A Man-Portable, Photoionization Time-of-Flight Mass Spectrometer

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Abstract: This article discusses a feasibility demonstration for a 30-lb field-portable chemical analysis system with detection capability comparable to that of a benchtop system. Syagen constructed and operated a prototype instrument with the use of a novel atmospheric sampling photoionization source coupled to a quadrupole-ion-trap, time-of-flight mass spectrometer (QitTof). The keys to reducing weight and power were the development of a notebook-computer data-acquisition system and a new low-power ion-trap RF source. Detection limits of 10–100 ppb and 5–50 pg were measured for a variety of compounds including phosphonates and aromatics. An air and liquid sampler was developed and shown to have a response time of 1–10 s, depending on mode of operation. The QitTof analyzer and processor can record mass spectra at 200 Hz, making it suitable for fast gas chromatography. © 2000 John Wiley & Sons, Inc. Field Analyt Chem Technol 4: 204–215, 2000

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Introduction

Low-cost, high-resolution, field-portable chemical analysis systems are needed to meet critical detection requirements for environmental monitoring and sampling, and for the specific problem of chemical-agent battlefield detection and nonproliferation monitoring. New technologies are needed to bring lab-quality performance to the field.

The focus of this work was to demonstrate the feasibility of a field-portable high-performance mass spectrometry (MS) for general environmental assessments and for the specific need to quickly and accurately detect chemical agents resulting from leaks or releases and for conducting high-throughput screens of decommissioned production facilities in support of treaty compliance monitoring. Other applications include military force protection and chemical demilitarization, as well as civilian applications such as high-profile event security, emergency first-responder protection, and hazardous-materials investigations. These applications require systems that can detect in real time (1–10 s) a host of target compounds at ultralow concentrations (e.g., 1–100 ppb air sampling, 10–100-pg residue) in the presence of a complex matrix that would otherwise obscure signals of interest because of overlapping signal.

In this article, we will describe a system that achieves the following capabilities:

- A 30-lb feasibility study man-portable MS system.
- High-performance based on quadrupole ion-trap, time-of-flight (QitTof™) technology.
- Near-universal detection of chemical agents and related compounds with the use of a photoionization (PI) technique.

This article will also discuss the applications of this instrument capability to a wide range of detection needs, including the interface to fast chromatographic techniques.

A number of mass-spectrometer manufacturers have offered field-mobile units (e.g., Bruker's MEM line, Varian's Saturn Air) with gas chromatography (GC) capabilities; however, these are typically not man-portable. Viking Instruments, recently acquired by Bruker, offers a portable GC/MS (SpectraTrak) billed as a real-time monitor for toxic air, water, and soil pollutants; however, its portability is limited by weight and the need to attach a mechanical pump separately. The Hapsite by Inficon is a man-portable GC/MS.

There are several developments of field-portable TOF MS systems. Kore and Comstock make field-portable TOF MS systems that use electron ionization (EI). The Kore instrument is an elegant design that uses an ion pump and membrane introduction system and gives good detection limits, low battery life, and response/recovery times of a few minutes.[1] Comstock uses a turbomolecular pump that can handle

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higher sample throughputs; hence direct sampling is feasible with response times on the order of 1 s. TOF MS apparatus can be made very compact in size. The Johns Hopkins group ıve engineered some miniature TOF MS configurations for ıne Applied Physics Lab TinyTOF program.[2] These reductions in size are made possible by the availability of compact pumps and fast digitizers. TinyTOF is focused on biological detection with laser desorption/ionization. Though novel, miniature TOF devices have been demonstrated; the electronics and data acquisition systems are still being miniaturized.

Miniature mass-spectrometer concepts including quadrupoles, quadrupole arrays,[3,4] and magnetic sectors[5] are being developed for space-based and other applications. These interesting devices may be suitable for field work if interfaced to an appropriate vacuum system.

The unique characteristics of the present system compared to existing technologies are the combination of novel photoionization source, high-performance TOF MS, high sampling rate, MS/MS potential, differential pumping for high gas throughput, and a low-power, low-weight total system configuration.

Experiment

Photoionization Method

Syagen has developed a photoionization source (PI) source that offers the potential to conduct rapid screens of rgeted compounds in complex mixtures without requiring a separation stage such as gas chromatography (GC). This capability can be used to conduct large numbers of analyses and diverting only samples that test positive for more quantitative analysis by on-demand GC/MS.

