Exploitation of Very Small Particles to Enhance the Probative Value of Carpet Fibers

Award 2012-DN-BX-K041

David A. Stoney, Ph.D. and Paul L. Stoney, MBA
Stoney Forensic, Inc.
14101-G Willard Road
Chantilly, VA 20151

Cedric Neumann, Ph.D.
Two N's Forensics, Inc.
Brookings, SD 57006

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An essential part of this project was the collection of carpet fiber specimens by crime scene investigators in multiple jurisdictions under realistic crime scene conditions. More than 50 investigators participated in these collections, representing nine agencies. We are very grateful for this participation, without which this project could not have been completed. The essential pathway allowing the investigators' participation involved agency cooperation and the work of coordinators who distributed carpet fiber collection kits to their colleagues, followed up on collections, sent the kits to Stoney Forensic and in many cases did a number of collections themselves. The agencies themselves are documented in the body of this work, but we wish to make a special note thanks to the individual collection coordinators: Eric Collins, John Murdock, Christine Snyder, Natasha Wheatley, Gary Licht, Tye Kushner, Christopher Federinko, Michael Grubb, Tanya Dulaney and Micah Anzoie.

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Abstract

Very small particles (VSP) are ubiquitous in our environment and are virtually ignored by forensic science. These particles range in size from an order of magnitude smaller than conventional trace evidence, down to the molecular level (now routinely exploited through DNA analysis). We move about in a soup that is a combination of VSP that provides an extraordinary, largely untapped resource for forensic associations and source attribution.

Prior research provided proof of principle that VSP, ubiquitous on the surfaces of carpet fibers, can be used to associate individual fibers with their carpet source.

The present program goals were to: (1) refine the process for exploiting very small particles (VSP) to associate residential carpet fibers with their source carpet, (2) apply this process under realistic casework conditions, and (3) deliver a working prototype for both the methods of analysis and the measurement of the probative value of comparisons. Specific program objectives were to:

- Apply and test the methods under realistic conditions of carpet fiber transfer and crime scene sampling
- Expand and improve VSP target particle type classification criteria based on analysis of forensic performance characteristics
- Design, develop, and deliver a practical method for the measurement of the degree of correspondence between two VSP profiles
- Design, develop and deliver practical, quantitative measures of the probative value of this degree of correspondence
- Present the program results to the forensic science practitioner and research communities in a forum allowing considered feedback and discussion

Program goals and objectives were met. Field collections of carpet fibers were collected by crime scene practitioners under realistic casework conditions. VSP were isolated and analyses were conducted using SEM/EDS analytical protocols in an operational crime laboratory setting. Computational methods were designed allowing sets of hundreds to thousands of VSP to be simply characterized. Classifiers were designed to associate and discriminate among specimens. Quantitative measures of correspondence and probative value were designed and successfully applied to VSP data collected under this program as well as that collected during prior proof of principle research. Particle sets larger than 500 showed strong promise for quantitative associations with their sources. The use of larger numbers of target particle types (TPTs) showed strong promise to improve the performance of classification and association. Presentation and discussion of program results with forensic practitioners and researchers identified several important topics for clarification and follow-on research.

The usefulness of VSP to provide objective, quantitative associations and measurements of probative value has been established. This confirms the potential to remove fundamental limitations to the probative value of carpet fiber evidence.

The development of quantitative methods for measurements of VSP correspondence and probative value are of broad significance for the future of trace evidence analysis, providing the impetus and direction for a fundamental change in the way that forensic trace evidence is conceptualized, analyzed and used in the criminal justice system. The results of this research are likely extendable, with minor modifications, to other trace evidence types, and are expected to contribute significantly for those types of trace evidence that have long been considered of low evidential value. Furthermore, entirely new approaches to trace evidence are enabled by exploiting VSP profiles, such as comparing different types of trace evidence with one another and comparing VSP defined by crime scene or suspect environments to those on virtually any item of physical evidence.

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Executive Summary

Our prior research demonstrated that hundreds to thousands of very small particles (VSP) cling to the surfaces of individual carpet fibers and established proof of principle that these particles can be used to compare carpet fibers with candidate carpet sources.

The present project has established that realistic field collections of carpet fiber evidence and currently available forensic laboratory capabilities are sufficient for collection and analysis of VSP adhering to carpet fibers. The project has also successfully developed quantitative methods to determine the degree of correspondence between sets of VSP and to measure the probative value of the degree of correspondence.

This project focused on one specific trace evidence application (carpet fibers) and one specific instrumental particle analysis method (computer-assisted SEM/EDS) to exploit a fundamentally different approach to trace evidence analysis.

The development of quantitative methods for measurements of VSP correspondence and probative value are of broad significance for the future of trace evidence analysis, providing the impetus and direction for a fundamental change in the way that forensic trace evidence is conceptualized, analyzed and used in the criminal justice system.

The results of this research are likely extendable, with minor modifications, to other trace evidence types, and are expected to contribute significantly for those types of trace evidence that have long been considered of low evidential value. Furthermore, entirely new approaches to trace evidence are enabled by exploiting VSP profiles, such as comparing different types of trace evidence with one another and comparing VSP defined by crime scene or suspect environments to those on virtually any item of physical evidence.

Problem and Purpose

There is a fundamental limitation to the probative value of many of the most common types of trace evidence (e.g., fibers, glass, paint) because their characteristics are determined by their manufacture. As mass-produced commodities, probative value is limited to class associations. Multiple-transfer cases shatter this limitation. These are cases where a set of different trace evidence materials, found on a suspect, correspond to sources at a crime scene, and/or the reverse: where a set of trace evidence materials, found at the crime scene, correspond to suspect-related sources. The well-known case of Atlanta child murders provides an excellent example, where fibers corresponding to the trunk of Wayne Williams' car, his bedroom carpet, his bedspread, and his blanket were all found together on multiple victims. When the possibilities of correlation can be discounted, the probative value can become extraordinarily high, even when probabilities for the occurrence of individual trace evidence types are modest, or subject to inherent imprecision in their estimates. The co-occurrence of multiple events of modest frequency is the foundation for all highly probative types of physical evidence, including DNA and fingerprint identifications. The potential is also there for trace evidence.

This research is part of an effort to radically improve trace-evidence analysis, systematically addressing the fundamental limitations affecting the strength and measurement of probative value, by exploiting the very small particles (VSP) that are present on virtually every material or object. These VSP "ride piggy-back" on conventional trace evidence. They also occur on or in other items of evidence – e.g., on drug packaging, weapons, contraband and clothing. They occur in complex mixtures and include a tremendous variety of particles that are acquired when manufactured materials are exposed to alternative environments. These particles reflect cumulative exposures and conditions; they will be highly characteristic of the local environment Their presence, identity and relative quantities provide an untapped source of individuality that can be used to augment associations from conventional trace evidence.

There is a tremendous potential here: every trace evidence case becomes a multiple-transfer case, with the adhering fine particles providing an independent quantitative means to test hypotheses of common origin. Consider: if *these* carpet fibers came from *that* carpet, then the multivariate occurrence of a quantitative profile of VSP, present on *that* carpet, ought to be present, subject to statistical sampling, on *these* fibers.

To unlock this potential, research is required that (1) determines which VSP have useful forensic performance characteristics, (2) develops suitable methods for detection and measurement, and (3) provides data on variation and occurrence that enable reliable statistical interpretation.

Prior NIJ research has provided proof of principle that VSP, ubiquitous on the surfaces of carpet fibers, can be used to associate individual fibers with their source carpet. Hundreds to thousands of VSP occur on the surfaces of individual carpet fibers. The particles can be efficiently removed and analyzed by computer-assisted SEM/EDS, resulting in highly characteristic profiles of target particle types (TPTs). When sufficient VSP are recovered from individual fibers, there is a close correspondence between these TPT profiles and those from the originating carpet area.

This foundational research had extraordinary implications for both carpet fiber evidence and for trace evidence analysis in general. Proof of principle was established that the analysis of VSP on the surface of carpet fibers could remove fundamental limitations to probative value, augmenting class associations with independent, quantitative testing of common origin using populations of VSP.

The proof of principle research was conducted using carpet fibers cut from multiple areas of multiple carpets and a set of well-defined, frequently occurring particle types. This report describes the next stage of research, designed to bring these methods to fruition.

The goals of the present research were to (1) refine the process for exploiting very small particles (VSP) to associate residential carpet fibers with their source carpet, (2) apply this process under realistic casework conditions, and (3) deliver a working prototype for both the methods of analysis and the measurement of the probative value of comparisons.

To meet these goals we defined five objectives:

1. Apply and test the methods under realistic conditions of carpet fiber transfer and crime scene sampling.

2. Expand and improve VSP target particle type classification criteria based on analysis of forensic performance characteristics.
3. Design, develop, and deliver a practical method for the measurement of the degree of correspondence between two VSP profiles.
4. Design, develop and deliver practical, quantitative measures of the probative value of this degree of correspondence.
5. Present the program results to the forensic science practitioner and research in a forum allowing considered feedback and discussion.

Research Design

Carpet fiber specimens from wall-to-wall carpeting were collected under realistic crime scene conditions. Collections were made from 90 residences by crime scene practitioners working within nine separate jurisdictions within the United States. A specially designed kit was used for efficient collection of two carpet fiber specimens:

Carpet fibers transferred by frictional contact to a lint-free inspection glove (representing transferred fiber traces from the source)

Carpet fibers collected with a hook-type lint brush (representing a reference sample from the carpet source)

Fibers were recovered from the kits and particles were extracted from the fibers using pre-filtered reagent grade ethanol with sonication in a micro-centrifuge tube for ten minutes. This was followed by filtration to recover the particles, drying and mounting for computer-assisted SEM analysis. Process blanks were included alongside each batch of processed specimens (pre-filtered ethanol sonicated for ten minutes in an empty tube and otherwise treated in an identical manner).

SEM/EDS analyses were efficiently conducted in an operational forensic science laboratory under realistic casework conditions. Analyses were conducted on a total of 190 specimens: 90 carpet source reference specimens, 90 corresponding transferred trace specimens and 10 process blanks.

The computer-assisted SEM/EDS analysis was performed on an Aspex Corporation 3025 SEM-EDS system using the Automated Feature Analysis (AFA) program within the Aspex Corporation Perception software. Software settings were selected to restrict particle characterization based on standard x-ray K-shell emission lines for 18 elements: Sodium (Na), Magnesium (Mg), Aluminum (Al), Silicon (Si), Phosphorous (P), Sulfur (S), Chlorine (Cl), Potassium (K), Calcium (Ca), Titanium (Ti), Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Cobalt (Co), Nickel (Ni), Copper (Cu) and Zinc (Zn). These elements were chosen (1) following a review of the manufacturer's recommendations indicating that the AFA software performed best for a number of elements below 20, (2) to avoid overlapping x-ray energies, and (3) to provide broad coverage of x-ray energies appearing in the range of 1 to 10 KeV.

These SEM/EDS results were designated the 2012 Particle Dataset. Particle data collected and previously described under NIJ Award 2010-DN-BX-K244 were designated the 2010 Particle

Dataset. This dataset consists of SEM/EDS particle analysis results from 39 carpet area sources (taken to represent source references) and 81 individual fibers originating from some of these sources (taken to represent transferred traces). Of the 39 sources, twelve are individual sources (from one area of a carpet) and the remaining 27 come from nine carpets, with three areas taken from each of the nine carpets. The 81 individual fibers consist of three fibers from each of the 27 carpet areas.

Computational methods were designed and applied to the two particle datasets using statistical packages in R. Datasets were filtered to reduce noise represented by (1) particles having no dominant elemental composition detected under the analysis conditions, and (2) elements present in low quantities for any given particle. Target particle types (TPTs) were defined based on Normal Mixture Modeling using the mclust package of R based on a random sampling of 8000 particles from reference source datasets. Sets of TPTs were defined with the number of specified TPTs selected as 10 and as 80.

Two alternative strategies were used to determine TPT profiles. Under Strategy 1, 10 TPTs were defined and used for categorization of all reference sources. Under Strategy 2, 80 TPTs were defined and the 10 most populated TPTs for each source were used for characterization of that source.

Multinomial distributions were defined for reference sources based on the numbers of particles corresponding to each of the TPTs. For comparison of TPT profiles, the TPT categories of the reference sources were used. When a new set of particles from a new specimen was considered, its particles were categorized into the TPTs previously defined for the reference source. The probability density of the observed count in the new specimen was assigned in each of the N multinomial densities (corresponding to each of the reference sources). This probability was used as the measure of correspondence to each of the reference sources. For classification, the new specimen was assigned to the reference source with the highest probability.

Measurements of probative value were defined using a Bayesian classifier applied to the multinomial probability densities, assuming an equal prior among all N classes. This results in posterior probabilities obtained using the classifier for all N sources. A corresponding likelihood was calculated as a measure of evidential weight, based on assumptions of the representativeness of the N sources.

The 2010 Dataset, the Full 2012 Dataset, and a High Particle 2012 Subset where each characterized based on (1) the general discrimination of the system, (2) the matching ability of the system (based on the use of training and test sets), and (3) the performance of the system for the matching of sources to traces. Rates of correct and incorrect classification were determined. These, along with network and DET diagrams were used for the assessment of system performance.

Findings and Conclusions

The findings in this project are based on the analysis of carpets present within a limited geographical range and with unknown histories of environmental exposure. Furthermore, these

carpets were not selected based on characteristics such as manufacturing origin, commercial source, age, or composition. Indeed, these aspects of the carpets are unknown. Accordingly, the findings presented here may well be affected by these alternative conditions. The present work, with field collections under realistic conditions, occupies a position between narrowly controlled experiments on the one hand, and a more comprehensive, systematic sampling that is necessary to understand the nature of particle populations. As an essential intermediate step, this work helps to define and assess practical procedures that are necessary for efficiently conducting follow-on work and for providing a basis to choose among alternative lines of investigation.

There were nine specific findings:

1. It has been established that realistic field collections of carpet fiber evidence and currently available forensic laboratory capabilities are sufficient for collection and analysis of VSP adhering to carpet fibers.

Collection of carpet fiber evidence by crime scene investigators across the country, using simple, efficient collection protocols, has resulted in useful specimens suitable for VSP recovery and preparation for SEM/EDS analysis.

Analysis of these VSP specimens, using computer assisted SEM/EDS in an operational forensic science laboratory has been efficient, with less than two hours instrument time per specimen and the batching of analyses in groups of 10 to 20 specimens at a time. The resulting analytical data from these particle sets were sufficient to permit quantitative associations among specimens and the determination of probative value.

2. Compared to controlled research collections, field collections of carpet fiber evidence by crime scene investigators resulted in lower particle numbers.

The specimens in this program, collected by field personnel under realistic crime scene conditions, showed fewer particles compared to fiber specimens cut from carpets and collected by research personnel under controlled conditions.

The manner of collection is one likely cause of this difference. Specimens collected in this program were subject to particle losses by abrasion, whereas those previously collected were not.

3. Sets of hundreds to thousands of particles from carpet fibers can be characterized using a single-dimensional vector.

This project has demonstrated that complex particle sets numbering in the thousands, with each particle characterized by multivariate data, can be characterized successfully and usefully exploited using a single-dimensional vector. The computational processes employed for this characterization have minimal input parameters, notably the specification of the number of TPTs. Following data filtration to reduce noise, the method employs readily available, open processes for normal mixture modeling.

These objective computational methods replace the heuristic processes, dependent on expert selection and estimation of many parameters, which were used in prior research for definition of TPTs.

4. Classifiers can be designed to associate / discriminate particle sets originating from common/different source(s).

This project has designed and demonstrated the usefulness of classifiers that can be applied to associate or discriminate among particle sets originating from the same or different sources. A classifier based on the multinomial distribution has been developed based on the population of TPTs observed in specific reference source samples. Newly encountered particle profiles, based on the same TPTs, are compared to each of the sources using the multinomial distribution and classification is assigned to the reference source in which the new profile would occur with highest probability.

5. Quantitative measures of correspondence can be defined based on the criteria used for classification.

Comparison of the probabilities of the occurrence of a TPT profile within each of the reference sources results in a useful, quantitative measure of correspondence. This allows objective ranking and assessment of relative strengths of association.

These objective computational methods again replace heuristic processes that were used in prior research for perception and demonstration of close associations among particle sets.

6. There are alternative reasons, currently unresolved, for low levels of matching between sources and traces.

The classification results for traces of known origin were far from perfect. That is, classification errors were frequent. For the 2010 Dataset, correct classification rates for the specific carpet area (among 39 sources and 12 blanks) were 26% under Strategy 1 and 35% under Strategy 2. Correct classification rates for the carpet itself (among 21 sources and 12 blanks) were 46% under Strategy 1 and 60% under Strategy 2.

For the Full 2012 Dataset, correct classification rates (among 90 sources and 10 blanks) were lower: 22% under Strategy 1 and 21% under Strategy 2. For the High Particle 2012 Subset (among 20 sources and 10 blanks) classification rates were higher: 50% under Strategy 1 and 40% under Strategy 2.

Specific causes for classification errors cannot be determined without further research, but there are at least three alternative reasons for less than perfect classification: the absence of evidence

representative of the source, low variability among sources, and a poor performance of the system used to detect and exploit variability among sources.

7. Particle sets larger than 500 show strong promise for reliable quantitative associations with their sources.

A requirement of high numbers of particles for reliable classification is reasonable, and demonstrated by the results obtained for the 2012 Dataset. A high particle subset of the data (with particle numbers higher than 500) resulted in classification rates that increased from 22% to 50% using Strategy 1 and from 21% to 40% using Strategy 2.

8. Larger numbers of TPTs show strong promise to improve the performance of classification and association.

Contrasting Strategy 1 and Strategy 2 indicates that larger numbers of TPTs will improve the performance of classification and association. The effect is most clear for the overall discrimination of the system in the Full 2012 Dataset, as shown in Figure 11. Improvement is less clear in the subsequent classification steps for this dataset, with Strategy 2 showing comparable, but lower correct rates of classification. As previously noted, the 2010 Dataset shows much better classification rates under Strategy 2.

Overall, larger numbers of TPTs show promise to improve performance of classification and association. Strategy 2, with larger numbers of TPTs, is expected to become more important as the number of sources increases.

9. The meaningfulness of current measures of correspondence and probative value are restricted to closed set associations.

As noted earlier, the correspondence measures and likelihood ratios determined under this project are subject to specific assumptions made in the context of this research. These are most notably (1) the assumption of equal priors for the calculation of the correspondence measure and (2) the implied assumptions of equal weight and overall representativeness of the references sources for the calculation of the denominator of the likelihood ratios.

Importantly, the procedures developed under this program show the form, feasibility and method for these quantitative measurements. However, the meaningfulness of these measures, outside of the specific research context of this program, will only come from the expansion of the numbers of references, better understanding of within-item variation, testing the assumptions of population representativeness, and validation using relevant operational specimens.
With these qualifications regarding the extension of the results beyond a closed dataset, the application to such closed datasets is directly enabled by this research. For example, investigative determination of associations among particle sets recovered on and within items of evidence is ready to be conducted using the methods that have been developed.

