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Proper Assessment of the JFK Assassination Bullet Lead Evidence from Metallurgical and Statistical Perspectives

ABSTRACT: The bullet evidence in the JFK assassination investigation was reexamined from metallurgical and statistical standpoints. The questioned specimens are comprised of soft lead, possibly from full-metal-jacketed Mannlicher-Carcano (MC), 6.5-mm ammunition. During lead refining, contaminant elements are removed to specified levels for a desired alloy or composition. Microsegregation of trace and minor elements during lead casting and processing can account for the experimental variabilities measured in various evidentiary and comparison samples by laboratory analysts. Thus, elevated concentrations of antimony and copper at crystallographic grain boundaries, the widely varying sizes of grains in MC bullet lead, and the 5–60 mg bullet samples analyzed for assassination intelligence effectively resulted in operational sampling error for the analyses. This deficiency was not considered in the original data interpretation and resulted in an invalid conclusion in favor of the single-bullet theory of the assassination. Alternate statistical calculations, based on the historic analytical data, incorporating weighted averaging and propagation of experimental uncertainties also considerably weaken support for the single-bullet theory. In effect, this assessment of the material composition of the lead specimens from the assassination concludes that the extant evidence is consistent with any number between two and five rounds fired in Dealey Plaza during the shooting.

KEYWORDS: forensic science, JFK assassination investigation, bullet lead analysis, forensic materials comparisons, bullet metallurgy, Mannlicher-Carcano bullet grain sizes, weighted statistical analyses

More than 40 years have passed since the 1963 assassination of U.S. President John F. Kennedy in Dallas, TX. Many consider it the most important murder mystery of the 20th century, and many also still regard it as unsolved. An extensive investigation by the Warren Commission soon after the incident concluded that Lee Harvey Oswald acted as a lone gunman, shooting from a sixth-floor window of the Texas School Book Depository on Dealey Plaza (1). However, a number of anomalies and remarkable findings in the Warren Commission Report gave rise to several alternate theories of the assassination, virtually all of which involved a conspiracy by one or more organized groups (2). A wealth of information about this singular case is available, both as government-held primary documentation (3) and as critical assessments of official conclusions (4).

The principal physical evidence in the investigation related to firearms information: ballistics data, specimens of bullet lead, and Oswald's palm print on the suspect rifle. An Italian-made, 6.5-mm Mannlicher-Carcano (MC) bolt-action carbine, with a 4× telescopic sight, was found abandoned in the Depository, along with three spent 6.5-mm-caliber cartridge casings. One unfired round remained in the rifle. The Warren Commission's "lone gunman" conclusion necessitated that the MC rifle be the only source of the gunshot wounds sustained by both President John F. Kennedy (JFK) and Texas Governor John B. Connally (JBC), as well as for all other shots fired in Dealey Plaza that day. Two of the three bullets fired from this gun were concluded to have produced all of the wounds to JFK and JBC (one shot allegedly missed both men). Of the three shots fired, the third shot was apparently the head wound fatal to JFK. Either the first or the second shot supposedly wounded both men, and the bullet that apparently caused those wounds has become a central focus of many conspiracy theorists. This full-metal-jacketed (FMJ) bullet, labeled CE-399 by the Warren Commission, was to have passed through JFK's neck, entered JBC's body under his right arm, shattered a rib, exited through his chest, splintered his right wrist, and wounded his left thigh. Despite all of this destruction, CE-399 was recovered intact and relatively undamaged on a stretcher at Parkland Memorial Hospital in Dallas. Indeed, CE-399 weighed 159 grains (10.3 g) and had lost, at most, 2–3 grains (0.13–0.19 g) during its travel. This complex trajectory and extensive human damage, and the apparent contradiction by the moderately pristine condition of the recovered bullet, is popularly known as the "single-bullet" theory by protagonists and as the "magic-bullet" theory by others. It has been claimed by some as proof that this trajectory was caused by two or more bullets, and it has provided a basis for conspiracy theories involving additional shooters (e.g., from the grassy knoll on Dealey Plaza). (Skeptics of the single-bullet theory might consider an interesting technical analysis performed by Lattimer et al. in 1995 (5), however.)

In response to appreciable controversy over the Warren Commission Report, the U.S. Congress conducted additional studies and evidentiary investigations into the assassination more than a decade later. As part of those proceedings, Professor Vincent P. Guinn (VPG) reanalyzed the bullet-lead evidence in the case and testified on the results before the House Select Committee on Assassinations (HSCA) in 1978 (6). He also published them in the scientific literature 1 year later (7). VPG reported an "extremely large variability" in the antimony content of Mannlicher FMJ bullets, which were manufactured by the Western Cartridge Company (WCC). He further reported that, in distinct contrast to other ammunitions within his experience (about 165 known brands and different production lots), this variation allowed him to reliably

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individualize bullets, not from lot to lot, but definitely among bullets from the same box sold commercially. Consequently, VPG testified that there was highly reliable evidence for two, and only two, bullets among the various fragments of lead recovered from the assassination, that both bullets were from MC rounds, and further, from his recent analyses, that it was very probable that the three metal fragments recovered from JBC's wrist (CE-842) derived from CE-399, the stretcher bullet. Likewise, the two lead fragments from JFK's brain (CE-843) were from another single bullet, but definitely not CE-399.

These more modern analyses and assessment by an eminent nuclear scientist gave much added weight to, and reinforcement of, the single-bullet theory. Recent papers by Rahn and Sturdivan (8,9) have presented arguments to support this conclusion. However, VPG did not interpret his measurements with knowledge of the basic metallurgy of lead alloys, standard lead smelting, and bullet manufacturing practices. His conclusions are unsupported from those vantage points. He also essentially disregarded his own previous findings wherein he quantified the antimony, copper, and arsenic contents of 75 lots of bullets from various manufacturers (10). In that study he found that less than half of the 75 lots of bullets were uniquely characterized by the concentrations of these three elements, considered individually or together. Finally, he was unaware that the small sample size he was constrained to contributed to variability in his measurements because some of the elements he quantified were not distributed uniformly within the samples at this scale. It seems incongruous therefore, that from quantitation of only one element (antimony) in the JFK assassination, he could make such definitive statements about the bullet and fragments. In addition, the error analysis for the uncertainties reported in his data was a minimal effort, and, had more appropriate statistical analyses of those data been performed, the conclusion of two specific bullets would have been weakened from that perspective as well.

Trace Analysis: Data Collection Versus Interpretation for Bullet Lead Compositions

The quantitation and comparison of bullet lead chemical compositions is a subset of the more general area of trace evidence analysis, widely used in forensic science. Trace analysis is used in crime scene investigation to compare an object found at the scene of a crime with similar objects associated with a suspect. The intent is to find any commonality among the items that might link the suspect to the crime. Typical trace analyses can involve the shape, color, structure, and composition of such items as fibers, hair, fluids, gunshot residue, bullets, broken glass, metal fragments, etc. Compositional trace-element analysis quantifies the elemental composition of the objects to be compared in an attempt to determine whether they had a common source and might thus be related. In the following discussion, we consider only the methodology as it applies to the comparison of bullets by composition, but the principles apply to all of trace evidence analyses and comparisons.

For bullets, there are two simple steps to this analysis: (1) data collection; this includes the identification and quantification of the major, minor, and trace elements present in the bullets, and (2) interpretation of the data to determine the likelihood of a common origin.

Several premises are necessary for the comparison of bullet lead compositions to prove useful for linking a suspect to the crime scene. These are critical in providing a foundation for the validity of the comparisons and cannot be assumed by the investigator. The considerations for bullet lead evidence are:

(1) A fundamental requirement is that each source of the bullets is not like all, or many other, sources of these bullets. That is, each source must be distinguishable from all other sources. Were this not true, then the probability of a chance or random similarity among bullets may be too high to draw any valid conclusions about linking a suspect to a crime scene. A valid and representative database of sources must be characterized to determine whether sources are always unique, sometimes unique, or never unique.

(2) The second fundamental requirement is that the elemental analyses must be sufficiently encompassing to individually characterize each bullet being compared. If only one or two elements are quantified, and many sources of bullets have indistinguishable amounts of those one or two elements but different amounts of other elements, then the comparison would be of little or no value. It is interesting to note that, in previous studies, VPG and his coworkers found that the three elements antimony, copper, and arsenic together were not adequate to reliably differentiate among bullets from known different sources (10). Yet, VPG characterized the JFK bullets by antimony concentrations alone.

