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Particle Analysis for the Detection of Gunshot Residue. I: Scanning Electron Microscopy/Energy Dispersive X-Ray Characterization of Hand Deposits from Firing

Several methods of bulk elemental analysis, such as flameless atomic absorption, flame emission spectroscopy, neutron activation analysis, and photoluminescence spectroscopy, can reliably and quantitatively determine the amounts of antimony and barium (antimony and lead in the case of photoluminescence) removed from the hand. The information thus furnished, however, in most cases is not sufficient to constitute presumptive evidence of the presence of gunshot residue. Many analyses are inconclusive because the amounts of antimony and barium (lead) are less than certain "thresholds" considered necessary because these elements are not unique to gunshot residue. Firings from .22 caliber weapons, unless the cartridge is known to be a Federal brand, are not usually analyzed because domestic rimfire primers, except Federal, do not contain antimony. Understandably, there has been great interest in alternative analysis methods capable of furnishing additional information of potentially higher specificity for gunshot residue.

A few authors have remarked on the apparently characteristic appearance of micrometre-sized particles of gunshot residue that are observable in the scanning electron microscope (SEM) [*1-3*]. Several have pursued investigations of this phenomenon [*4-6*]. Following a detailed study, we have developed the use of the SEM, equipped with energy dispersive X-ray (EDX) analysis capability, into a practical tool for the detection of gunshot residue that has achieved a high rate of success in extensive case work. The report [*7*] describing all of this work in detail has been written so that it can be used as a training manual as well. It is recommended that anyone wishing to practice the SEM method obtain a copy of the report from the authors. In this series of three articles, we attempt only to acquaint the reader with the major findings. The present paper describes the nature of the residue from small arms cartridges as found on the hands of shooters and analyzed by SEM/EDX. The criteria for identification are given. The second paper in the series will similarly describe certain occupational residues that need to be distinguished from gunshot residue. The final paper will describe and discuss the results of about 100 case analyses performed for law enforcement agencies.

Capsule Summary of the Method and Its Capability

Particle analysis employs an SEM equipped with an X-ray analysis capability so that

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gunshot residue removed from the hand by a simple adhesive lift technique can be examined at high magnification. When viewed in this way, gunshot residue consists of discrete, micrometre-sized particles, predominantly spheroidal, and often of characteristic appearance. The X-ray analyzer will identify all chemical elements heavier than sodium contained in each individual particle. The only elements possible for gunshot residue are those that can be derived from the constitution of the bullet, a coating or jacket over the bullet, and ingredients of the primer. The morphology of the particles allows them to be readily found among the general debris (skin salts, minerals, and adhesive) lifted from the hand, and the chemical composition identifies them. Some particles are uniquely identifiable as gunshot residue by virtue of only their compositions. Other compositions are less distinctive but, when combined with morphological information, are still typical of gunshot residue. Least characteristic are irregularly shaped particles composed of only lead, but even these can often be distinguished from particles from the exhaust of an automobile, which is the most common source of environmental lead contamination.

The ability to identify gunshot residue particles uniquely and to distinguish them from environmental sources of lead, barium, and antimony eliminates the threshold problem inherent in bulk elemental analysis. Although the amount of gunshot residue on the hand of a live subject declines rapidly with time, this independence from a quantitative restriction makes detection possible for up to 12 h after a firing in favorable cases and accounts for the superior success rate of particle analysis as compared to previous methods.

Characterization of Hand Deposits from Firing

Composition and Morphology

Most often, morphological criteria are employed to find likely residue particles in a systematic search in the SEM, and X-ray analysis of each particle is then used to decide whether it is (1) gunshot residue, (2) probably gunshot residue, (3) possibly gunshot residue, (4) something other, known, or (5) something other, unknown.

Compositional Criteria for Identification—The following four compositions have thus far been observed only in gunshot residue and are therefore considered characteristic:

(1) lead, antimony, and barium;
(2) barium, calcium, and silicon, with a trace of sulfur;
(3) barium, calcium, and silicon, with a trace of lead if copper and zinc are absent;[2] and
(4) antimony and barium.

Any particle having one of these compositions may also contain one or several of the following and only the following elements: silicon, calcium, aluminum, copper, iron, sulfur, phosphorus (rare), zinc (only if copper is also present), nickel (rare, and only with copper and zinc), potassium, and chlorine. Some tin may be present in obsolete ammunition. The following compositions are consistent with gunshot residue but are not unique to it:

(1) lead and antimony;
(2) lead and barium;
(3) lead;
(4) barium if sulfur is absent or present only as a trace; and
(5) antimony (rare).

[2]This composition, but with copper and zinc also present, occurs in residue from stud guns (a firearm used in construction for driving nails, rivets, and staples). This entry is an addition to the list published in Ref 7. The reader is cautioned that the criteria may undergo reevaluation with continued experience.

Again, any of the additional elements listed above, and only those, may be present. The first two compositions, although not unique, have been found in only a few occupational residues [*8*]. They are thus fairly characteristic although not conclusive.

