R2-A.1: Improved Swab Design for Contact Sensing

I. PARTICIPANTS

<table>
<thead>
<tr>
<th>Faculty/Staff</th>
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<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>Stephen P. Beaudoin</td>
</tr>
<tr>
<td>Bryan Boudouris</td>
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<th>Graduate, Undergraduate and REU Students</th>
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<tr>
<td>Name</td>
</tr>
<tr>
<td>Melissa Sweat</td>
</tr>
<tr>
<td>Darby Hoss</td>
</tr>
<tr>
<td>Sean Fronczak</td>
</tr>
<tr>
<td>Jennifer Laster</td>
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<tr>
<td>Jordan Thorpe</td>
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II. PROJECT DESCRIPTION

A. Project Overview

This project is an important element of the overall ALERT strategy to enhance air travel security. Like project R2-D.1, it is focused on checkpoints by contact sampling of carry-on baggage. Existing methods for contact sampling use traps that are applied manually to extract explosives residues from suspicious bags. These traps are then placed in an ion mobility spectrometer (IMS), where any explosive residue is desorbed from the trap when the temperature is raised to roughly 250°C over a period of approximately 8 seconds. Commercial-off-the-shelf (COTS) traps are optimized to survive repeated exposure to the IMS desorber, but not to extract residue from the surfaces being interrogated.

Considerable effort has been placed on finding ways to improve the sensitivity, accuracy, and response time of IMS tools. However, these efforts have been undertaken without a great deal of consideration of the essential first step in residue detection, which is the extraction of the residue from the surface of interest. This project addresses directly this key step by pursuing rational trap design by optimizing trap properties leading to superior residue harvesting from surfaces. This effort involves several steps, including:

- Investigating the mechanical properties of explosives residues and relating these properties to the effectiveness of residue removal from surfaces.
  - This effort was so substantial that it was split off to be a standalone project (R2-D.1).
- Performing rational trap design:
  - To optimize the effectiveness of traps at harvesting residues from surfaces.
  - To retain chemical and mechanical integrity at IMS operating temperatures.
  - To interrogate substrates of interest effectively.
  - To adhere to residues of explosives effectively.
Figure 1 shows the flowchart for a new synthetic process we have developed to make nano/micro structured traps for residue removal from surfaces. These traps are comprised of PPy-DBS (polypyrrole doped with dodecylbenzenesulfonate). They are conductive to minimize electrostatic charging, and also to enable the use of electrostatic forces to assist in the collection of explosives residues on surfaces. In addition, based on the lithographic methods employed to make them, a seemingly endless distribution of features can be fabricated on the trap surfaces. These features will be optimized to allow for more effective interrogations of surfaces of interest in air transport environments.

Figure 2 on the next page shows some arrays of PPy-DBS pillars of varying topography fabricated in our labs. As can be seen, the aspect ratio of the ‘pillars’ on the traps (aspect ratio = ratio of finger height to diameter at the top) can be readily tailored, as can the shape of the pillars. In this case, the shape varies between rectangular pyramids with blunted tops and rounded edges to cylindrical pyramids with blunted tops and rounded edges. We have been able to fabricate traps with a wide range of pillar aspect ratios that can effectively interrogate surfaces with a very broad range of topographies representative of air transportation environments. Work is ongoing to characterize the mechanical properties of the pillars as a function of the fabrication conditions and pillar physical properties (absolute length and diameter as well as aspect ratio), as well as the effect of thermal cycling on these properties. The key mechanical properties are their elastic modulus, which reflects their ability to deform without yielding, as well as their Poisson's ratio, which discusses the extent to which a pillar will expand laterally under a normal compressive load. Finally, their coefficient of friction against representative surfaces under load and controlled motion are being assessed.
In prior reports, ongoing work to document the thermal stability of the polymeric swabs, the effects of the topography of the surface that is being swabbed on the swabs’ effectiveness, and preliminary data on the swabs’ effectiveness were reported. These all suggested that the swabs were promising. A significant missing piece of information was the adhesion force between the swabs and residues, particularly the residues of compounded explosives. Measuring this force represents one of the great challenges in the particle/powder processing community, as the compounded residues are viscous liquids that move under any load that is applied to measure their adhesion behavior. As a result, any existing measures of adhesion properties are rendered useless when it comes to these materials. To address this concern, we accomplished a major scientific goal that has gone unsolved for more than 30 years, since the invention of atomic force microscopy (AFM). Specifically, we developed a non-contact adhesion force measurement technique. This method measures the deflection behavior of an AFM cantilever as it approaches a surface. Figure 3 on the next page shows the behavior of an AFM cantilever approaching a surface of interest, in the case where the van der Waals (vdW) force controls the adhesion. Figure 4 on the next page shows the key dimensions of the sphere used to model the cantilever tip. To evaluate the adhesion force, Equation 1 is used:

$$ A = -\frac{8 k_c (d_c)^3}{9 R_t} $$

where $k$ = the cantilever spring constant, $A$ is the system Hamaker constant (a constant that describes the effect of the composition of the cantilever, tip, and intervening medium on the adhesion), $R_t$ = the radius of curvature of the sphere used to model the cantilever tip, and $d_c$ = the cantilever tip deflection at the point of cantilever-surface contact.
Figure 3: Qualitative plot of an AFM deflection curve. The cantilever and surface begin far enough away from each other such that no tip deflection, \( d \), is registered (A). As the cantilever approaches the surface, the tip-surface vdW interaction becomes significant and the tip deflects towards the surface (B). Eventually, the tip-surface interaction overwhelms the restoring force of the cantilever, and the tip appears to suddenly “jump-into-contact” with the surface. This “jump-into-contact” distance, \( \Delta d \), is defined as the difference between the tip deflections at the jump point (\( d_{\text{jump}} \)) and the point of first contact (\( d_{\text{contact}} \)) with the surface. The tip is pressed further into the surface, resulting in a positive deflection, and is then retracted (C). Once the restoring force of the cantilever overwhelms the tip-surface vdW interaction, the tip jumps back out of contact (D).

Figure 4: Classical model for AFM cantilever tip showing key dimensions.
When this method is used to describe the tip-surface interaction, the approach is to measure $d_x$, $k_x$, and $R_t$, and to then determine the value of the remaining unknown, $A$. When the value of this constant is known, then the adhesion between the two surfaces (cantilever and opposing surface) is described, and it is straightforward to describe the adhesion between any two surfaces made from these materials. By measuring the adhesion constant between the cantilever and an explosive residue of interest (C4, for example), and between the cantilever and the swab of interest, simple combining rules can be used to determine the force constant between the residue and the swab, as a function of the composition of the swab and residue.

Figure 5 shows the results of our method. In this figure, the ratio $\frac{A_{app}}{A}$ describes the ratio of the Hamaker constant determined experimentally using our method to the true system Hamaker constant. As can be seen, this method allows Hamaker constants to be determined with roughly 2.5% error, which is unprecedented. Now that the method is validated, it can be used to determine Hamaker constants for explosives-swab and explosives-surface combinations of all types, independent of whether or not the explosives are particulate or compounded in form.

Another new result developed this year involves the use of a centrifuge with a modified analytical method to describe the adhesion between an explosive powder or a population of residues (such as in a fingerprint) and a surface. This method solves one of the great unsolved problems in particle technology, which has gone unsolved for over a century. Specifically, it allows the behavior of a powder to be described, including the effects of the size, roughness, shape, and mechanical properties of the individual particles in the powder, in terms of a simple expression for an idealized powder (perfect spheres) with an adjustable distributed adhe-
sion constant that is fitted using experimental data developed with the centrifuge. Figure 6 (on the next page) shows a schematic of the method, illustrating the simple method of operation. Figure 7 shows the agreement between the observed and modeled removal of a silica powder (thousands of particles) from a stainless steel plate, in addition to the fitted effective Hamaker constant distribution that captures all of the effects of the size, shape, roughness, and deformation of the particles. When these results were presented at the Trace Explosives Detection workshop in Charlottesville in April 2016, which is the leading forum worldwide for the dissemination of new work in the area of explosives detection, they were presented as the last talk in the workshop. At the conclusion of the talk, one of the workshop organizers observed that the work “was like Jimi Hendrix closing Woodstock”. With the advent of this method, it will be possible for the trace explosives detection community to evaluate the adhesion of any explosive to any surface using only a simple set of experiments and a simple, closed-form modeling paradigm.

![Figure 6: Schematic demonstrating the mechanism of operation of the centrifuge technique. The particles are removed from the plates in the centrifuge when the inertial force resulting from the centrifuge rotation exceeds the adhesion force between the particles and the surface. As shown on the right, the plate may have any manner of topography and the method will still be effective. Milligram-level quantities of powder (explosives) will provide thousands of data points that can be used to ‘tune’ the adhesion force models that result from the method.](image)

![Figure 7: (Left) The percentage of particles remaining as a function of rotational speed (●) obtained experimentally, and (○) obtained via simulation of an ideal, smooth powder with an effective Hamaker constant distribution. (Right) (●) Average effective Hamaker constants (normalized by particle size) and (line) lognormal fit of the effective Hamaker constants.](image)

**B. Biennial Review Results and Related Actions to Address**

**B.1. Project strengths**

- If the growth and optimization of the meso-structured swabs can be accomplished, this will be very
promising.

