Integrated Impactor/Detector for a High-Throughput Explosive-Trace Detection Portal

Matthew R. Fulghum, Michael J. Hargather, and Gary S. Settles

***Abstract*— The design of a very-high-flow-rate inertial particle impactor with integrated sampling for use in a walk-through explosive-trace detection portal is presented. This impactor is designed to collect particles of explosives from the aerodynamic wake of a walking subject, which requires a sampling capability of ~ 1 m^3/s and must reliably collect particles of ≥ 5-μm diameter. An impactor cross-section of 0.3 x 0.3 m was used, with three linear slot nozzles and corresponding impactor blades. The central impactor blade has a rotating impaction surface with an integrated heater for automated thermal desorption of the impacted material. An ion mobility spectrometer is used to interrogate the desorbed vapor for trace explosives detection. The process of sampling a subject and interrogating its aerodynamic wake for explosives requires about 8 s totally, allowing very-high throughput sampling for security-screening purposes.**

***Index Terms*— Automation, high-volume processing, ion mobility spectrometry, particle impactor, security screening, trace explosives detection.**

I. Introduction

APPROXIMATELY two million passengers fly every day in the United States according to the Bureau of Transportation Statistics [1], and all must go through airport security screening. The throughputs of previous explosive detection methods have been prohibitively low for use on such a large scale, requiring twenty seconds or more per passenger. To optimize passenger throughput, a screening-time goal of six seconds per passenger has been traditionally recognized.

Meeting this throughput goal for explosives sampling requires a very fast, high-air-volume detection method. This method should adequately sample the whole body of the subject for maximum sensitivity to trace explosives, and return reliable results (minimum false positives) as fast as possible. While there have been several attempts in the past to perform real-time interrogation of subjects for the presence of explosives [2], [3], none have met the throughput goal stated above. While the trace detection step of the process is important, equally important is the issue of concentrating the trace signal into a volume which the sensor is capable of interrogating. This, too, was not adequately resolved in prior devices. Ion mobility spectrometers, the sensor used in this paper and common in the literature, have an extremely limited volumetric flow rate which cannot sample the huge volume of air around a human being within a reasonable span of time unless some form of pre-concentration is used.

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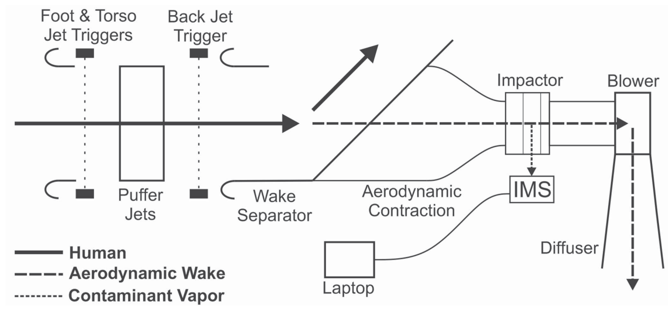

Fig. 1. Schematic of the wake sampling portal.

This paper demonstrates how the use of an impactor with integrated desorber can remove particles from the bulk flow, desorb them into vapor in a much-lower-volume secondary flow, and interrogate the vapor quickly using existing technology in order to meet the screening-time goal of the portal while maintaining acceptable sensitivity.

To sample the whole body, a walk-through portal was developed to sample the human aerodynamic wake [4]–[10]. As a subject walks, a wake develops behind him/her which can readily entrain liberated particles. If a subject has been handling explosives, it is likely that explosive particles will stick to the subject's skin and clothing. "Puffer" air jets designed into the wake portal, which are triggered as the subject walks past them, dislodge these particles from the subject and cause them to become entrained in the aerodynamic wake. A bend in the walking path causes the subject to change direction, but the inertia of the subject's wake carries it into a sampling inlet [4]. This sampler has an impactor for collecting particles from the separated wake and a blower for expelling the remaining airstream to the environment. A schematic of the entire wake sampling portal is shown in Fig. 1.