The compositions, shapes, and sizes of a collection of particles found in a sample should fall into a pattern consistent with the distributions described in later sections. Furthermore, particles that are consistent with gunshot residue individually should not be found with otherwise similar particles that are inconsistent with gunshot residue [*8*]. For example, an ample deposit of particles in the consistent category, but with none of the unique ones, would be considered probably gunshot residue if there are no particles inconsistent with gunshot residue but similar enough in composition and morphology to the consistent ones that they might have a common origin. This reservation does not apply if these inconsistent particles (but not the consistent ones) can be assigned to a known separate origin. Examples of particles with a clearly identifiable separate origin are automobile exhaust and lighter flint residue. In the presence of inconsistent particles not clearly identifiable in this manner, the entire sample is rejected as evidence for gunshot residue. If so few consistent (and no other) particles are found that one cannot know whether or not they are typical of the presumably larger population originally present, then the only finding that can be issued is that some particles have been found that are consistent with but are not unique to gunshot residue. Such a finding can still be of value in those cases where the only question to be answered is a choice between one suspect or another.

Bullet and Primer Particles—Cartridges with bare lead bullets give residues that contain a large excess of lead-only particles (or lead-plus-copper particles if the bullet is coated). Jacketed bullets give substantially fewer lead-only or lead-plus-copper particles. For this reason, it is inferred that most of the lead particles are derived from the bullet and, in this report, are classified as bullet particles, provided that, in addition to lead, they contain only elements that can come from a coating or jacket, and provided that they contain no more than a trace of antimony.[3]

Particles that contain more than traces of barium, antimony, or silicon are classified as primer particles.

These definitions may somewhat underestimate the number of particles actually derived from the primer. Primers also contain lead, and since primer residue is very heterogeneous, some pure lead particles could originate in the primer.

The simple division into bullet and primer particles is highly useful for descriptive purposes, but it is arbitrary. Most of the spheroidal (see the following section) particles are thought to arise by condensation from the vapor state. Given sufficient time, all vapors will mix thoroughly. The heterogeneous nature of residue is probably due to the limited mutual solubility in the solid state of metals and compounds. This causes them to segregate upon solidification. The solid residue from primer mixtures consists, after detonation, only of compounds (for example, lead styphnate is likely to produce lead oxide rather than lead). On the other hand, metals evaporating from the bullet (lead, copper if present) will turn only partially into oxides or sulfides before they condense. The portion that remains metallic will condense into the separate metal particles that are designated bullet particles in this discussion, whereas the oxidized portion may dissolve in the primer particles. This is why copper from bullet coatings or jackets is found in both types of particles.

Morphology and Size—The four types of objects found in gunshot residue are described in the following paragraphs. In the majority of cases, 70 to 100% of the particles in a sample of gunshot residue are spheroidal. These may be perfect spheres, or they may be stretched, dented, or otherwise distorted, but "three-dimensional roundedness" is a characteristic of this classification. The surfaces of the spheroids may be smooth or fuzzy,

[3]"Trace" refers to an amount that is "just detectable" by the method.

scaly, or covered with smaller spheres. Occasionally, they are capped, perforated, broken, or stemmed. A few examples are shown in Fig. 1. A more complete picture atlas is part of the original report [7].

The vast majority of the spheroidal particles have diameters of less than 5 μm. For practical reasons, no attempt is made to detect and count particles less than 0.5 μm in diameter. When characterizing a particular residue, we counted the number of particles in each of several size ranges. Because the numbers decline drastically with increasing size, the larger size ranges are chosen to be wider through the use of a logarithmic scale with base 4 for the diameters. Each size range is four times as wide in particle diameters as the next smaller one, and its midpoint is four times that of the next smaller range. The resulting scale is as follows:

Designation	*Range, μm*	*Midpoint, μm*
A	0.5 to 2.0	1.25
B	2.0 to 8.0	5.00
C	8.0 to 32.0	20.00
D	>32	...

Most of the remaining gunshot residue particles (rarely more than 30%, depending on the ammunition) are irregular. These are particles that have the same compositions as the spheroidal particles but do not share the spheroidal or globular shape. They are irregular fragments, not infrequently somewhat flattened and flaky-looking. It is important to note that they do not exhibit any features suggestive of crystal fragments: there are no crystal faces or edges. Gunshot residue is not visibly crystalline, although diffraction methods (X-ray or electron diffraction) do give crystal patterns. The sizes of the irregular particles vary over a wide range, from less than one to several hundred micrometres. Because quite often they are few in number, no statistics concerning their size distributions have been taken. Like the spheroidal particles, their compositions divide