Implications for Policy and Practice

1. The usefulness of VSP to provide objective, quantitative associations and measurements of probative value has been established. This confirms the potential to remove fundamental limitations to the probative value of carpet fiber evidence, providing additional impetus and direction for fundamental changes in the way that forensic trace evidence is conceptualized, analyzed and used in the criminal justice system.
2. The results of this research are likely extendable, with minor modifications, to other trace evidence types, and are expected to contribute significantly for those types of trace evidence that have long been considered of low evidential value.
3. An entirely new approach to trace evidence is enabled: comparing different types of trace evidence with one another by way of their adhering VSP.
4. An additional, high priority use for existing crime laboratory SEM/EDS analytical capabilities and related practitioner skills can now be anticipated, guiding the allocation of laboratory resources.
5. A need can be anticipated for policies and practices for evidence collection and processing of crime scenes that are sensitive to requirements for the preservation and analysis of VSP.

Implications for Further Research

This project has established that realistic field collections of carpet fiber evidence and currently available forensic laboratory capabilities are sufficient for collection and analysis of VSP adhering to carpet fibers. The project has also successfully developed quantitative methods to determine the degree of correspondence between sets of VSP and to measure the probative value of the degree of correspondence. These results provide both the impetus and direction for follow-on research.

The carpet fiber application itself has been a useful test-bed for development of the analytical and computational methods, but this application is not likely to be the most immediately available for implementation. Further research is needed that will (1) rigorously measure within and between variability for carpets, (2) determine how susceptible shed fibers are to contamination and loss of VSP profiles, and (3) explore the compatibility of fiber collection methods with the recovery of VSP from fibers.

More generally, and more significantly, the quantitative methods developed under this program are ready to be applied to (4) other trace evidence types, and (5) datasets generated by other particle analysis methods.

The most immediate application for the quantitative methods developed under this program are for (6) investigative associations of items of evidence with readily available and abundant adhering particles.

Additionally, there is strong impetus for (7) more general development and validation of quantitative methods for the use and interpretation of VSP.

I. Introduction

There is a fundamental limitation to the probative value of many of the most common types of trace evidence (e.g., fibers, glass, paint) because their characteristics are determined by their manufacture. As mass-produced commodities, probative value is limited to class associations. This has long been appreciated [1-4] and has been emphasized in the summary assessments in the NRC report.[5] Furthermore, determination of the evidential value of these class associations is extraordinarily problematic. Surveys conducted to determine frequencies of random occurrence of alternative class characteristics are an excellent foundation for expert opinion, but do not allow for quantitative interpretations due to ill-defined populations, the lack of a foundation for randomness within a population, changes in manufacturing practices over time, and variations among analytical methods.[2,3,6] Absent multiple transfers and exceptional circumstances,[7,8] probative value remains difficult to determine and limited by the possibility, or the suggestion of the possibility, that the evidence came from an alternative mass-produced item.

Multiple-transfer cases shatter this limitation. These are cases where a set of different trace evidence materials, found on a suspect, correspond to sources at a crime scene, and/or the reverse: where a set of trace evidence materials, found at the crime scene, correspond to suspect-related sources. When the possibilities of correlation can be discounted, the probative value can become extraordinarily high, even when probabilities for the occurrence of individual trace types are modest, or subject to inherent imprecision in their estimates. The co-occurrence of multiple events of modest frequency is the foundation for all highly probative types of physical evidence, including DNA and fingerprint identifications, and is an inherent aspect of some types of trace evidence, including the comparison of multi-layered structural paints and the comparison of soil specimens.

The present research program is part of an effort to radically improve trace-evidence analysis, systematically addressing the fundamental limitations affecting the strength and measurement of probative value, by exploiting the very small particles (VSP) that are present on virtually every material object.[6]

Four founding principles guide this effort:

1. Mixtures of particles have a great potential to proceed systematically toward individualization by providing enhanced probative value via their joint occurrence, with individual particle types occurring at modest, estimable frequencies with testable correlations.

2. Particles are always present in mixtures.

3. As we consider very small particles (VSP), their abundance increases, along with the complexity of the mixture.

4. VSP occurring on the surfaces of commonly used trace evidence types (and on virtually any evidence item) can be recovered, identified, and quantified leading to independent testing of the hypotheses of common origin.

The first principle has already been discussed, with specific reference to DNA, fingerprints and multiple-transfer evidence as precedence.

Given the value of mixtures, the second principle guides us toward a broader perspective and to recognize that mixtures are always present. The traditional focus of forensic particle trace evidence work is on only a small set of particle types, including fibers, glass, paint, and hair. Target particles such as these are defined by casework circumstances, and corresponding particles are sought as evidence of transfer and contact.[9] The significance of these particles is that (1) their transfer can be reasonably predicted, based on a hypothesis of contact and (2) they can be efficiently detected among the mixtures of particles that are always present. Other co-occurring particles, that are either smaller, or that do not have a discrete, recognizable crime scene or suspect source, are largely ignored as "noise."

The third principle guides us to focus on smaller particles. As we consider them, we have more particles, and the mixture becomes more complex. There is a nearly ten-thousand-fold dimensional gap between the size of conventional trace evidence types (> 50 μm) and those routinely recovered and analyzed by conventional DNA analysis (< 5 nm). The biggest of these particles within the gap are those seen by higher power light and electron microscopy – the respirable or near respirable dusts, which are traditionally ignored in forensic investigations, with the notable exception of gunshot residue (GSR).[10]

The fourth principle states that we can recover, identify and quantify and make practical use of VSP that adhere to the surfaces of conventional trace evidence particles or that are found on virtually any other item of physical evidence. These VSP "ride piggy-back" on conventional evidence. They occur in complex mixtures and include a tremendous variety of particles that are acquired when manufactured materials are exposed to alternative environments. These particles reflect cumulative exposures and conditions; they will be highly characteristic of the local environment[11] and their presence, identity and relative quantities provide an untapped source of individuality. There is a tremendous potential here: every trace evidence case becomes a multiple-transfer case, with the adhering fine particles providing an independent quantitative means to test hypotheses of common origin. Consider: if *these* carpet fibers came from *that* carpet, then the multivariate occurrence of a quantitative profile of fine particles, present on *that* carpet, ought to be present, subject to statistical sampling, on *these* fibers.

To unlock this potential, research is required that (1) determines which VSP have useful forensic performance characteristics, (2) develops suitable methods for detection and measurement, and (3) provides data on variation and occurrence that enables reliable statistical interpretation.

NIJ funded research has shown that very small particles (VSP), ubiquitous on the surfaces of carpet fibers, can be used to associate individual fibers with their carpet source.[12] Hundreds to thousands of VSP occur on the surfaces of individual carpet fibers. The particles can be efficiently removed and analyzed by computer-assisted SEM/EDS, resulting in highly

characteristic profiles of target particle types (TPTs). When sufficient VSP are recovered from individual fibers, there is a close correspondence between these TPT profiles and those from the originating carpet area.

This foundational research had extraordinary implications for both carpet fiber evidence and for trace evidence analysis in general. Proof of principle was established that the analysis of VSP on the surface of carpet fibers could remove fundamental limitations to probative value, augmenting class associations with independent, quantitative testing of common origin using populations of VSP.

The proof of principle research was conducted using carpet fibers cut from multiple areas of multiple carpets and a set of well-defined, frequently occurring particle types.[12,13] This report describes the next stage of research, designed to bring these methods to fruition.

The goals of the present research were to (1) refine the process for exploiting very small particles (VSP) to associate residential carpet fibers with their source carpet, (2) apply this process under realistic casework conditions, and (3) deliver a working prototype for both the methods of analysis and the measurement of the probative value of comparisons.

To meet these goals we defined five objectives:

1. Apply and test the methods under realistic conditions of carpet fiber transfer and crime scene sampling.
2. Expand and improve VSP target particle type classification criteria based on analysis of forensic performance characteristics.
3. Design, develop, and deliver a practical method for the measurement of the degree of correspondence between two VSP profiles.
4. Design, develop and deliver practical, quantitative measures of the probative value of this degree of correspondence.
5. Present the program results to the forensic science practitioner and research in a forum allowing considered feedback and discussion.

II. Methods

A. Collection of Carpet Fiber Specimens

Carpet fiber specimens from residential wall-to-wall carpeting were collected by crime scene practitioners working within nine separate jurisdictions within the United States, as listed in Table 1. Collectors used a specially designed kit for efficient collection of two carpet fiber specimens:

- Carpet fibers transferred by frictional contact to a lint-free inspection glove (representing transferred fiber traces from the source)
- Carpet fibers collected with a hook-type lint brush (representing a reference sample from the carpet source)

Additionally, the kit provided for collection of three surface wipes from horizontal surfaces in the same room where the carpet fiber samplings were taken. One wipe each was taken from a baseboard area, the top of a door frame, and an available mid-height surface. (These control samples were collected as they would be impossible to collect at a later time and were deemed to be of possible value for follow-on research to better understand the source and variability of VSP.)

The complete kit is illustrated in Figure 1 which shows a page that was included with the kit shipments and served as an introduction for the practitioner collectors. The Instruction Sheet and instructions for each of the collections are included as *Appendix A. Carpet Fiber Sampling Kit.*

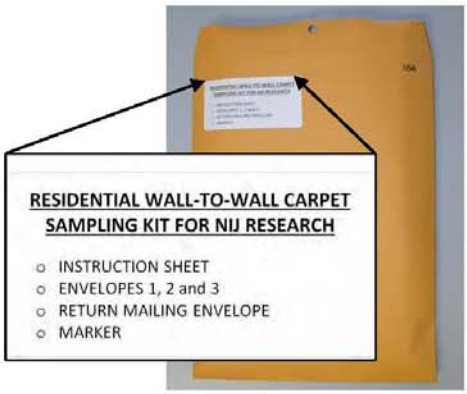
Table 1. Agencies Contributing Carpet Fiber Collection Kits for this Project

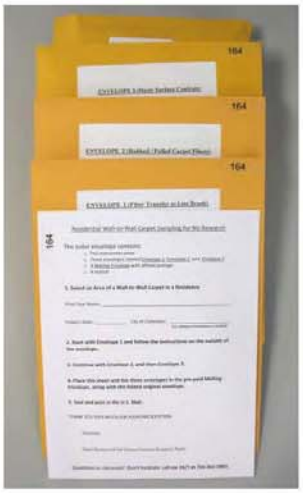
Contra Costa County Sheriff's Office Criminalistics Laboratory, Martinez, CA
Forensic Laboratory Services Division, Seminole County Sheriff's Office, Sanford, FL
Idaho State Police Forensic Services, Meridian, ID
Iowa Division of Criminal Investigation, Criminalistics Laboratory, Ankeny, IA
Oakland Police Department Criminal Investigation Division, Oakland, CA
Patton Township Police Department, State College, PA
San Diego County Sheriff's Regional Crime Laboratory, San Diego, CA
San Diego Police Department Forensic Science Section, San Diego, CA
Scientific Services Bureau, Los Angeles County Sheriff's Department, Los Angeles, CA

Residential Wall-to-Wall Carpet Sampling Kits for NIJ Research

Thank you for your participation in this project.
A box containing 15 self-contained sampling kits is in the mail to you.
Although all needed instructions are inside the individual kits, this is a description that will give you an overview of the contents and approach.

The kits are in unsealed envelopes with an index number and label listing the contents.





The Instruction Sheet

- Asks for the date, the city, and the collector's name.
- Guides the collector sequentially to Envelopes 1, 2 and 3.

Envelope 1 (Fiber Transfer to Lint Brush)

- Instructions on Outside of Envelope
- Zip-lock bag inside with folding lint brush
- Carpet is brushed, brush closed, back to bag, back to envelope, & clasp closed

Envelope 2 (Rubbed/Pulled Carpet Fibers)

- Instructions on Outside of Envelope
- Zip-lock bag inside with large nylon inspection glove
- Carpet is rubbed/pulled, glove inverted, back to bag, back to envelope, & clasp closed

Envelope 3 (Dusty Surface Controls)

- Instructions on Outside of Envelope
- Three zip-lock bags inside with inspection gloves
- Dusty surfaces (as illustrated on bags) are wiped, glove inverted, back to bag, back to envelope, & clasp closed

Pre-Paid Addressed Return Envelope

- Insert the Instruction Sheet, Envelopes 1,2 & 3, and the original kit envelope into the pre-paid, addressed, self-sealing envelope
- The envelope is sealed and put in the US Mail

THANK YOU

The Stoney Forensic NIJ Research Team

Figure 1. Overview of the complete collection kit. This page was included with the kit shipments and served as an introduction for the practitioner collectors.

B. Fiber Recovery and Isolation of Particles from Fibers

Under a stereomicroscope on a clean bench, forceps were used to recover three to 12 fibers from each of the two carpet fiber specimens in the sampling kit. Kits with less than three carpet fibers in one of the two specimens were rejected and not processed further. Specimen numbers for trace and reference fibers from the same kit were coded to obscure the identity of mated pairs until after analysis.

VSP were removed and recovered from the fibers by ethanol extraction and filtration using polycarbonate filters with 0.4 μm pore size. The method of Bowen and Stoney [14] was followed, except that (1) 13mm polycarbonate filters were used in place of excised portions of 47mm filters, (2) these filters were cut in half prior to mounting for SEM, and (3) the filters were not carbon coated following extraction. The method is summarized below for convenience.

All procedures were conducted on a clean bench. Prior to starting, a significant volume (roughly 100 mL) of reagent grade ethanol (99.5%) was filtered through a polycarbonate filter (Millipore Isopore™ Membrane Filters, 0.4 μm HTTP). All test tubes, transfer pipets, forceps and razor blades were pre-washed with the particle-free ethanol.

Approximately 0.5 mL of pre-filtered reagent grade ethanol (99.5%) was transferred to a 1.5 mL micro-centrifuge tube using a transfer pipet. The fibers to be extracted were placed inside the tube using forceps. The tube was then sonicated in an ultrasonic cleaner (Cole Palmer model 08849-00) for ten minutes.

For filtration a 13mm polycarbonate filter (Millipore Isopore™ Membrane Filters, 0.4 μm HTTP) was placed on a 47mm filter support pad and then directly onto a vacuum filtration apparatus (with no upper funnel attached). The vacuum was applied to the filter and then a wide-tipped (1.5mm ID) transfer pipet was used to slowly transfer the ethanol suspension of VSP to the filter while the vacuum pulled the ethanol through the filter. The filter was left on the support pad to dry, after which it cut in half along its diameter and transferred to carbon tape on an each of two separate SEM stubs using forceps. One SEM stub was selected for analysis and the other reserved for possible future study.

A process control blank was prepared alongside each batch of processed specimens (pre-filtered ethanol sonicated for ten minutes in an empty tube and otherwise treated in an identical manner).

C. Computer Assisted SEM/EDS Analysis of Particles

The computer-assisted SEM/EDS analysis was performed on an Aspex Corporation 3025 SEM-EDS system using the Automated Feature Analysis (AFA) program within the Aspex Corporation Perception software. Analysis was performed under low vacuum conditions (0.1 torr) utilizing a 20.0kV accelerating voltage, backscatter electron detector (BSED), working distance of approximately 14.6mm, and spot size of approximately 33%. The magnification for the analysis was 1,200X with the number of electronic fields set at a maximum of 5 x 5. A grid dimension of 512 x 512 was used with a dwell time per pixel of 2μs for searching and 16μs for measuring. The size criteria for analysis were a minimum size of 0.3μm and a maximum size of

80.0µm. The maximum number of particles analyzed, as set by program parameters, was 10,000. EDS parameters had a nominal duration of 3s, a maximum of 6s, a minimum count of 1500 and a target count of 2500. An EDS Copper calibration check was performed prior to, and following each analysis.

Software settings were selected to restrict particle characterization based on standard x-ray K-shell emission lines of the 18 elements listed in Table 2. These elements were chosen (1) following a review of the manufacturer's recommendations indicating that the AFA software performed best for a number of elements below 20, (2) to avoid overlapping x-ray energies, and (3) to provide broad coverage of x-ray energies appearing in the range of 1 to 10 KeV. A more complete discussion of the choice of elements is provided in *Appendix B. Discussion of SEM/EDS Analysis Parameters.*

Raw datasets for each computer-assisted SEM/EDS run consisted of a set of run parameters and results along with individual particle analysis data. Run parameters and results were: starting and ending times, beam energy, working distance, spot size, detector, video settings (contrast, brightness), specimen identification (stub, sample number, description, client name), operator, instrument, area analyzed and particle count. Individual particle data were a particle index number, particle area, the four elements in the particle's EDS spectrum having the highest x-ray counts, the corresponding four x-ray counts, live analysis time, total x-ray counts for the particle and the calculated percentages of each of the 18 specified elements.

Table 2. The 18 Elements Detected by the Automated EDS Procedure

Sodium (Kα, Kβ)	Magnesium (Kα, Kβ)	Aluminum (Kα, Kβ)
Silicon (Kα, Kβ)	Phosphorous (Kα, Kβ)	Sulfur (Kα, Kβ)
Chlorine (Kα, Kβ)	Potassium (Kα, Kβ)	Calcium (Kα, Kβ)
Titanium (Kα, Kβ)	Vanadium (Kα, Kβ)	Chromium (Kα, Kβ)
Manganese (Kα, Kβ)	Iron (Kα, Kβ)	Cobalt (Kα, Kβ)
Nickel (Kα, Kβ)	Copper (Kα, Kβ)	Zinc (Kα, Kβ)

D. 2010 Particle Dataset

Particle data collected and previously described under NIJ Award 2010-DN-BX-K244 were re-analyzed using the computational methods developed during this project. The dataset consists of SEM/EDS particle analysis results from 39 carpet area sources (taken to represent source references) and 81 individual fibers originating from some of these sources (taken to represent transferred traces). Of the 39 sources, twelve are individual sources (from one area of a carpet) and the remaining 27 come from nine carpets, with three areas taken from each of the nine carpets. The 81 individual fibers consist of three fibers from each of the 27 carpet areas.

Analytical parameters for this dataset, compared with those used described in the previous section, are provided in *Appendix B. Discussion of SEM/EDS Analysis Parameters.*

E. Data Analysis

Statistical analysis was performed using R Version 3.0.3.[15] as described below.

Filtering of Noise. The particle data were filtered to (1) remove particles that failed to show any dominant composition as represented by the calculated percentages of the elements and (2) remove elements that were only present in minute amounts. Two parameters were defined to determine the presence of a dominant composition (1) the total proportion P of the composition of a particle represented by N elements, and (2) the number N of elements. Parameters of 60% composition represented by 5 elements were set based on an analysis of 167,000 particles recovered from carpet fibers previously reported under project 2010-DN-BX-K244. (Selecting only those particles where a maximum of five elements are needed to represent 60% of their composition, retained approximately 98% of the original 167,000 particles.) . In addition, the percentage composition contributed by the next (6^{th}) element was examined and this element was also retained if it accounted for more than 10% of the total composition of the particle. In order to keep the integrity of the compositional aspect of the data and of its structure, the "noise elements" were not removed, but their contribution to the composition of the particle was set to zero. The proportions of the remaining elements were not rescaled, in accordance with recommended practices.[16] Particles that did not have N elements representing more than the set threshold for their composition were considered as noise and discarded.