Of present interest is the collector section of the wake portal, which combines a very-high-volume particle impactor with an integrated sampler for automated detection of trace amounts of thermally-desorbed explosives. While this process has been automated before, this device is unique in its large scale. It collects micron-range [11] particles from an airstream of about 1 m^3/s, thermally desorbs them, and transports the

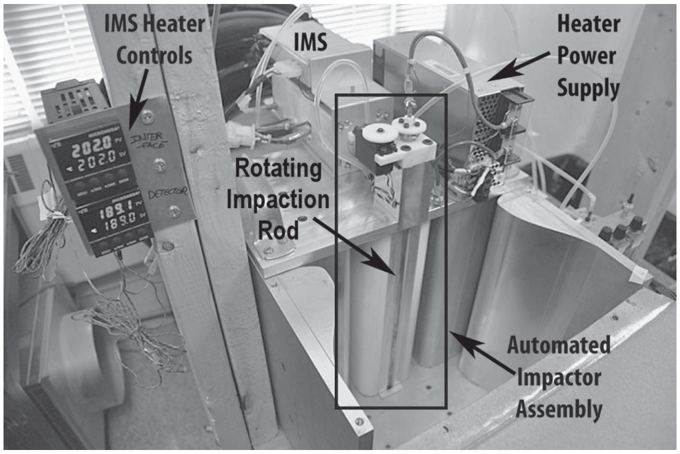

Fig. 2. Completed impactor assembly with integrated desorption and sampling. Impactor nozzles in front of instrumented blade have been removed to show the rotating impaction rod and heater strip.

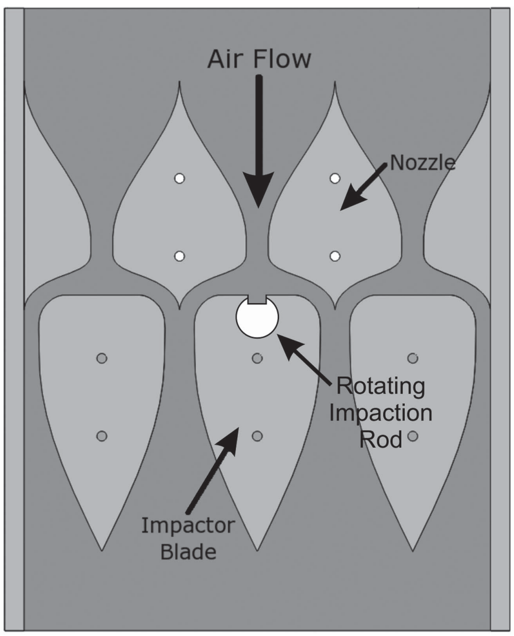

Fig. 3. Top down view of the impactor section geometry.

resulting vapor to a carrier flow of about 10 cc/s for sampling by an ion mobility spectrometer (IMS).

This collection is accomplished by impacting particles upon a heated notch in a rotating rod installed in one impactor blade. When sampling of the airstream is complete, the rod is rotated 180 degrees and the notch is heated to the desired desorption temperature. Carrier gas is allowed to flow into the bottom of the notch, up the length of the heater strip, and then into the IMS, where it is sampled. The impaction surface is rotated back into place for the next subject while a computer analyzes the data from the IMS for trace explosives.

A photograph of the automated impactor with integrated desorption and sampling can be seen in Fig. 2, where the slot nozzles in front of the instrumented blade have been removed for illustration purposes.

II. Apparatus

A. Impactor

The impactor section of the wake portal consists of three linear slot nozzles and three corresponding impactor blades, and is shown in Fig. 3. These nozzles are 0.305 m tall, and the overall width of the impactor section is also 0.305 m, for a total flow area of 0.093 m^2. Each nozzle inlet is 0.014 m wide and as tall as the impactor section, for an inlet area of 0.0043 m^2. An impactor of this size was necessary to handle the extremely high airflow of the human wake while still being able to capture the necessary range of particle sizes using a realistic blower power input. A 5.5 kW blower motor, driven by a Hitachi L200 variable frequency drive, provided the fan power requirements. However, in order to adequately sample the human aerodynamic wake the pressure drop through the impactor had to be minimized. The human aerodynamic wake has a volumetric flowrate of approximately 1200 L/s, but the final impactor design has a flow capacity of 750–850 L/s at about 3.8 kW of blower motor power, so approximately 30% of the wake is not captured. 5.5 kW was set as a constraint by typical power availability at security screening stations, and the performance specifications of commercially available blower fans at the required volumetric flow rate of air set the upper limit for permissible dynamic pressure drop across the impactor. These factors make sampling the entire 1200 L/s impractical, however the current design and power input were selected as the best-available compromise for a prototype portal. While failing to sample the entire human aerodynamic wake may reduce the sensitivity of the portal and lead to false negatives in cases where the signal is very weak, in a production design the impactor and blower could be scaled further to accommodate the full human aerodynamic wake and eliminate this issue.