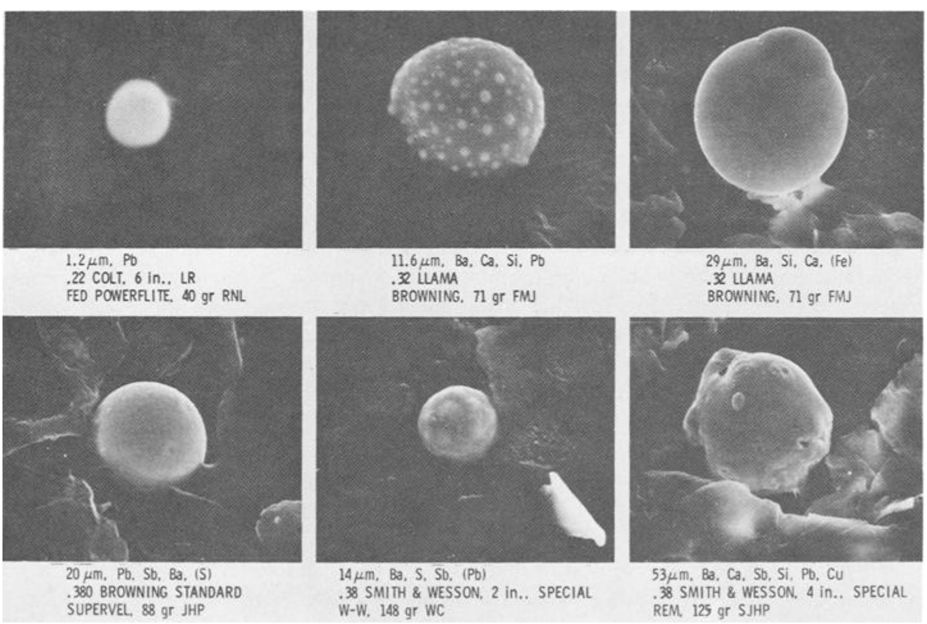

FIG. 1—*Examples of spheroidal particles.*

them into bullet and primer particles. While this information has been recorded, it is not quoted here. Sometimes the ratio of irregular bullet to primer particles is similar to that of the spheroidal particles, and sometimes it is not. However, because of the frequently small numbers involved, these ratios may not be meaningful.

Despite the nondescript (our original term for them) appearance of the irregular particles, experienced operators have learned to recognize them. Sometimes they have obvious, distinguishing features. For example, cracks running through the particles are rather characteristic. The larger irregular particles often have several of the small spheroidal particles attached to them, and this is highly characteristic. Figure 2 shows some irregular particles.

A third type of particle of very limited occurrence is the cluster, consisting of from five to several hundred spheroidal particles attached to one another, somewhat like a bunch of grapes. Sometimes the cluster is further attached to an irregular particle as if on a tray, or an irregular particle runs through the center of the cluster. They have been observed with some frequency in residue from 9-mm cartridges, less often from .357 Magnum cartridges, and quite infrequently from .38 Special cartridges. Clusters appear to be primarily a product of high power or high velocity.

The final type of object that may occur in gunshot residue is a fragment of smokeless powder. It is always referred to as a "flake" in this report to set it apart from the "particles," which are inorganic. The flakes range in size from micrometres to almost a millimetre. They are few in number and are mostly seen in residue collected immediately after firing. Quite often, a few spheroidal particles are embedded in the surface of a flake.

The spheroidal particles are thought to result by rapid condensation from a vapor, whereas the irregular particles may be produced by the solidification of droplets of molten material on interior surfaces of the gun.

Procedures and Results

Characterization of Residue—To characterize the residue from a particular cartridge

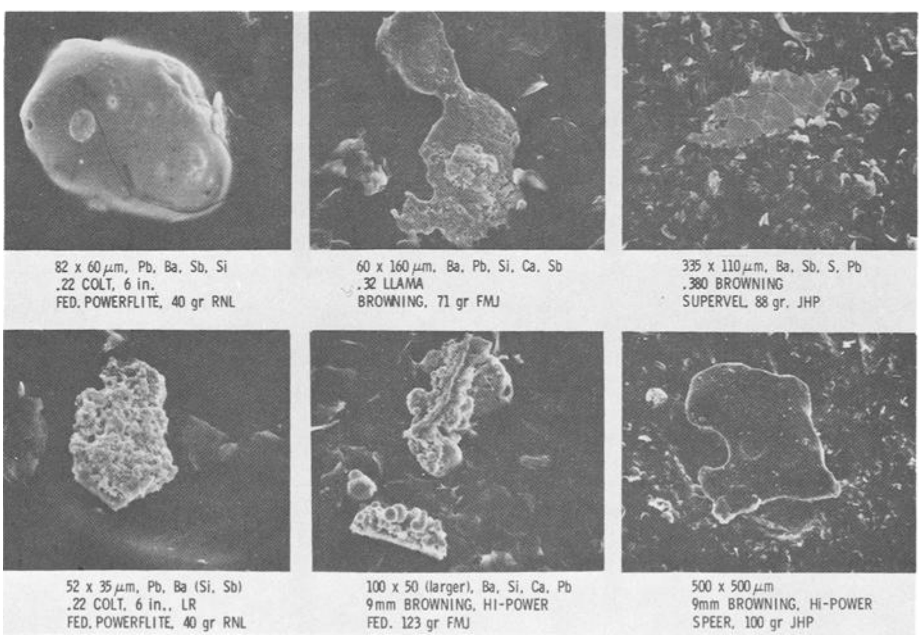

FIG. 2—*Four irregular particles, a cluster* (bottom, middle), *and a flake* (bottom, right).

it is essential to start with a clean gun, or else residue from previous firings may be mixed with residue from the current firing. On several occasions, antimony-containing particles were found in test firings of .22 caliber ammunition whose primer did not contain antimony. The antimony was never in evidence if the gun was given a thorough cleaning prior to firing the antimony-free ammunition. Particles containing copper seem to have even more tenacious retention characteristics.[4] If coated or jacketed bullets have been previously shot from a weapon, it is common to find a few particles containing copper in residue from plain lead bullets. These are few in number compared with coated or jacketed ammunition, which usually gives residue in which many more particles contain copper. Zinc may be observed to accompany copper in some particles. Some coatings or jackets are yellow brass, containing 30 to 35% zinc, in which case most particles containing copper also contain zinc.