Definition of Target Particle Types. Target particle types (TPTs) were defined using an unsupervised hierarchical clustering algorithm relying on Normal Mixture Modeling. The algorithm is implemented in the R library mclust [5,6]. This package allows for finding the optimal mixture model that represents the distribution of the data. In such a model, each class (cluster) is represented by one of the multivariate normal distributions in the mixture. The posterior probability of class for each data point is calculated according to a Bayes rule for each of the normal density functions.

In unsupervised hierarchical clustering, the scientist sets the number of classes G (in this case the number of TPTs) and the algorithm optimizes the parameters of each one of the G components such that the overall mixture best describes the data. The mixture model makes sense mathematically speaking (data points are similar to each other in the eyes of the algorithm), but they are an abstract construction of alternative variables and classification possibilities. Thus, the TPT classes created by the algorithm are not necessarily representative of chemically recognizable particle types. TPTs were defined using a random sampling of 8000 particles from references source datasets. This paper describes different strategies for associating fibers, which relies on two different designs for the sets of TPTs: sets of TPTs were defined with G = 10 and G = 80.

Determination of TPT Profiles. Two alternative strategies were used for determination of TPT profiles. Under Strategy 1, 10 TPTs were defined based on the reference dataset, as described above in Definition of Target Particle Types. The TPT profile for any sample was determined by categorization of each of that specimen's particles into the most closely fitting TPT, based on a computation of the particles' probability of class membership in each of the TPTs.

Under Strategy 2, 80 TPTs were defined, again based on the reference dataset, as described above in Definition of Target Particle Types. Then for each individual comparison between a set of "trace fibers" and a series of target sources, the particles on both trace and control samples were classified in the 80 TPTs; however, only the 10 most populated TPTs on the trace were selected for the comparison, which with the remaining particles were grouped into an 11th class. This grouping was repeated in the specimen based on the TPTs selected for the trace.

Measurement of Degree of Correspondence among TPT Profiles. The comparison between TPT profiles relied on the properties of the multinomial distribution (see *Appendix O. Mathematical Expression of the Multinomial Distribution*). The counts for the *k* TPTs selected for any given specimen were used to determine the *k* probabilities of a multinomial distribution of the TPTs for that specimen. An example of these counts for the specimens used in the study is presented in Table 3.

Table 3. Example of a Table of TPT Counts as Defined from the 2010 Dataset References

Counts of particles for each source (rows) across 10 TPTs (columns)

source	1	2	3	4	5	6	7	8	9	10
A1	21	74	337	272	156	242	127	351	553	71
A2	223	362	179	204	17	952	70	299	600	12
A3	56	119	793	475	169	356	339	315	278	43
BH1	599	151	121	97	136	255	84	360	321	82
BH2	635	173	510	251	288	304	211	387	139	108
BH3	304	125	105	96	916	98	62	237	209	811
BV1	9	21	236	264	44	43	104	133	16	11
BV2	72	39	707	748	228	105	503	176	27	20
BV3	116	16	296	217	72	55	165	82	14	15
F1	4	21	63	60	39	21	78	34	10	1
F2	5	36	109	94	72	354	94	79	12	8
F3	8	6	58	34	33	6	41	59	10	3
MT1	29	148	770	393	327	119	472	590	64	69
MT2	25	73	796	324	81	235	274	154	30	20
MT3	28	34	385	143	50	220	134	92	34	7
PH1	5	28	57	26	12	148	13	597	93	22
PH2	8	78	30	14	29	176	8	2013	564	11
PH3	22	108	220	77	87	301	86	1569	460	25
PL1	6	85	147	94	38	42	81	177	2248	5
PL2	10	27	285	237	134	102	233	188	350	26
PL3	35	95	412	241	177	124	170	592	818	30
PV1	18	57	1231	441	251	231	281	369	39	60
PV2	24	70	1174	388	451	146	236	322	129	56
PV3	11	15	232	107	144	48	62	141	15	6
R1	3	19	68	47	42	23	42	43	186	10
R2	6	122	661	429	91	56	431	1095	58	42
R3	63	278	244	211	130	66	199	791	944	20
R4	23	71	731	381	106	39	377	236	296	59
R5	143	101	566	434	165	165	139	320	833	82
R6	58	121	674	385	208	106	288	607	464	52
R7	412	111	641	365	95	184	212	258	665	47
V1	61	46	538	317	198	176	186	378	530	71
V2	23	31	310	185	122	55	143	360	58	28
V3	69	44	694	409	286	314	279	313	74	63
V4	8	31	159	84	89	24	103	107	116	25
V5	2	9	101	56	30	16	49	73	27	16
W1	19	28	712	303	61	418	159	264	125	12
W2	17	58	1040	491	167	94	324	277	390	53
W3	5	6	153	92	25	14	62	113	67	11

When a new set of particles from a new sample was considered, its particles were categorized into the TPTs previously defined for the reference source(s). The probability of the observed count in the new sample was assigned using the multinomial probability mass functions for each of the reference sources. These conditional probabilities were used as the measure of correspondence of the new specimen with each of the reference sources. For classification, the new specimen was assigned to the reference source with the highest conditional probability (equal priors for each of the sources were considered).

Measurement of Probative Value of Corresponding TPT Profiles. Given a set of *N* possible sources, each represented by its counts for each of the TPTs, a table of TPT counts for each possible source was used (as above) to determine the *k* probabilities associated with the *k* TPT categories in the multinomial distribution of a given particle type in each source. When a new set of particles of questioned source was considered, its particles were categorized into the TPTs and the probability density of the count was assigned in each of the *N* multinomial densities. A Bayesian classifier[19] was then applied to these *N* probability densities, assuming an equal prior among all *N* classes.[1] This results in posterior probabilities were obtained using the classifier for all *N* sources:

Eq. 1
$$\Pr(S_j|E) = \frac{\Pr(E|S_j)\Pr(S_j)}{\Pr(E|S_1)\Pr(S_1) + \ldots + \Pr(E|S_N)\Pr(S_N)}$$

A corresponding likelihood was calculated as a measure of evidential weight, based on assumptions of the representativeness of the *N* sources:

Eq. 2
$$LR(E,S_j) = \frac{\Pr(E|S_j)(1-\Pr(S_j))}{\sum_{i=1,i\neq j}^{D}\Pr(E|S_i)\Pr(S_i)} = \frac{(N-1)\Pr(E|S_j)}{\sum_{i=1,i\neq j}^{D}\Pr(E|S_i)}$$

General Discriminating Power of the System. The general discriminating power of the system[20] was analyzed by comparing the different reference sources to each other. A distance matrix among the different reference source signals was determined based on the multinomial distribution. Relationships among reference sources were plotted using network diagrams. These diagrams graphically represent the associations between different objects. In our case, each dot on the plot represents a source of fibers, and each arrow represents the association between a set of fibers from a particular source to a given source. Arrows between dots indicate that a specimen has been associated to the wrong source, while short arrows pointing to a single dot indicate that a specimen has been correctly associated to that source.

An example of a network diagram is given in Figure 2. Each specimen is represented by a numbered colored circle. Network diagrams are a means to graphically represent the discrimination among the specimens. There is no scale applicable to the axes of the diagram, nor

[1] The representation of the probability of (the evidence given the source) as the probability of (the source given the evidence) depends explicitly on the assumptions of an equal prior (equal probability within a closed set). See the discussion in section IV.A.9. of the Conclusions.

is there any significance to the color of the circles representing the different sources. The circles are grouped to minimize the crossing of the links among them. Isolated circles (without gray lines) indicate that those sources are differentiated from all of the other specimens. A gray arrowhead just to the right of an isolated circle and pointing toward the circle indicates that that specimen has sufficient character that the system correctly associates the specimen with itself. Arrows starting from one circle and leading to another represent that the data from the first circle are insufficient to differentiate it from the second. For example, the system matches Specimen Z2E (in this case a blank) to Specimen 59 (as well as many other specimens). This is not unexpected result for blank samples, as they often have insufficient character to be differentiated from multiple sources. However, note that the diagram indicates that Specimen 59 is not associated with Specimen Z2E, as there is no arrow in that direction. Specimen 59 has sufficient character that it the system differentiates it from the control sample.[2]

Matching Ability of the System. Following best scientific practices, the matching ability of the system was examined by separating the particle data in the reference sources into a training set and a test set. The training set (2/3 of the original dataset) was used to define the set of TPTs as described above, to measure the respective proportions of particles with these TPTs in each source, and to study some aspect of the general discrimination potential of the system. The purpose of the test set (1/3 of the original dataset) is to test the system on a dataset that was not used to estimate the parameters of the system. Since the test set is an independent and identically distributed sample of the particles from the set of particles recovered from the "source" fibers, the test set is used to establish a baseline performance of the system in ideal conditions. Using the procedures described above, TPT profiles were determined and multinomial distributions were defined based for each of the *N* sources using the particles in the training set. For evaluation of the matching ability of the system, the training set sources were used as "references," and the particles remaining in each of the specimens' test set were used as *N* new specimens, to be compared with the "references."

The degree of correspondence and measurement of probative value were determined for each specimen in the test set to each source as defined by the training set. Rates of correct and incorrect classification were determined based on classification to the source of highest probability.

Where there were misclassifications among specimens based on matching the new specimen to the source of the highest probability, the system was analyzed using Detection Error Threshold (DET) diagrams and examination of the rank of the probability for true source, in relation to the probabilities of the remaining sources.

Examples of three DET diagram for different systems are given in Figure 3. A DET diagram shows the trade-off between rates of false positives and false negatives as the threshold for decision-making is varied. The line shows the result as the decision threshold is varied. If the threshold is set at one extreme, one gets many false positives; if it is set at the other extreme, one gets many false negatives. A useful system will show that a position on the curve can be selected

[2] This type of one-way, or "asymmetric" association arises in the sense that Pr(count of TPT on sample 1 | prob of TPT on sample 2) is not equal Pr(count of TPT on sample 2 | prob of TPT on sample 1) because the multinomial probability function takes into account not only the probability for each category, but also the count .

that results in acceptable balance between false positives and false negatives. In Figure 3, the DET chart on the left shows a reasonably well-functioning classification system, characterized by a portion of the line coming close to the origin of the diagram, where both false positive and false negative rates are low. The DET chart in the center shows a very poorly functioning system. False positive and false negative rates are both high for most thresholds. The system to the right in Figure 3 shows intermediate performance.

Matching Sources to Traces. The performance for comparison of sources to traces was examined as above for *Matching Ability of the System*, using the full particle data in the reference sources to define their TPT profiles and multinomial distribution. The particle sets from each of the traces were then compared by determining the degree of correspondence and probative value for each the trace specimens to each of the sources. Results were evaluated using rates of correct and incorrect classification, network diagrams, DET diagrams and charts showing the ranking of the true source.

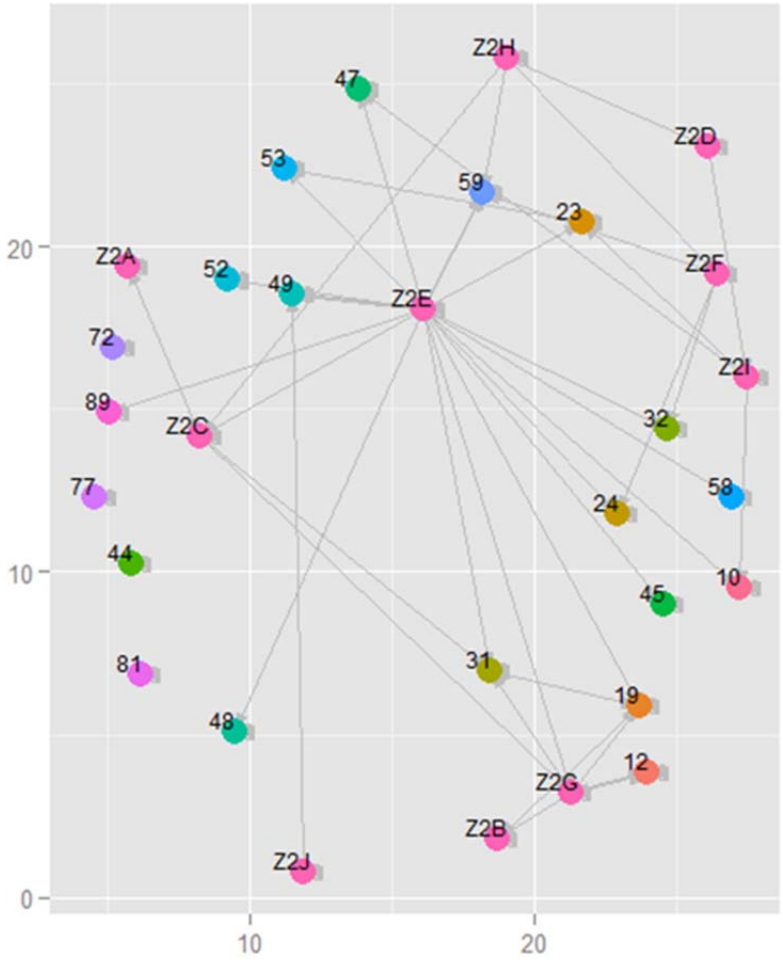


Figure 2. An example of a Network Diagram used to represent the discrimination resulting from a classification system. See explanation in text.

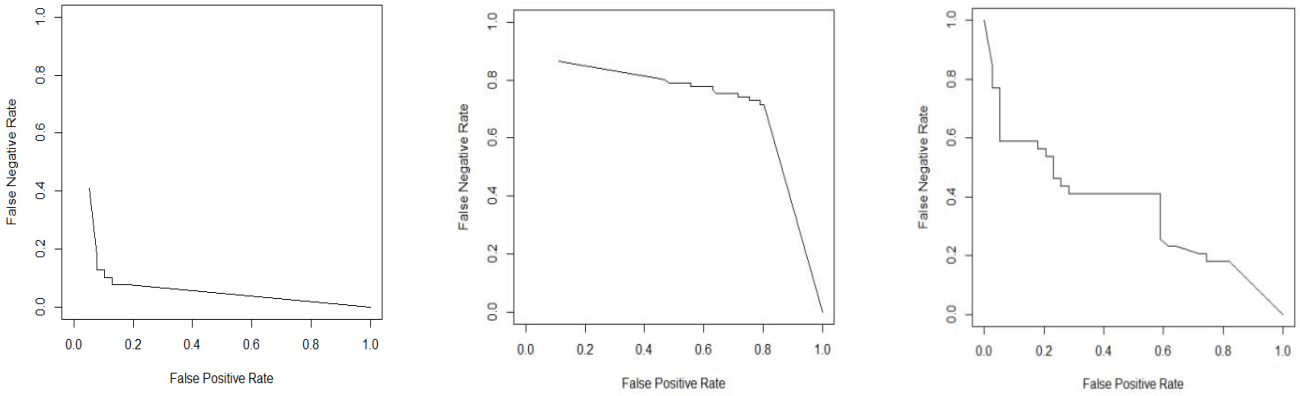


Figure 3. Examples of a Detection Error Threshold (DET) diagrams used to represent the potential usefulness of classification system. See explanation in text.

III. Results

A. Carpet Fiber Field Collections and Fiber Recovery

A total of 100 Residential Wall-to-Wall Carpet Sampling Kits were returned from the nine agencies listed in Table 1. Of these kits, 14 were rejected due to the presence of less than three carpet fibers in one or both of the specimens. Six additional kits were used by Stoney Forensic for supplementary collections, bringing the total number kits with suitable fiber recovery to 90. These kits yielded 90 carpet source reference specimens and 90 corresponding transferred trace specimens.

The makeup of these 90 kits, by jurisdiction and city, is summarized in Table 4. Fifty cities are represented in 6 states, collected by nine agencies, along with six supplementary kits collected by the PI. California is heavily represented, with 54 of the 90 kits. Details are given in *Appendix C. Summary of Specimen Designations.*

Table 4. Summary of Origin of Carpet Fiber Collections for Specimens Analyzed

Collection Agency	Kits	State	Cities Represented
CCSO	13	CA	11: 1 with 3 kits; 9 with 1 kit each
IDCI	1	IA	1 with 1 kit
ISP	8	ID	4: 1 with 3 kits; 2 with 2 kits; 1 with 1 kit
LASD	6	CA	6 with 1 kit each
OPD	3	CA	2: 1 with 2 kits; 1 with 1 kit
PTPD	10	PA	5: 1 with 5 kits; 1 with 2 kits; 3 with 1 kit each
SCSO	11	FL	6: 1 with 3 kits; 3 with 2 kits; 2 with 1 kit each
SDCS	27	CA	9: 1 with 17 kits; 2 with 2 kits; 6 with 1 kit each
SDPD	5	CA	4: 1 with 2 kits; 2 with 1 kit each
SFI	6	VA	4: 1 with 3 kits; 3 with 1 kit each
Total	90	6	50*

*two cities were represented in two jurisdictions

B. Computer-Assisted SEM Analyses

The computer-assisted SEM analyses were conducted on the 180 specimens and 10 process blanks and are provided in *Appendix D. Computer-Assisted SEM-EDS Analysis Dataset*. There are three separate folders in Appendix D. Folder "Appendix D-1 References R01 to R90" contains 90 comma-separated Excel spreadsheets with the data for the 90 reference specimens. Folder "Appendix D-2 Traces T01 to T90" contains the 90 corresponding traces in the same format. Folder "Appendix D-3 Blanks BZ2A to BZ2J" contains the files for the 10 process blanks.

The key for specimen designations is provided as part of *Appendix C. Summary of Specimen Designations.* This file shows the following information for each specimen: Collection Kit

Number, Date of Collection, Collection Agency, City of Collection, Specimen Kit Designation, EDS Specimen Designation, Specimen Type and Dataset Designation.

Particle numbers recovered and analyzed from the 90 References are summarized in Table 5. Those from the 90 Traces are summarized in Table 6 and those from the 10 Process Blanks are summarized in Table 7.

Descriptive statistics are found Table 8.[3] On the average, References showed 957.7 particles (n = 90, SD = 2270.7); Traces showed 231.6 particles (n = 90, SD = 1105.7); and blanks showed 170.8 particles (n = 10, SD = 149.7).