The major advantage of PI relative to other ionization methods is the ability to choose a narrow-band ionization energy that is sufficiently high to ionize and detect most molecules of interest, yet sufficiently low to avoid detection of the most common constituent of air. For this work we have developed a high-performance ionizer with a modified drive circuit that consumes <5 W and delivers significantly enhanced photon flux relative to commercial light sources. A variety of photon energies may be used, but for this work, radiation of about 10 eV was generated from a rare-gas discharge. Details of the source will be presented at a later date. The following describes the general performance properties:

- ***Near-universal detection efficiency:*** Nearly all compounds of interest have ionization potentials below the radiation energy, hence are ionized efficiently. Ion signal is linear with concentration and not affected by the presence of other compounds.
- ***Minimal-fragmentation molecular-ion spectra:*** Because ionization occurs just above the ionization thresholds, there is very little excess ion energy that might cause fragmentation.[6]
- ***Suppression of background air and water signal:*** The ionization energy lies below the ionization potentials of 99.999+% of the most common air constituents (e.g., N_2, O_2, H_2O, CO_2, CO, Ar, etc.). This enables high dynamic range detection of trace constituents of interest.

A schematic diagram that illustrates these features is presented in Figure 1. The vast majority of larger molecules, including those relevant to chemical and biological (CB) detection, have ionization energies (IPs) below 10 eV. By comparison, electron ionization (EI) involves high-energy electrons that can ionize air and lead to extensive ion fragmentation of target molecules. A comparison of PI and EI mass spectra of the chemical agent surrogates dimethyl methylphosphonate (DMMP) and diisopropyl methylphosphonate (DIMP) is presented in Figure 2 and shows a considerable reduction in the complexity of the molecular signals by PI. A competitive method of soft ionization is

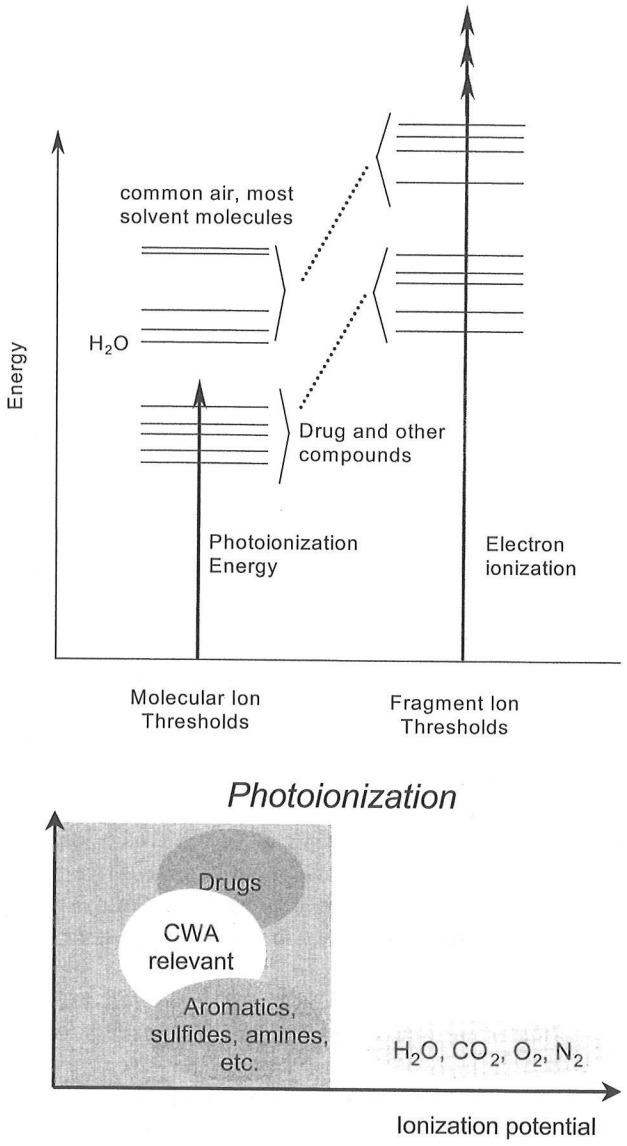

FIG. 1. Schematic representation of threshold photoionization in selectively ionizing important classes of compounds while avoiding detection of common air constituents that might otherwise interfere or limit dynamic range. Gray area represents region of high ionization efficiency.