Residues were characterized by firing a single cartridge, one-handed, with clean hands. The firing hand was then sampled by a standardized procedure, and the process was repeated by using either the other hand of the same person or that of another person. (The numbers of particles listed in Tables 1 through 4 apply when the standard sampling disk is used as described in this report. The use of other equipment or procedures will require the numbers to be multiplied by a normalization factor.) From three to seven cartridges (five in most cases) were fired, involving from two to five different persons. The samples were then analyzed and the results averaged. Standard deviations for particle counts ranged from 30 to 125%. The mean standard deviation was 76% and the standard deviation of the standard deviations was 30%. The deviations include the random variations from cartridge to cartridge, the differences between hands, and the residual fluctuations resulting from extrapolation from the disk area actually surveyed to the total area of the disk.

TABLE 1—*The .22-caliber*

Test	Spheroidal Particles		Irregular Particles Above Spheroidal, %	Velocity		Type of Gun	Barrel Length	
	n	Fraction from Bullet		fps	m/s		in.	mm
24	16 800	0.97	0.4	815	248	revolver	2½	63.4
25	17 700	0.99	1.9	848	258	revolver	2½	63.4
21	3 550	0.93	1.0	858	262	revolver	2½	63.4
Mean[d]	9 800	0.96	1.5	853	260	...	...	...
23	2 426	0.92	4.5	969	295	revolver	2½	63.4
71	346	0.88	7.2	1000	305	automatic	4¾	120.7
81	239	0.80	20.5	1066	325	revolver	6	152.4
83	110	0.72	23.6	1168	356	revolver	6	152.4

[a] 40 grain = 2.59 g; RNL = round nose lead; N/A = not applicable.

[b] Range A = 0.5 to 2 μm; Range B = 2 to 8 μm; Range C = 8 to 32 μm.

[c] Minor.

[d] The mean of two cartridges with nearly the same velocity (Tests 25 and 21).

[4] Recent experiments with tracers have shown that even quite thorough gun cleaning by conventional means will not eliminate all residue. This work will be described in a future report.

Standard deviations for the ratio of bullet to primer particles tended to be significantly lower than the standard deviations for total particle counts. For example, in one test series the mean of six determinations was 5315 ± 3622 (68%) for total particles, while the mean for the percentage of primer particles was 50.5 ± 14.4 (29%). In another test series, the mean of five determinations was 203 ± 81 (40%) for total particles and 65.4 ± 10 (15%) for the percentage of primer particles.

Assuming a standard deviation of 100% for particle counts, it follows that variations by factors of three of more from the mean are highly unlikely. With some exceptions, variations of this magnitude were not observed.

Particle counts eight to ten times the mean were observed in a few firings. This was tentatively attributed either to deterioration of the smokeless powder or to a defective primer that caused less than full power to be developed, with a resulting lowered muzzle velocity and a higher particle count. Higher particle counts could also result from misalignment of the firing chamber and barrel, which would cause shaving of the bullet. Lower than expected particle counts can be attributed to a defective adhesive coating of the collection disk (resulting in a lower collection efficiency) or to faulty procedures.

Particles containing antimony are defined as particles in which antimony is a major or minor constituent, not those particles containing trace amounts of antimony. The designation of components as major or minor is based on X-ray intensities rather than on concentrations. The antimony content of bullet lead ranges from near 0 to 3.5%, except when reloaders use lead not specifically intended for bullet manufacture. When this occurs, the antimony content may exceed 4%. Shotgun pellets can range up to 6.5% [9]. In the analysis of residue from some firings, trace amounts of antimony were found in many of the bullet particles. Such residue probably came from bullets with an anti-

cartridge test results. [a]

Bullet		Bullet Particles per Size Range, [b] %			Primer Particles per Size Range, [b] %			Particles Containing Copper, %		
Weight, grain	Type and Brand	A	B	C	A	B	C	Bullet	Primer	Irregular
40	Federal Champion, RNL	94	...[c]	...[c]	39	56	...[c]	N/A	N/A	N/A
40	Remington Pistol Match, RNL	92	...[c]	...[c]	99	...[c]	...[c]	N/A	N/A	N/A
40	Western Super X, RN, Lubaloy	91	...[c]	...[c]	36	58	...[c]	76	13	53
...	...	...	...	...	...	...	...	...	...	...
40	Federal Powerflite, RNL	85	...[c]	...[c]	46	44	...[c]	N/A	N/A	N/A
40	Western Super X, RN, Lubaloy	83	...[c]	...[c]	28	58	...[c]	38	2	12
40	Western Super X, RN, Lubaloy	44	53	...[c]	30	45	...[c]	44	19	49
40	Federal Powerflite, RNL	48	42	...[c]	10	23	48	N/A	N/A	N/A