Table 5. Numbers of Particles Recovered and Analyzed from References

Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count
R01	181	R16	1678	R31	716	R46	390	R61	1310	R76	57
R02	1004	R17	238	R32	674	R47	935	R62	56	R77	4474
R03	256	R18	280	R33	115	R48	515	R63	312	R78	181
R04	37	R19	538	R34	206	R49	2153	R64	302	R79	209
R05	93	R20	1454	R35	99	R50	451	R65	29	R80	337
R06	241	R21	35	R36	119	R51	391	R66	166	R81	5256
R07	31	R22	377	R37	117	R52	2273	R67	16	R82	1161
R08	104	R23	549	R38	51	R53	1774	R68	993	R83	912
R09	97	R24	567	R39	97	R54	402	R69	42	R84	342
R10	1289	R25	346	R40	428	R55	746	R70	56	R85	285
R11	331	R26	82	R41	373	R56	1009	R71	937	R86	121
R12	1089	R27	388	R42	268	R57	336	R72	18,170	R87	386
R13	468	R28	210	R43	581	R58	3867	R73	180	R88	158
R14	1034	R29	289	R44	781	R59	9739	R74	333	R89	1136
R15	636	R30	271	R45	3782	R60	473	R75	13	R90	213

Table 6. Numbers of Particles Recovered and Analyzed from Traces

Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count	Specimen	Particle Count
T01	1518	T16	420	T31	553	T46	697	T61	441	T76	753
T02	515	T17	361	T32	1785	T47	2443	T62	531	T77	1937
T03	203	T18	1509	T33	4156	T48	2120	T63	72	T78	342
T04	20	T19	3363	T34	331	T49	2751	T64	59	T79	126
T05	183	T20	182	T35	229	T50	694	T65	78	T80	250
T06	340	T21	106	T36	678	T51	1132	T66	140	T81	582
T07	68	T22	477	T37	40	T52	3535	T67	64	T82	426
T08	17	T23	1735	T38	55	T53	2083	T68	158	T83	168
T09	107	T24	924	T39	386	T54	1087	T69	150	T84	344
T10	1216	T25	2457	T40	503	T55	57	T70	94	T85	227
T11	116	T26	54	T41	232	T56	397	T71	309	T86	746
T12	1209	T27	569	T42	612	T57	213	T72	3,235	T87	569
T13	250	T28	422	T43	327	T58	898	T73	251	T88	41
T14	128	T29	698	T44	793	T59	7102	T74	204	T89	997
T15	384	T30	903	T45	1820	T60	168	T75	84	T90	204

[3] Full descriptive statistics can be found in the Excel file *Appendix E. Particle Numbers Descriptive Statistics*.

Table 7. Numbers of Particles Recovered and Analyzed from Process Blanks

Specimen	Particle Count
BZ2A	220
BZ2B	468
BZ2C	251
BZ2D	174
BZ2E	11
BZ2F	45
BZ2G	312
BZ2H	26
BZ2I	179
BZ2J	22

Table 8. Descriptive Statistics for Particle Numbers Recovered and Analyzed

All References		All Traces		All Blanks	
Count	90	Count	90	Count	10
Mean	957.7	Mean	799.0	Mean	170.8
Standard Error	239.4	Standard Error	116.6	Standard Error	47.3
Standard Deviation	2270.8	Standard Deviation	1105.7	Standard Deviation	149.7
Median	344	Median	391.5	Median	176.5
Minimum	13	Minimum	17	Minimum	11
Maximum	18170	Maximum	7102	Maximum	468
Sum	86197	Sum	71913	Sum	1708

C. Application of Computational Methods to 2010 Particle Dataset

Particle data collected and previously described under NIJ Award 2010-DN-BX-K244 are provided in *Appendix F. Computer-Assisted SEM-EDS 2010 Analysis Dataset.* There are three separate folders in Appendix F. Folder "Appendix F-1 References" contains 39 comma-separated Excel spreadsheets with the data for the 39 reference specimens. Folder "Appendix F-2 Traces" contains the 81 traces in the same format. Folder "Appendix F-3 Blanks" contains the files for the 12 process blanks. The key for the 2010 Dataset specimen designations is provided as *Appendix G. Summary of 2010 Specimen Designations.* Summary particle sets are given in *Appendix H. Descriptive Statistics and Particle Numbers for 2010 Dataset.*

General Discriminating Power of the System – 2010 Dataset. The discrimination ability of the system for the 2010 dataset under Strategies 1 and 2 is shown by network diagrams in Figures 4 and 5.[4] Figure 4 includes the blanks and Figure 5 does not. The system shows complete discrimination among reference specimens using either strategy. As noted in the explanation of the network diagrams in the methods section, failure to discriminate blanks from specimens, as indicated by the arrows *from* blanks *to* specimens in Figure 4 (left), is not unexpected, as they often have insufficient character to be differentiated from multiple sources. A more unexpected result would have been the inability to discriminate specimens from blanks, which did not happen. This enables the conclusion that each of the specimens has enough TPT signal that they can be discriminate from each other, and from random background signal, at least in an ideal situation.

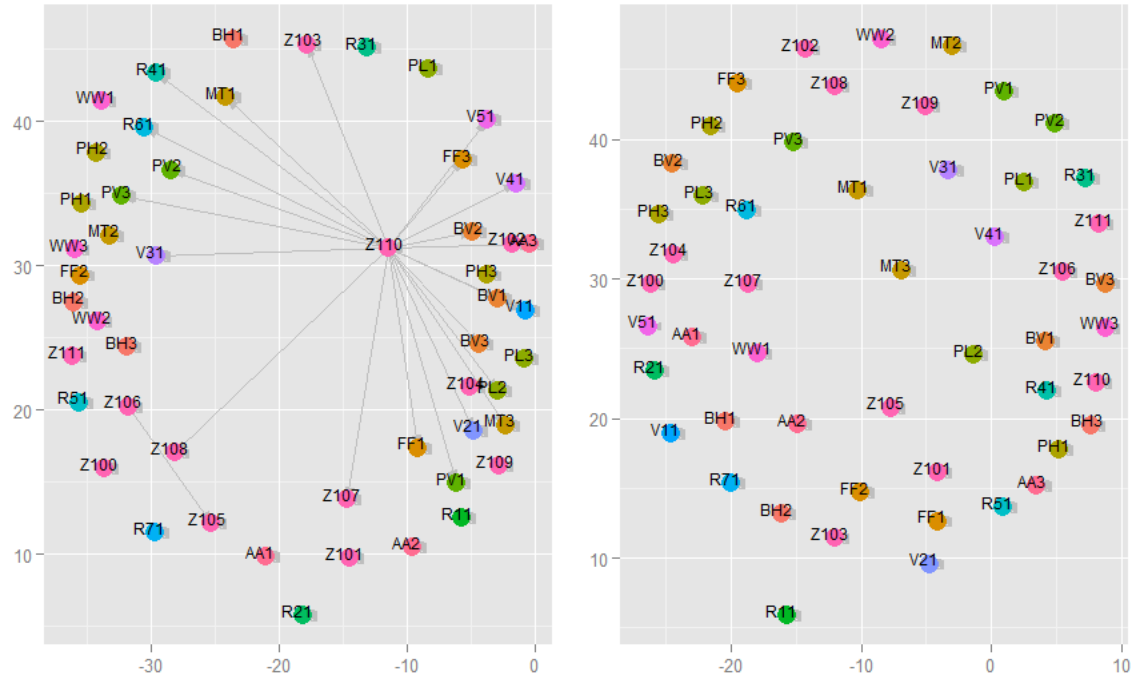


Figure 4. Network diagrams showing the general discrimination of the reference specimens and process control blanks for the 2010 Dataset using Strategy 1 (left) and Strategy 2 (right). (Blanks have an initial letter "Z.")

[4] General discussion of the format of network diagrams is given in the Methods Section II.E. Data Analysis.

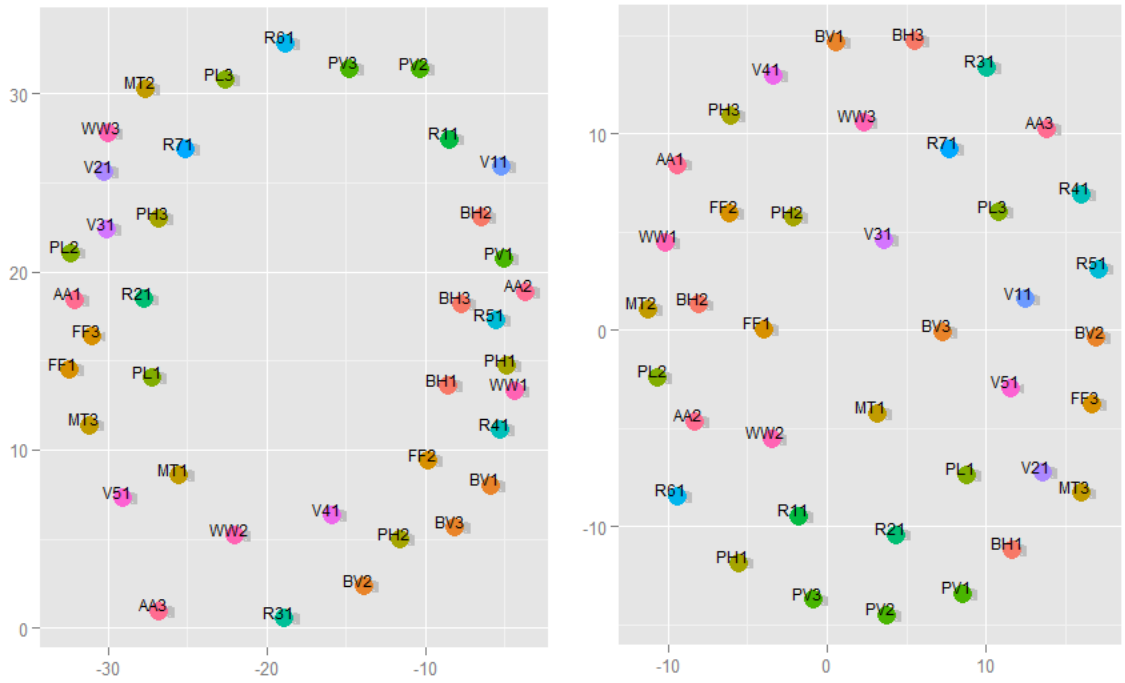


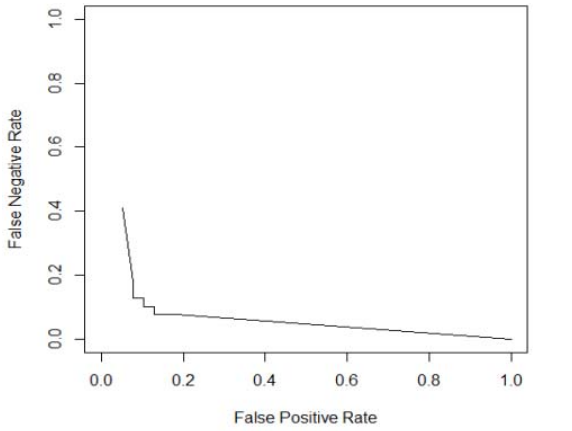
Figure 5. Network diagrams showing the general discrimination of the reference specimens for the 2010 Dataset using Strategy 1 (left) and Strategy 2 (right).

Matching Ability of the System – 2010 Dataset.[5] Figures 6 and 7 present the matching ability of the system when attempting to associate "traces" from the test set with "references " from the training set using Strategies 1 and 2. For matching to the same carpet area, Figure 6 shows a correct classification rate of 90% under Strategy 1 and 95% under Strategy 2. The DET diagrams correspond to these carpet area classifications. Correct classification rates for the same carpet are also given, which are 92% under Strategy 1 and 95% under Strategy 2. Network diagrams are shown in Figure 7,[6] where it is possible to observe that a small number of traces have been associated with the wrong source (e.g., PL2 and V11 at the bottom of the left hand side of Figure 7) or with the wrong carpet area (e.g. AA2 and AA1 on the right of the left hand side of Figure 7).

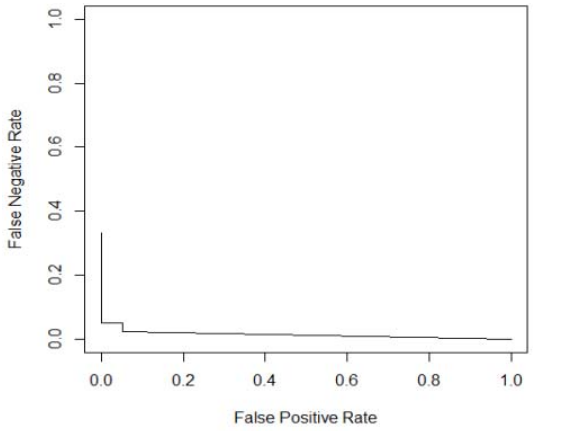
Matching Sources to Traces – 2010 Dataset. Results of application of the system to comparison of 2010 reference specimens to their corresponding traces are shown in Figures 8 and 9. For matching to the same carpet area, Figure 8 shows a correct classification rate of 26% under Strategy 1 and 35% under strategy 2. The DET diagrams correspond to these carpet area classifications. Correct classification rates for the same carpet are also given, which are 46% under Strategy 1 and 60% under Strategy 2. Figure 9 shows the rank of the probability for the true source under each of the two strategies.

[5] See the methods section for full descriptions of 'Matching Ability of the System' and 'Matching Sources to Traces.'

[6] General discussion of the format of network diagrams is given in the Methods Section II.E. Data Analysis.

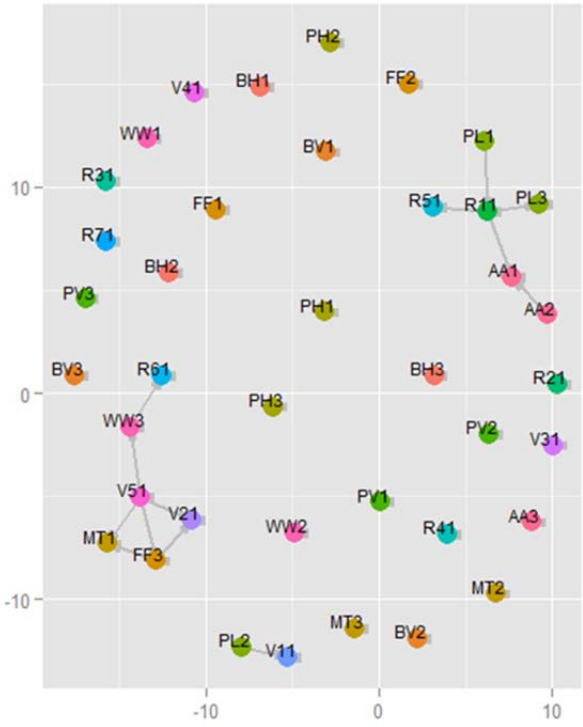


	Correct	Wrong
Carpet	0.92	0.08
Carpet Area	0.90	0.10



	Correct	Wrong
Carpet	0.95	0.05
Carpet Area	0.95	0.05

Figure 6. Classification performance for the 2010 Dataset under Strategies 1 and 2.



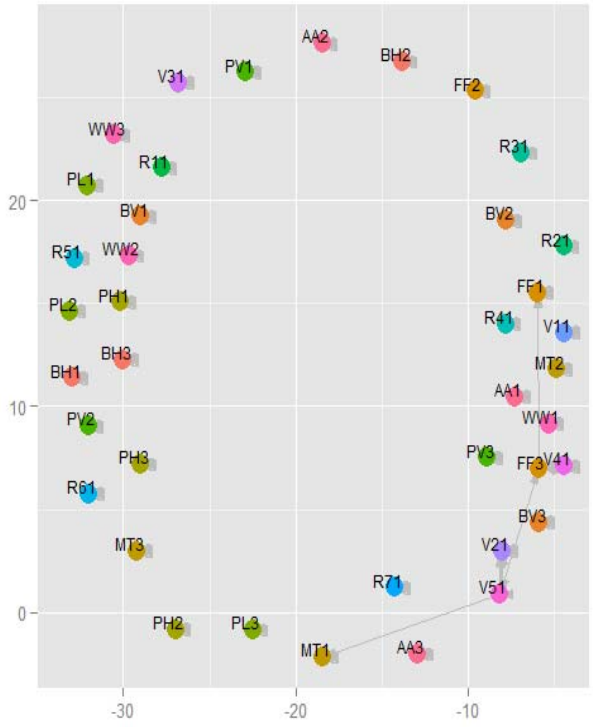
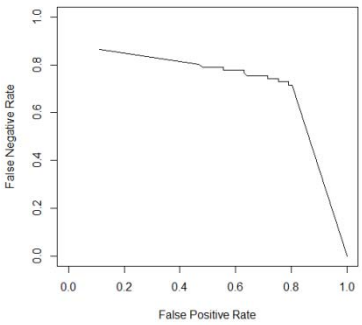
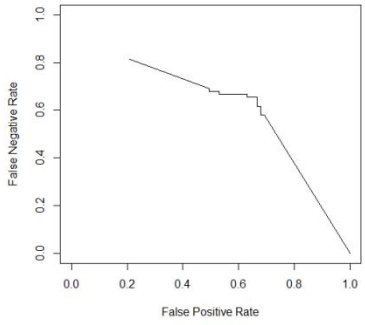


Figure 7. Network diagrams showing the matching ability of the system for the 2010 Dataset using Strategy 1 (left) and Strategy 2 (right).



	Correct	Wrong
Carpet	0.46	0.54
Carpet Area	0.26	0.74



	Correct	Wrong
Carpet	0.60	0.40
Carpet Area	0.35	0.65

Figure 8. Matching sources to traces performance for the 2010 Dataset under Strategy 1 (left) and Strategy 2 (right).

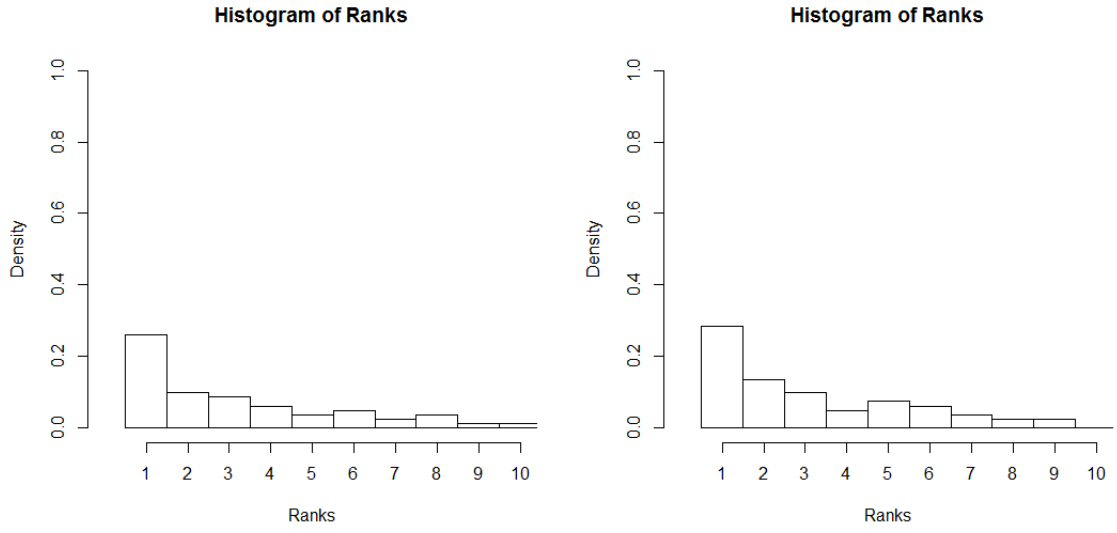


Figure 9. Rank of the probability for the true source in the 2010 Dataset under Strategy 1 (left) and Strategy 2 (right).