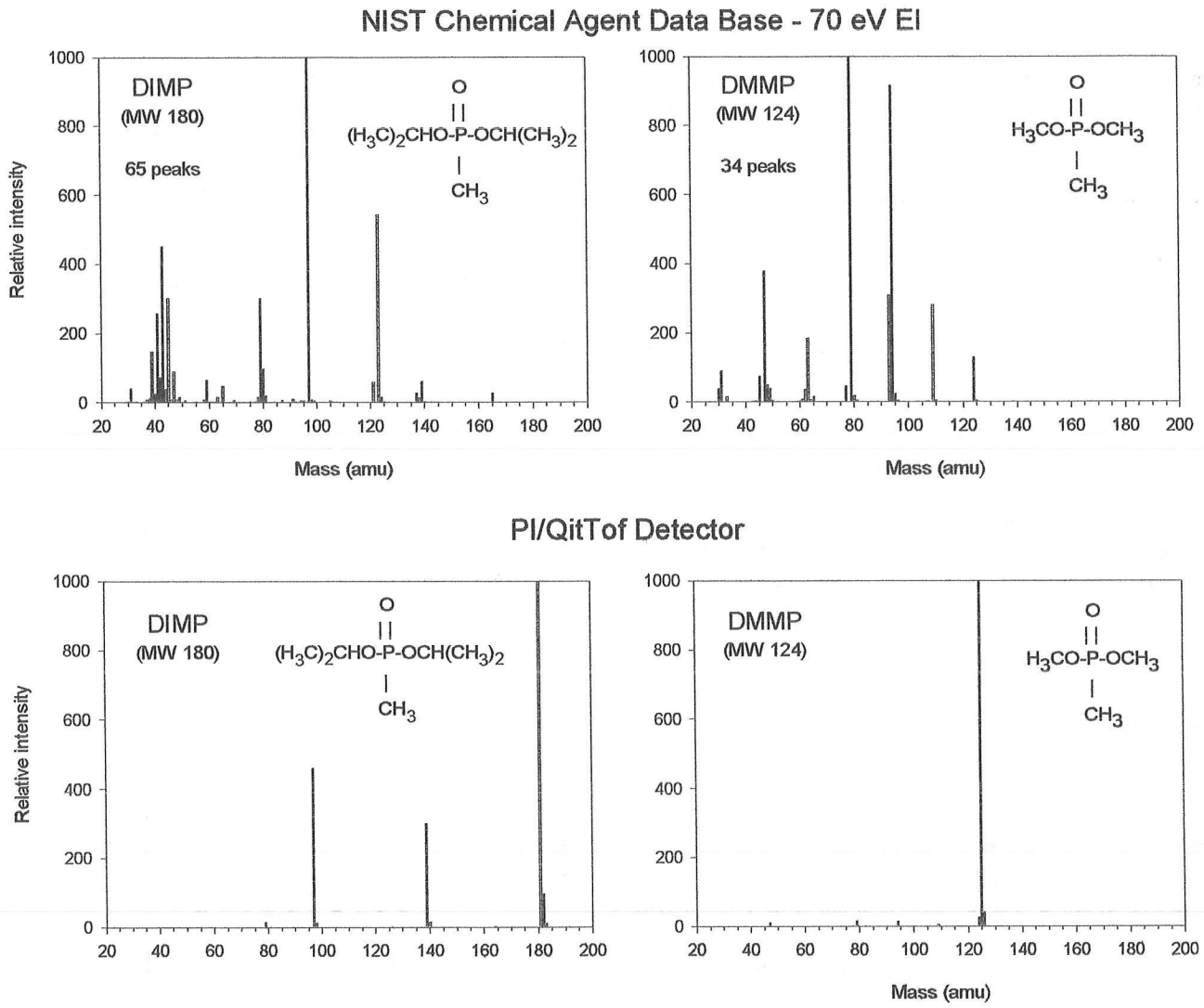

FIG. 2. Comparison of PI versus EI mass spectra of DMMP and DIMP showing significantly reduced fragmentation and distinct signature peaks for PI mass spectra.

atmospheric pressure chemical ionization (APCI).[7] APCI MS can be contrasted to PI in the following ways: (a) APCI is efficient only for molecules with high proton or electron affinity, (b) in APCI water tends to complex with ions, and (c) APCI is driven by thermodynamics, thus favoring the most stable ion and leading to a competition for charge that can greatly diminish the detectability of many target compounds.

