; (3) even if postfire contamination does not occur, subsequent and repeated heating in the fire environment makes interpretation of results uncertain; (4) the method is intrinsically subject to producing false positive and false negative results. False positives would indeed appear to be a problem, judging from Anderson's report [46] that he determined 1/3 of all the arc beads that he examined to be 'cause' beads. In the normal course of events, 'victim' beads should outnumber 'cause' beads by a huge fraction, since many fires cause extensive arcing, while generally there will only be one arc—at most—responsible for starting a fire.

CONCLUSIONS

After a comprehensive examination of the published studies, the author cannot find much promise with any of the methods that have been proposed for distinguishing between 'cause' and 'victim' beads. The reasons are the following:

(1) Many methods have been offered without any supporting theory. But the few theories that have been offered are inconsistent with the knowledge of the variety of behaviors that are found in room fires.
(2) With a few exceptions, all of the methods have been put forth as qualitative and subjective, without means of quantification.
(3) The methods typically have been based on studies using an extremely small number of experiments. In the few studies where sufficient samples were used to enable statistical conclusions to be drawn, the 'cause' and 'victim' bead populations showed sufficient overlap that only trends, not categorical distinctions, could be drawn. In the only study where comparison was made to a fairly large number of real-fire beads of known identity, the results were unacceptable (39% success).
(4) Almost all of the fire exposures in the laboratory-created beads have been very different from real room fires.

(5) None of the methods has been independently validated, although several validation attempts have been made and led to conclusions of irreproducibility.

(6) Most researchers proposing the various methods have suggested them in the spirit of ideas meriting further research, but Anderson has argued [29] that his method is robust enough that it already should be accepted for forensic purposes. However, his method does not appear to be more promising than any of the other methods.

In addition, it is not evident that any method could be developed in the future which is robust and reliable. This could only be possible if chemical or thermal exposure conditions were invariably different during the formation of 'cause' versus 'victim' arc beads. But distinctions of this kind have not yet been discovered.

ACKNOWLEDGMENTS

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