# TECHNICAL NOTE

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# A Reevaluation of the Aerospace Corporation Final Report on Particle Analysis—When to Stop Searching for Gunshot Residue (GSR)?

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**ABSTRACT:** Although the technique of scanning electron microscopy and energy-dispersive X-ray analysis (SEM/EDX) has gained widespread acceptance for the identification of gunshot residues (GSR), the time required (especially for manual searches) is still considered excessive. As a result, statistical considerations are commonly used to justify a reduction in the total specimen area to be searched. A detailed statistical analysis was presented in the Aerospace Corporation Final Report on Particle Analysis for Gunshot Residue Detection published in September 1977, and its conclusions have had significant influence in the forensic science community as concerns the determination of acceptable particle analysis search areas. A close examination of the Aerospace Corporation report has revealed a significant programming error which resulted in statistical probability errors ranging from 30% to well over ten orders of magnitude. Corrected results, presented in this paper, suggest that a great deal of caution should be exercised in applying statistical analysis to justify a reduction in search area. In particular, the probability of a false negative report increases rapidly as the number of gunshot residue (GSR) particles assumed to be present decreases. Since the investigator cannot know in advance the number of GSR particles present on a sample, the corrected Aerospace analysis suggests that statistical considerations may not provide sufficient justification for any significant reduction in the sample area to be searched.

**KEYWORDS:** forensic science, gunshot residues, statistical analysis, microscopy, X-ray analysis

The identification of gunshot residues (GSR) using the technique of particle analysis by scanning electron microscopy and energy-dispersive X-ray analysis (SEM/EDX) has been well described and documented during the past 15 years [*1–8*]. As a result, the technique has gained widespread acceptance and is currently being used throughout the forensic science community. A further consequence has been the development of microprocessor-controlled systems to automate the GSR search and identification process, at least two of which have been described in published papers [*7,8*].

Unfortunately, although significant advances have been made, the time required for particle analysis is still considered excessive and especially so for manual (nonautomated) searches. For this reason, it has become acceptable and commonplace to use statistical

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considerations to reduce the "necessary" specimen search area (since the time required to search 100% of a sample is often considered prohibitive). Such statistical considerations were investigated in some detail in the Aerospace Corporation Final Report on Particle Analysis for Gunshot Residue Detection [*1*] (hereafter referred to as the Aerospace report), and indeed, its conclusions have been commonly accepted as a basis for determining acceptable particle analysis search areas. The purpose of this paper is to notify the forensic science community of a minor error in this report which has significant consequences and to provide corrected results for their statistical calculations.

## Summary of the Aerospace Report Statistical Analysis

One goal of the Aerospace report's statistical analysis was to provide an answer to the following question:

> If no gunshot residue is found in the initially surveyed portion of a sample, how much more area needs to be examined before there is a satisfactorily high probability that nothing would be found in the remainder?

To answer this question, a method was established which was based on a GSR sampling disk divided into 131 columns or coordinates which were to be randomly searched. The simplifying assumption was made that if $N$ total GSR particles were present they would be randomly distributed such that $N$ columns contained only 1 particle each. Given these conditions, the probability of any randomly selected column being empty (no particles) is:

$$(131 - N)/131$$

where $(131 - N)$ is the total number of empty columns on the disk.

For instance, given 10 randomly distributed particles, the probability of finding the first column empty is $(131 - 10)/131$ or 0.92. The probability of 2 independent events both occurring is simply the product of the individual probabilities. Therefore, the probability of the next (second) randomly selected column *also* being empty is

$$[(131 - N)/131] \times [(131 - N - 1)/(131 - 1)]$$

For the case above of ten total particles, the probability of the first two randomly selected columns being empty is

$$(121/131) \times (120/130) = 0.85$$

The mathematics can be generalized for a random distribution of any number of particles, and the random selection of any number of columns for searching, to yield the following equation:

$$P_K = \prod_{i=1}^{K} (132 - N - i)/(132 - i)^*$$

where $N$ is the total number of GSR particles on the disk and $P_K$ is the probability of finding $K$ empty columns.

Note that the value of $P$ so calculated is a *minimum* probability because of the initial assumption that the particles are distributed such that no more than one falls in any one column (that is, no "clustering" occurs). In other words, given a total of ten particles, if two particles were to occupy one column, then the correct value of $P$ will be obtained by using a value of $N = 9$ in the above equation.

The Aerospace report presented a Fortran computer program which was written to make the above calculations. This program was used to produce the table of probabilities provided in the report as Table 10. Although the statistical analysis itself may be inherently sound, on close examination it was found that a minor error was made in the computer program. The error resulted in erroneous calculated probabilities for all values of $K$ (number of columns searched) greater than ten. The programming error is described and corrected results are provided in the following section.