The Syagen PI/QitTof MS can perform direct real-time monitoring of air and liquid samples. Aromatics, amines, alcohols, and many other classes of compounds give nearly pure molecular ion spectra. Examples of aromatic compounds are given in Figure 3. This test was also conducted to demonstrate the detectability of relatively non-polar compounds (particularly toluene and naphthalene), which APCI and electrospray ionization (ESI) have difficulty detecting. These spectra are characterized by strong molecular ion signals with negligible fragmentation. In some cases more than one peak is observed (e.g., DIMP); however, the tendency is to form a strong molecular ion peak M^+ and at most one or two other peaks that together form distinct signatures for that compound.

QitTof MS

The QitTof is a high-performance analyzer that has been adapted here for field-portable application. It is also well suited for use with the PI source. The overall PI/QitTof mass analyzer offers many benefits:

Quadrupole Ion Trap (QIT)[8–10]

- Stores ions from a continuous ionization source followed by pulsed extraction into the TOFMS

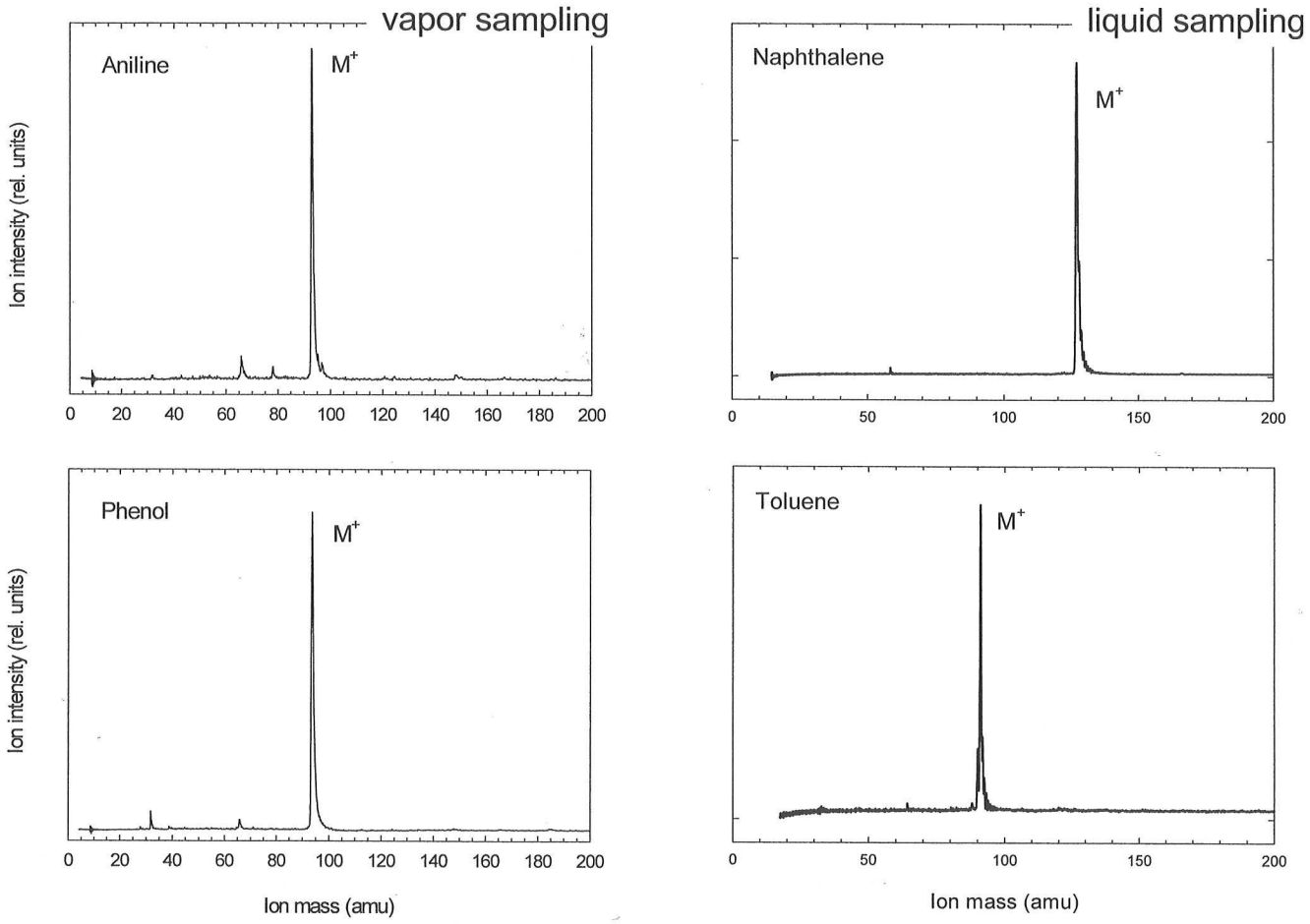

FIG. 3. Minimal-fragmentation PI MS recorded for air and liquid sampling of aromatics.

- Optionally conduct MS^n analyses
- Relatively high pressure operation (about 1 mtorr) permits its use as a differential pressure stage between the PI source and the TOFMS

Time-of-Flight Mass Spectrometry (TOFMS)[11,12]

- Multichannel mass detection and efficient collection of all ions
- Large mass range of detection
- Exceptionally low instrument noise because each mass peak is detected in a narrow time window (about 50 ns)

Compared to commercial orthogonal extraction TOFMS, the QitTof has the advantage of MS^n capability. Compared to mass-selective instability scanning ion-trap mass spectrometry (ITMS), the QitTof has several advantages: (a) fast mass analysis permits higher repetition rates and lower noise per detected ion mass bin, (b) mass resolution is much less sensitive to space-charge repulsion accounting for a greater ion trap capacity, (c) less ion fragmentation in the trap and more accurate intensity measurements because of use of a fixed, low-amplitude RF, and (d) better ion mass accuracy.

The mass resolutions measured in our laboratory range from $m/\Delta m$ values of about 100–200 for a 22-cm flight-path linear TOFMS to over 400 for a 38-cm coaxial reflectron configuration for mass 181 amu. Resolution of 1500 has been achieved in a conventional reflectron with a 1.2-m total flight path.