(3) No elemental determination is 100% precise and accurate. There will always be some degree of uncertainty in each of the measured elemental compositions. This error has several sources: inherent variability in the measurement technique, real differences in samples taken from the same specimen, and differences in sample preparation. Replication is the most common method used to account for and describe these inherent variabilities. However, uncertainty from all sources must be fully considered when comparing compositions that are only slightly different. It also means that some valid criterion must be used to decide whether two similar compositions are sufficiently alike to have come from the same source.

(4) The elemental compositions of bullets and shot made from lead alloys do not have an infinite range. The vast majority of bullets and shot are made from only several specific alloy compositions, and these alloys have small ranges of acceptable major, minor, and impurity elements. The major and minor alloying elements, such as antimony, tin (added in cast bullets), and arsenic (added in shot), are carefully controlled within certain specified ranges. The normal trace or impurity elements, such as tin, arsenic, copper, bismuth, and silver, are intentionally removed to low levels in the lead refining process, and none of these elements are allowed to range widely in the finished bullet product. Because the ranges of all of the analyzed elements are restricted to relatively narrow bands in bullet lead alloys, and there is some uncertainty in each compositional determination, then, as more specimens are analyzed, the chance of finding indistinguishable objects increases. If only one bullet from the crime scene and only one bullet from the suspect are compared, the chance of finding a "match" is much smaller than if several bullets from the crime scene are compared with 20 bullets from the suspect, all else being equal. Such a match result may be entirely attributed to the normal uncertainties inherent in elemental chemical analysis and may thus be an artifact of the methodology alone.

Data collection and their interpretation or assessment in the field of forensic science, while they may sometimes overlap, must be considered separate areas of expertise until proven otherwise. Each of these efforts requires a different knowledge base and hence different qualifications for the examiner or investigator performing the task. The first step, the elemental analysis, can be performed with any of a variety of proven analytical methods, the most suitable of which depends on what comprises the evidence and which elements are being measured. Quantitative measurements are preferred, but qualitative measurements can be acceptable. For bullets, an analytical chemist often does this first step. VPG was a member of a team of nuclear scientists in the 1960s and 1970s at Gulf General Atomic Corp. (San Diego, CA) developing neutron activation analysis (NAA) as a tool for general forensic examination and, in particular, for bullet-lead alloys and gunshot residue. They published several internal General Atomic reports and technical articles in the open literature on their findings (see, for example, (10–19)). VPG was a radioanalytical chemist and a leading expert in NAA, and consequently used that technique for the analysis of the Kennedy lead fragments. This analytic method and quantitation of the composition does not require extensive background knowledge of the objects being examined, such as manufacturing methods and variations, the number of sources of such samples, their general availability, and so forth. Data acquisition requires only competent characterization of the objects to be compared and the use of good scientific principles to assure that all sources of variability and potential error are taken into account and presented in the results.

It is, however, absolutely necessary that the analyst obtain a truly representative sample of each bullet or lead fragment that is examined. Any inherent or real variability in composition from place to place in a bullet (i.e., nonhomogeneity or heterogeneity of the bullet) must be recognized and considered in the final comparison of compositions. Thus, the total variability encountered in the elemental analysis must be recognized as deriving from the analysis technique, the sampling method, and the sample itself. Although extensive knowledge of the object is not required, some assessment of sample homogeneity (on both micro and macro scales) is required.

The comparison of bullets characterized by elemental compositions, and the subsequent interpretation of the collected data, do require knowledge in all of the areas discussed above, as well as knowledge about the general population of the bullet compositions. In order to perform interpretation and attribution, an investigator must have a realistic knowledge of the statistical ensemble of bullets. How common are different, similar, or indistinguishable compositions? Were the compositions measured adequately for meaningful comparison? Clearly, interpretation of the results requires a different set of skills and knowledge than those required for chemical/elemental analysis. In order to draw valid conclusions about the probability of a common origin among the samples being examined, the compositions must be compared with a representative database of other such similar objects.

A recent example of the importance of the distinction between the processes of sample chemical analysis and the interpretation of their results, as related to forensic analysis of bullet compositions, is a study published by the National Research Council of the National Academies (20). This study concluded that no scientific foundation had been established for concluding that two lead bullets or lead fragments with indistinguishable compositions necessarily had a common origin. Furthermore, it also found that the number of bullets of any given composition in a particular geographic area was unknown.

Therefore, the conclusion that two bullets with indistinguishable compositions definitely came from the same source was inappropriate and potentially misleading. The NRC study considered only the issues of multiple sources of lead with identical compositions and the unknown geographic distribution of bullets with indistinguishable compositions. We recognize that both of these factors may affect the interpretation of the JFK assassination evidence. However, as discussed below, there is another key issue in comparative bullet lead analysis that the NRC study did not address, and it is more important for correct interpretation of the JFK data measurements. If bulk material is inhomogeneous in composition at the scale of the size of the samples, then the specimen measurements may not necessarily represent the true material composition. If unrecognized, this source of increased variability in sample compositions can lead to unwarranted rejection of data, incorrect intercomparisons, and so forth.

The investigator must also assure that the elements and data used for comparison are valid descriptors of the sample, and that if there are known (expected or predictable) correlations among the measured elements, they cannot necessarily be treated as independent variables. For example, a determination that the amount of a particular element is below the detection limit of the analytic method (i.e., “not present” or “not detected”) in the bullets being compared does not imply that the amounts of that element are the same in all objects. It merely means that the analyst cannot measure the amount of that element because of instrumental limitations. The true quantities of the elements could be very different were they measured by a more sensitive analytical technique. The examiner simply does not know. It is therefore an obvious conclusion that the finding of an element below the detection limit in the objects being compared is of limited value and cannot be used as a valid property of these objects. Likewise, if an element is closely correlated with another element, they cannot both be considered independent variables and used as such in a statistical analysis or subsequent forensic presentation of the data.

The specific application of these fundamental concepts to bullet lead analysis is straightforward. If all bullet lead compositions (as measured by the elemental analysis method, in this case NAA) were the same, then no information could be gained by comparing compositions. Conversely, if every box of manufactured ammunition had bullets that were compositionally unique to that particular box, then very specific information could be gained by such comparisons. Reality lies somewhere between these two extremes. The correct interpretation of the compositional data measured in the JFK assassination requires an assessment of this reality. An investigator cannot interpret the compositional analyses without regard to the realities of bullet production. He or she must therefore have knowledge of, or at least consider the metallurgy of, lead alloys, lead smelting practices, and bullet manufacturing processes, as well as ammunition distribution practices. As will be shown, VPG did not factor such information into his interpretation of the assassination data, nor did he consider errors introduced by inherent variability of his small samples from the assassination fragments and the WCC MC bullets used for comparison purposes.

Statistical Analysis

Assassination Bullet Evidence and Analyses

The U.S. FBI had analyzed evidentiary lead fragments from the assassination by emission spectroscopy and NAA in 1963–1964. The results were judged inconclusive, and no interpretation of those data for investigative intelligence was made. In 1977, the National Archives transported the bullet evidence to the laboratory of VPG, where he conducted further NAA of the specimens for the HSCA. Instrumental NAA was an excellent analytic approach for such limited and unique samples because of its high sensitivity for the qualitative and quantitative analysis of many minor and trace elements, and for its nondestructive nature. Further, VPG would use high-resolution Ge(Li) spectrometry for the γ-ray analyses, a significant technical advance unavailable for the prior FBI examinations.

Measurement of material composition is often productive for forensic comparison of different specimens. If two samples differ markedly in a number of material comparison points, it is likely that they did not have a common origin. However, if they are very similar in composition, they may have had a common origin, but the possibility of a fortuitous match must be evaluated via an appropriate database of known materials measurements. NAA is an elemental analysis technique, and, for the JFK bullet leads, VPG focused on three common compositional elements that can have different concentrations depending on the specific ammunition source: antimony (Sb), silver (Ag), and copper (Cu).

The National Archives submitted 10 specimens from the JFK investigation to VPG, only seven of which were suitable for his analyses. Two of the candidate items were of only secondary concern, consisting of the unfired round in the MC rifle and a bullet fired at General Edwin Walker in April 1963. The other five evidence fragments were highly significant for the assassination scenario, and were designated Group I exhibits by VPG. They were: CE-399, the stretcher bullet; CE-567, a large lead fragment from the front seat of the Dallas limousine; CE-843, two fragments recovered from JFK's brain at autopsy; CE-842, three fragments recovered from JBC's wrist during surgery; and CE-840, fragments from the rear floor of the Dallas limo. Sample weights and descriptive remarks were tabulated by VPG (6, p. 517).