- The approach is sound.
- The swab has the promise for detecting other agents besides explosives, and could benefit other agencies, and this should be explored (this comment appeared twice).
- Reusable swabs should be cost competitive.

B.2. Project weaknesses

- Swabs that are optimal for sampling some surfaces, such as nylon, will not be optimal for sampling other surfaces, like plastic.
- The community may migrate to non-contact sampling, rendering this work obsolete.
- If the swabs are reused, they will not be valuable for the prosecution of criminals.

B.3. How do you plan to address the weaknesses in Year 4?

The weaknesses identified in project R2-A.1 include two concerns that would be relevant for all technologies being employed for contact sampling. Specifically, COTS swabs that were to be reused would incur the same chain of evidence concerns as our swabs, and COTS swabs would face the same obsolescence as ours if the community can successfully perform non-contact sampling. In Year 4, we will work on improving the thermal stability of the swabs by modifying the growth conditions, including the bath composition (these polymers are created using an electropolymerization process). By driving the thermal stability yet higher, it may be possible to volatilize all species on the swab, leaving behind a pristine swab that could be used for detection and prosecution. We have developed a method to describe the topography of large surfaces using a small amount of measurements. This allows us to characterize the topography of a wide range of surfaces in silico, which will then allow us to optimize the topography and mechanical properties of the swabs so that a single swab can operate effectively on a broad range of surfaces. Finally, we have just begun to explore a new line of inquiry in which we will fabricate bilayer traps. These traps will contain the same mesostructured polyppyrole fingers as the current swabs. However, the support on the traps will be IR-transparent. This will allow a trap to be placed in a portable IR spectrometer in the field for instantaneous assessment of residue. This capability to use an orthogonal detection scheme increases the reliability of the entire sampling process.

C. State of the Art and Technical Approach

Detection of improvised explosive devices (IEDs) in airports and other public areas is a fundamental concern for public safety [1]. Trace explosives particles are likely to contaminate the clothing and equipment of individuals in contact with these materials during IED manufacturing or transportation [2]. Sophisticated removal and detection techniques have been developed in order to identify persons with explosives particles adhered to their clothing and luggage [3, 5]. However, a more complete understanding of the affinity between the particles of interest and the detection device, typically a swab or trap, is required to improve current IED detection efficiency [6]. Similarly, adhesion between the explosives residues and the contaminated surfaces must also be better understood. Since the particles of interest are on the micrometer size scale, intermolecular interactions such as vdW, capillary, and electrostatic forces are of primary interest when describing the adhesive properties of these materials [7–10]. While the latter two forces are conditional and can change depending on testing conditions, vdW forces are always present. For this reason, vdW interactions are the primary forces that should be considered when studying explosives particle adhesion. Theoretical predictions tend to assume systems with smooth surfaces and well-characterized geometries [11–13]. However, real systems deviate from these ideal conditions as no surface is perfectly smooth. This causes experimental observations of vdW interactions to differ from theoretical predictions by as much as an order of magnitude [14]. Heterogeneity within a substrate’s surface morphology is commonly attributed as the principle cause
for such deviations [14, 15]. As a result, various modeling attempts have been made to account for this variation in the contact regime and its consequential effects on the vdW interactions between surfaces [16–21]. Recently, AFM topological maps from the surfaces of interest have been shown to be effective when used to simulate the vdW interactions [22, 23]. However, this characterization method presents a statistical problem since an AFM topographical scan is typically a few microns in length and represents a very small fraction of the total surface area of most surfaces of interest (such as a luggage handle or a laptop surface). In addition, one can expect to find a certain amount of variation amongst different scans.