TABLE 2—*The .38 Special*

Test	Spheroidal Particles		Irregular Particles Above Spheroidal, %	Velocity		Type of Gun	Barrel Length, in.
	n	Fraction from Bullet		fps	m/s		
15	7600	0.39	~0	665	203	revolver	2
11	3200	0.78	1	703	214	revolver	2
12	2900	0.96	0	706	215	revolver	2
41	6500	0.82	1.6	758	231	revolver	4
13	100	0.93	7	806	246	revolver	2
16	100	0.45	42	682	208	revolver	2
46	1400	0.73	40	767	234	revolver	4
14	75	0.35	8	875	267	revolver	2
44	200	0.32	21	885	270	revolver	4

[a] WC = wadcutter; RNL = round nose lead; LHP = lead hollow point; FMJ = full metal jacket; SJHP = semi-jacketed hollow point; N/A = not applicable; 2 in. = 50.8 mm; 4 in. = 101.6 mm; 125 grain = 8.10 g; 148 grain = 9.59 g; and 158 grain = 10.24 g.
[b] Range A = 0.5 to 2 μm; Range B = 2 to 8 μm; and Range C = 8 to 32 μm.
[c] Minor.

mony content near the high end of the quoted range. The detection limit for antimony in lead is poor because of the high absorption of lead for X-rays.

Copper is found in both bullet and primer particles if the bullet is coated or jacketed. The fraction of particles that contain copper and the division of that fraction among the various classes of particles have some degree of reproducibility for a given cartridge, but that reproducibility is poorer than for the other characteristics measured. Furthermore, the variations from one cartridge type to another appear quite irregular, without discernible systematic trends. The occurrence of a few copper-bearing particles in residue from ammunition with bare lead bullets has been attributed to retention in the gun of residue from previous firings with coated or jacketed bullets. This retention does occur, as explained in the antimony discussion. There are other mechanisms by which copper can enter the residue, but these mechanisms can only play a subordinate role, as evidenced by the fact that if copper-bearing particles are found at all in residue from bare lead bullets they are few in number. Quite rarely, microscopic fragments of brass are found in residue. These may have been torn from the front edge of the cartridge case. A quantity of brass may be vaporized from this edge and mix with the other residue vapors. Evidence for this occurrence is furnished by the infrequent observation of nickel in a residue particle that also contains copper and zinc. The nickel must come from the nickel plating of the brass case. It is also conceivable that copper could be evaporated from the anvil in the primer, but there is no evidence that this happens. Finally, copper may be present in some primers, but this does not appear to be common, if it occurs at all.

Standard deviations have been specified for normal distributions. However, there is strong evidence that the variations in particle counts have lognormal distributions [*7*]. The practical implication is that the appropriate standard deviation is not a quantity specified in the form $\pm x$ but is a multiplicative or divisive factor, whose value has ranged between 1.5 and 3.0 in this work.

cartridge test results.[a]

Bullet		Bullet Particles Per Size Range,[b] %			Primer Particles Per Size Range,[b] %			Particles Containing Copper, %		
Weight, grain	Type and Brand	A	B	C	A	B	C	Bullet	Primer	Irregular
148	Winchester-Western WC	90	...[c]	...[c]	41	59	...[c]	N/A	N/A	N/A
158	Remington, RNL	97	...[c]	...[c]	45	50	...[c]	N/A	N/A	N/A
158	Federal, RNL	91	...[c]	...[c]	96	...[c]	...[c]	N/A	N/A	N/A
158	Remington, RNL	91	...[c]	...[c]	64	30	...[c]	N/A	N/A	N/A
158	Winchester-Western Super X, LHP	42	45	...[c]	0	71	29	N/A	N/A	N/A
158	Remington Metal Point, FMJ	33	33	34	11	45	34	0	13	21
158	Remington Metal Point, FMJ	73	26	...[c]	16	57	24	1	2	4
125	Remington SJHP	48	40	...[c]	12	57	29	5	0	33
125	Remington, SJHP	53	45	...[c]	33	55	12	3	8	7

Results for Cartridges by Family—Gun-cartridge combination test firing results are identified by two-digit or three-digit numbers in subsequent sections and in the tables. All digits except the last digit of these numbers identify the gun. The last digit refers to the cartridge within a particular family. Reference 7 includes tables with full specifications for the weapons and cartridges identified by these numbers.

Five different .22-caliber brands or versions of 2.59-g (40-grain) round-nose ammunition were tested. One had Lubaloy®-coated bullets and the others were lead bullets without coatings. Two revolvers and one autoloading pistol were used, all with different barrel lengths. Seven different combinations of the three guns and five cartridges were tested and the residues were characterized. The results are listed in Table 1. The relationship between the total number of spheroidal particles and the muzzle velocity of the bullet is shown by the upper solid line on a semilogarithmic plot in Fig. 3. The least-squares equation for this line is

$$\log N = 9.59 - 0.00664v$$

where N is the total number of spheroidal particles on the sampling disk and v is the muzzle velocity in ft/s. The value of N declines one order of magnitude for each 145 ft/s (44 m/s) increment in velocity. Within the precision of the measurements, the decline is the same whether the velocity is increased by firing the same cartridge from increasingly longer barrels, as in the series (21, 71, 81) or (23, 83), or whether it is increased by firing more and more powerful cartridges from the same gun, as in test series (24, 25, 23) or (81, 83). This equivalence is emphasized because it does not seem to hold for .38-caliber cartridges.