The impactor was designed iteratively [12] using ANSYS Fluent software to refine an initial basic sharp-cornered impactor geometry for minimum pressure loss. The initial geometry used for the impactor design was based on the work of Marple & Willeke [13], [14], which uses dimensions for the nozzle entry width, throat width, impactor width, and jet-to-surface distance based on a width factor W. This width was set to allow three nozzles and impactor blades in the present impactor assembly.

The simulation was run and streamlines of the flow through the nozzle and around the impactor surface were plotted. Regions of recirculation in the flow were eliminated by redefining the geometry of the nozzle and impactor using streamlined contours that avoided flow separation. This process was repeated until recirculation was no longer notably present in the final simulation. By using this streamlining method, pressure loss through the impactor can be minimized. From the Fluent simulation, the pressure loss across the impactor for the initial geometry was approximately 5.5 kPa compared to approximately 0.5 kPa for the refined geometry. The completed impactor assembly had 0.85 kPa of pressure loss based on subsequent experimental testing.

Before the impactor section, there is an aerodynamic contraction that smoothly accelerates the captured wake

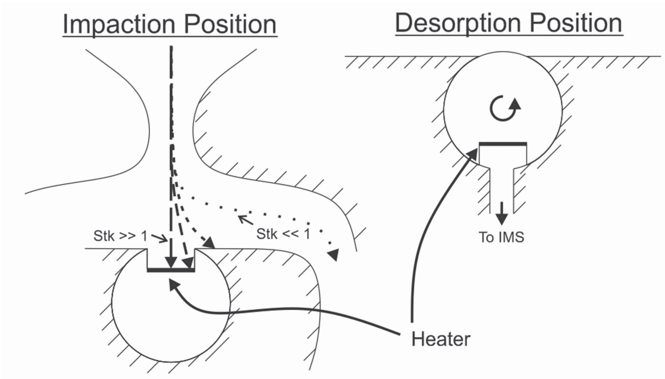

Fig. 4. Schematic showing the operation of the rotating rod with heated impaction surface.

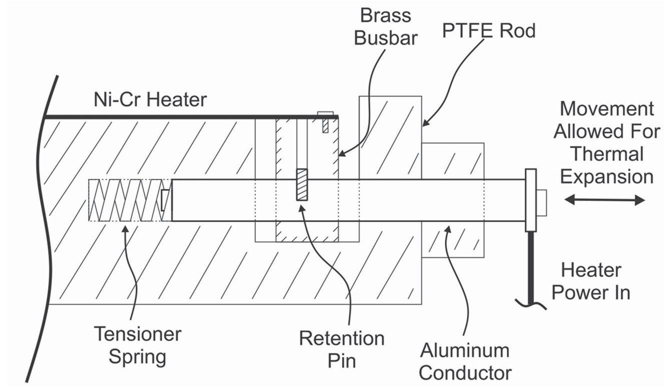

Fig. 5. Heater strip tensioning system used in the design.

toward the impactor. The opening of the contraction is 1.07 m tall and 0.72 m wide, for an area of 0.77 m^2, leading into the 0.093 m^2 impactor section mentioned earlier. The flow is contracted further by the impactor nozzles to 0.0043 m^2. In total, this leads to a contraction ratio of 180. Since RMS velocity variations due to turbulent eddies in the human wake are reduced by a factor of the square of the contraction ratio axially and its square root laterally [15], turbulence in the incoming wake should not affect impactor performance.