A great deal of attention has been placed on optimizing IMS protocols for detecting explosives residues in air travel security environments, yet little attention has been paid to the first step in IMS-based detection, which is contact sampling of residues using traps. To optimize this aspect of trace explosives detection, the following must be performed:

1. Measure the force of adhesion between explosives residues, traps, and surfaces of interest using the new non-contact adhesion approach described above.
2. Assess the mechanism of detachment of residues from surfaces during contact sampling.
3. Determine the effects of trap, residue, and surface characteristics on residue harvesting.
4. Measure the effects of environmental conditions and swabbing protocols on 1-3 above.
5. Measure the representative topography of surfaces of interest.
6. Determine the effects of residue and trap characteristics, and desorber operating conditions, on the effectiveness of residue desorption from swabs during IMS.
7. Develop the centrifuge method so that the community can use it to measure and model the adhesion of explosives to surfaces so that they may develop optimal contact sampling methods. Note that this aspect of the work is so sufficiently large in scope that it cannot be accomplished within the limits of this project. A new project to develop the method and create an adhesion constant database for use by the community is proposed through the ‘new project selection’ process that is currently underway.

All but items #2 and #7 on the above list are within the planned work of this project. Current approaches to evaluate the effectiveness of contact sampling have been minimal, and limited to studies of swabbing effectiveness under simulated airport security conditions [24]. Such studies do not provide adequate scientific data to support mechanistic understanding of the process of residue harvesting. Project R2-D.1 is working to assess the mechanism of the detachment of residues from surfaces during contact sampling, as described in item #2 listed above.

Current military specifications for the Royal Demolition Explosive (RDX) and pentaerythritol tetranitrate (PETN) list ranges in particle diameters from 44 to 2000 μm and 44 μm to 800 μm [25–27]. Due in part to the wide range of particle diameters, variability exists regarding the size of particles found in C4 or Semtex on a surface during swipe sampling [6, 24, 28–30]. Notably, the size of particles deposited by a thumbprint on a surface of interest has not been fully evaluated, and the ability to recreate a standard print is greatly lacking [6, 24, 28–30]. Further, some swabs and substrates are woven materials, leading to an entrapment problem that has not been fully evaluated [28, 30]. Moreover, the development in sampling technique has not been firmly established [6]. For IMS, certain standards apply: a swab must effectively remove solid particulates from a surface, withstand temperatures up to 300°C as employed by the IMS, and be affordable [6, 28]. Most current studies consider either cloth or Teflon-coated fiberglass swabs [6, 24, 28–30].

Several parameters are usually not controlled during the development of a successful wiping technique [30]. In particular, variability exists in the applied force of a swipe, the surface area covered, the swab material, the roughness of the swab and substrate materials, and the swipe velocity, among other characteristics [6, 24, 30]. The applied load may range from approximately 3 to 60N [6, 29]. The Verkouteren group claims first
that the critical parameters in determining removal efficiency are applied load and the translational force required to overcome the frictional resistance to maintain a constant velocity [6]. The group also claims a direct linear correlation between increased applied force of swiping and particle removal efficiency [6, 29, 30]. The viscosity at the speeds representative of those found in an airport security setting has not been tested. Verkouteren reports a swipe speed of 0.7 cm/s, while methods reported by the Environmental Protection Agency (EPA) indicate swipe sampling speeds of 10 and 17 cm/s [6, 31]. Note that the speed of a swipe directly correlates to the strain rate, and thus the viscosity of the non-Newtonian binder.

Generally, previous studies have focused on manipulating applied force and attempting to create consistent methods to be employed by swab operators [6, 24, 30]. However, the above studies do not typically analyze the effects of roughness on the adhesion of a particle to either the swab or the substrate. Overall adhesion forces are not fully evaluated, as most tests performed attempt purely to establish a methodology. The deformation and failure of the composite are not evaluated.

D. Major Contributions

Year 3

1. Continued Optimization of Swab Fabrication
   We continued the optimization of deposition/growth conditions for fabrication of new state-of-the-art swabs for contact sampling.

2. Continued Evaluation of Thermal Stability of Swabs
   By changing the surfactant used during swab growth, we improved the thermal properties of the swabs so that they are stable to temperatures as high as ~250°C.

   Developed a novel, first-in-the-world approach for measuring the adhesion between explosives residues, swabs, and surfaces, which will allow for the measurement of the adhesion of compounded explosives such as C4 and Semtex with unprecedented accuracy.

4. Novel method for measuring the adhesion of an explosives powder or population of explosives residues to a surface based on a modification of the classical centrifuge method.

Year 2

1. Preliminary Optimization of Swab Fabrication
   We performed preliminary optimization of deposition/growth conditions for fabrication of new state-of-the-art swabs for contact sampling.

2. Thermal Stability of Swabs
   By changing the surfactant used during swab growth, we improved the thermal properties of the swabs so that they are stable to temperatures as high as ~230°C.