Along with the drastic decline in the total number of spheroidal particles with increased velocity goes a modest but definite change in the ratio of bullet to primer particles. The

TABLE 3—*The 9-mm parabellum (Luger) and .380 ACP (9-mm short) test results.*[a]

	9-mm Parabellum		.380 ACP	
	Test 61	Test 62	Test 53	Test 51
Spheroidal particles				
n	166	26	244	52
Fraction from bullet	0.40	0.19	0.17	0
Irregular particles above spheroidal, %	4.8[b]	57.7[c]	22.6[d]	23[e]
Velocity				
fps	1144	1195	840	1044
m/s	349	364	256	318
Type of gun	automatic	automatic	automatic	automatic
Barrel length				
in.	4⅔	4⅔	4 7/16	4 7/16
mm	118.5	118.5	112.7	112.7
Bullet weight				
grain	123	100	95	88
g	7.97	6.48	6.16	5.70
Bullet type and brand	Federal, FMJ	Speer, SJHP	Remington, FMJ	Supervel,[f] JHP
Bullet particles per size range,[g] %				
A	3	0	73	N/A
B	42	60	27	N/A
C	51	40	0	N/A
Primer particles per size range,[g] %				
A	1	0	3.5	0
B	25	29	51	21
C	50[h]	62[i]	34	77
Particles containing copper, %				
Bullet	3	0	0	N/A
Primer	3	0	4	12
Irregular	50	23	2	25

[a]FMJ = full metal jacket; SJHP = semi-jacketed hollow point.
[b]1.2% irregulars, 3.6% clusters.
[c]50% irregulars, 7.7% clusters.
[d]21% irregulars, 1.6% clusters.
[e]21% irregulars, 2% clusters.
[f]Bullet totally enclosed.
[g]Range A = 0.5 to 2 μm; Range B = 2 to 8 μm; and Range C = 8 to 32 μm.
[h]Plus 24% Size D (732 μm).
[i]Plus 12% Size D (732 μm).

percentage of bullet particles decreases from 97 to 72% over the range covered by the tests. Over the same range, there is a substantial increase in the proportion of irregular particles. Expressed as an added percentage over and above the spheroidal particles, which are taken as 100% in each case, the irregulars increase from near 0 to over 23%. A further change with increasing velocity is a gradual increase in the average size of the particles. For example, the percentage of bullet particles in the smallest size category (Size A) decreases from 94 to 48%, with a corresponding increase in the larger categories. Table 1 shows the following striking exception to this rule: in Test 25, 99% of the primer particles fell into Size A, well outside the trend of the remaining tests. The primer of this particular cartridge does not contain any barium compounds. There is reason to believe that the presence of barium favors the formation of larger particles. Particles in which barium is predominant tend to be among the largest observed.

TABLE 4—*The .357 Magnum cartridge test results.*[a]

	Test 103	Test 102	Test 101	Test 104
Spheroidal particles				
n	6650	252	383	225
Fraction from bullet	0.95	0.72	0.84	0.89
Irregular particles above spheroidal, %	4	18	15	11
Velocity				
fps	1425	1217	1447	1522
m/s	434	371	441	464
Type of gun	revolver	revolver	revolver	revolver
Barrel length				
in.	6	6	6	6
mm	152.4	152.4	152.4	152.4
Bullet weight				
grain	158	158	125	110
g	102.4	102.4	8.10	7.13
Bullet type and brand	Western Super X, SWC, Lubalov	Norma, SPFN, SJ, SWC	Remington High Speed, SJHP	Supervel, JSP, SJFN
Bullet particles per size range,[b] %				
A	92	93	96	79
B	...[c]	...[c]	...[c]	20
C	...[c]	...[c]	...[c]	...[c]
Primer particles per size range,[b] %				
A	71	46	39	17
B	21	32	23	67
C	...[c]	14	32	...[c]
Particles containing copper, %				
Bullet	96	62	74	58
Primer	83	48	29	38
Irregular	96	28	55	38

[a]SWC = semi-wadcutter; SPFN = soft-point flat nose; SJ = semi-jacketed; SJHP = semi-jacketed hollow point; JSP = jacketed soft point; SJFN = semi-jacketed flat nose.
[b]Range A = 0.5 to 2 μm; Range B = 2 to 8 μm; and Range C = 8 to 32 μm.
[c]Minor.

The .38 Special tests involved six cartridges and two revolvers with different barrel lengths. Four of the cartridges had bare lead bullets of either round-nose, wadcutter, or hollow-point construction. One cartridge had a full-metal-jacket round-nose bullet, and the last a semi-jacketed hollow point. Altogether, nine gun-cartridge combinations were tested (Table 4).

The decline in the number of spheroidal particles with increasing muzzle velocity is again apparent. The other trends that were quite regular for the .22 cartridges are much less regular, or absent. Instead, the distributions divide the cartridges into two distinct groups. With the exception of the wadcutter, the cartridges with bare lead bullets produce residues with a high percentage of bullet particles and a very low percentage of irregular particles, while the jacketed bullets (both full and semi) give residues that are much lower in bullet particles and much higher in irregular particles.

The similar behavior of fully jacketed and partly jacketed bullets can be understood by noting that the so-called full-metal-jacket, while covering the nose of the bullet, leaves its base exposed. The semi-jacket covers the base of the bullet, but (with some exceptions) it leaves part of the nose exposed, so that in both cases the lead of the bullet is partly covered and partly exposed.