The matrix for correspondence measures of each reference specimen to each of the traces is given in *Appendix I. Matrix of Correspondence Measures for 2010 Dataset.* There are two datasets, one for Strategy 1 and the other for Strategy 2.[7] Table 9 shows a portion of the Appendix, with the full values given in scientific notation and with some cells shaded for reference. Each row contains the probabilities of observing the trace TPT profile in each of the reference sources. For example, Trace AA11 is the first of the traces listed in the table. (This is a one of three single fibers from Carpet A, Area 1). The value of 7.3E-04 appearing in the AA1 column is the probability of observing the AA11 TPT profile, given the TPT profile of AA1. AA1 would be the correct class of the single fiber AA11 and, indeed, this value is one of the highest probabilities in the row. However, there is a higher value of 6.00E-03 appearing in the column for reference source AA3 (shaded in orange). The classification system, based on the highest probability, would match the trace AA11 to source AA3 (another area of the same carpet). Similarly, Traces AA12 and AA13 (two other single fibers from this Carpet A, Area 1) are incorrectly matched to Source BV3 (a different carpet, as shaded in red). On the other hand, Traces AA21, AA22 and AA23 (three individual fibers from Carpet A, Area 2) are correctly matched to their carpet area of origin (shaded in green). Likewise, Trace AA31 and Trace AA33 are incorrectly matched to Source BH2, and Trace AA32 is correctly matched to Source AA3.

Table 9. A Portion of Appendix I. Matrix of Correspondence Measures for 2010 Dataset (Strategy 1)[8]

	Reference Sources								
Traces	AA1	AA2	AA3	BH1	BH2	BH3	BV1	BV2	BV3
AA11	7.30E-04	6.50E-39	6.00E-03	8.90E-19	1.60E-07	4.00E-42	1.50E-22	1.10E-19	9.50E-10
AA12	1.80E-16	1.10E-35	2.40E-03	3.70E-23	1.60E-05	6.80E-59	3.80E-17	4.00E-14	7.30E-02
AA13	7.70E-41	5.00E-110	5.70E-04	1.70E-77	7.90E-20	8.50E-178	2.00E-44	4.50E-24	1.00E+00
AA21	7.50E-106	1.00E+00	5.00E-84	3.20E-06	1.60E-16	1.90E-238	0.00E+00	0.00E+00	1.30E-139
AA22	1.50E-151	1.60E-07	1.10E-105	1.00E+00	2.10E-11	0.00E+00	0.00E+00	0.00E+00	9.70E-168
AA23	0.00E+00	1.00E+00	0.00E+00	3.20E-91	1.00E-214	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AA31	1.80E-07	3.00E-06	5.70E-03	1.00E-05	7.80E-02	4.60E-25	2.70E-14	2.30E-12	2.20E-03
AA32	4.10E-23	1.60E-51	1.00E+00	9.10E-32	1.90E-04	2.10E-107	1.40E-37	1.60E-44	1.20E-08
AA33	5.90E-06	9.70E-17	5.20E-01	7.40E-09	3.10E-01	4.10E-26	2.00E-10	4.80E-10	3.90E-02

[7] Each dataset is presented on two spreadsheets. One has the calculated probabilities in scientific notation (necessary for calculation of likelihood ratios) and the other with a threshold display of 10-3 (for ease of viewing).
[8] Reference Sources appear as columns, while Traces appear as rows. For example, the designations AA1, AA2 and AA3 are three separate source areas of the same carpet (Carpet A) and the designations AA11, AA12 and AA13 are three separate traces from area AA1 of Carpet A.

The matrix for likelihood ratios as a measure of evidential weight in support of the origin of the each trace from each specific reference source are given in *Appendix J. Matrix of Likelihood Ratios for 2010 Dataset.* There are two spreadsheets, one for Strategy 1 and the other for Strategy 2. Table 10 shows a portion of the appendix, with some cells shaded for reference. Each row contains the likelihood ratio in support of the origin of the trace from each of the specific reference sources, under the specific assumptions specified in the Methods section (notably, equal priors as an assumption for the correspondence measure and representativeness of the references sources for the population). Cells in Table 10 are highlighted where the likelihood ratios exceed 100. Green highlights are used for these likelihood ratios in support of the true origin and red highlights for those in support of an incorrect origin. Note that there is extremely strong support for the origin of Trace AA23 from its true Source, AA2. Lower levels of support, though still high, are given for Traces AA21 and AA32 with their true sources and for Traces AA13 and AA21 with incorrect origins.

Table 10. A Portion of Appendix J. Matrix of Likelihood Ratios for 2010 Dataset (Strategy 1)[9]

	Reference Sources								
Traces	AA1	AA2	AA3	BH1	BH2	BH3	BV1	BV2	BV3
AA11	3.70E-02	3.30E-37	3.00E-01	4.40E-17	8.10E-06	2.00E-40	7.40E-21	5.30E-18	4.80E-08
AA12	8.80E-15	5.30E-34	1.20E-01	1.90E-21	8.20E-04	3.40E-57	1.90E-15	2.00E-12	4.00E+00
AA13	3.80E-39	2.50E-108	2.90E-02	8.70E-76	4.00E-18	4.20E-176	1.00E-42	2.20E-22	8.70E+04
AA21	3.70E-104	1.60E+07	2.50E-82	1.60E-04	8.00E-15	9.60E-237	0.00E+00	0.00E+00	6.70E-138
AA22	7.40E-150	7.90E-06	5.30E-104	3.20E+08	1.00E-09	0.00E+00	0.00E+00	0.00E+00	4.90E-166
AA23	0.00E+00	1.60E+92	0.00E+00	1.60E-89	5.00E-213	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AA31	9.10E-06	1.50E-04	2.90E-01	5.00E-04	4.20E+00	2.30E-23	1.30E-12	1.10E-10	1.10E-01
AA32	2.00E-21	7.80E-50	2.00E+04	4.50E-30	9.40E-03	1.10E-105	6.90E-36	8.00E-43	6.10E-07
AA33	2.90E-04	4.80E-15	5.50E+01	3.70E-07	2.30E+01	2.10E-24	9.80E-09	2.40E-08	2.00E+00

[9] Reference Sources appear as columns, while Traces appear as rows. For example, the designations AA1, AA2 and AA3 are three separate source areas of the same carpet (Carpet A) and the designations AA11, AA12 and AA13 are three separate traces from area AA1 of Carpet A.

D. Application of Computational Methods to the Full 2012 Particle Dataset

This section presents the results on particle data collected under the current project and described above in section IIIB.

General Discriminating Power of the System – Full 2012 Dataset. The discrimination ability of the system for the 2012 dataset under Strategies 1 and 2 is shown by network diagrams in Figures 10 and 11.[10] Figure 10 includes the blanks and Figure 11 does not. Not all specimens are discriminated from one another. However, Strategy 2 shows much better discrimination than Strategy 1 for this dataset.

Matching Ability of the System – Full 2012 Dataset.[11] Figures 12 and 13 present the matching ability of the system when attempting to associate "traces" from the test set with "references" from the training set using Strategies 1 and 2. Figure 12 shows a correct classification rate of 51% under Strategy 1 and 58% under Strategy 2. Corresponding network diagrams are shown in Figure 13.

Matching Sources to Traces – Full 2012 Dataset. Results of application of the system to comparison of 2012 reference specimens to their corresponding traces are shown in Figures 14 to 16. Figure 14 shows a correct classification rate of 22% under Strategy 1 and 21% under Strategy 2. Network diagrams are shown in Figure 15 and Figure 16 shows the rank of the probability for the true source under each of the two strategies.

The matrix for correspondence measures of each reference specimen to each of the traces is given in *Appendix K. Matrix of Correspondence Measures for Full 2012 Dataset* and the matrix for likelihood ratios as a measure of evidential weight in support of the origin of the each trace from each specific reference source is given in *Appendix L. Matrix of Likelihood Ratios for Full 2012 Dataset*. There are two datasets in each of these two appendices, one for Strategy 1 and the other for Strategy 2.[12]

[10] General discussion of the format of network diagrams is given in the Methods Section II.E. Data Analysis.
[11] See the methods section for full descriptions of 'Matching Ability of the System' and 'Matching Sources to Traces.'
[12] In Appendix K, each dataset is presented on two spreadsheets. One has the calculated probabilities in scientific notation (necessary for calculation of likelihood ratios) and the other with a threshold display of 10-3 (for ease of viewing).

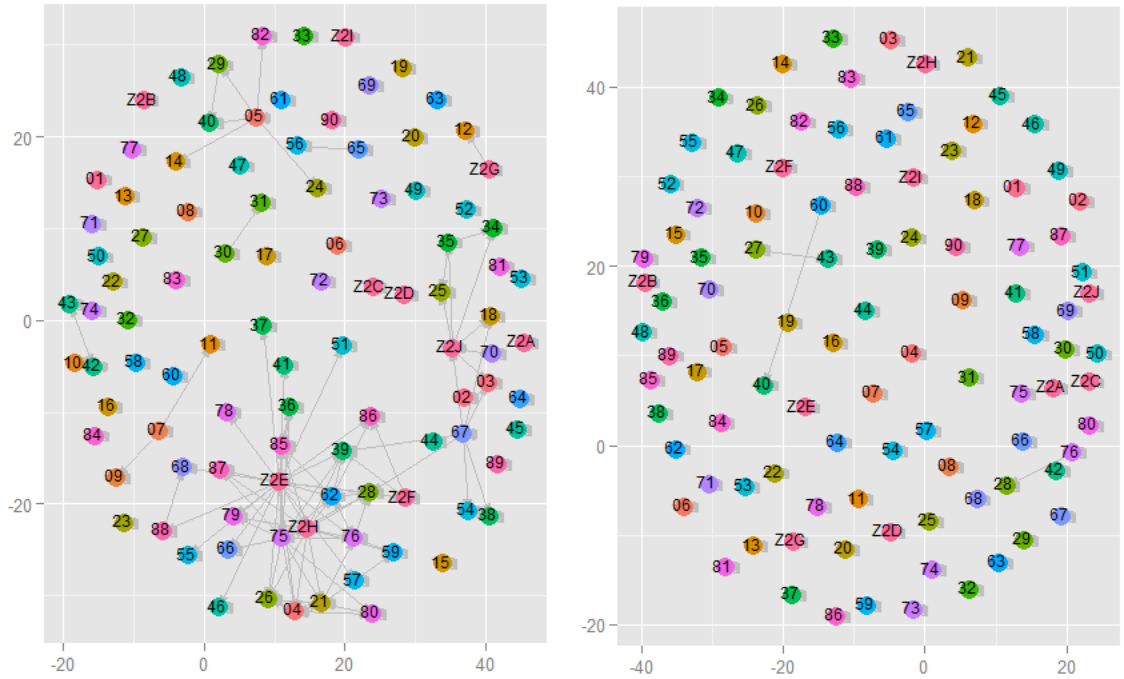


Figure 10. Network diagrams showing the general discrimination of the reference specimens and process control blanks for the 2012 Dataset using Strategy 1 (left) and Strategy 2 (right). (Blanks have an initial letter "Z.")

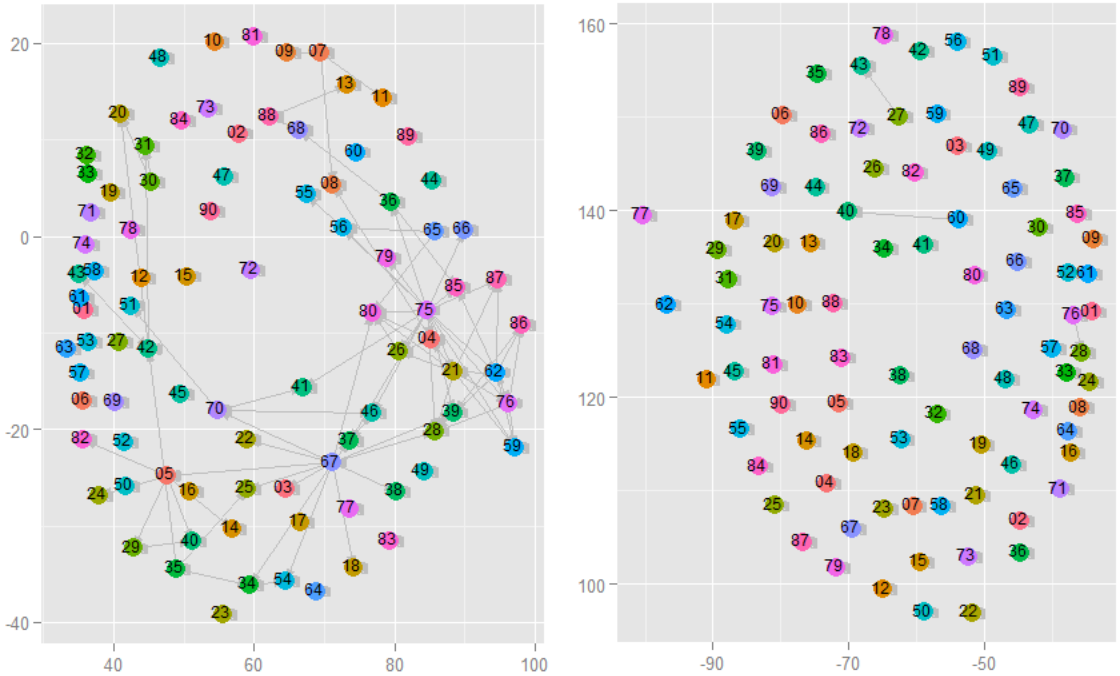
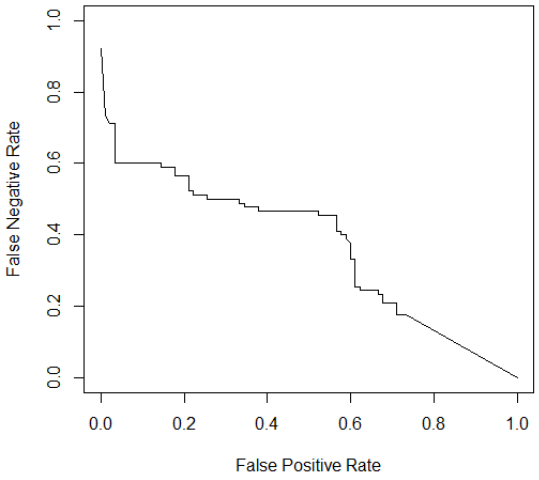
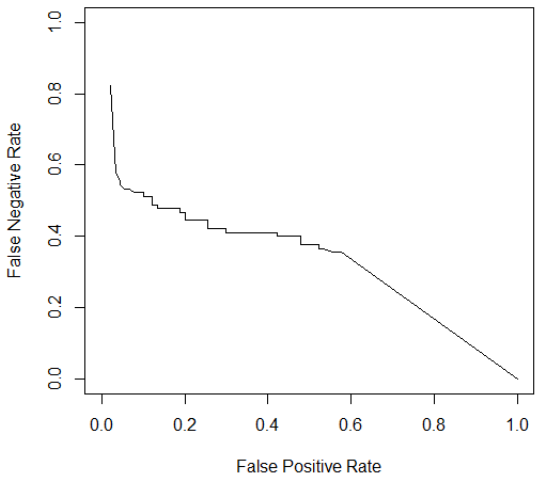


Figure 11. Network diagrams showing the general discrimination of the reference specimens for the 2012 Dataset using Strategy 1 (left) and Strategy 2 (right).



	Correct	Wrong
Carpet	0.51	0.49



	Correct	Wrong
Carpet	0.59	0.41

Figure 12. Classification performance for the Full 2012 Dataset under Strategy 1 (left) and Strategy 2 (right).

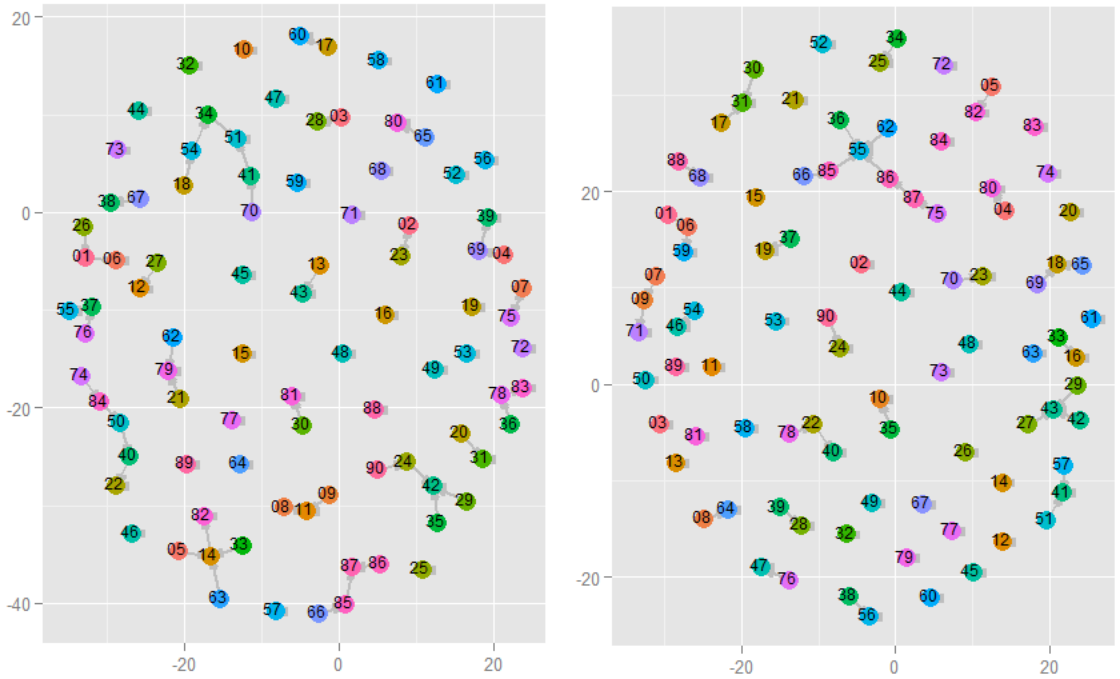
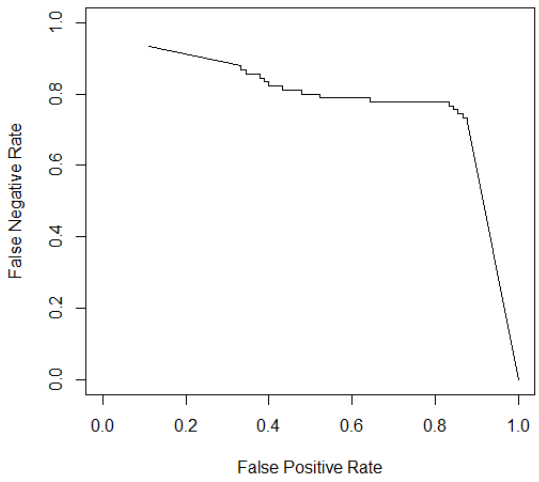
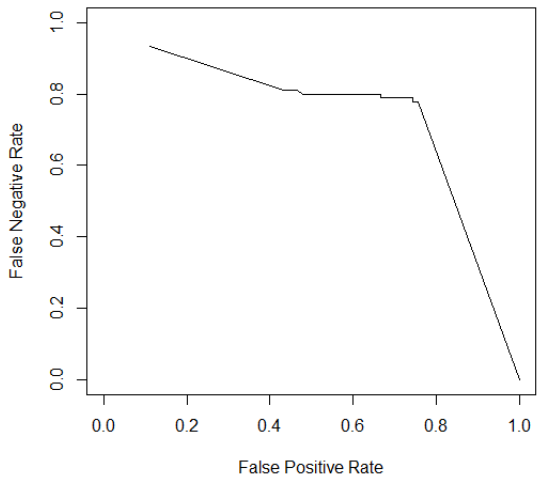


Figure 13. Network diagrams showing the matching ability of the system for the Full 2012 Dataset using Strategy 1 (left) and Strategy 2 (right).