B. Rotating Impaction Rod

The rotating impaction surface consists of a 25.4 mm diameter rod with a milled notch on one side, extending 38 mm above and below the wake portal impactor walls. A thin NiCr electrical resistance heater is mounted in this notch. When the rod is facing toward the impactor nozzles, airborne particles impact upon the inside surface of the notch. When the rod is rotated into the interrogation position, the heater is powered to thermally desorb impacted particles at approximately 200 °C. A heated, dehumidified stream of air introduced at the bottom of the notch carries the desorbed vapor to a port at the top of the notch, which feeds it directly into the IMS. A diagram of the operation of the rotating impaction surface is shown in Fig. 4.

The critical dimensionless parameter for impaction efficiency is the Stokes (Stk) number, defined below, where ρ_p is the density of the particle, u_{ave} is the average velocity of the air as it passes through the nozzle, D_p is the particle diameter, W is the width of the nozzle slot, and μ is the viscosity of the air

$$Stk = \frac{\rho_p u_{ave} D_p^2}{9\mu W}.$$

Particles with Stk $\ll$ 1 will follow the air streamlines as they pass around the impactor, while particles with Stk $\gg$ 1 will not be able to follow the airstream and will impact upon the surface. From prior testing of the wake portal impactor with talc particles, and scaled using the Stokes number for the density and expected size distribution of explosive contaminant particles, it was determined that the majority of particles of interest impact within five millimeters on either side of the centerline of the impactor blades [12].

From this observation, the notch in the rotating rod was milled ten millimeters wide. To allow adequate gas flow in the interrogation position, this notch was milled 3 mm deep. These dimensions allow for one complete sampling of air in the notch volume in just over one second, at a carrier gas flowrate of 600 cc/min, which was limited by the flowrate capabilities of the IMS detector used in this device.

For prototyping purposes, only the center impactor blade has been instrumented, however in a production design it would be possible to instrument and sample using all three blades to further improve instrument sensitivity. This would, however, require more IMS capacity to handle the increased flowrate of carrier gas that would be necessary to adequately sample the extra notches.

C. Desorber

The heater used in this design to desorb impacted particles consists of a 0.406 m long, 0.127 mm thick Ni-Cr resistance heater ribbon laid along the notch, with power supplied from brass bus bars mounted at the end of the heater. Heater power is supplied by an adjustable power supply controlled by software in a closed loop. This software monitors heater resistance, converts this to temperature, and adjusts the heater voltage to hold the temperature close to a setpoint of 200 degrees Celsius. One bus bar is fixed in place, bolted into the rod, while the other bus bar is capable of sliding axially within the channel to account for thermal expansion in the heater between room temperature and its maximum heated temperature. These bus bars are powered by conductors passed through the ends of the rod and held in place by setscrews. 14 AWG copper wire cables are bolted to these conductors to carry power to the heater from its power supply. To minimize risk of surface contamination, the heater strip is not bolted onto the surface of the notch, but is instead held against the surface by a spring tensioning system, shown in Fig. 5.

The bus bar shown in this figure is bolted to an aluminum rod that serves both as a conductor for the heater power and as a guide rod that only allows the bus bar to move axially as the heater expands and contracts. Spring force on the inside end of the conductor forces the bus bar away from the rod, tensioning the heater strip so that it cannot buckle or expand away from the surface of the notch.

Since the heater utilized for this design is a bare electrical resistance heater strip, and the power for the heater is supplied through either end of the rod, it was necessary to manufacture the rod from an insulating material. PTFE was selected, as it can withstand very high temperatures and is extremely resistant to chemicals. The PTFE rod is rated for 260 degrees Celsius in continuous operation, which is significantly above the maximum heater strip temperature used to desorb impacted particles, so it should not pose any problem with melting or outgassing which might affect the instrumentation. Unlike most other plastics, PTFE is also unaffected by acetone, which is used to dissolve explosive residue from surfaces for cleaning and decontamination during assembly, or if the device becomes contaminated in use.

In normal operation, the heater will desorb impacted explosive particles fully within the time period during which the notch is being heated and sampled. However, samples that are much larger than what the device is designed for may take significantly longer than this to adequately desorb and dissipate from the carrier gas loop. Being able to wipe down the device with acetone greatly speeds the self-cleaning process of the desorber in this case.