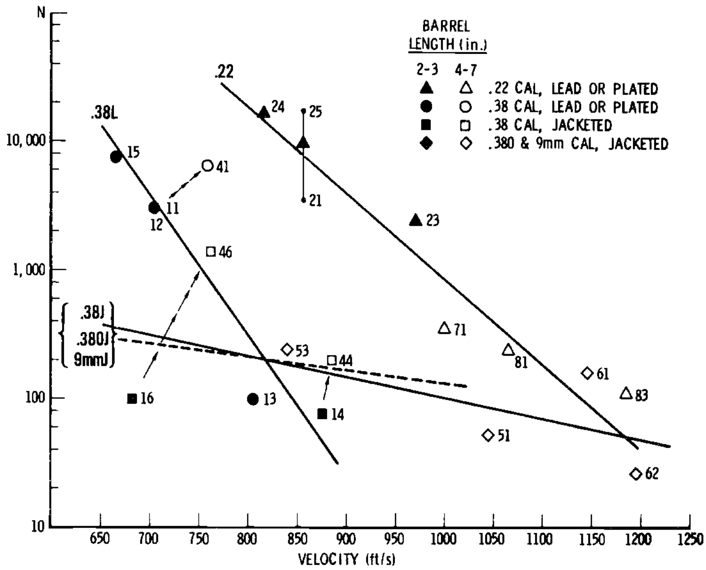

FIG. 3—*Number of spheroidal particles versus muzzle velocity.*

Only a speculative explanation can be offered for the anomaly of the wadcutter's lower percentage of bullet particles. The wadcutter is unique in that its bullet is totally recessed into the case. There are some indications that most of the residue found on the hand may be produced early in the firing cycle. If most of the residue was produced before the bullet is entirely free of the case, the case could act like a part-jacket.

The data in Table 2 again show one anomaly in the size distribution of the primer particles, in Test 12. This was a Federal cartridge, and its primer contained less barium than the primers used in most other .38-caliber cartridges.

The many class differences between jacketed and nonjacketed .38-caliber cartridges make it unlikely that both groups should be plotted on a single line to express the number of particles versus velocity relationships. In fact, when this was tried and a least-squares line was put through all the points, some of the points were far off the line. For this reason, the data were evaluated separately for the two groups (see Fig. 3). The steeply sloped line applies to the lead bullets. The equation of the line is $\log N = 11.6 - 0.0108v$. The dotted line, whose equation is $\log N = 3.15 - 0.00102v$, is the least-squares extrapolation of the four tests for jacketed bullets. This dotted line was also a good fit for two tests of .380 and two tests of 9-mm ammunition, all jacketed. Although these are different types of cartridges, their bullet diameters within the usual tolerances are the same as .38 Special ammunitions, and some of the bullets themselves are interchangeable. Consequently, a new least-squares calculation was performed for the combined group of the four jacketed .38-caliber cartridges and the four others. This resulted in the solid line that differs very little from the dotted line in Fig. 3. Its equation is $\log N = 3.64 - 0.00162v$.

However, it must be noted that in contrast to the .22-caliber cartridges, a 102-mm (4-in.) barrel gave more residue on the hand than the same ammunition shot from a 51-mm (2-in.) barrel, in spite of the higher velocity it produced. This difference was observed for all three of the pairs tested, namely (11, 41), (16, 46), and (14, 44), which are connected by arrows in Fig. 3. This behavior suggests that the number of particles ejected onto the hand is not only inversely proportional to the bullet's muzzle velocity, but also has a weaker direct relationship to barrel length, possibly because of the stripping effect of the rifling on the bullet. In the case of the .22-caliber cartridges, longer barrels produced considerable increases in velocity, causing the velocity effect to predominate. For the .38 Specials, the increase in velocity was much more modest, allowing the direct effect of barrel length to be observed. The existence of these effects seems established, but the reasons for their existence are not understood.

Only two types each of the 9-mm and .380 ACP (9-mm Short) cartridges were tested. Some of the regular trends noted for the .22-caliber cartridges are apparent in this ammunition, as shown in Table 3. Test 51 requires additional comment because the percentage of spheroidal bullet particles dropped to zero. The jacket of this bullet resembles the semi-jackets found on most other hollow points in that it covers the base of the bullet but, unlike other hollow points, it rises along the sides of the bullet to the edge of the hole in the nose. This is called a totally enclosed bullet, and the formation of bullet particles would be expected to be suppressed more severely than in the case of a jacket that leaves some of the lead exposed. Despite the consistency of this explanation, it was not valid in the testing of another totally enclosed bullet in a one-round firing. A Winchester-Western 9-mm Luger cartridge with a 6.48-g (100-grain) jacketed hollow point bullet gave 30% spheroidal lead particles. As previously stated, a small but unknown fraction of the bullet particles may come from the primer. Therefore, the effect of total enclosure needs further investigation. On the whole, the fraction of bullet particles seems to correlate with the area of exposed lead in the bullet.

A single revolver with a 152-mm (6-in.) barrel was used to test three .357-caliber cartridges with jacketed bullets and one cartridge with a Lubaloy-coated bullet.