The NAA concentrations of antimony, silver, and copper obtained by VPG for these samples, as reported in his HSCA testimony, are reproduced in Table 1. He also measured trace levels of aluminum, manganese, sodium, and chlorine in the evidence, but they were unimportant for further consideration.

From these data, VPG concluded that CE-399 and CE-842 were the same bullet, and that CE-567, -843, and -840 derived from yet another, but also the same, bullet. It would appear that he must have based this conclusion entirely on the antimony measurements. The average of the antimony concentrations ($<[\mathrm{Sb}]>$) of the stretcher bullet and JBC wrist fragments, using VPG's math techniques, is (815 ± 25) ppm. For the other four Table 1 measurements, $<[\mathrm{Sb}]> = (627 \pm 20)$ ppm, and it would appear that two distinct groups are indeed evident, even were the error bars expanded to 3σ values. Equivalent calculations for the silver data give $<[\mathrm{Ag}]> = (8.8 \pm 1.3)$ and (8.1 ± 0.3) ppm, respectively. The overlapping error bars of the average silver values would preclude the two-group conclusion from these data. The copper data would indicate three distinct groups at face value. However, VPG dismissed his copper measurements from any subsequent interpretation because he believed them to be subject to erratic contamination from the 1.5-mm-thick copper (actually gilding metal) jacketing material of the MC bullets (e.g., CE-842 in Table 1). Consequently, only the antimony data in VPG's HSCA testimony will be further considered here.*

TABLE 1—*VPG neutron activation analysis results of JFK assassination bullet-lead specimens; errors are 1σ (6).*

I. D. (CE-)	Weight (mg)	[Sb] (ppm$_w$)	[Ag] (ppm$_w$)	[Cu] (ppm$_w$)
399	10.7	833 ± 9 (1%)	7.9 ± 1.4	58 ± 3
567	50.5	602 ± 4 (0.7%)	8.1 ± 0.6	40 ± 1
843	41.9 and 5.4	621 ± 4 (0.6%)	7.9 ± 0.3	40 ± 2
842	16.4 and 1.3	797 ± 7 (0.9%)	9.8 ± 0.5	994 ± 7
840-1	33.4	638 ± 4 (0.6%)	8.6 ± 0.3	44 ± 2
840-2	33.8	647 ± 4 (0.6%)	7.9 ± 0.5	42 ± 2

VPG Error Reporting

However, VPG provided ancillary data in his HSCA testimony that considerably weakened his forensic conclusions. He also chose to assign but minimum errors to his reported results. Although the crux of the present paper is the bullet production and metallurgical considerations that can explain the small variations in antimony and copper contents reported in Table 1 from well-known principles, we also present a more comprehensive discussion of the apparent accuracies of the historic [Sb] values, strictly from measurements reported by VPG in (6).

Instrumental NAA by the comparator method can be an excellent technique for avoiding many potential sources of random and systematic error in empirical data. Questioned specimens are compared directly with reliable primary standards when sample geometry and handling, neutron irradiation, and radioactivity counting protocols are maintained constant between them. No radiochemical separations are performed on the unknown samples to inject potential experimental bias. Further, the uncertainties in many NAA parameters, such as analyte half-lives, nuclear γ-ray intensities, cross sections, Ge(Li) efficiency calibration, and so forth, cancel exactly in the mathematical ratio between unknown and standard. Consequently, no propagation of these errors is necessary for an overall experimental accuracy.

However, there are inherent uncertainties in instrumental NAA. The first is an experimental error arising solely from radioactivity counting statistics. It is a limiting error, and is merely the minimum uncertainty that can be assigned to any datum obtained by radiation detection. This lowest possible error, at the 1σ confidence level spanning 68% of the population of a Gaussian distribution, is all that VPG reported for his measurements of the JFK evidence, as he freely described in both testimony and published paper. For a research γ-spectrometer system, this uncertainty is typically very small unless an analyte is close to its limit-of-detection, and, indeed, the relative errors in VPG's [Sb] measurements ranged from 0.6% to 1% (Table 1). VPG stated in his testimony that he estimated the total uncertainties in his data to be on the order of 2–3 times the standard deviations calculated just from counting statistics. They were actually somewhat higher.

VPG calculated unweighted means and their resultant standard deviations for his counting-error statistical analysis. However, that approach is optimum only when the data to be averaged have unknown uncertainty estimates, or when the relative errors are all equivalent (i.e., have equal weights). Neither was true for the JFK assassination NAA measurements. For those data, weighted averages (e.g., $<[\mathrm{Sb}]>_w$) could have been computed to compare various populations, with each individual input value adjusted by the instrumental weighting factor of $1/\sigma^2$ (21). When computing a weighted average, the uncertainty in the result is calculated by two

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*There are two inconsistencies in VPG's data for the HSCA (6) and those published in the journal (7). For the latter, he chose to combine the CE-840 fragments into one entry, which was a simple average of his two HSCA entries (i.e., CE-840-1 and -2 in Table 1). However, the other was a discrepancy in the reported value for [Ag] in CE-399: (8.8 ± 0.5) ppm (7). We do not know which is correct. However, should it be the *Anal. Chem.* datum, the mean values for CE-399/CE-842 and CE-567/CE-843/CE-840 become $<[\mathrm{Ag}]> = (9.3 \pm 0.7)$ and (8.1 ± 0.2) ppm, respectively. In that case, the two-population conclusion from the Ag data would also be defensible at the 1σ error level.

separate equations, one providing the normal standard deviation of the mean and the other the external standard error. The latter takes Deming's external consistency into account (22), and the reported error of the weighted average is the larger of the two. This is standard statistical practice for averaging data with unequal uncertainties (see, e.g., (23)).

Had VPG used weighted averaging for his analyses, the uncertainty of many of his reported results would have improved. Thus, in Table 1, for the stretcher bullet and JBC wrist fragments, $<[\mathrm{Sb}]>_{\mathrm{w}} = (811 \pm 17)$ ppm, while for the other four entries $<[\mathrm{Sb}]>_{\mathrm{w}} = (627 \pm 10)$ ppm. The former value provides a decrease in relative error from 3.1% (i.e., the unweighted mean and standard deviation) to 2.1%, while the latter would decrease the relative uncertainty from 3.2% to 1.6%. Similarly for the Table 1 [Ag] data, $<[\mathrm{Ag}]>_{\mathrm{w}}$ computations would decrease the relative errors from 15% to 6%, and from 4% to 2%, respectively. Even with weighted-average calculations, though, VPG's conclusions in support of the single-bullet theory would have remained unchanged. However, because only the minimal counting-statistics errors were ever considered, the resultant error bars should be considered more representative of experimental precisions than true accuracies. But VPG actually measured and reported additional data in the HSCA proceedings that could improve those error estimates.

Weighted Statistical Analyses and Overall Accuracy

In appendices to his HSCA testimony ((6), pp. 538–50), VPG provided several tables of ancillary measurements that can be evaluated to provide better estimates of the overall accuracy of his JFK assassination results. In the analyses that follow below, data reported by VPG are assessed at face value from a different statistical perspective; only [Sb] measurements are considered; 1σ errors are propagated; and calculations of weighted means are utilized whenever feasible (i.e., by the prior assignment of minimal individual uncertainties by VPG).

VPG obtained specimens of the four production lots of MC 6.5-mm cartridges that had been manufactured by WCC, all produced in 1954 for the U.S. Army, and designated as lots 6000, 6001, 6002, and 6003. He analyzed exemplars from each lot and concluded that, because there was so much [Sb] variability from bullet-to-bullet (thus allowing individualization), the various WCC lots were indistinguishable from each other (Appendix D in (6)). VPG discussed and interpreted these measurements in terms of data ranges and did not report any sample means for the four lots. However, if $<[\mathrm{Sb}]>_{\mathrm{w}}$ values are calculated from his tabulated data and compared, the error bars of the four weighted population averages do overlap each other at the 1σ level (see Fig. 1). This computation therefore agreed with VPG's assessment that the different Mannlicher lots could not be distinguished from each other by compositional analysis.

As stated above, radioactivity counting statistics are but minimum errors in the overall accuracies of NAA experimental results for individual bullet specimens. Two other potential factors are the precision of repetitive measurements on the same sample and the homogeneity of composition within a given bullet. Variability in each of these areas would result in increased errors above counting statistics, and inclusion of their effects would result in better estimates for the true accuracies of reported results.