Thirty-Pound Field-Portable Feasibility

The field-portable feasibility was demonstrated in steps by testing each subcomponent or unit separately and then bringing them together for final testing. The major components are described below and their final weight and power are summarized in Table 1.

Head Unit—PI/QitTof Analyzer and Vacuum System. The PI/QitTof analyzer used for all measurements reported here is illustrated in Figure 4. The analyzer mounts directly onto the field-portable instrument (Figure 5) and onto the 50-lb class lab demonstration instrument (not shown). The analyzer assembly is partitioned into an ionizer and QIT region (source) and a TOFMS region (detection), each of which is separately pumped. By pumping the source region independently, much greater sample throughput into

TABLE 1. Approximate power and weight requirements for field-portable feasibility demonstration.

MS head unit Weight: 17 lb Power: 55 W (35-W sleep mode) **Electronics unit** Weight: 7 lb Power: 5 W (22-W sleep mode)	**Processor unit** Weight: 4 lb Power: 15 W (8-W sleep mode)

the vacuum is possible without severely loading the detection region. The portable instrument employs a split-flow turbomolecular pump (TMP) that provides about 16 l/s of source pumping and 40 l/s of detection pumping and is backed by a 10-l/min diaphragm pump that achieves a base pressure of about 1 torr. Under load, the diaphragm pump operated at about 2-l/min pumping speed at 2 torr, corresponding to a vacuum throughput of 4 torr/l/min or 5 atm/cm^3/min.

Processor Unit—Data Acquisition. A Canon Innova 490 notebook PC was used for this project because of its availability, and not for its weight and power (6 lb, 25 W). Other processor configurations may be used, from lightweight notebook PCs (<5 lb, <15 W) to embedded processors, including ruggedized solutions. The major issue that was addressed for processing is finding a suitable waveform acquisition system. A National Instruments 20 megasample/s (MS/s), 20-MHz bandwidth, 8-bit ADC PCMCIA plug-in card was tested. The sampling rate is at the low end of that desirable for recording TOFMS spectra; however, the device performed quite acceptably in this regard and exceptionally on data-transfer rate and integration with a flexible software program. Full MS download rates of up to 200 Hz were achieved, although this was largely because of the low number of total points recorded per spectrum. An example of a TOF mass spectrum recorded with this system is presented in Figure 6 for a ppm-level sample of DMMP and DIMP in room air.