	Correct	Wrong
Carpet	0.22	0.78



	Correct	Wrong
Carpet	0.21	0.79

Figure 14. Classification performance of the system (traces to sources) for the Full 2012 Dataset under Strategy 1 (left) and Strategy 2 (right).

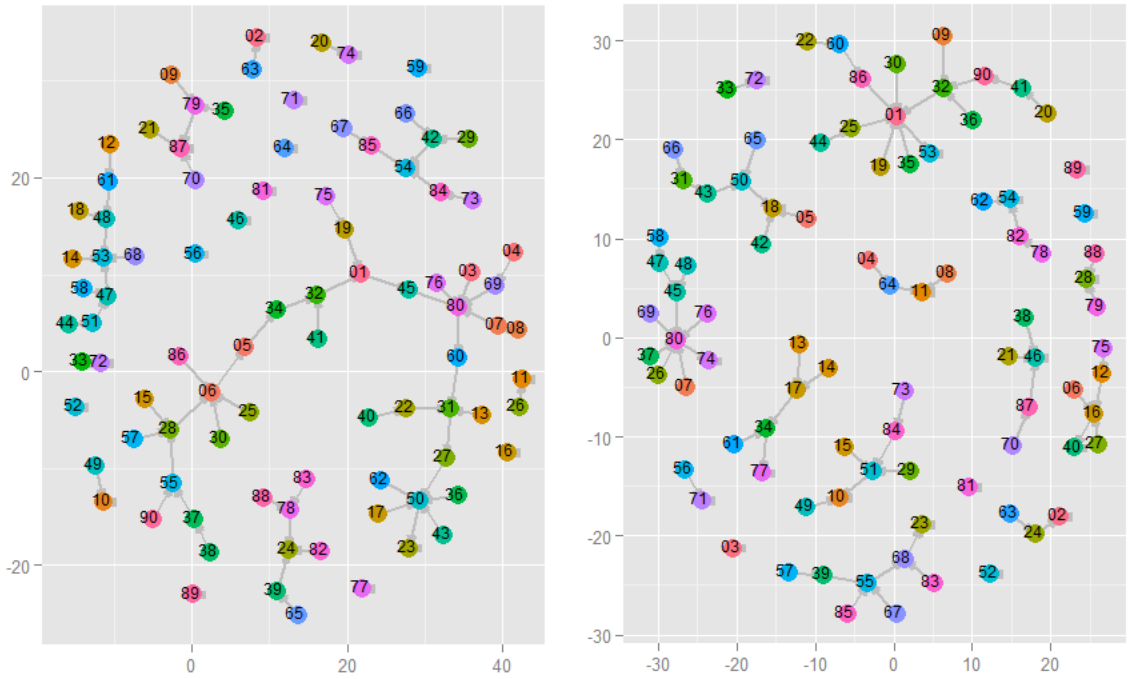


Figure 15. Network diagrams showing the classification performance of the system (traces to sources) of the system for the Full 2012 Dataset using Strategy 1 (left) and Strategy 2 (right).

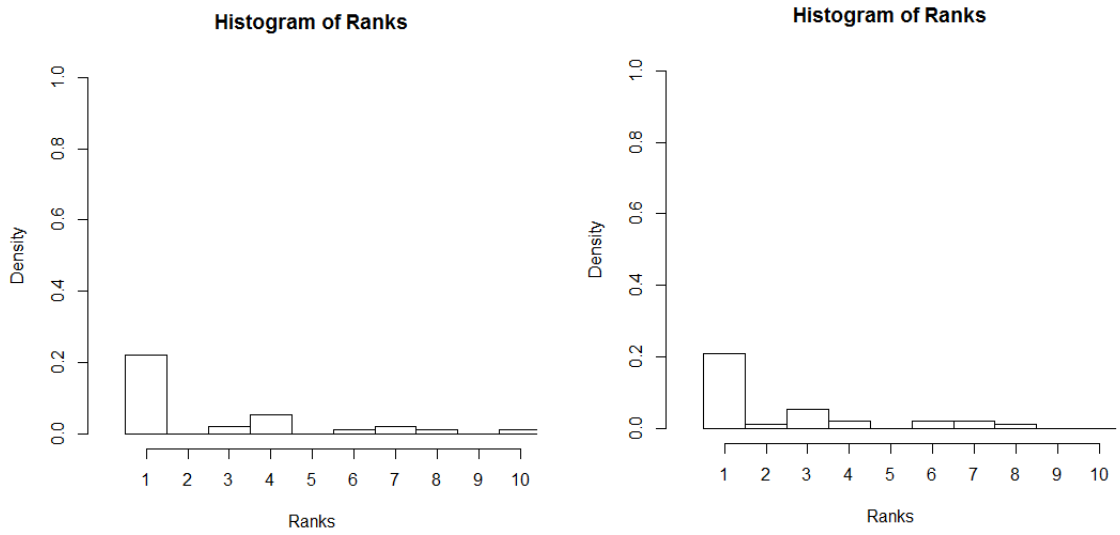


Figure 16. Rank of the probability for the true source in the Full 2012 Dataset under Strategy 1 (left) and Strategy 2 (right).

E. Application of Computational Methods to High Particle 2012 Subset

Many of the 2012 Dataset specimens had very low particle numbers. We suspected that this was one of the causes for the overall lower performance of the system on the 2012 data compared to that from 2010. Accordingly, we decided to select a high particle subset of the 2012 specimens and to test the system performance on this subset. We selected 20 paired specimens (reference and trace) where each of the specimens contained at least 500 particles.

General Discriminating Power of the System – High Particle 2012 Subset. The discrimination ability of the system for the High Particle 2012 subset under Strategies 1 and 2 is shown by network diagrams in Figures 17 and 18.[13] Figure 17 includes the blanks and Figure 18 does not. The system shows complete discrimination among reference specimens using either strategy.

Matching Ability of the System – High Particle 2012 Subset.[14] Figures 19 and 20 present the matching ability of the system when attempting to associate "traces" from the test set with "references" from the training set under Strategies 1 and 2. Figure 19 shows a correct classification rate of 80% under Strategy 1 and 100% under Strategy 2. Corresponding network diagrams are shown in Figure 20.

Matching Sources to Traces – High Particle 2012 Subset. Results of application of the system to comparison of High Particle 2012 Subset reference specimens to their corresponding traces are shown in Figures 21 to 23. Figure 21 shows a correct classification rate of 50% under Strategy 1 and 40% under Strategy 2. Network diagrams are shown in Figure 22 and Figure 23 shows the rank of the probability for the true source under each of the two strategies.

The matrix for correspondence measures of each reference specimen to each of the traces is given in *Appendix M. Matrix of Correspondence Measures for High Particle 2012 Subset* and the matrix for likelihood ratios as a measure of evidential weight in support of the origin of the each trace from each specific reference source is given in *Appendix N. Matrix of Likelihood Ratios for High Particle 2012 Subset*. There are two datasets in each of these two appendices, one for Strategy 1 and the other for Strategy 2.[15]

[13] General discussion of the format of network diagrams is given in the Methods Section II.E. Data Analysis.
[14] See the methods section for full descriptions of 'Matching Ability of the System' and 'Matching Sources to Traces.'
[15] In Appendix M each dataset is presented on two spreadsheets. One has the calculated probabilities in scientific notation (necessary for calculation of likelihood ratios) and the other with a threshold display of 10-3 (for ease of viewing).

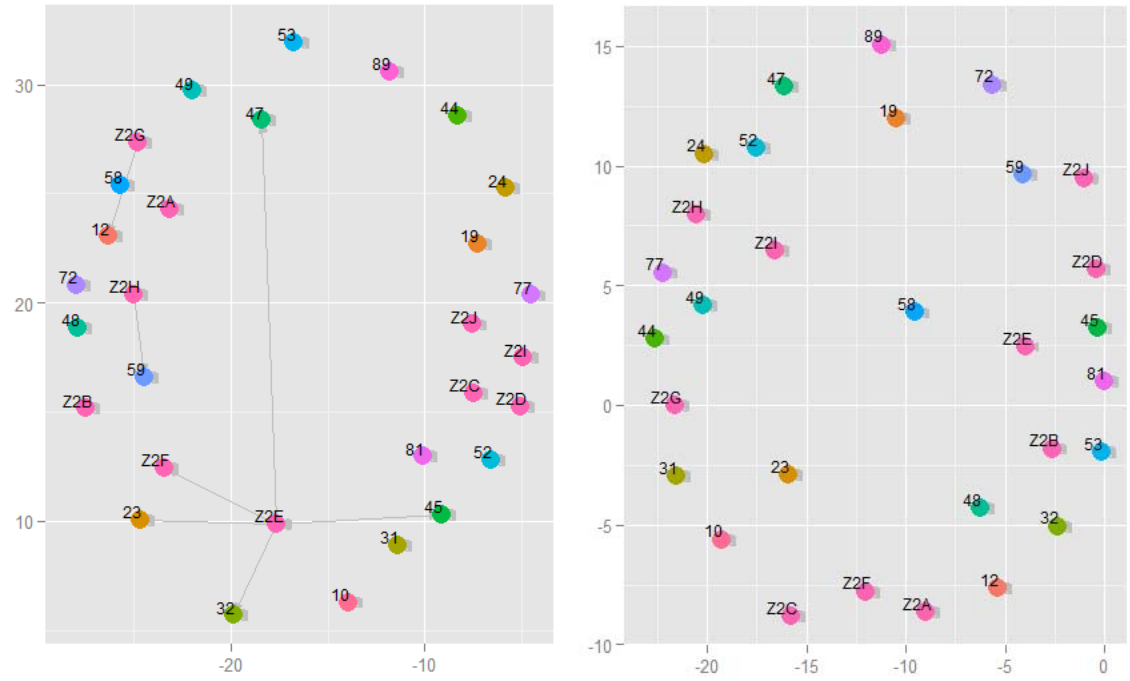


Figure 17. Network diagrams showing the general discrimination of the reference specimens and process control blanks for the High Particle 2012 Subset using Strategy 1 (left) and Strategy 2 (right). (Blanks have an initial letter "Z.")

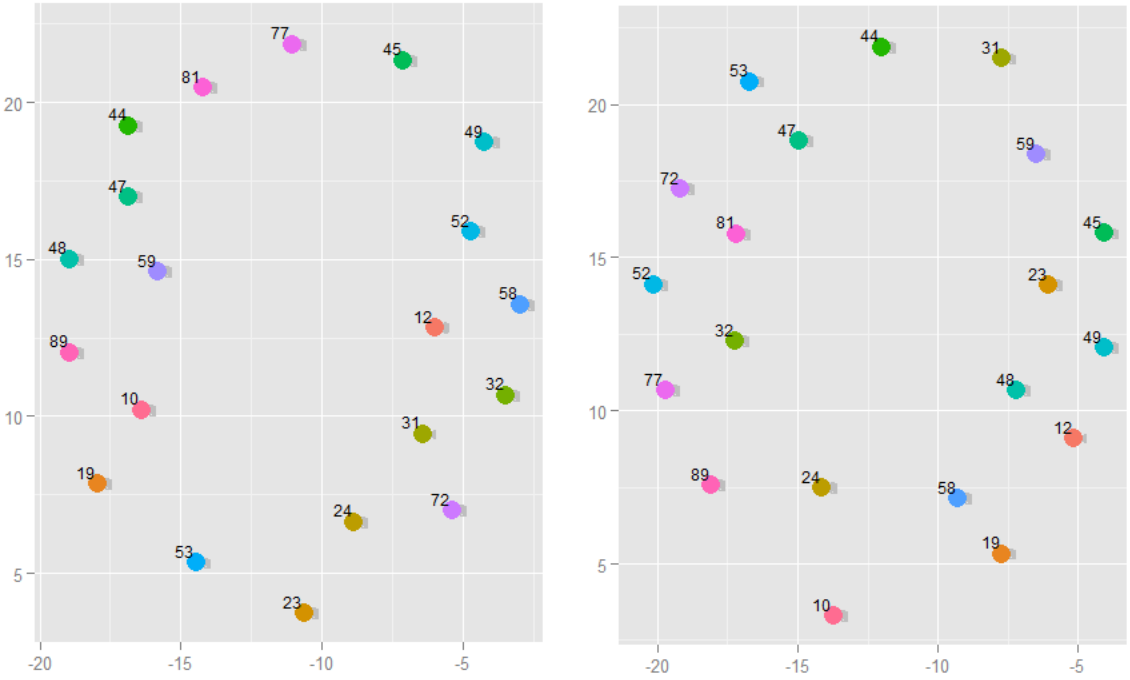
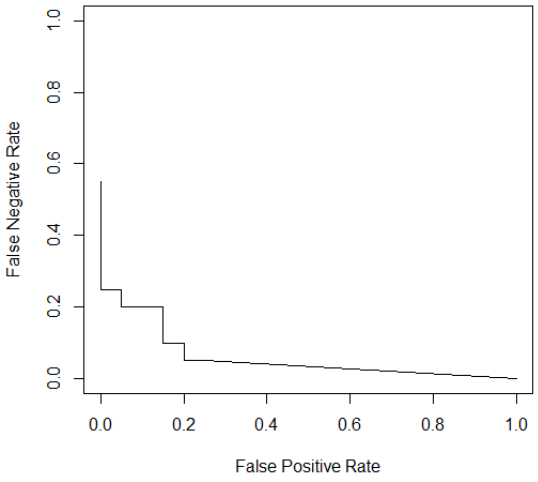
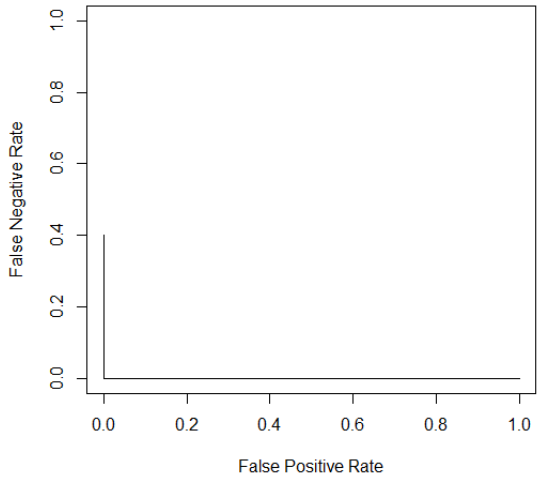


Figure 18. Network diagrams showing the general discrimination of the reference specimens for the High Particle 2012 Subset using Strategy 1 (left) and Strategy 2 (right).

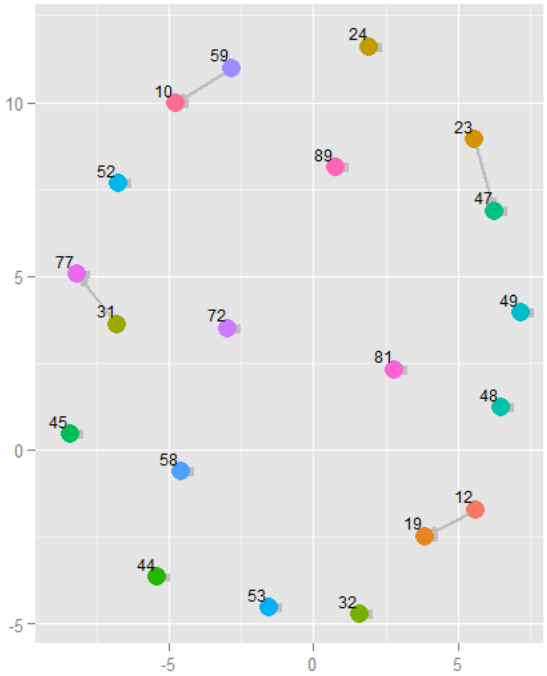


	Correct	Wrong
Carpet	.80	0.20



	Correct	Wrong
Carpet	1.00	0.00

Figure 19. Classification performance for the High Particle 2012 Subset under Strategy 1 (left) and Strategy 2 (right).



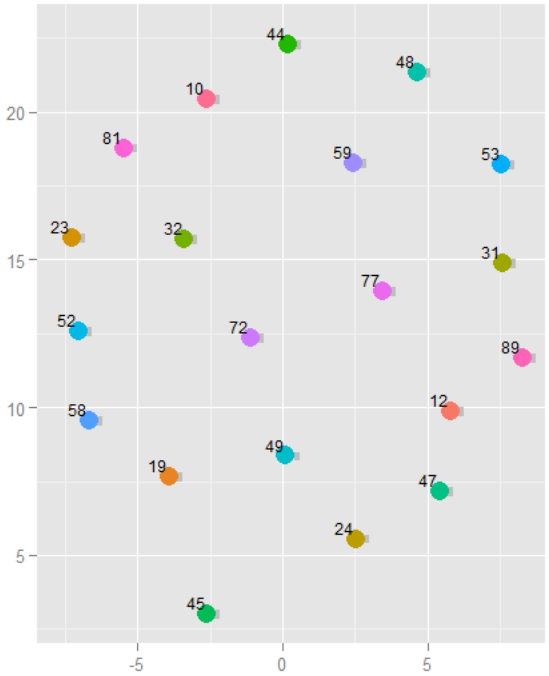
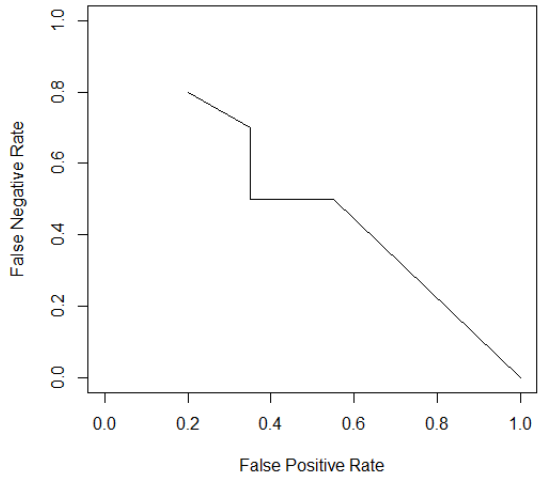
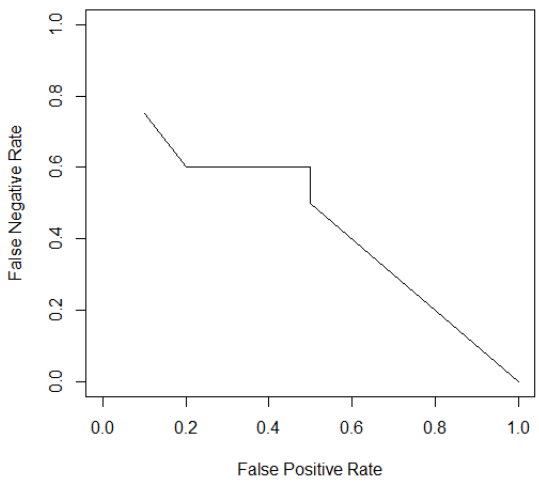


Figure 20. Network diagrams showing the matching ability of the system for the High Particle 2012 Subset using Strategy 1 (left) and Strategy 2 (right).