VPG conducted repetitive analyses on samples from two individual MC bullets, from lots 6001 and 6002, with each specimen assayed four times. The $<[\mathrm{Sb}]>_{\mathrm{w}}$ values for those measurements were (676 ± 39) and (971 ± 28) ppm, respectively. It so happens that these means are exactly the same as the (unweighted) numbers reported by VPG, but, as above, the relative errors again decreased, from 11% to 5.7% and from 3.3% to 2.9%, by weighting the calculation. Thus, an average value of the "repeated measurements" error in VPG's NAA antimony assays was the midpoint between 5.7% and 2.9%, or 4.3%.

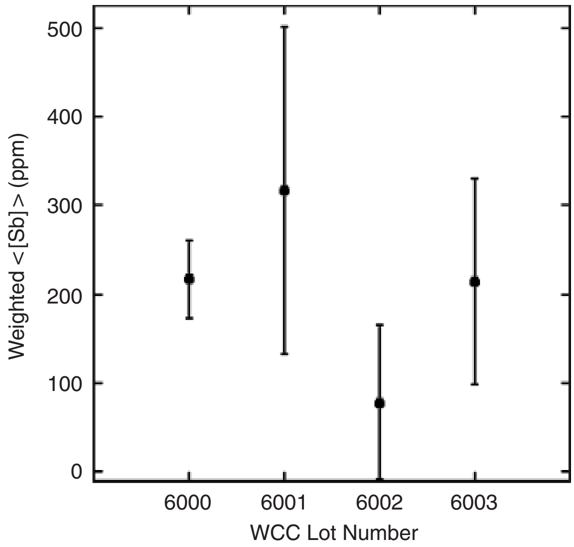

FIG. 1—*Weighted-average [Sb] values of different lots of Mannlicher-Carcano 6.5-mm ammunition (data from (6)). Error bars are 1σ confidence levels.*

VPG also interrogated the homogeneous distribution of antimony, silver, and copper within three individual MC rounds, one each from production lots 6001, 6002, and 6003 (Appendix F in (6)). He did so by dividing a single 50–60 mg drilling from each bullet (used in his lot-to-lot variability study) into four aliquots of 10–15 mg each and analyzing each fraction separately by NAA.

The $<[\mathrm{Sb}]>_{\mathrm{w}}$ values calculated from his measurements are:

$$\begin{aligned} &\text{Lot 6001}: & <[\mathrm{Sb}]>_{\mathrm{w}} &= (1129 \pm 36)\ \text{ppm (relative error} = 3.2\%);\ n = 4 \\ &\text{Lot 6002}: & &= (740 \pm 150)\ \text{ppm (relative error} = 21\%);\ n = 4 \\ &\text{Lot 6003}: & &= (441 \pm 63)\ \text{ppm (relative error} = 14\%);\ n = 4 \end{aligned}$$

VPG concluded, without further explicit analysis, that this baseline work indicated reasonable intrabullet homogeneity within single Mannlicher rounds. However, from the above relative-error data, a computed estimate of this effect can be made from his empirical measurements. Thus, the (unweighted) average of his evaluation of antimony homogeneity in WCC bullets, as reflected in the spread of the NAA results, was an apparent inhomogeneity of 13% ($n = 3$). (Again, this value is lower, here by approximately a factor of two, than the analogous result calculated from the standard deviations of VPG's unweighted treatment.)

Were they independent factors, the average 4.3% repetition error and 13% inhomogeneity error would be combined in quadrature with the mean of the counting errors in VPG's assassination evidence measurements (0.7%; Table 1) to provide a better estimate of the effective accuracies for the reported JFK [Sb] values. However, the experimental conduct of NAA is such that both the counting uncertainty and replication error are reflected within the homogeneity measurements. Consequently, the best empirical estimation for the overall accuracy of the measured JFK [Sb] data from analyses reported by VPG is the 13% inhomogeneity error.

Assigning 13% uncertainties to VPG's measured [Sb] values, and calculating weighted averages of the two assassination groupings, results in $<[\mathrm{Sb}]>_w = (814 \pm 75)$ ppm for the CE-399/CE-842 pair and (626 ± 41) ppm for the other four evidence specimens. Although these computed means are the same as those that would be calculated by VPG's methodology, the relative 1σ error values are factors of four greater than those that would result solely from the counting-statistics uncertainties. The error bars of these two average values, then, no longer require more than 3σ-expansion to overlap, and they now do so at slightly greater than 1.6σ, representing 89% of a Gaussian population. This contrasts with VPG's minimal uncertainties and unweighted statistics, which resulted in minimum overlap of error bars at a confidence level of $>4\sigma$, representing statistical coverage of $>99.99\%$ of both bullet populations. A graphical representation of this comparison is shown in Fig. 2. Note that, with the more complete error propagation, the two groups overlap at the 2σ confidence level historically used by the FBI when comparing bullet leads (24,25). Therefore, by using the same measured data and a more comprehensive alternative statistical analysis, the certainty of two, and only two, bullets in the JFK evidence specimens is not as strong as it had perhaps seemed.

The above error propagation and assessment assumed that a Gaussian distribution was reasonable for the evidentiary populations considered by the JFK investigation. As all were characterized by small-number averages (maximum $n = 4$), it is not obvious what other statistical modality might be a better choice, and VPG did choose Gaussian statistics for his original evaluation.

Bullet and Bullet Lead Production

In order to properly compare and interpret VPG's composition measurements, one must have an understanding of the normal variation in bullet lead among bullets of the same kind, as well as the homogeneity of a single bullet. These depend on how lead alloys are produced and whether MC bullets in particular were constantly homogeneous on the scale of the 1–50 mg sample sizes.

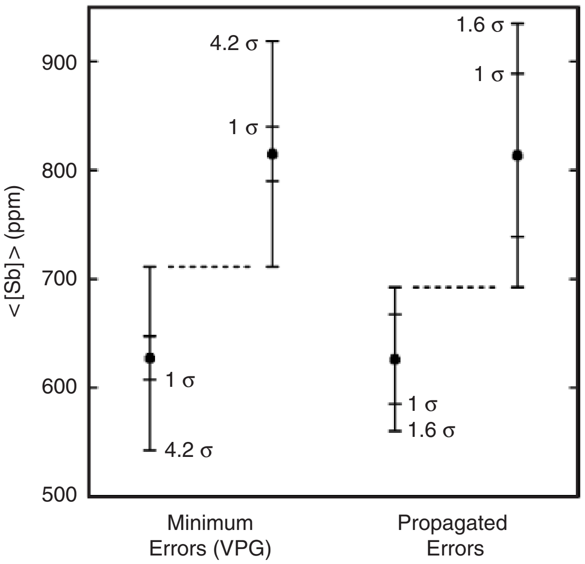

FIG. 2—*Comparison of JFK assassination bullet evidence error analyses: minimal radioactivity counting uncertainties (left) versus fuller propagation of experimental error (right). Two distinct sample populations may be affirmed until error bars overlap, at which point the data become consistent with but one population. Minimum overlap for VPG's reported errors occurs at a confidence level of* 4.2σ*, corresponding to statistical coverage of* $>99.99\%$ *of both Gaussian population distributions. However, the analogous overlap occurs at* 1.6σ*, or 89% of the populations, with enhanced propagation of errors.*

The elemental composition of bullet lead alloys is determined primarily during the lead smelting/refining process and not during the bullet manufacturing process. However, small compositional changes may occur if the lead alloy is remelted and cast before bullet-wire extrusion by the bullet manufacturer. These changes may be important to the interpretation of trace element analysis, particularly at the present time when an analyst can reliably quantify many more elements. However, whether or not such changes occur has never been investigated. A detailed description of the recycling and smelting of lead alloys as it pertains to the ammunition community has been presented recently in the forensic literature (26), and can also be found in several historic texts (27–29).

Lead materials used for commercial bullet production are of three basic types: (1) lead–tin alloys, which are used for individually cast bullets; (2) lead–antimony alloys, which are used for extruded or swaged bullets; and (3) soft or unalloyed lead, which is used for jacketed bullets. Each of these classes of binary lead alloys may, however, be used for any of the bullet types, although commercial ammunition manufacturers do not generally do this for economic reasons. In the first type of bullet alloy, used for individually cast bullets, tin is added to lead bullion to improve the fluidity of the molten alloy and to lower its melting point. This enhances the complete filling of the bullet mold. Common bullet-casting alloys contain 2–5% tin. Antimony may also be added to casting alloys to harden the bullets. In the second type of bullet alloy, which represents the vast majority of commercial bullets, only antimony is added to the soft lead bullion. Antimony again serves to harden the lead. Metallurgically, it strengthens the lead by solid-solution strengthening and by forming a precipitated crystalline phase within the lead matrix (30–32). Antimony can be present from 0% to approximately 12%, although the majority of swaged bullets contain 0.5–2.5%. More than half of all commercial bullets sold contain approximately 0.7% antimony.