The .357-caliber cartridge is approximately the same caliber as the .38 Special or 9-mm cartridges but, unlike them, it uses a longer cartridge case, larger powder charge, and a magnum primer. Three points are not sufficient to define the correct line with confidence, especially since several of these tests had high standard deviations. The ammunition had been stored for some time. Nevertheless, the three points (not shown in Fig. 3) are not inconsistent with a line that has the same slope as that for the jacketed .38-caliber cartridges. The displacement of the line towards larger numbers of particles can be attributed to the longer barrel and possibly the magnum primer. The point for the one coated bullet tested lies well above the others, again suggesting separate curves for jacketed and non-jacketed bullets. For the jacketed bullets, the percentages of bullet particles are high, but the jackets are relatively short and leave a substantial amount of lead exposed. The effect of velocity on the particle size distributions is evident in Table 4.

Only one other cartridge (.32 ACP) was characterized, and information on several more was obtained from test firings submitted by law enforcement agencies along with case evidence. The case test firings must be approached with some caution for characterization purposes because the data were taken under less uniform circumstances, with weapons in unknown condition, and with ammunition of unknown age. The greatest value of these data is for the cases from which they were taken.

In the tests performed at The Aerospace Corporation, only handguns ranging in condition from fair to new were used, and the only important parameters appeared to be the length of the barrel (regardless of make or model, or whether it was a revolver or semi-automatic. Derringers and guns of unusual construction were not tested). It is reasonable to expect, however, that a gun in poor condition may not give the same results. The condition of the barrel and, in revolvers, the alignment of the firing chamber with the barrel, could have an appreciable influence on the production of bullet particles. Abnormal clearances at the cylinder or breach end would affect the number of particles that can escape and the velocity with which they are ejected. The age of the ammunition can have a major effect on its overall performance. It is well known that ammunition can deteriorate. Police departments tend to consider ammunition unreliable if it is from six months to a year old. On the other hand, there are many examples of functional ammunition several decades old. One may speculate that a major factor that determines this difference, but which cannot be ascertained by inspection, is how air-tight the seal is between bullet and case or between primer and case.

The .25 ACP, .32 ACP, .32 S&W, and .45 ACP cartridges fall reasonably close to the appropriate (jacketed or nonjacketed) .38 Special cartridge curves (see Fig. 3) at the indicated velocities and barrel lengths in total numbers of particles. The smaller calibers are on the low side in their fraction of bullet particles and on the high side in average particle size, compared to the .38 Special cartridges. Judging from a very small number of cases, the .44-Magnum ammunition gives extremely large numbers of particles, larger than that of any other cartridge residue examined. A case test firing with a Velox exploding bullet, .38 Special caliber, also gave copious residue.

Conclusion

The characterizations of gunshot residue from a broad range of hand gun cartridges have been found adequate for successful analyses of actual cases and in favorable circumstances have permitted placing some limitations on the type of ammunition that may have been used.

References

[1] Diedericks, R., Camp, M. J., Wilimoosky, A. E., Haas, M. A., and Dragen, F. R., "Investigations into the Adaptability of Scanning Electron Microscopy and X-Ray Fluorescence Spectroscopy to Firearms Related Examinations," *Association of Firearms and Toolmarks Examiners' Journal*, Vol. 6, No. 4, Aug. 1974.

[2] Keeley, R. H., "Some Applications of Electron Probe Instruments in Forensic Science," *Proceedings of the Analytical Division of the Chemical Society*, Vol. 13, June 1976, pp. 178-181.

[3] Boehm, E., "Applications of the SEM in Forensic Medicine," *Proceedings of the 4th Annual Scanning Electron Microscopy Symposium*, Claitor's Publishing Div., Baton Rouge, La., 1977, pp. 553-560.

[4] Nesbitt, R. S., Wessel, J. E., and Jones, P. F., "Detection of Gunshot Residue by Use of the Scanning Electron Microscope," *Journal of Forensic Sciences*, Vol. 21, No. 3, July 1976, pp. 595-610.

[5] Andrasko, J. and Maehly, A. C., "Detection of Gunshot Residues on Hands by Scanning Electron Microscopy," *Journal of Forensic Sciences*, Vol. 22, No. 2, April 1977, pp. 279-287.

[6] Matricardi, V. R. and Kilty, J. W., "Detection of Gunshot Residue Particles from the Hands of a Shooter," *Journal of Forensic Sciences*, Vol. 22, No. 4, Oct. 1977, pp. 725-738.

[7] Wolten, G. M., Nesbitt, R. S., Calloway, A. R., Loper, G. L., and Jones, P. F., "Final Report on Particle Analysis for Gunshot Residue Detection," ATR-77(7915)-3, The Aerospace Corporation, El Segundo, Calif., Sept. 1977.

[8] Wolten, G. M., Nesbitt, R. S., Calloway, A. R., and Loper, G. L., "Particle Analysis for the Detection of Gunshot Residue. II: Occupational and Environmental Particles," *Journal of Forensic Sciences*, Vol. 24, No. 2, April 1979, pp. 423-430.

[9] Guinn, V. P., "Recent Studies Involving Bullet-Lead Fragments," presented at the 49th Semiannual Seminar, California Association of Criminalists, Indian Wells, Calif., 12-14 May 1977.

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