D. Electronics

The ion mobility spectrometer (IMS) used for this project is a GE/Ion Track Ion Trap Mobility Spectrometer [16]. This IMS has a simple voltage output, which makes it easy to integrate with the data acquisition system used for the wake portal. Additionally, it has a dedicated power supply which can be set in either positive-or negative-ion modes. For the explosives detection work here, the IMS was left in the negative-ion mode, but the positive-ion mode can be used to detect many types of illicit drugs if the situation requires.

A TDK-Lambda SWS600L-15 power supply provides power for the heater strip. This power supply provides up to 43 A continuously at 15 V (645 W), and can be ramped from 0–120% of its rated output voltage with a 0–6 V input, allowing very fine control of the heater power ramp.

MICROMEGA CN77000 PID controllers from Omega Engineering Inc. are used to control the detector and interface temperatures of the IMS, as well as the block heaters for the rotating impaction surface assembly.

A 0.01 Ω current-sensing resistor was placed in series with the heater strip in order to monitor the current draw of the heater during operation. The voltage drop across the heater strip was also measured. These measurements are used to determine heater power and resistance.

Data acquisition for the entire wake portal was handled by a National Instruments DAQPad 6015 A/D converter. Analog outputs were used for controlling the blower speed of the wake portal and the voltage ramp of the heater power supply. Analog inputs are sensed for the torso-, back-, and shoe-jet photodiodes, the IMS output, heater current and voltage, and blower current.

E. Software

A control and analysis program for the wake sampling portal was developed in LabVIEW that automates the sampling of a subject's wake and its interrogation for explosive trace contamination. This software also handles interpretation of the output signal from the IMS, thus avoiding the use of proprietary IMS software originally for that purpose. This allows the customized method of handling the signal and interrogation timing needed for this portal. As everything is handled in a single program, response to a detected explosive comes immediately after the interrogation cycle is completed, without the need to process the data in a separate software suite.

When the program is ready for a new human subject, it goes into a wake sampling mode and there waits for a subject to trip the photodiodes along the walking path. After the subject passes the torso photodiode, the torso puffer jets are fired to remove particles on the subject's torso. Passing the back photodiode triggers the back puffer jets, and starts a wake sampling timer, that counts the time the impactor requires to sample the majority of the subject's aerodynamic wake (approximately three seconds).

After this timer expires, the program switches into explosives detection mode. The impaction surface is rotated into the interrogation position, and the heater ramp is turned on, to bring the heater strip up to desorption temperature. The heater power is held at 450 W for ~ 1.7 s to drive the heater strip to approximately 200 °C, and then the power is held at 200 W for the remainder of the sampling period to maintain strip temperature. Due to the small thermal mass of the heater strip, once the heater power is turned off it cools rapidly to around 50 °C by the time the portal is ready to process the next subject. While the strip is heating, the IMS is constantly being scanned, along with measurements of heater voltage and current. Should the heater exceed a set current limit, such as in the case of a short circuit, the heater power supply is shut down and the operator is alerted.

As an additional diagnostic, heater resistance is calculated from the measured voltage and current. This resistance is then converted to an approximate on-computer-screen temperature plot, using a resistance-temperature fit produced by correlating steady-state temperature measured by a thermocouple to measured resistance. While not as precise as a direct thermocouple reading, this resistance-to-temperature conversion requires no added equipment and does not have the response time issues encountered using thermocouples to measure the temperature of small thermal masses.

After interrogation is complete, the impaction surface is rotated back into the sampling position, and the data acquired from the IMS is segmented into individual scans. A plot of the ion peaks with respect to drift time is presented, as is typical for commercial IMS devices. An average background signal is presented, comprised of the initial half-second of IMS scans, along with the overall signal average, where ion peaks are typically clearly visible. An example of these plots is shown in Fig. 6 for a test with RDX, the explosive which was used for testing the wake portal. RDX detection is typical of the