The third type of bullet lead is the least expensive of the three materials and is used for jacketed bullets. The soft, refined lead is not intentionally alloyed with any other elements, and it was the composition used in the jacketed MC bullets central to the Kennedy assassination. The lead used for the cores of the WCC MC bullets was specified to be #0 soft lead (99.85% lead) (6). Jacketed bullets consist of a gilding-metal outer jacket encasing a lead core. Gilding metal is a common binary copper alloy containing 5–10% zinc. WCC MC bullets were manufactured with a CDA 220 bronze, which has a nominal 90% copper and 10% zinc composition (6). The jacket is produced as an empty shell, and the lead core is physically pressed into it. Although either lead–tin or lead–antimony alloys can be used for the core of jacketed bullets, ammunition manufacturers generally do not incur the additional expense of using them because the core is merely an economic, high-density filler material. Popular names for this unhardened lead include common lead, soft lead, pure lead, and unalloyed lead. Today, the normal specifications for soft lead require $<0.1\%$ antimony.

Fabrication of a jacketed bullet is straightforward. A larger diameter billet of soft lead is extruded through a die to form wire of the correct diameter for the bullet core. The individual cores are cut to length from this wire. The hollow, gilding-metal jacket is preformed to the desired shape, and the lead core is inserted as a press-fit. Final sizing of an assembled bullet can be done as necessary. The lead wire for the core is extruded from cylindrical billets of lead that are usually 10–15 cm in diameter and weigh approximately 50 kg. These billets may either be cast at the bullet manufacturing plant from ingots supplied by the lead smelter, or directly at the lead smelter. The overall or bulk composition of a lead billet does not change once the billet has been cast and the lead solidified. However, if the billet is measurably inhomogeneous in internal composition because of segregation effects, the physical extrusion process can rearrange the areas of inhomogeneity and lead to measurably different compositions, either along the length of the extruded wire or from the center to the outside of the wire (26). This effect will, in general, be subtle and must be investigated carefully.

Irrespective of whether the lead ingots or billets used for bullets come from a primary smelter that treats lead ore directly from mines, or from a secondary smelter that recycles lead from automobile batteries, lead pipe, lead sheathing, etc., the refining (that is, purification) processes are essentially identical. Secondary smelters/refiners provide 70–90% of the lead alloys used in the U.S. today. (The terms refining and smelting are sometimes used interchangeably within the lead industry. Smelting is a combination of the words "*s*inter" and "*melting*." It refers properly only to the process used to obtain lead metal from the ore. Refining is the process used to purify metallic lead, whether the source of the impure lead is a smelting furnace or a lead recycling furnace. The common usage is to refer to both primary and secondary operations as smelters.)

In the refining step, major contaminant elements, such as sulfur, oxygen, tin, arsenic, copper, bismuth, silver, and antimony, are removed to acceptable levels for the alloy being produced. Different chemical protocols and cooling processes are used to remove each element, and often several elements are removed from the melt by the same treatment. For example, a controlled cooling to just above the melting point of the lead bullion removes the higher concentrations of copper, arsenic, and antimony. This is known as "softening" the lead. The lower density elements and/or their oxides float and form a surface layer that is skimmed off. As another example, tin, arsenic, and antimony are removed together, but at different predictable rates, during a separate, controlled oxidation treatment. Chemical treatments are used to further refine the lead and may vary somewhat from smelter to smelter. The interested reader is referred to Hofmann and others (27–29) for a detailed discussion. Secondary smelters do not generally have the capability of removing bismuth and silver, so they can lower the concentrations of these elements only by dilution. That is the reason that bismuth and silver have been noted to have such nonvarying compositions for long periods of time (24–26). Refining readily produces lead bullion of $\geq 99.90\%$ purity, and common lead and corroding lead (UNS L50045 and UNS L50042, respectively) contain $\geq 99.94\%$ lead. Soft leads for bullets can contain up to approximately 0.1% antimony with no observable alteration of forming characteristics during bullet manufacture. The exact specifications for bullet lead alloys are rather closely guarded industrial secrets because of the intense sales competition between manufacturers; however, the compositions can be directly estimated by simply analyzing the products that are being sold.

It is the expressed intent of a lead smelter to supply the same product to a customer every time a shipment of a specified lead alloy is made. Consequently, the elemental composition of consecutive shipments of the same alloy will be very similar. In fact, multiple lots (melts) of lead have been found to be indistinguishable in the five elements commonly used for comparative bullet lead analysis (24,26).

Essential Metallurgy

VPG noted that the MC ammunition "was found to differ sharply from typical bullet leads" because "Although individual bullets were found to be fairly homogeneous in their antimony and silver concentrations, they differed greatly from bullet to bullet amongst samples taken from the same box." Thus, "it would be possible to distinguish one bullet (or bullet fragment) from another, even though they both came from the same box of MC cartridges" (6). As will be shown below, the variations in antimony, silver, and copper contents are quite similar in all bullet leads and not "sharply different." In fact, VPG was noting large relative differences (but small absolute-value differences) in small quantities of the measured antimony and copper. These same differences are seen in lead alloys with higher antimony and copper contents, but they are smaller *relative* differences. The common occurrence of segregation (both microsegregation and macrosegregation, although microsegregation is the major concern for this study), as discussed below, explains VPG's observations and the variability in his measured antimony and copper data.

The JFK MC bullets were FMJ and contained a soft lead core. The only exposed lead on the exterior surface of this type of bullet is at the tail, or back end, of the bullet. According to VPG's NAA data, the lead cores of the bullets he sampled from WCC lots 6000–6003 contained approximately 600–900 ppm_w antimony and approximately 17–4516 ppm copper (with most of the copper concentrations in the 20–400 ppm_w range). In both of these aspects, the WCC MC bullets are quite similar to other commercial FMJ rifle ammunition.

The lead fragments from the assassination scene weighed from 1.3 mg to 7.13 g. The latter weight corresponds to the weight of a complete lead core (a nominal 110 grains). VPG analyzed samples of the assassination evidence that weighed from 5.4 to 50.5 mg. The samples that he analyzed from the four lots of WCC MC bullets for comparison purposes weighed from 44–58 mg. All of the drillings for the comparison samples were taken from the tails, i.e., the nonjacketed ends, of the bullets. VPG used a cleaned drill bit each time and scraped the surface clean of any oxidized lead before drilling. It is therefore highly unlikely that jacket material contaminated these drillings. We note here that the copper jacket of these bullets weighed 3.3 g (a nominal 51 grains), and this value added to the lead-core weight results in Winchester's advertised bullet weight of a nominal 161 grains (6).

It is thus clear that VPG chose to use nominal 50-mg lead samples from the boxed WCC ammunition for comparison with the fragments from the assassination. At the time, this likely seemed a reasonable tactic to follow. However, the obvious question that must be answered in any review of VPG's work is whether samples of this size were true representatives of the average bulk composition of the lead core. For example, if the bulk material was not homogeneous on the 50-mg sample scale (and smaller, down to 5.4 mg in the JFK evidence), then some variation of compositions among samples from the same bullet should be expected. Likewise, comparison of samples from different bullets with only slightly differing compositions may show overlap. Erroneous conclusions could then be made when assessing common sources of compared samples.

The soft lead core of MC bullets, like all common industrial metal alloys, consists of many small single crystals or grains of metal, each of which has a different crystallographic orientation. These grains are first formed during solidification of the alloy when it is cast from the liquid. The solid generally forms from the liquid in a dendritic or "Christmas tree" pattern. As the primary, secondary, and tertiary dendrite arms grow in thickness, the remaining liquid is gradually captured between the interlocking arms. In the binary lead–antimony system, the first solid to form is lower in antimony content (it is essentially pure lead) than the subsequent solid. The arms thus exhibit "coring." That is, the centers of the arms have lower antimony content than that outer region of the arms. The last interdendritic liquid to solidify has the highest antimony content. When two growing dendrite arms meet, a grain boundary is formed because the arms do not have the same crystallographic orientation at that junction. The grain boundary contains the highest antimony content, and this compositional variation in a casting is called microsegregation. It occurs because the material has departed from the equilibrium condition predicted by the phase diagram during the cooling process (30,32).