3. Topography of Swabbed Surfaces
   We determined the relationship between the number of locations on a surface where one performs topographical measurements and the accuracy of the topography statistics determined. This is the basis for the protocol that will be implemented in order to determine the swabbing challenge on various materials of interest in air transportation security settings.

4. Model Contaminated Surface
   We developed and implemented a model, highly-engineered surface, in combination with fluorese-
cent beads (model contaminants) to create a new ‘standard’ swabbing challenge. With this standard challenge, we were able to assess the superior performance of the swabs being developed here in comparison to COTS swabs.

Year 1

1. Viscosity of Binders in Compounded Explosives

The viscosities of the binders used in C-4 and Semtex H were evaluated. This included the measurement of the shear stress, viscosity, and normal stress values as a function of shear rate. As expected, both binders exhibited non-Newtonian, shear-thinning behavior. There are several important distinctions between each composite. First, the Semtex binder is significantly more viscous than the C-4 binder. The viscosity ranged from 810 to 2030 Pa*s for Semtex compared with 20 to 350 Pa*s for C-4. The C-4 binder is more stable with respect to shear rate, whereas any minute change in shear rate creates a significant change in the viscosity of the Semtex binder.

2. Residue Failure Under Load

The dynamic behavior of granulated/compounded materials, including silica particles in C-4 and Semtex binders, was documented. The goal was to assess the process by which the granules deformed and failed under load, as this is a good representation of the way they will behave when they are removed from a surface during contact sampling. We observed many similarities between the behavior of composites made with Newtonian binders (model systems) and those made with non-Newtonian binders, but ultimately learned that it was not possible to make a model out of Newtonian binders that would be a good representation of the real compounded explosive.

3. Inverse Gas Characterization

Cohesive Hamaker constants (the van der Waals force constants in effect for materials adhering to themselves) were evaluated using inverse gas chromatography. Constants were determined for RDX, PETN, trinitrotoluene (TNT), ammonium nitrate (AN), ammonium nitrate fuel oil (ANFO) at 2, 5 and 10% fuel oil, and ammonium nitrate paraffin (ANPA) at 2, 5 and 10% paraffin. These constants agreed well with those obtained from contact angle measurements and optical constants or Lifshitz’s theory (data was available for a limited amount of samples). It should be noted that due to limitations of the theory associated with this method, the constants evaluated in this manner were only lower bounds of the true constants [32–35].

4. Swab Prototypes

Polypyrrole was electrodeposited in a unique apparatus to create nano-/micro-structured swabs for use as advanced contact sampling tools. The windows for material deposition were explored and preliminary progress was made linking the thermal stability of the materials to the deposition conditions.

E. Milestones

Specific milestones to be achieved in the upcoming year include:

1. Testing of advanced swabs against model surfaces of interest as defined by the Department of Homeland Security (DHS).
2. Development of growth protocols to allow for the fabrication of swabs with ‘fingers’ of varying aspect ratio and varying height on same swab.
3. Characterization of adhesion characteristics of new swabs.
4. Successful testing of new swabs at removing residues from surfaces of interest to DHS.
5. Further development of a non-contact method to evaluate the Hamaker constant describing the ad-
hesion between residues, swabs, and surfaces.

6. Modification of the surface of swab fingers to improve the recovery of residues from surfaces and their release in IMS desorbers.

Major milestones remaining are of two types. For the polypyrrole swabs currently being developed for use with IMS exclusively, we will demonstrate the recovery of threat-levels of residues from target surfaces, and will show that the fractional recovery with our swabs is higher than with COTS materials. Next, we will demonstrate that our swabs are reusable many times over, and that they do not liberate any harmful byproducts during IMS processing. Finally, we will perform Generation 1 optimization of the size and shape of the fingers on the swab to help the swabs to be more effective in the field. In terms of the non-contact residue adhesion measurement method, we will develop it to describe the adhesion of compounded explosives to swabs and surfaces, and will share the results with the community so that it may develop improved protocols to recover these residues during contact sampling. It is expected that the part of this study that focuses on the baseline swabs, with one level of optimization (pitch and aspect ratio of the fingers), will be completed by May 2017. The adhesion work will likely be completed by May 2018.