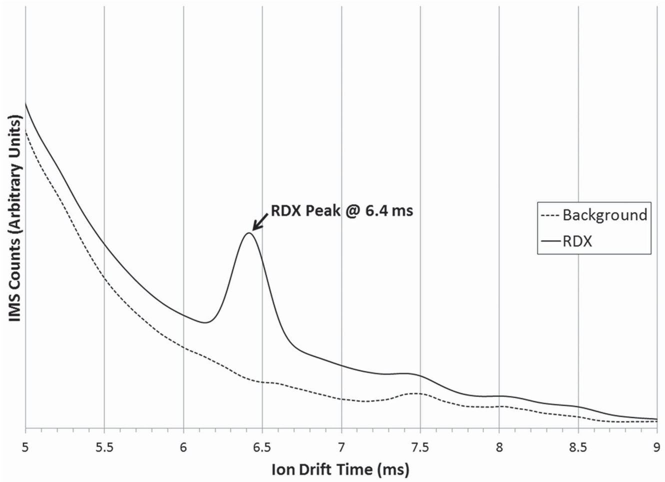

Fig. 6. IMS output plots showing RDX peak visible against background signal.

range of explosive compounds that are routinely detected by IMS, and the signal analysis procedure does not differ for other explosives.

A peak detection routine processes all of the IMS scans to detect peaks that are statistically significant above background noise. Peaks that are above a threshold set in the program are marked with cursors on the plot, pointing them out to the operator. This peak detection scheme examines both peak height and duration, allowing small deviations in measured ion drift time. By doing so, this eliminates false positives due to electrical noise and increases sensitivity to peaks that might be near background levels but are still statistically significant.

III. Testing Methodology

The goal of this device is to enable high-throughput screening of the entire human body for explosive traces. To this end, testing was performed using known trace amounts of explosive transferred to muslin patches and then taped onto either the chest, back, or shoes of a subject. Then the subject was asked to walk at a brisk pace through the wake sampling portal. The system's response and total time of processing were measured as figures of merit.

Tests were considered positive if the peak tracking program detected the explosive, in which case the signal-strength plot of the tracked peak was saved. The peak signal strength above background and time from when the subject first enters the portal until the peak appears were recorded.

Particles liberated from different areas on the subject's body become entrained in different locations within the human aerodynamic wake, and in turn impact at varying locations along the impaction surface. Because of the limited carrier gas flowrate and the volume of the impaction notch, it takes slightly over a second to fully sample the notch volume for desorbed vapors. Recording when the signal peaks after interrogation begins serves as a check for false positives due to signal drift, and could possibly be used to determine where on the subject the explosive contamination might be found, although this was not examined in the present program.

A test was considered negative if the peak tracking program did not detect the explosive. In this case the output of the IMS at the expected drift time for the explosive being tested was saved for direct comparison to the positive tests. Blank patches were also used to check for false positives that could potentially arise due to environmental contamination by trace explosives or inadequate clearing of subjects between tests.

Patches were produced for testing by placing known amounts of explosive in solution as drops on Teflon tabs with a syringe [17]. These tabs were allowed to air-dry over several hours to leave particles of solid explosive behind. These tabs were then dragged across the surface of a 0.75×0.75 cm muslin patch in a Z-shaped pattern to dry-transfer the explosive to the patch. Reference [18] provides more information on patch preparation, including typical amounts of explosive used in testing.

When ready for testing, the patch was affixed to the test subject with the explosives side facing outward. The patches were allowed a "soak time" of 15 minutes to come to thermal equilibrium with the subject, after which the test was run. A pre-test sample was taken to determine background levels for the IMS, and the temperature and humidity of the room air were recorded.

The subject then walked through the portal at a brisk pace of ~ 1.5 m/s, and the human wake was sampled. The data from the test were saved and the speed with which the subject walked through the portal was recorded. To ensure that the subject was clear for the next test, he/she underwent an air shower to dislodge any remaining particles and walked through the portal again to be sure that only a background level of explosive remained. These post-test data were also saved for future reference. For every five explosive patches, two blank patches were run.

A calibration curve for the IMS was produced by placing a known amount of RDX in solution directly onto the impactor heater strip, running the sampling routine, and measuring the peak signal strength. A typical example of this calibration curve is shown below in Fig. 7. A nonlinear calibration is typical of IMS detection [19].

To ensure that day-to-day results from patch testing were comparable, RDX in solution was deposited on the heater strip at the start of the day and sampled to check for calibration drift.