Microsegregation is common in lead alloys and has been observed for lead–antimony alloys containing as little as 0.01 wt% (100 ppm_w) antimony (33). An excellent discussion of the phenomena of normal segregation, inverse segregation, and gravity segregation in lead–antimony alloys containing 0.01–13% antimony is presented in a series of articles by Simon and Jones (33–35). They found normal segregation in all hypoeutectic alloys ($<11\%$ antimony), whether slow cooled or chill cast. They note and explain from first principles that the relative effects of antimony segregation are more prominent with lower antimony content alloys, and that the closer the alloy composition approaches the eutectic composition (11% antimony), the less notable are the effects.

Segregation can be readily seen optically in alloys containing several percent antimony. However, it is quite difficult to detect in low antimony content alloys, such as the MC soft lead. Simon and Jones developed special etching and replication techniques for studying low antimony content alloys. A representative microstructure reproduced from Simon and Jones (33) is shown in Fig. 3. It demonstrates antimony segregation in a 100-ppm_w antimony alloy with a 60-μm grain size. This composition is comparable to the lowest antimony concentration that VPG measured. The structure was etched with acetic acid/hydrogen peroxide to show only the antimony distribution. With this etch, pure antimony is etched black, whereas pure lead remains unaffected. Thus, the darkest regions in Fig. 3 are the highest in antimony content. Depending on the bulk alloy composition, the antimony-enriched area can approach the eutectic composition of 11.2% antimony (33).

The authors of this study concluded: "The results obtained appear to lead to the conclusion that a homogeneous alloy of uniform solid solution cannot be produced by any present casting process unless further heat treatment is employed."

Segregation is thus the normal, expected phenomenon, and metallurgists go to great lengths to minimize its deleterious effects on the mechanical and corrosion properties of most engineering alloys. The lead–antimony alloys used for lead acid battery grids are homogenized to improve corrosion resistance (33). All certified composition standards, such as those available from NIST, also undergo extensive homogenization treatments. In the manufacture of ammunition, however, segregation of minor and trace elements in the lead is not considered important because the material is not used as a structural or corrosion-protection material. The performance of a bullet is not affected by such segregation. We note that no homogenization heat treatment is used for ingots or billets of bullet lead alloys, and we therefore expect segregation effects to be present for antimony in the lead used for the MC bullets.

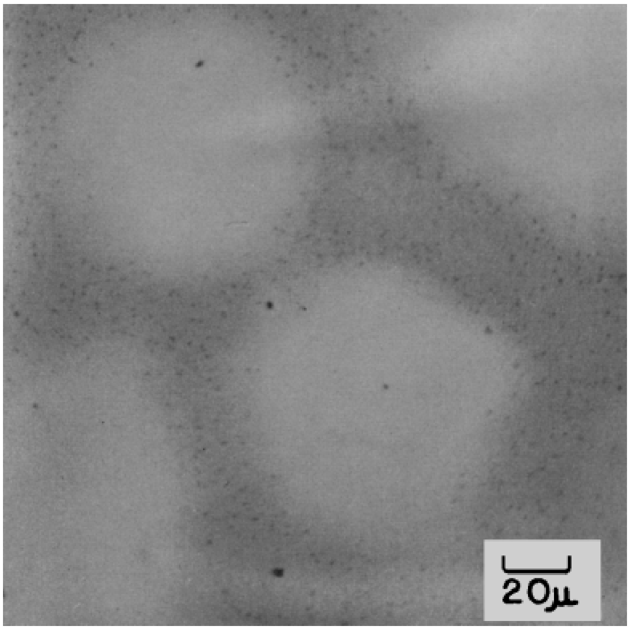

FIG. 3—*Etched surface of a slowly cooled lead alloy, containing 100 ppm antimony, showing distribution of solid solution at dendritic boundaries. Elevated antimony areas etch darker. Grain size approximately 100 μm. From Simon and Jones (33), used by permission.*

Segregation also occurs later during cooling in the solid state, as well as during solidification. A narrow region of atomic misfit, where the lattices of adjacent grains do not match in orientation, separates the grains. This region is called the grain boundary. Because of the atomic misfit, the grain boundaries are more open in structure and can accommodate nonlead atoms more easily than the regular lattice of lead atoms in the interior of the grains. That is, the grain boundaries are energetically favorable sites for preferential accumulation of nonlead atoms (30,31). Diffusion of trace and minor elements to the grain boundaries is a well-known and documented phenomenon in the field of metallurgy. If enough of the foreign atoms diffuse to the boundary, a new crystal phase may precipitate. If not, a grain-boundary "atmosphere" of these atoms forms. This is the rule, rather than the exception, for all alloys in which the solubility of the trace element decreases with decreasing temperature, and it has been well studied for lead alloys (27–29). If diffusion processes are too slow, a new particle of the favorable phase may form in the grain interior. Therefore, either new phases are formed in the interior of the grain in the solid state, or grain boundaries become a preferred concentration location for elements above their solubility limit in the solidified grain. Diffusion to the grain boundaries competes with the lowering of system energy when a new phase nucleates in the grain interior. Rapid cooling favors nucleation in the grain interior, while slow cooling, such as air cooling, favors diffusion to grain boundaries.

Which of these phenomena, and/or how much of each occurs, is a complex function of the trace element involved, the solubility limits for that element, and the cooling rate. Not all elements segregate in the same way since the size of the impurity atom, the diffusion rate of that element, and the crystal structure of any new phases all affect how segregation occurs. Metallurgists regularly use the interrelationship of these phenomena to modify the physical and chemical properties of engineering metal alloys. For soft lead of sufficiently high purity, where the trace-element levels are always below the equilibrium solubility limit, there are no major second phases formed. The solubility limits for elements such as tin, silver, bismuth, and arsenic are large enough that no second phases are expected in soft lead, although enough segregation likely occurs to form grain-boundary atmospheres where the concentrations of these elements may be slightly higher in the grain-boundary region.

VPG used only antimony in his comparisons of the various bullets and lead fragments. Prior metallurgical studies had demonstrated that visible segregation of antimony occurs at levels of antimony in the 100 ppm_w range (33), much smaller than the 600–900 ppm_w present in the MC bullets. Such segregation could easily result in large relative differences in local antimony content. Thus, grain size of the MC bullets becomes a critical issue for correct interpretation of the antimony compositional data. Segregation, such as that shown in Fig. 3, could easily cause local variations in antimony content of $\pm$ 100–200 ppm_w in the 50-mg MC material. VPG also collected data on the copper content of the samples, but he rejected assessment of the copper data because of the variability that he measured. However, segregation of copper is also to be expected and may explain the very large variation measured by VPG.

Copper is practically insoluble in lead at room temperature. The lead–copper eutectic composition corresponds to 700 ppm_w copper (36). The solubility limit of copper in pure lead is less than 70 ppm_w at room temperature, as evidenced by the copper precipitates observed at that concentration via optical microscopy (27). The exact solubility limit at room temperature is, however, unknown. We would therefore expect copper to segregate as a separate phase at the boundaries and/or form grain-boundary atmospheres in soft leads, because they normally contain from 20 to 1000 ppm copper. Figure 4 shows an example of a chill-cast microstructure of pure lead (50–200 μm grains) containing 400 ppm_w copper, wherein the copper forms a distinct new phase at the grain boundaries in the eutectic structure. A similar structure is expected at lower copper concentrations, but the quantity of copper particles observed at the grain boundaries would be less. Copper may also segregate via a different route. When a kettle of molten soft lead is refined, it is stirred forcefully up to the point of casting to keep it as homogeneous as possible. The temperature of the melt will be in the range of 350–500°C, and the density of the melt will be essentially that of lead, or approximately 13.2 g/cm^3. The melting point of copper is 1083°C, and its density at the melt temperature, where it is solid, is about 8.9 g/cm^3. Any small particles of copper remaining in the melt will tend to float. This phenomenon of layering occurs for several low-solubility elements and impurity compounds commonly found in lead alloys. Intermetallics, sulfides, oxides, and silicate stringers are routinely found entrapped in most metal alloys (27,30). During solidification, the solid particles of copper are reinserted into the liquid phase by the advancing (solid phase) dendrites. The copper will be ultimately trapped in the last liquid to solidify, i.e., at the grain boundaries. These particles of copper can be relatively large compared with those that precipitate during the eutectic transformation.