Electronics Unit. The source of high voltage for the TOF and detector voltages was a low-power source and a resistive voltage divider chain to provide the multiple voltages needed, and consumed about 5 W of power. The PI source power supply consumed about 3 W. The major power components are the QIT RF source and clamping circuit that is activated during pulse out and the pulsing circuits for ion extraction into the TOF. The RF source operates at 1 MHz

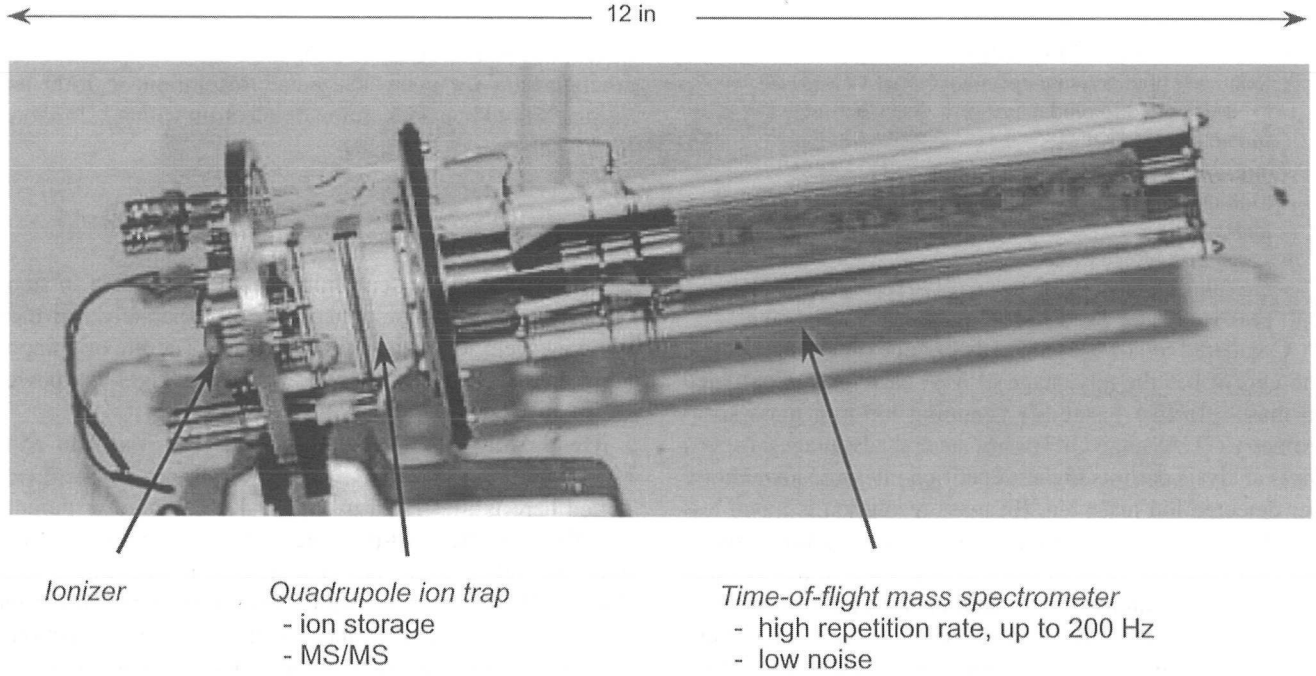

FIG. 4. Picture of PI/QitTof assembly developed and used for the feasibility demonstration. Key features are light weight, compact design (1.5 lb, 12 in. long) and differential pumping partition between QIT and TOF MS regions.