	Correct	Wrong
Carpet	.50	0.50



	Correct	Wrong
Carpet	0.40	0.60

Figure 21. Classification performance of the system (traces to sources) for the High Particle 2012 Subset under Strategy 1 (left) and Strategy 2 (right).

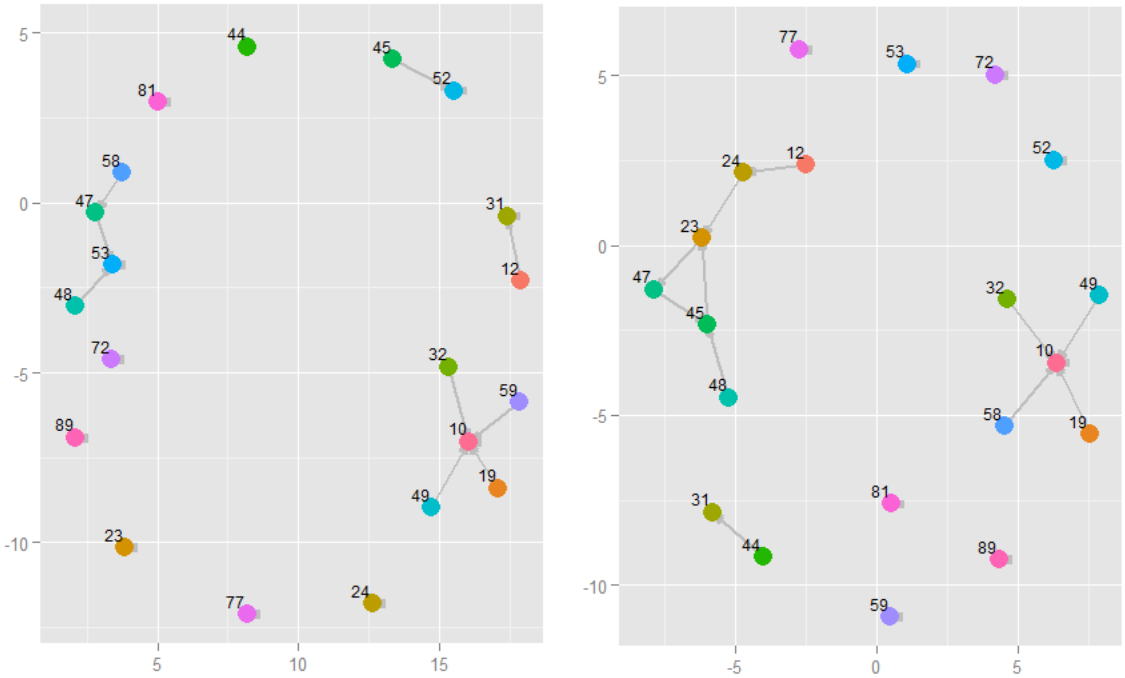


Figure 22. Network diagrams showing the classification performance of the system (traces to sources) of the system for the High Particle 2012 Subset using Strategy 1 (left) and Strategy 2 (right).

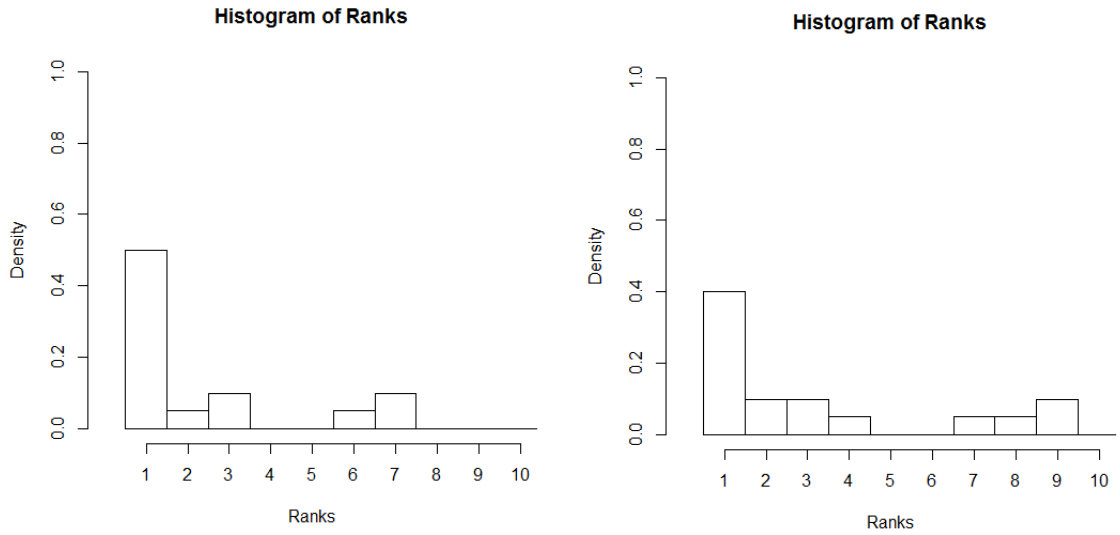


Figure 23. Rank of the probability for the true source in the High Particle 2012 Subset under Strategy 1 (left) and Strategy 2 (right).

IV. Conclusions

This context for this program includes the findings of our work under Award 2010-DN-BX-K244. Of particular relevance to this project was the establishment of proof of principle that particle distributions found on carpet fibers could contribute substantially to the weight of evidence linking fibers to a specific carpet. This conclusion followed from a set of findings including that:

1. Hundreds to thousands of very small particles (VSP) are present on the surfaces of individual carpet fibers.
2. VSP can be efficiently recovered and analyzed by computer-assisted SEM/EDS analysis.
3. Carpets vary widely in the types and quantities of small particles adhering to their fiber surfaces.
4. Given sufficient recovered particles, highly characteristic profiles of target particle types are consistently represented in the particles from individual test fibers from the same carpet, and consistently absent among those from different carpets.

The present findings build upon these by (1) refining the processes for exploiting VSP to associate residential carpet fibers with their source carpet, (2) applying this process under realistic casework conditions, and (3) constructing working prototypes for both the methods of analysis and the measurement of the probative value of comparisons.

A. Discussion of Findings

The findings in this project are based on the analysis of carpets present within a limited geographical range and with unknown histories of environmental exposure. Furthermore, these carpets were not selected based on characteristics such as manufacturing origin, commercial source, age, or composition. Indeed, these aspects of the carpets are unknown. Accordingly, the findings presented here may well be affected by these alternative conditions. The present work, with field collections under realistic conditions, occupies a position between narrowly controlled experiments on the one hand, and a more comprehensive, systematic sampling that is necessary to understand the nature of particle populations. As an essential intermediate step, this work helps to define and assess practical procedures that are necessary for efficiently conducting follow-on work and for providing a basis to choose among alternative lines of investigation.

Ten findings are discussed in this section:

1. It has been established that realistic field collections of carpet fiber evidence and currently available forensic laboratory capabilities are sufficient for collection and analysis of VSP adhering to carpet fibers.
2. Compared to controlled research collections, field collections of carpet fiber evidence by crime scene investigators resulted in lower particle numbers.
3. Sets of hundreds to thousands of particles from carpet fibers can be characterized using a single-dimensional vector.
4. Classifiers can be designed to associate/ discriminate particle sets originating from common/different source(s).

5. Quantitative measures of correspondence can be defined based on the criteria used for classification.
6. There are alternative reasons, currently unresolved, that contribute to low levels of matching between sources and traces.
7. Particle sets larger than 500 show strong promise for reliable quantitative associations with their sources.
8. Larger numbers of TPTs show strong promise to improve the performance of classification and association.
9. The meaningfulness of current measures of correspondence and probative value are restricted to closed set associations.
10. Presentation and discussion of the program results with forensic practitioners and researchers has identified several important topics.

1. It has been established that realistic field collections of carpet fiber evidence and currently available forensic laboratory capabilities are sufficient for collection and analysis of VSP adhering to carpet fibers.

Collection of carpet fiber evidence by crime scene investigators across the country, using simple, efficient collection protocols, has resulted in useful specimens suitable for VSP recovery and preparation for SEM/EDS analysis.

Analysis of these VSP specimens, using computer assisted SEM/EDS in an operational forensic science laboratory has been efficient, with less than two hours instrument time per specimen and the batching of analyses in groups of 10 to 20 specimens at a time. The resulting analytical data from these particle sets were sufficient to permit quantitative associations among specimens and the determination of probative value.

2. Compared to controlled research collections, field collections of carpet fiber evidence by crime scene investigators resulted in lower particle numbers.

The specimens in this program, collected by field personnel under realistic crime scene conditions, showed fewer particles compared to fiber specimens cut from carpets and collected by research personnel under controlled conditions.

The 2010 Dataset (from 2010-DN-BX-K244) showed an average of 2800 particles for reference sources (10 fibers), 730 particles for traces (single fibers) and 180 particles for process blanks. The 2012 Dataset (this project) showed averages of 960 particles for reference sources (6 to 12 fibers), 800 particles for traces (6 to 12 fibers) and 170 particles for process blanks. References for the new dataset are seen to have less than 1/3 of the particles formerly encountered and while the total particle numbers for traces are comparable, the 2010 Dataset traces are represented by single fibers, whereas those for 2012 are from sets of 6 to 12 fibers.

The manner of collection is one likely cause of this difference. As noted above, the 2010 collections were performed by cutting fibers directly from the carpet. Particles adhering to the

fibers, that might have been subject lost by abrasion, were not subjected to such forces. For the 2012 collections, shed fibers were collected using rubbing or brushing methods that provided abrasive forces, potentially reducing the number of adhering particles.

Another likely cause of this difference is the change of the specimen processing protocol. For the 2010 Dataset particles from each specimen were extracted and filtered through an area of approximately 25 mm^2. After drying, filters were carbon-coated. For the 2012 Dataset, particles were filtered through an area of approximately 130 mm^2, after which the specimen was divided in half and analyzed without carbon coating. These differences would be expected to reduce the available particles by half and there may also be increased possibilities of particle losses in the absence of carbon coating.

Differences in the analysis parameters are another possible source of differences in particle numbers, as the analysis depends on steps of (1) initial particle recognition based on the detection of backscatter electrons and (2) selection of particles based on threshold levels of x-ray signals associated with specific elements.

In any event, the numbers of particles recovered did allow particle analyses, definition of TPT profiles, comparison of these profiles, and the assignment of measures of probative value.

3. Sets of hundreds to thousands of particles from carpet fibers can be characterized using a single-dimensional vector.

This project has demonstrated that complex particle sets numbering in the thousands, with each particle characterized by multivariate data, can be characterized successfully and usefully employed using a single-dimensional vector.[16] The computational processes employed for this characterization have minimal input parameters, notably the specification of the number of TPTs. Following data filtration to reduce noise, the method employs readily available, open processes for normal mixture modeling.

These objective computational methods replace heuristic processes, dependent on expert selection and estimation of many parameters, which were used in prior research for definition of TPTs.

4. Classifiers can be designed to associate/ discriminate particle sets originating from common/different source(s).

This project has designed and demonstrated the usefulness of classifiers that can be applied to associate or discriminate among particle sets originating from the same or different sources. A classifier based on the multinomial distribution has been developed based on the population of TPTs observed in specific reference sources. Newly encountered particle profiles, based on the same TPTs, are compared to each of the sources using the multinomial distribution and

[16] See *Appendix O. Mathematical Expression of the Multinomial Distribution* for more explicit definition of this vector.

classification is assigned to the reference source in which the new profile would occur with highest probability.

5. Quantitative measures of correspondence can be defined based on the criteria used for classification.

Comparison of the probabilities of the occurrence of a TPT profile within each of the reference sources results in a useful, quantitative measure of correspondence. This allows objective ranking and assessment of relative strengths of association.

These objective computational methods again replace heuristic processes that were used in prior research for perception and demonstration of close associations among particle sets.

6. There are alternative reasons, currently unresolved, for low levels of matching between sources and traces.

The classification results for traces of known origin were far from perfect. That is, classification errors were frequent. For the 2010 Dataset, correct classification rates for the specific carpet area (among 39 sources and 12 blanks) were 26% under Strategy 1 and 35% under Strategy 2. Correct classification rates for the carpet itself (among 21 sources and 12 blanks) were 46% under Strategy 1 and 60% under Strategy 2.

For the Full 2012 Dataset, correct classification rates (among 90 sources and 10 blanks) were lower: 22% under Strategy 1 and 21% under Strategy 2. For the High Particle 2012 Subset classification rates (among 20 sources and 10 blanks) were higher: 50% under Strategy 1 and 40% under Strategy 2.

Specific causes for classification errors cannot be determined without further research, but there are at least three alternative reasons for less than perfect classification: the absence of evidence representative of the source, low variability among sources, and a poor performance of the system used to detect and exploit variability among sources.

The absence of evidence representative of the source occurs, for example, when a carpet is unusually clean. Just as there will be many crime scenes where useful levels of fiber transfer do not occur, there is no guarantee that fibers will be sufficiently loaded with particles to carry a useful signal. Our research has shown that useful levels of particles are frequently carried by fibers, and that particle sets of several hundred particles can be sufficient for strong associations, but our understanding is not yet full enough to determine, before the comparison stage, whether there is sufficient particle signal present to properly interpret an observed lack of correspondence.

Low variability of among sources is unlikely to be a limiting factor. This variability was checked for each of the datasets and discrimination among sources was excellent for the experiments using the training and test sets. However, this discrimination is based on single samples from

each reference set. Within-source variability remains an important source of variation which is yet to be studied.

The performance of the present system to detect and exploit variability among sources may be a contributing factor, as the system has not been optimized and the number of sources that have been characterized is small. However, the system does perform well. We are able to use objective, quantitative measures to correctly classify many sources and to objectively rank sources based on their similarity to a specimen.

7. Particle sets larger than 500 show strong promise for reliable quantitative associations with their sources.

The prior heuristic analysis of the 2010 Dataset showed strong associations when sufficient particles were recovered. With few exceptions, when totals were over 1000, the TPT occurrences from individual fibers closely followed those from their originating area. The patterns were highly characteristic and often showed rough proportionality among TPTs. With lower totals (e.g. 300 to 800 particles), many traces still showed reasonable semi-quantitative similarities with their originating area.

Application of objective quantitative methods (under Strategy 1, for example) increased the number of correct classifications from the 2010 Dataset from 12 of 81 traces (15%) to 26% (increasing to 46% for associations with the overall carpet, as opposed to the specific carpet area).

A requirement of high numbers of particles for reliable classification is reasonable, and demonstrated by the results obtained for the 2012 Dataset. A high particle subset of the data (with particle numbers higher than 500) resulted in classification rates that increased from 22% to 50% using Strategy 1 and from 21% to 40% using Strategy 2.

Overall the results indicate that there is strong promise for reliable quantitative associations for particle sets larger than 500.

8. Larger numbers of TPTs show strong promise to improve the performance of classification and association.

Contrasting Strategy 1 and Strategy 2 suggests that larger numbers of TPTs will improve the performance of classification and association. The effect is most clear for the overall discrimination of the system in the Full 2012 Dataset, as shown in Figure 11. Improvement is less clear in the subsequent classification steps for this dataset, with Strategy 2 showing comparable, but lower correct rates of classification. As previously noted, the 2010 dataset shows much better classification rates are observed under Strategy 2.

Overall, larger number of TPTs show promise to improve performance of classification and association. Strategy 2, with larger numbers of TPTs, is expected to become more important as the number of sources increases.

9. The meaningfulness of current measures of correspondence and probative value are restricted to closed set associations.

As noted earlier, the correspondence measures and likelihood ratios determined under this project are subject to specific assumptions made in the context of this research. These are most notably (1) the assumption of equal priors for the calculation of the correspondence measure and (2) the implied assumption of equal weight and overall representativeness of the references sources for the calculation of the denominator of the likelihood ratios.

Importantly, the procedures developed under this program show the form, feasibility and method for these quantitative measurements. However, the meaningfulness of these measures, outside of the specific research context of this program, will only come from the expansion of the numbers of references, better understanding of within-item variation, testing the assumptions of population representativeness, and validation using relevant operational specimens.
With these qualifications relative to the extension of the results beyond a closed dataset, the application to such closed datasets is directly enabled by this research. For example, investigative determination of associations among particle sets recovered on and within items of evidence is ready to be conducted using the methods that have been developed.

10. Presentation and discussion of the program results with forensic practitioners and researchers was fruitful and has identified several important topics.

A recurring question of concern to practitioners was the likely incompatibility of VSP recovery and analysis with the use of tape lifts for the recovery of fibers. Tape lifts are a common, efficient and extremely useful means of fiber collection and it is almost certain that fibers collected by this method would have many fine particles removed and lost in the tape adhesive. This is clearly an issue that will need to be explored in follow-on research.

Another recurring issue of concern was the lack of actual identification of the individual particles. Aspects of this discussion were (1) that robust identifications would preclude the efficient analysis of hundreds to thousands of particles, and (2) that particle identifications can subsequently be made, as deemed useful, on the same specimen.

Another issue of interest to practitioners was the variation seen among TPT profiles from different areas of the same carpet. The 2010 Dataset demonstrated that such differences are common, allowing each of several areas of a single carpet to be treated as a separate source. This situation is similar to that for soil evidence, where differences in soil characteristics often occur between reference specimens taken a short distance from one another. This is an aspect of forensic soil examinations that is routinely taken into account by comprehensive spatial sampling covering the areas of interest. A similar approach could be taken for VSP on carpets, but the

variations seen among different areas of a carpet are also likely to be more easily generalized than variations seen in soil. Further study of within-item variation for VSP on carpets is indicated to see if this variation can be reasonably generalized. Additionally, computational methods are of interest that would examine multiple reference specimens from one source, identify their commonality, and use this commonality as the basis for comparison with traces.

Practitioners noted the possibility that some of the particle types might actually originate from the carpet, as in small particles of the carpet backing being shed with wear. Discussion included the point that such wear could be viewed as an example of a characteristic acquired through use, rather than as one determined by manufacture.

One issue of interest to researchers were uncertainties of the "relevance"[21] of VSP to the activities of interest in the investigation. Broken glass at a point of entry, for example, is known to be "relevant" to the crime, as are other selected transfers of trace evidence. Discussion on this topic included the observation that the carpet fibers themselves carried the limitation of uncertain "relevance" to the crime. (Such uncertainties do not render trace evidence unusable, but they do make interpretations more complex.)

Researchers also noted similarities between DNA interpretation approaches and those for Particle Combination Analysis, with TPTs having a role analogous to specific alleles of interest and the detailed compositional information of thousands of particles having a role analogous to DNA sequences.

Researchers were also interested in the reproducibility of the SEM/EDS analytical method and suggested an in-depth study of this reproducibility.

B. Discussion of the Underlying Technology and Scope

The exploitation of VSP to test the association of carpet fibers is a new approach, and one that lacks the comfort of actual particle identification and actual tracing of the source of the multitude individual particles. This differs from the exisiting paradigm where identification is a pre-condition to the use of particles, and where specificity in the measured characteristics provides the route to forensic utility. As discussed in the Introduction, the existing paradigm leads to fundamental limitations in our ability to interpret trace evidence. The impetus for the present research is to augment what is now being done, using VSP that we are currently ignoring, and using methods that will allow the combination of multiple characteristics that have measureable, testable frequencies of occurrence. These need to be valid characteristics, but they do not need to be particle identifications.