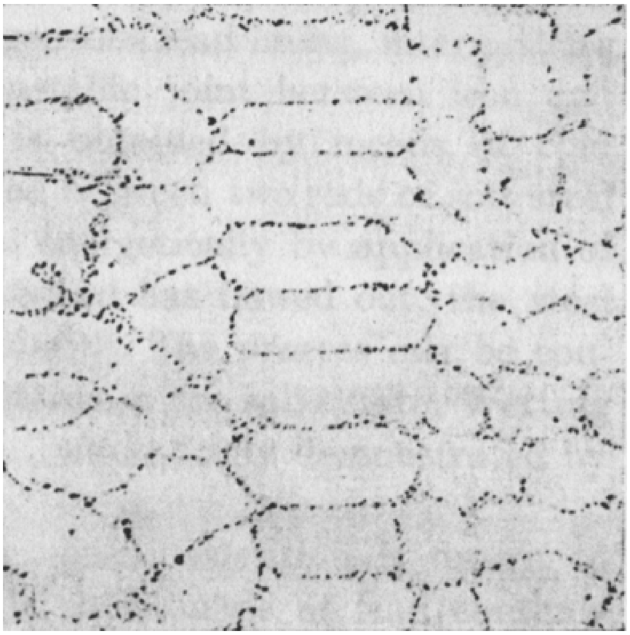

FIG. 4—*Lead/400-ppm copper alloy, chill cast and nearly pure eutectic structure. The lead crystallized as dendrites, and copper precipitated at dendrite boundaries (dark areas). Original magnification* × *150. From Hofmann (27), used by permission.*

The solubility of copper is relevant to the JFK data because VPG measured copper in the assassination fragments between 40 and 994 ppm_w (Table 1), and in the WCC evaluation bullets between 10 and 4516 ppm_w. He dismissed these data from consideration in his assessment because of the wide variations in the measured values. He attributed the variability to contamination from the jacket, but it could well have resulted from a different cause. If the grain size was sufficiently large where he obtained some of his samples, then 5–50 mg sample sizes may have been too small for reliable copper reproducibility. Moreover, it is highly unlikely that jacket contamination would have occurred in the comparison samples taken from the unjacketed tails of the unfired WCC MC bullets. The several very high concentrations of copper that he measured were most likely caused by the precipitation or entrapment of copper particles during processing.

MC Grain Size

Using Figs. 3 and 4 as visual aids, if the sample size of a lead specimen approaches the grain size, and the antimony and copper trace elements are segregated at the boundaries, then the variability of sample compositions will increase. For example, if all samples were large enough to contain on the order of 50 or more grains, they will encompass a good average quantity of both grain-boundary material and interior grain material and will be reasonable representatives of the true average composition of the alloy. However, if the samples are only the size of, e.g., one to three grains, then each sample will likely contain different relative proportions of grain-boundary material and interior grain material. This situation can result in increased compositional variability among ostensibly equivalent samples. The answer to questions of whether sample sizes were appropriate in the JFK assassination investigation, and whether they could have contributed to variability of the results, is then effectively reduced to that of assessing grain sizes.

To measure the grain size in MC ammunition, lead core samples from WCC lots 6000 and 6003 were mounted and prepared for metallographic examination.[†] The cores, as removed from the jackets, were approximately 6.5 mm in diameter and 8 mm in length. The jackets were cut from the cores by means of a hacksaw oriented longitudinally with the core, and were then peeled from the core. This protocol resulted in embedding some gilding metal

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[†] These exemplars were loaned for this study from WCC MC ammunition owned by Tom Pinkston of McKinney, TX, and were bullets designated #2, #8 and #10 according to his indexing system.

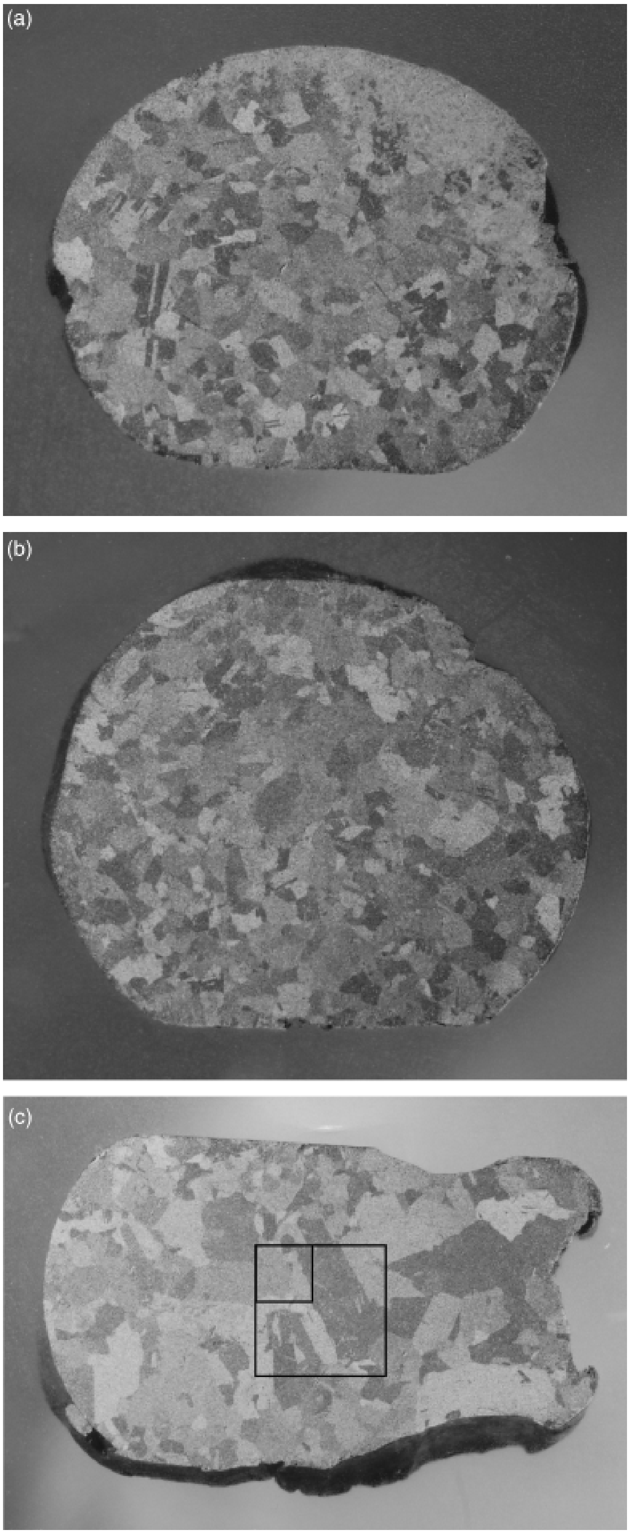

FIG. 5—*Sequential cross-sections from Western Cartridge Company Mannlicher-Carcano lot 6000, bullet #2 (Pinkston notation), macro-etched to show grain size: (a) Pinkston section A; (b) Pinkston section E; and (c) Pinkston section I. Overlaid boxes in (c) depict 50-mg and 5-mg cubes. Section I was somewhat flattened during jacket removal. Original magnification × 14.*

in the lead at the sawing locations, but this artifact was readily recognized in the subsequent cross-sections. The cores were divided into thirds, and a thin cross-sectional slice was cut from each third. The samples were chemically macro-etched to reveal overall grain structure for grain-size analysis. The etchant consisted of solutions of 15 g of ammonium molybdate in 100 mL of distilled water and 58 mL of concentrated nitric acid in 42 mL of distilled water. The two solutions were mixed together just before etching the samples by submersion. When etched with this solution, each individual grain appears optically lighter or darker than its neighbors because of variations in chemical etching characteristics arising from the different crystallographic orientations of the grains.

Figures 5 and 6 show the macrostructures of two bullets from WCC MC lot 6000. It was observed that the individual grain sizes spanned a large range, from less than 100 μm to greater than 1000 μm. The average grain dimension was approximately 500–1000 μm, and several grains were > 1200 μm in length. From a metallurgical viewpoint, the range of individual grain sizes in these specimens was quite large, to an extent that determining a valid ASTM average grain size was not meaningful. The grain size was not always uniform within any particular cross-section, nor was it uniform from slice to slice within each individual bullet. That is, the grain size was highly variable in each bullet. [The notches observed in several of the slices (at the east and west locations in Fig. 5*a* and the north and south locations in Fig. 6*a*, for example) are from the saw cuts to remove the jacket. Small amounts of embedded gilding metal were readily apparent at these locations via optical microscopy at × 10, and they had a characteristic brass color.]