F. Future Plans

We have obtained coupons of coated and uncoated aluminum, and acrylonitrile butadiene styrene (ABS) plastic with rough and smooth finish. DHS has identified these surfaces as being relevant to air transportation security environments. Model residues from project R2-D.1 will be applied to these coupons, and the removal of the residue from the surfaces will be studied using the swabs developed in this project in a homemade slip-peel tester. Based on the results from these studies, we will modify the swab design and swabbing protocols. In addition, we will measure the topography of these surfaces using the methodology outlined above (see section C, item #3) with a goal of determining a representative roughness distribution on each of the surfaces. This will be used as a driver for the design of the shape of the surface of the novel swabs that we are creating in this project. The challenge is to create a swab that can effectively swab many different surfaces, and the adhesion-relevant roughness distributions that we will develop will allow this to be accomplished. Specifically, we will develop novel fabrication protocols that will allow for us to create swabs whose surfaces have a distribution of feature heights that is tuned to the distribution of heights on the surfaces of interest. This will allow for us to create swabs that have the best chance of recovering residues from these surfaces. We will create first-principles models of the adhesion force distribution as a function of distance from the swabs’ ‘fingers’. This distribution, combined with the residue dynamics information under development in R2-D.1, will be used to optimize the separation distance between fingers on the swabs, and will also inform the swabbing protocols.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

1. Improve the detection of trace explosives on luggage and persons through contact sampling/IMS.
   a. Metrics: Research in the Beaudoin lab has shown that swab-based contact sampling may miss as much as 30% of the residues on a surface. The goal of this research is to substantially improve the detection rate by enabling the design of swabs that effectively interrogate surfaces and harvest residues.

2. Develop and validate the adhesion forces between compounded explosives and swabs and surfaces.
   a. Metrics: Presently, no data exists on the adhesion between compounded explosives and any surfaces. The goal of this research is to collect and disseminate this data, which will enable the community to understand the nature of the contact sampling problem.
B. Potential for Transition

The recipe for creating the swabs has a pending patent application. We will contact commercial partners to test and license the technology when it is field-ready. The potential for transition is high. Preliminary results have already demonstrated the superior performance of these traps at harvesting residues.

C. Data and/or IP Acquisition Strategy

The IP is already developed and a patent is filed on the swabs. The performance of the swabs will be tested by placing known quantities of residues on surfaces of interest and measuring the ability of the swabs to remove the residues compared to existing COTS swabs. These removal studies will be conducted under controlled, applied load and swipe speed conditions, consistent with the current Task Order on Contact Sampling Effectiveness, of which Prof. Beaudoin is the technical lead.

D. Transition Pathway

We share advances in the swab research with users and potential commercialization partners via conference presentations, reports, and journal articles. We also collaborate with companies, such as Morpho Detection, who perform testing on our swabs and validate their performance. The requisite information is collected and transferred at regular intervals, and we expect to have our first generation of swabs ready to go into the transition pipeline within 8 months.

E. Customer Connections

Stefan Lukow at Morpho Detection is making measurements with the swabs we are creating. As a result, they have an interest in this project. We have also shared the swabs with FLIR in Purdue’s Research Park, and plan to share them with Smiths Detection, Implant Science Corporation, and Bruker Corporation.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

1. Course, Seminar, and/or Workshop Development
   a. Trace Explosives Sensing for Security Applications (TESSA) workshops: Organized and led a series of four workshops since the beginning of this project, attended by roughly 100 members of the trace explosives detection community for the purpose of developing a common, well-accepted approach for baselining contact sampling effectiveness.

2. Student Internship, Job, and/or Research Opportunities
   a. Two PhD students who worked on the project have graduated and accepted positions at a national lab and TSL, which is consistent with the Homeland Security mission. Six undergraduates are now work in Beaudoin's lab, including four females, one Latina, and one African American student (all U.S. citizens), on this project and R2-D.1.

3. Interactions and Outreach to K-12, Community College, and/or Minority Serving Institution Students or Faculty
   a. A high school student participated in research in my lab over the last year. She was in the lab full-time during the summer of 2015 and remains a part of my group, although on a reduced-time basis.

4. Other Outcomes that Relate to Educational Improvement or Workforce Development
a. Coordinated transfer of High Tech Tools and Toys program to Purdue First Year Engineering Program.

B. Peer Reviewed Journal Articles


C. Other Publications


D. Other Conference Proceedings


E. Student Theses or Dissertations Produced from This Project

1. Harrison, A. “Detailed investigations of capillary and van der Waals forces in the adhesion between solids.” PhD Dissertation, Chemical Engineering, Purdue University, August 2015.

F. Requests for Assistance/Advice

1. From DHS
   a. Requested to lead the TESSA (Trace Explosive Sensing for Security Applications) activities, including the TESSA02 Workshop on August 5 – 6, 2015.

V. REFERENCES


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