## Programming of the Statistical Analysis

The Aerospace report's original computer program and the resultant table of probabilities are reproduced in Appendix I. The general structure of the program can be described with reference to the three program loops (Do 1, Do 2, and Do 5). The purpose of the outer loop (Do 1) is to set the value of $N$, the total number of particles on the disk, for subsequent calculations. The next loop (Do 2), nested within Loop 1, sets the value of $K$, the number of columns to be searched. In the original program, the parameter $K$ is set to 1, 10, 20, 30, 40, and 50 in successive Do 2 loops to produce a table of probabilities for various numbers of searched columns. Using the values of $N$ and $K$ set in the previous loops, the final loop (Do 5), which is nested within the Do 2 loop, computes the value of $P$. More specifically, the probability of finding the first column empty is calculated in the first loop at program Line 15 as the variable PRO (see Appendix I). The third loop (Do 5) then uses the probability equation to successively "update" this variable as Columns 2 through $K$ are searched (in the original program, $K$ is represented by the Do 5 loop index IC).

The computational error occurs during the third and successive iterations of the Do 2 loop (which, as stated above, progressively increments the value of $K$). In these successive loops the value of PRO is not reset to its original value calculated at Line 15, but remains set at whatever probability value was calculated for the previous values of $N$ and $K$. It is this value which is then incorrectly used in the computational loop (Do 5). The nature of the programming error causes the magnitude of the error in calculated probability to increase as the number of columns searched ($K$) increases. A corrected version of the original program as well as the resultant table of probabilities is given in Appendix II. In this corrected table, the results have been extended to a search of up to 70 columns with as few as 3 total GSR particles on the sample disk.

## Comparison of Corrected and Uncorrected Results

As stated above, the results of the original program are correct in the first two rows of the probabilities table. The following discussion applies only to searches of more than ten columns. The magnitude of the error varies greatly, but systematically, from a minimum error of about 30% to errors which exceed ten orders of magnitude. Since the error is rapidly compounded in successive iterations of Loop 2, the magnitude of the error increases rapidly as the number of columns searched increases. The magnitude of the error also increases as the number of particles assumed present increases.

An example of the typical error can be given with reference to the search procedures used in the Aerospace report. In their project, an upper limit of 25% (about 30 columns) was set on the area to be surveyed. The original table indicated that this procedure left an 8% probability that 5 particles remained on the unsearched portion and a 0.6% probability that 10 particles remained. The corrected results show that this procedure actually leaves a 27% probability that 5 particles remained to be found and about 7% probability that 10 particles remained.

## Discussion

A quick survey of the tables of probability confirms what is intuitively obvious. The probability of finding all searched columns empty *decreases* (1) as more columns are searched and (2) as the total number of particles present in the sample increases. Since the investigator cannot know in advance the number of particles that are present, a logical way to proceed would be to assume the worst case (that is, assume a small number of particles). In many cases, the identification of three unique gunshot residue particles has been considered significant, especially for those cases in which sample collection took place after a long post–firing interval. For this reason, the corrected table of probabilities was extended to searches for 3 total particles. As the number of particles decreases, the probability of not finding them increases rapidly. For instance, using the Aerospace report procedure of searching 25% (30 columns) of the sample area, we find almost a 50% probability of not finding the 3 particles which are present. Put a different way, given a sample with 3 randomly distributed GSR particles, in approximately 1 out of every 2 searches on such samples none of the particles will be found (that is, about 1 of every 2 such searches will lead to a false negative report). Indeed, even if over half the sample is searched (70 columns), 1 of every 10 such searches will find *none* of the particles, resulting in false negative reports.

As already stated in a previous section, these probabilities are calculated with the assumption that no clustering occurs and are thus *minimum* probabilities. If five total GSR particles lie in only three columns, then the above discussion for the case of three particles will apply. When only a few particles are present, the potential effect of such clustering becomes significant because the probability of not finding them after long searches increases rapidly. For example, let us assume that the three particles discussed above were to fall in one sample column in a particular case. There will be a 75% probability that none of the particles will be found after searching 25% of the sample. Indeed, to reduce this to a 10% probability (of finding none of the particles), it would be necessary to search 90% of the sample.

The conclusions we may draw from the above calculations and discussions can be stated simply: much caution should be exercised when applying statistical considerations to determining the fractional area of a sample to search and in formulating one's conclusions based on the results of such a search. If the goal is to obtain a "satisfactorily high probability that nothing would be found in the remainder" of the disk, which was the original intent of the Aerospace report, then it would seem from their own (corrected) analysis that most of the sample must be examined.