A cube of lead weighing 50 mg would have edges of 1635 μm in length. Likewise, 10-, 5-, and 1-mg cubes would have edge lengths of 960, 760, and 440 μm, respectively, and lines depicting the edges of 5- and 50-mg cubes are shown in Fig. 5*c*. The grain sizes measured in these representative WCC MC samples correspond to lead specimen sizes that approach, and sometimes exceed, the sample sizes analyzed by VPG. The range of grain sizes is so large that 50-mg specimens may be representative of the local bulk bullet composition in certain areas where the grain sizes are small, such as seen in Fig. 5*a*. In other areas, however, such as the center of Fig. 6*c*, this specimen size may incorporate only one to three grains. Hence, some or all of the variability seen in VPG's antimony and copper measurements could be attributed to small sample sizes. Certainly, 5–10 mg samples should be suspect with respect to being representative of the bulk composition. Longitudinal sections of MC bullets showed this same variability in grain size. Pinkston bullet #10 from lot 6003 is shown in Fig. 7 as an example of the grain sizes seen in longitudinal sections.

These considerations apply directly to the four sub-samples from the initial 50-mg samples that VPG used to interrogate the homogeneity of individual bullets from the WCC comparison lots. If the 10–15 mg subsample inhomogeneities were, in fact, the explanation for the variability of the antimony homogeneity data presented by VPG for 6001C, 6002A, and 6003A in Appendix F (6), then statistical averaging techniques of any variety would be inappropriate for the data. The counting errors correlate inversely with the quantity of antimony present, but, because acquisition of his comparison specimens was effectively beset by sampling error, the average composition of any particular bullet could not be known as accurately as the application of any statistics would indicate. The end-result of these metallurgical considerations is that, from the antimony concentrations measured by VPG in the specimens from the JFK assassination, there is no justification for concluding that two, and *only* two, bullets were represented by the evidence. Nor is there justification for concluding that three, four, or five bullets were more or less likely than two bullets.

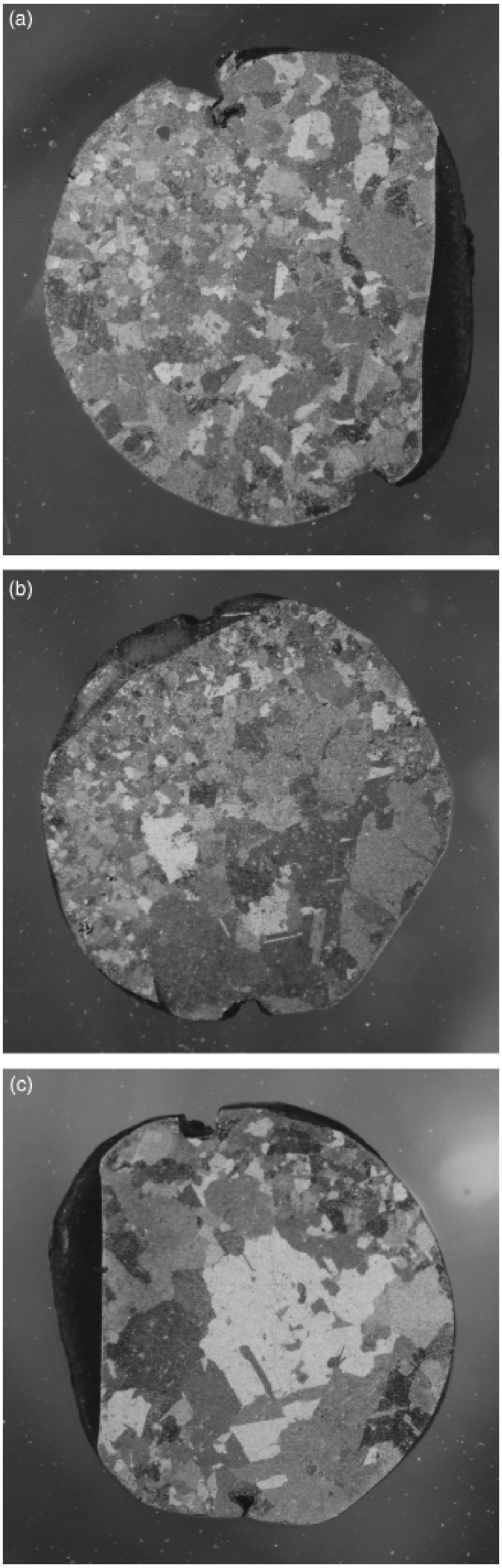

FIG. 6—*Sequential cross-sections from lot 6000, bullet #8 (Pinkston notation), macro-etched to show grain size: (a) section A, (b) section E, and (c) section I. Original magnification* × *14*

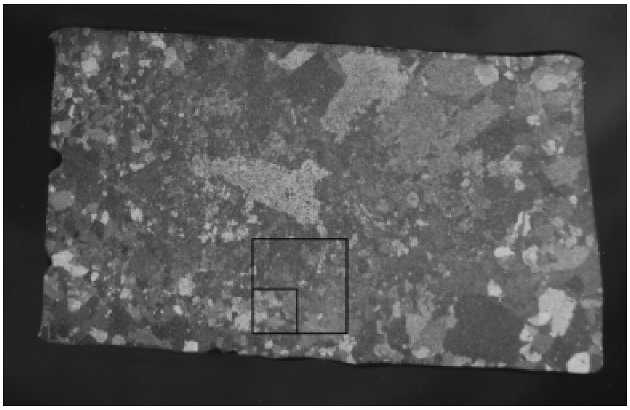

FIG. 7—*Longitudinal cross-section from lot 6003, bullet #10 (Pinkston notation). Overlaid boxes depict 50- and 5-mg cubes. Original magnification* × *10.9.*

The copper data present somewhat more challenge in interpretation in that two very high copper measurements were made by VPG in 6001A (2766 ppm_w) and 6002D (4516 ppm_w). If these values were due to jacket contamination, activated zinc isotopes should also have been present in the γ-ray spectra, reflecting approximately 270 and approximately 450 ppm_w, respectively, for these samples. It is not known whether such nuclides were observed by VPG. However, the very low solubility, and segregation or physical entrainment of copper particles, is a likely explanation for the variability measured in VPG's copper data.

Conclusions

A more complete statistical treatment of VPG's empirical data demonstrates that the inherent variability in known samples of single bullets, as well as a full propagation of error of pertinent uncertainties, must be taken into account to elevate experimental precisions to overall accuracies. Counting statistics alone do not fully represent the accuracies of the NAA measurements. Repetitive measurement precision and sample homogeneity must also be factored in at a minimum. Under the (incorrect) conclusion that exactly two bullets are specified by the antimony measurements of the JFK bullet evidence, such consideration increased an assessment of the relative accuracy of the measured data to 13%, a factor of ~ 20 greater than the precision indicated by counting statistics alone. This accuracy reduced the minimum overlap of errors of the two Gaussian distributions from $>4\sigma$ to 1.6σ, resulting in a reduction from 99.99% to 89% inclusion of the populations.

The basic metallurgical phenomena of segregation, grain-boundary atmosphere formation, and precipitation of second-phase particles in the lead matrix must be considered when interpreting the data obtained by VPG. Prior studies have shown that these effects occur in soft leads analogous to the MC lead central to JFK assassination considerations. The large and variable grain sizes found in bullets from WCC MC ammunition lots 6000 and 6003 show that the 1–50 mg specimen sizes that VPG was restricted to for the JFK analyses could have contributed to, or been the sole source of, the variability found in the antimony and copper data. Furthermore, VPG's own earlier bullet lead studies showed that quantitative comparison of even three elements was inadequate to completely characterize individual bullets from different sources. Hence, the relatively small differences reported in antimony composition alone in the JFK data are not adequate to differentiate among the possibilities of a single or multiple bullets. The fragments from the assassination scene, solely on the basis of compositional analysis, could have derived from one to five individual bullets. The compositional data are inconclusive.

We therefore assert that, from perspectives of standard metallurgical practice and statistical assessment of the fundamental NAA measurements (and despite the opinion of Rahn and Sturdivan that their assessment is definitive and puts the matter to rest), a conclusion of material evidence for only two bullets in the questioned JFK assassination specimens has no forensic basis. Although collateral information from the overall investigation might very well narrow the choices, as stand-alone primary evidence, the recovered bullet fragments could be reflective of anywhere between two and five different rounds fired in Dealey Plaza that day. Only the near-complete mass of CE-399, the stretcher bullet, precludes the conclusion of one to five rounds. Moreover, the fragments need not necessarily have originated from MC ammunition. Indeed, the antimony compositions of the evidentiary specimens are consistent with any number of jacketed ammunitions containing unhardened lead.

Acknowledgments

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