Five important conceptual aspects of the present approach amplify this distinction and merit further discussion:

1. Useful particles and the question of particle "noise."
2. The Use for Exclusion and Implications of False Negatives
3. SEM/EDS methodology as used for particle analysis in this program.
4. Alternative approaches to the definition and use of TPTs.
5. Verification of results through additional particle characterization or identification.
6. The overall state of readiness for this technology.

1. Useful particles and the question of particle "noise."

There are at least four separate ways to conceptualize “noise” as it relates to the analytical and interpretive efforts in this program:

- Particles types occurring at low frequency in the specimen
- Elements occurring at low concentration in particles
- Particle types occurring in process blanks
- Ubiquitous particles

Particle types occurring at low frequency in the specimen. If particles are present in very low frequencies in a specimen, they are not likely to be useful, and may be considered “particle noise.” The concept is that to be useful for association, particles must be recognized as a meaningful representation of a source. For this to occur they need to occur repeatedly, so that they would reasonably be transferred when a particle set is transferred from the source. An analogy can be made to other forms of forensic transfer evidence, where some characteristics of the source are incompletely represented when transferred. In this program only frequently occurring particle types, as defined mathematically by normal mixture modelling, were used for comparisons.

Elements occurring at low concentration in particles. “Elements” in the context of this research program, are x-ray counts within defined energy windows. Low levels of x-rays occur as

background noise in the SEM/EDS system. There is a direct analogy to issues relating to signal to noise ratios in other forms of instrumental analysis and signal detection. In this program SEM/EDS instrument parameters were used as one means to address this source of noise, as were the methods used for filtering of the x-ray data for individual particles.

Particle types occurring in process blanks. Particles that originate during the collection or analytical processes, or from contamination, are uninformative. The analogy is to the results of reagent or substrate controls. Blanks were handled in this program by treating each blank as a separate source.

Ubiquitous particles. Particle types occurring frequently in all specimens are uninformative. An analogy is to the presence of undyed cotton fibers, found on clothing. The nature of defining TPTs by normal mixture modelling addresses this, as particles occurring frequently in all specimens would not meet selection criteria for maximizing discrimination among specimens.

2. The Use for Exclusion and Implications of False Negatives

The question arises as to whether the failure to observe a correspondence in VSP can be taken as an exclusion of a possible source. Are the non-associations true exclusions (correct) or false negatives (error)?

Several of the principle findings from the previous section of this discussion are directly relevant. One of the findings (number 7 in the previous section) is that particle sets larger than 500 show strong promise for quantitative associations with their sources; another (number 5) is that, regardless of the number of particles, quantitative measures of correspondence can be defined based on particle profiles; a third (number 9) stresses that the meaningfulness of current measures of correspondence and probative value are restricted to closed set associations; and lastly (number 6) that there are alternative reasons, currently unresolved, for low levels of matching between sources and traces.

Within a narrowly defined scope (closed set associations, equal prior probability), the present work explicitly enables decisions of exclusion to be made, and for errors associated with these decisions to be quantified. However, more importantly, the present work allows the calculation of probative value (whether supporting association, or supporting an alternative source). The measures of correspondence and probative value allow the calculation of a likelihood ratio. A decision threshold for exclusion may be set, if desired, based on the likelihood ratio, but the likelihood ratio itself is a more informative and more accurate representation of the evidential value. The percentages for correct and incorrect classification given in Figures 6, 8, 12, 14, 19 and 21 are those of false positive or false negative associations. We provide DET curves which show both type I and II error (see page 24 and Figure 3). In the interpretation of these data, we do not suggest to discard non corresponding TPT profiles, but rather to have a threshold of number of particles below which results will be inconclusive either way. For a set of particles whose number exceeds this threshold, and where the TPT profile does not correspond to a source, then that would be reported.

Moving from interpretations based on assumptions of representativeness and a closed set of carpet sources, to one based on an open population of carpet sources, will require additional research, as discussed later in this section, under part D. Implications for Further Research.

3. SEM/EDS methodology as used for particle analysis in this program.

The SEM/EDS methodology used for particle analysis in this program is a method of particle characterization, not a method of particle identification. To analyze thousands of particles in specimen, within a reasonable period of time, we must (at least with today's technology) sacrifice the specificity of identification. The choice of SEM/EDS methodology (as employed here) also limits the range of particles that will be characterized: those that fail to emit high quantities of x-rays in the energy windows attributable to selected inorganic elements will not be recognized or recorded in any way. These limitations are a conscious trade-off, made in pursuit of the exploitation of the ubiquitous presence of hundreds to thousands of particles.

The SEM/EDS process used in this program begins with the specification of a series of elements, along with associated x-ray energy windows. When a particle is initially recognized by the system, through the backscatter of electrons, x-rays falling within these energy windows are collected. If there are sufficient x-rays collected in these windows over a specified period of time, the particle is officially recognized and a spectrum of x-ray energies is collected. Elemental composition, as a percent, is *inferred* from the spectrum of x-ray energies by a software algorithm. This algorithm uses standard x-ray spectra for specified elements as vectors, fitting these vectors to the observed x-ray spectrum and assigning the percent composition based on this fit.

This process is quite distinct from the analytical use of SEM/EDS for particle identification. The two methods are not mutually exclusive: individual particles can be revisited and analyzed as needed, taking the time required for analysis, to the limits of the capability of the instrument and specimen.

4. Alternative approaches to the definition and use of TPTs.

There are three general approaches to the definition of TPTs. In the proof of principle research conducted under Award 2010-DN-BX-K244, we used broad groupings based on primary particle composition as represented in EDS signals, along with expert selection of particle types.

In the present approach we defined TPTs through computational methods, creating sets of 10 TPTs that were used to define particle profiles for sources and traces. Sensitivity analysis was not part of this study: we were not optimizing the system, nor were we attempting to calculate an accurate error rate. As noted earlier, these TPTs are mathematical abstractions – particles similar to each other in the eyes of the algorithm. Furthermore, if the whole experiment were repeated with a new dataset of similar size, one would not expect the same TPT clusters. The TPT is not meant to represent the clustering of the particles in the population, it is only meant to provide parameters to the multinomial distribution of each source for the specific situation represented by

the dataset, and to enable some discrimination between the sources. It is not the specific TPTs that define the method used here, but a process incorporating the definition and use of TPTs. There are other alternatives for computationally generated TPTs that could be explored. Notably, there is no requirement that TPTs be actually defined. Computational methods can work with the raw data, omitting this intermediate step. Preliminary investigation suggests that this would be as effective, though not necessarily more effective, than the present system.

The third approach, at the other extreme, is the definition of TPTs based on libraries of actual particle types, along with associated variations. This follows a more conventional analytical approach and is not without precedent. However, this approach is more suited for applications focusing on a well-defined set of particles of interest (such as naturally occurring minerals) where it is feasible to conduct meaningful up-front selection, calibration and standardization of EDS profiles. Nonetheless, an alternative strategy that remains unexplored is to define a set of actual particle types that are believed to be sufficiently present, detectible, and variable in specimens of interest, followed by the use of procedures that search only for these particle types.

5. Verification of results through additional particle characterization or identification.

As noted under point 2 above, the process of SEM/EDS characterization employed in this program can be directly supplemented by the analytical use of SEM/EDS for particle identification. That is, if the methods in this program indicate a *possible* association between two specimens, based on correspondence measures and estimates of probative value, this association is *testable* through a verification process that employs SEM/EDS in a more critical mode of particle identification. Not only can elemental profiles be explicitly analyzed, but particle morphologies, sizes and homogeneity can be compared. These examinations can be performed on the same specimens that have been used for the initial characterization and comparison processes.

6. The overall state of readiness for this technology.

The overall state of readiness for this technology, using the DOD Technology Readiness Levels shown in Table 11, is at Level 6. There is a representative prototype system for the comparison of particle profiles, ready to be tested in a relevant environment. We recommend testing of the application, for investigative use, on closed-set libraries of operational specimens where linkages among specimens will be useful. Several such applications are discussed in the next section.

Table 11. DOD Technology Readiness Levels[22]

Technology Readiness Level	Description
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

C. Implications for Policy and Practice

Five specific implications for policy and practice are discussed in this section:

1. The usefulness of VSP to provide objective, quantitative associations and measurements of probative value has been established. This confirms the potential to remove fundamental limitations to the probative value of carpet fiber evidence, providing additional impetus and direction for fundamental changes in the way that forensic trace evidence is conceptualized, analyzed and used in the criminal justice system.
2. The results of this research are likely extendable, with minor modifications, to other trace evidence types, and are expected to contribute significantly for those types of trace evidence that have long been considered of low evidential value.
3. An entirely new approach to trace evidence is enabled: comparing different types of trace evidence with one another by way of their adhering VSP.
4. An additional, high priority use for existing crime laboratory SEM/EDS analytical capabilities and related practitioner skills can now be anticipated, guiding the allocation of laboratory resources.
5. A need can be anticipated for policies and practices for evidence collection and processing of crime scenes that are sensitive to requirements for the preservation and analysis of VSP.

1. The usefulness of VSP to provide objective, quantitative associations and measurements of probative value has been established. This confirms the potential to remove fundamental limitations to the probative value of carpet fiber evidence, providing additional impetus and direction for fundamental changes in the way that forensic trace evidence is conceptualized, analyzed and used in the criminal justice system.

This project has shown that quantitative methods of comparison and association can follow from the exploitation of the next (finer) dimension of particles. One potential use of these particles in one specific trace evidence application has been explored. The implications for policy and practice are profound. The fundamental limitation to the probative value of trace evidence, noted in the NRC report,[5] stems from conventional trace evidence characteristics being determined by their manufacture. As mass-produced commodities, probative value is limited to class

associations, with qualitative, expert assessments of evidential value. The analysis of VSP, riding "piggy back" on the surface of other trace evidence particles, can remove this fundamental limitation, by adding independent, quantitative, objectively measured fine particle profiles that have accumulated from the environment during use in a specific location. This will lead to much more sensitive testing of associations, and more certain and convincing associative evidence.

2. The results of this research are likely extendable, with minor modifications, to other trace evidence types, and are expected to contribute significantly for those types of trace evidence that have been considered of low evidential value.

The results of this research have implications for other types of trace evidence: for example, there are VSP adhering to other types of fibers, hair, glass, and paint. Some types of evidence, now of extremely low value for trace evidence associations (such as undyed cotton fibers) may become highly useful for association based on the VSP that adheres to them. The morphological examination of hair, for example, is vulnerable to criticism based on subjectivities and variations in methodology. The examination can likely be supplemented by comparisons of adhering VSP. In extension of the research to these areas, the methodologies and interpretations will be similar. That is, separate studies of fine particle populations for each type of trace evidence are unlikely to be necessary, since what is being compared are the particles from the environments. This is a noteworthy advantage over the use of new types of trace evidence that would each require their own separate study of population frequencies.

3. An entirely new approach to trace evidence is enabled: comparing different types of trace evidence with one another by way of their adhering VSP.

Any trace evidence type can act as the specific carrier of a more general "VSP signal." Any fiber from a residence, for example, can carry VSP corresponding to any other fiber. They need not be fibers from the same carpet. Extending this further, VSP on a knife or tool left at a crime scene can, for example, be linked with VSP from a suspect's residence or from his pocket; or VSP on the edges of tape on the inside of an IED can be linked with that found on the edges of an entirely different kind of tape in a suspect's workshop.

4. An additional, high priority use for existing forensic laboratory SEM/EDS analytical capabilities and related practitioner skills can now be anticipated, guiding the allocation of laboratory resources.

The computer-assisted SEM/EDS methods used for analysis of VSP on carpet fibers were specifically developed with a view toward utilization of existing forensic laboratory equipment and related practitioner skills. This project has directly demonstrated that the methods can achieve effective results within the constraints of an operational forensic laboratory.

5. A need can be anticipated for policies and practices for evidence collection and processing of crime scenes that are sensitive to requirements for the preservation and analysis of VSP.

As methods for the exploitation of VSP come closer to implementation, a need for appropriate evidence collection and processing methods can be anticipated. These methods will include collection of appropriate control samples and information that would help to interpret the presence of VSP that may be present. The requirements for actual collection practices will only be clear after additional research, but at this point a need for such methods can be anticipated.

D. Implications for Further Research

This project has established that realistic field collections of carpet fiber evidence and currently available forensic laboratory capabilities are sufficient for collection and analysis of VSP adhering to carpet fibers. The project has also successfully developed quantitative methods to determine the degree of correspondence between sets of VSP and to measure the probative value of the degree of correspondence. These results provide both the impetus and direction for follow-on research. Each of the numbered points in the paragraphs below is briefly discussed in this section.

The carpet fiber application itself has been a useful test-bed for development of the analytical and computational methods, but this application is not likely to be the most immediately available for implementation. Further research is needed that will (1) rigorously measure within and between variability for carpets, (2) determine how susceptible shed fibers are to contamination and loss of VSP profiles, and (3) explore the compatibility of fiber collection methods with the recovery of VSP from fibers.

More generally, and more significantly, the quantitative methods developed under this program are ready to be applied to (4) other trace evidence types, and (5) datasets generated by other particle analysis methods.

The most immediate application for the quantitative methods developed under this program are for (6) investigative associations of items of evidence with readily available and abundant adhering particles.

Additionally, there is strong impetus for (7) more general development and validation of quantitative methods for the use and interpretation of VSP.

1. Rigorously Measuring Within and Between Variability for these TPTs

Variability, both within and between carpets, must be better understood. Investigation of within-carpet variability will require testing of carpet samples taken comprehensively from entire rooms, entire buildings and entire areas of vehicles. Shed fibers, as opposed to cut fibers from fabric, will need to be included in these tests. The length of such fibers may be an important parameter to include among those studied.

Investigation of between-carpet variability will require testing of carpets from different geographical areas, and testing multiple locations in the same geographical area. As with research on performance characteristics, knowledge of the actual source of the particles, when determinable, will lead to greater understanding of the factors contributing to their variability.

2. Determining How Susceptible Shed Fibers are to Contamination and Loss of VSP Profiles

Forensic applications will be based on the transfer of carpet fibers from a source carpet to an object or person. During or post transfer, VSP profiles on carpet fibers are subject to contamination (acquisition of additional VSP) or losses (loss of some of the originally adhering VSP). These changes may occur very slowly, and at low levels, or may occur quickly. There may be exchange with those VSP on a receiving substrate. Losses, should they occur, may be proportional (all VSP affected evenly) or disproportional (some types of VSP markedly more subject to retention or loss). The levels of occurrence of any such effects are unknown. If they occur, they need not greatly affect the methodology in actual application, but they must be understood in any case.

3. Exploration of the Compatibility of Fiber Collection Methods and VSP Recovery from Fibers

Related to the previous area, there is a need to examine the consequences of fiber recovery methods (such as taping and scraping). Trade-offs among collection and examination techniques may be indicated.

4. Application to Additional Trace Evidence Types

As noted under Implications for Policy and Practice, the results of the present research program are likely extendable, with minor modifications, to other trace evidence types, and are expected to contribute significantly for those types of trace evidence that have been considered of low evidential value. The two types specifically mentioned were undyed cotton fibers, currently considered of nearly no probative value for association, and hairs, currently vulnerable to criticism based on subjectivities and variations in methodology. The ability of VSP to test associations for these two evidence types would have a highly significant, immediate impact.

5. Application of Other Instrumental Analysis Methods

SEM/EDS is not the only candidate for the analysis of VSP. Particle profiles can be analyzed by a growing number of high-throughput methods based on light or electron microscopy, Raman microscopy, FTIR microspectroscopy, Raman microspectroscopy or even methods of molecular biology as applied to non-human DNA. Additional techniques will be forthcoming and each should be evaluated for a possible niche in the forensic analysis of VSP.

6. Investigative Associations of Items of Evidence

Again, as noted under Implications for Policy and Practice, an entirely new approach to trace evidence is possible using VSP: comparing different types of trace evidence with one another. Any trace evidence type can act as the specific carrier of a more general “VSP signal.” These methods are essentially comparing an environment (via its VSP profile) to items that could have

originated from that environment. *Any* item or piece of trace evidence originating from a crime scene can potentially be linked to that crime scene using the crime scene's VSP profile.

7. General Development and Validation of Quantitative Methods for the Use and Interpretation of VSP

Parallel to the specific development and validation of quantitative methods for carpet fiber applications, research providing inputs to more general applications will include better understanding of forensic performance parameters of a broader set of TPTs, generalizations (as possible) of their within- and between-item variability, correlations among them, and the limits of contamination and loss during contact and transfer.

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VI. Dissemination of Research Findings

1. Presentations Resulting from this Award (as of 6/30/14)

Stoney, DA. "Exploitation of Very Small Particles to Enhance the Probative Value of Carpet Fibers," Pills and Particles: Toxicology and Linking Trace Evidence, National Institute of Justice Live Forensic Research Seminar Series, Webinar, June 4, 2013; June 6, 2013; June 11, 2013

Stoney, DA. "Exploitation of Very Small Particles to Enhance the Probative Value of Carpet Fibers," National Institute of Justice 2013 Research Grantees Meeting, Washington, DC, February 19, 2013.

Stoney, DA and Neumann, C. "Computational Methods Supporting Particle Combination Analysis: Application to Very Small Particles on the Surface of Carpet Fibers," Criminalistics Section, American Academy of Forensic Sciences 66th Annual Meeting, Seattle, WA, February 20, 2014.

Stoney, DA and Stoney, PL. "Particle Combination Analysis: A Fundamentally New Investigative Approach," Jurisprudence Section, American Academy of Forensic Sciences 66th Annual Meeting, Seattle, WA, February 21, 2014.

Stoney, DA and Stoney, PL. "Particle Combination Analysis: Very Small Particles on the Surfaces of Carpet Fibers as Multiple-Transfer Evidence," (Workshop) California Association of Criminalists Spring 2014 Seminar, San Diego, CA, May 6, 2014.

Stoney, DA and Stoney, PL. "Unleashing Next Generation Forensic Trace Evidence Analysis: Inferences and Quantitative Associations from Particle Combinations," California Association of Criminalists Spring 2014 Seminar, San Diego, CA, May 8, 2014.

Stoney, DA and Neumann, C. "Particle Combination Analysis: Very Small Particles on the Surfaces of Carpet Fibers as Multiple-Transfer Evidence," Presentation to NIST Forensic Sciences Group, Gaithersburg, MD, May 9, 2014.

Stoney, DA. "Particle Combination Analysis: Very Small Particles on the Surfaces of Carpet Fibers as Multiple-Transfer Evidence," Presentation to University of Lausanne Forensic Science Program, Lausanne, Switzerland, June 10, 2014.

2. Publications Resulting from this Award (as of 6/30/14)

Bulman, P. "A New Look at Carpet Fibers." In *NIJ's Innovative Research Spans Variety of Forensic Fields*, NIJ Journal No. 272, posted May 2013.