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# APPENDIX I

**Original Program**

```
              PROGRAM AREA (INPUT, OUTPUT, TAPE5 = INPUT, TAPE 6 = OUTPUT)
              DIMENSION NC(6), PROB(5,6)
              DATA (NC(I), I = 1,6 /1, 10, 20, 30, 40, 50/
              NT = 131
              T  = FLOAT(NT)
     COMMENT  NC = C = NUMBER OF COLUMNS SEARCHED
     COMMENT  NT = T = TOTAL COLUMNS ON DISK
     COMMENT  NE = E = NUMBER OF EMPTY COLUMNS, EQUAL DISTRIBUTION, ASSUMED
     COMMENT           FOR PARTICLES, WHOSE TOTAL IS SET PROGRESSIVELY AS
     COMMENT           5, 10, 15, 20, 25 IN THE FIRST LOOP THAT FOLLOWS
              DO 1  I = 1,5
                    NP = 5 * I
                    NE = NT - NP
                    E = FLOAT(NE)
                    PRO = E/T
                    DO 2 J = 1,6
                          IC = NC(J)
                          IF (J-1) 4,3,4
     3                    GO TO 2
     4                    DO 5 K = 2,IC
                                CK = K - 1
     5                          PRO = PRO * (E-CK)/(T-CK)
     2                    PROB(I,J) = PRO
     1              CONTINUE
              WRITE(6,6) ((PROB(I,J), I = 1,5), J = 1,6)
     6        FORMAT(1H1,10X,10H PARTICLES,6X,1H5,8X,2H10,8X,2H15,8X,2H20,8X,
              $2H25//11X,9H COLUMNS//14X,1H1,5X,5(E10.3)/13X,2H10,5X,5E10.3
              $)/13X,2H20,5X,5(E10.3)/13X,2H30,5X,5(E10.3)/13X,2H40,5X,
              $5(E10.3)/13X,2H50,5X,5(E10.3))
              CALL EXIT
              END
```

| Particles → | 5 | 10 | 15 | 20 | 25 |
|---|---|---|---|---|---|
| Columns | | | Probability | | |
| 1 | 0.96 | 0.92 | 0.89 | 0.85 | 0.81 |
| 10 | 0.67 | 0.44 | 0.28 | 0.18 | 0.11 |
| 20 | 0.30 | 0.085 | 0.02 | 0.006 | 0.001 |
| 30 | 0.083 | 0.006 | 0.0004 | $2.3 \times 10^{-5}$ | $1 \times 10^{-6}$ |
| 40 | 0.013 | 0.0001 | $1 \times 10^{-6}$ | $9 \times 10^{-9}$ | $5 \times 10^{-11}$ |
| 50 | 0.001 | $1 \times 10^{-6}$ | $6 \times 10^{-10}$ | $3 \times 10^{-13}$ | $6 \times 10^{-17}$ |

# APPENDIX II

**Corrected Program**

```
          PROGRAM AREA (INPUT, OUTPUT, TAPE5 = INPUT, TAPE 6 = OUTPUT)
          DIMENSION NC(6), PROB(5,6)
          DATA (NC(I), I = 1,6 /1, 10, 20, 30, 40, 50/
          NT = 131
          T  = FLOAT(NT)
COMMENT   NC = C = NUMBER OF COLUMNS SEARCHED
COMMENT   NT = T = TOTAL COLUMNS ON DISK
COMMENT   NE = E = NUMBER OF EMPTY COLUMNS, EQUAL DISTRIBUTION, ASSUMED
COMMENT            FOR PARTICLES, WHOSE TOTAL IS SET PROGRESSIVELY AS
COMMENT            5, 10, 15, 20, 25 IN THE FIRST LOOP THAT FOLLOWS
          DO 1  I = 1,5
                NP = 5 * I
                NE = NT - NP
                E = FLOAT(NE)
                DO 2 J = 1,6
                     PRO = 1.0
```

```
          IC = NC(J)
          DO 5 K = 1,IC
               CK = K - 1
    5          PRO = PRO * (E-CK)/(T-CK)
    2     PROB(I,J) = PRO
    1     CONTINUE
      WRITE(6,6) ((PROB(I,J), I = 1,5), J = 1,6)
    6 FORMAT(1H1,10X,10H PARTICLES,6X,1H5,8X,2H10,8X,2H15,8X,2H20,8X,
      $2H25//11X,9H COLUMNS//14X,1H1,5X,5(E10.3)/13X,2H10,5X,5E10.3
      $)/13X,2H20,5X,5(E10.3)/13X,2H30,5X,5(E10.3)/13X,2H40,5X,
      $5(E10.3)/13X,2H50,5X,5(E10.3))
      CALL EXIT
      END
```

| Particles → | 3 | 5 | 10 | 15 | 20 | 25 |
|---|---|---|---|---|---|---|
| Columns | | | | Probability | | |
| 1 | 0.98 | 0.96 | 0.92 | 0.89 | 0.85 | 0.81 |
| 10 | 0.79 | 0.67 | 0.44 | 0.28 | 0.18 | 0.11 |
| 20 | 0.61 | 0.43 | 0.18 | 0.071 | 0.027 | 0.010 |
| 30 | 0.46 | 0.27 | 0.067 | 0.016 | 0.0034 | 0.0007 |
| 40 | 0.33 | 0.16 | 0.022 | 0.0029 | 0.0003 | $3 \times 10^{-5}$ |
| 50 | 0.23 | 0.086 | 0.0066 | 0.0004 | $2 \times 10^{-5}$ | $1 \times 10^{-6}$ |
| 60 | 0.16 | 0.044 | 0.0016 | $5 \times 10^{-5}$ | $1 \times 10^{-6}$ | $2 \times 10^{-8}$ |
| 70 | 0.10 | 0.020 | 0.0003 | $4 \times 10^{-6}$ | $3 \times 10^{-8}$ | $2 \times 10^{-10}$ |