IV. Results

Testing consisted of 64 patch tests with explosives and 24 blank patches, on the torso, back, and shoes. Of the blank patches, none tested positive for explosives. On average, the signal from torso patches reached maximum around 2.5 s after impaction and shoe and back patches reached maximum around 2.8 s after impaction. With three seconds allowed for impaction of particles from the human wake, this gives a time to signal maximum of around 5.5 s and 5.8 s respectively. A signal timeline plot for positive explosive tests versus clear patch tests on the torso is shown below in Fig. 8 to illustrate signal peaking.

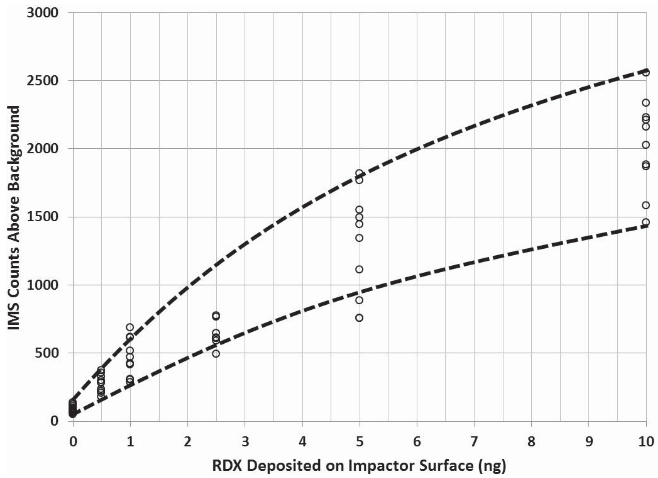

Fig. 7. Calibration curve for IMS used to check day-to-day results. Dashed lines: acceptable range of signal.

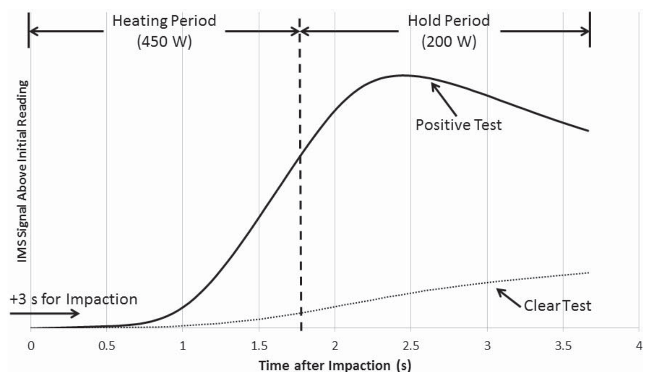

Fig. 8. Signal timelines for explosive-laden and clear patches applied to the torso, showing positive tests peaking and rolling off before the end of the interrogation period.

One goal of the wake sampling portal was to fully process a subject in six seconds to maximize throughput. While the peak signal is easily resolved within six seconds, the processing speed of the computer used to run the portal software took an additional two seconds to complete processing of the signals, and so the overall time to sample a subject averaged around eight seconds total in the present tests. Faster processing and a shorter overall sampling period are clearly possible.

V. Conclusion

The peak signal strength is not necessarily a useful figure for all applications, and if this is the case the interrogation could be halted after around five seconds, which should allow higher throughput without significantly reducing the device's sensitivity. Throughput could be almost doubled by adding a second heated notch to the opposite side of the rotating impaction rod, so that a subject can walk through and be sampled while the previous subject's wake is being interrogated.

Instrumenting all three impactor blades would improve sensitivity somewhat by sampling all of the particles impacted from the sampled wake, rather than only the particles that impact the central blade.

The wake sampling portal, as shown here with integrated impaction and sampling, allows fast whole-body sampling of trace explosives and other contaminants, and essentially meets the goal of six seconds per subject for total sampling time. This device shows that it is possible to adequately sample the human aerodynamic wake, which is around 1 m^3/s of airflow, despite the limited volumetric flowrate of ion mobility spectrometers, in the 10 cc/s region. With additional modifications described above, it should be capable of handling even larger airflows with improved sensitivity.

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