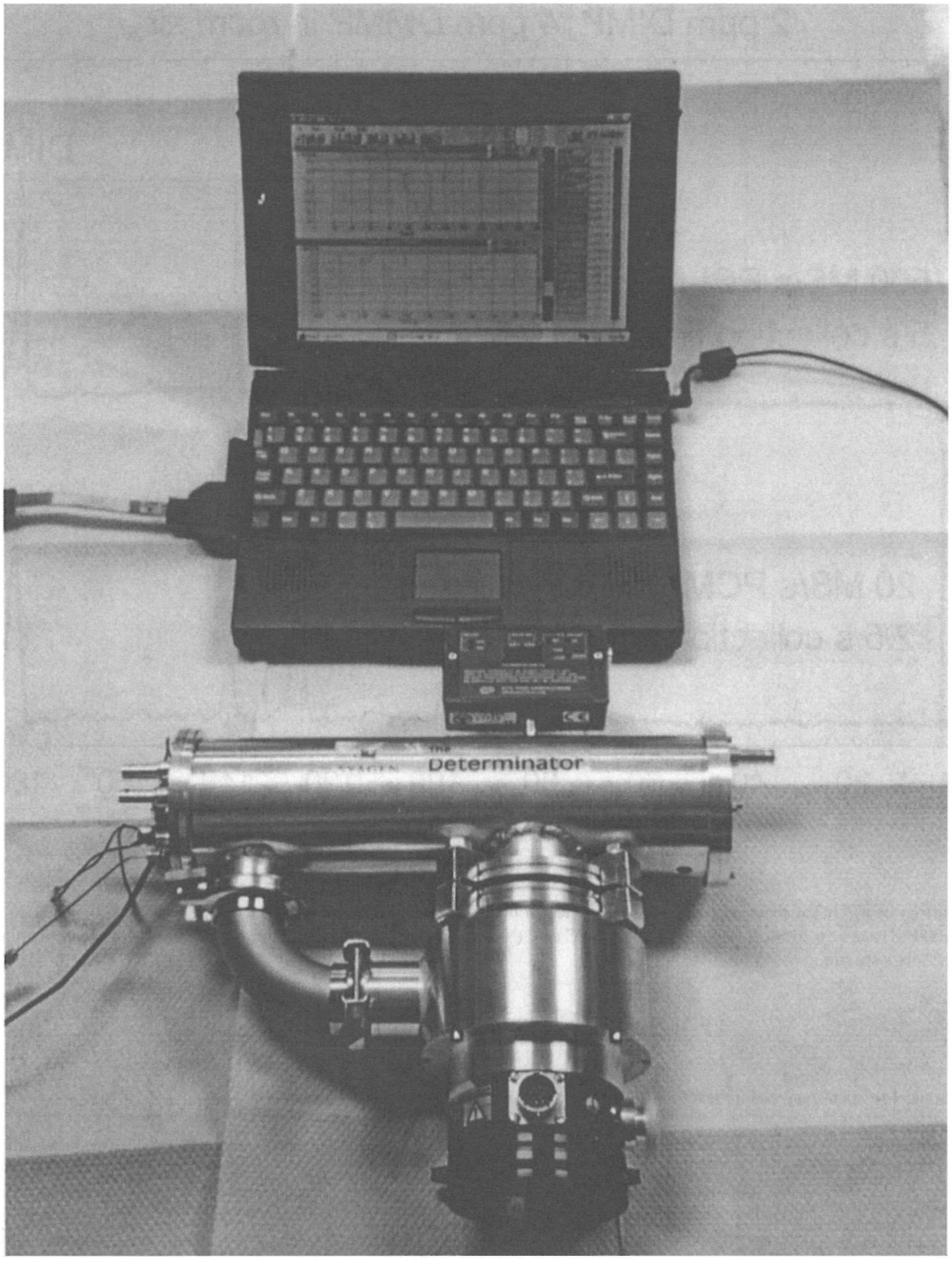

FIG. 5. Picture of prototype PI/QitTof mass spectrometer and processor units. Not shown are the backing pump and electronics.

and has variable amplitude up to 1500 $V_{p\text{-}p}$. This value is capable of stabilizing ion masses up to 1000 amu, although only low-molecular-weight compounds were tested for this project. The new extraction pulse circuit allows bipolar pulsing, in which opposite polarity pulses are applied to each QIT endcap. The amplitude is adjustable up to 500 V for each polarity. The QIT and pulse extraction circuits consume less than 20 W of power at 60 Hz operation.

This work was conducted over a 6-month period of time. While the actual 30-lb system was being fabricated, initial demonstrations were conducted on a 50-lb class instrument with turbomolecular pumps that were throttled down to emulate the pumping speed of the 30-lb class system. The same ionizer/QitTof stack was used in all cases. It should also be noted that all components for the 30-lb feasibility study were not tested simultaneously. Toward the end of the program,

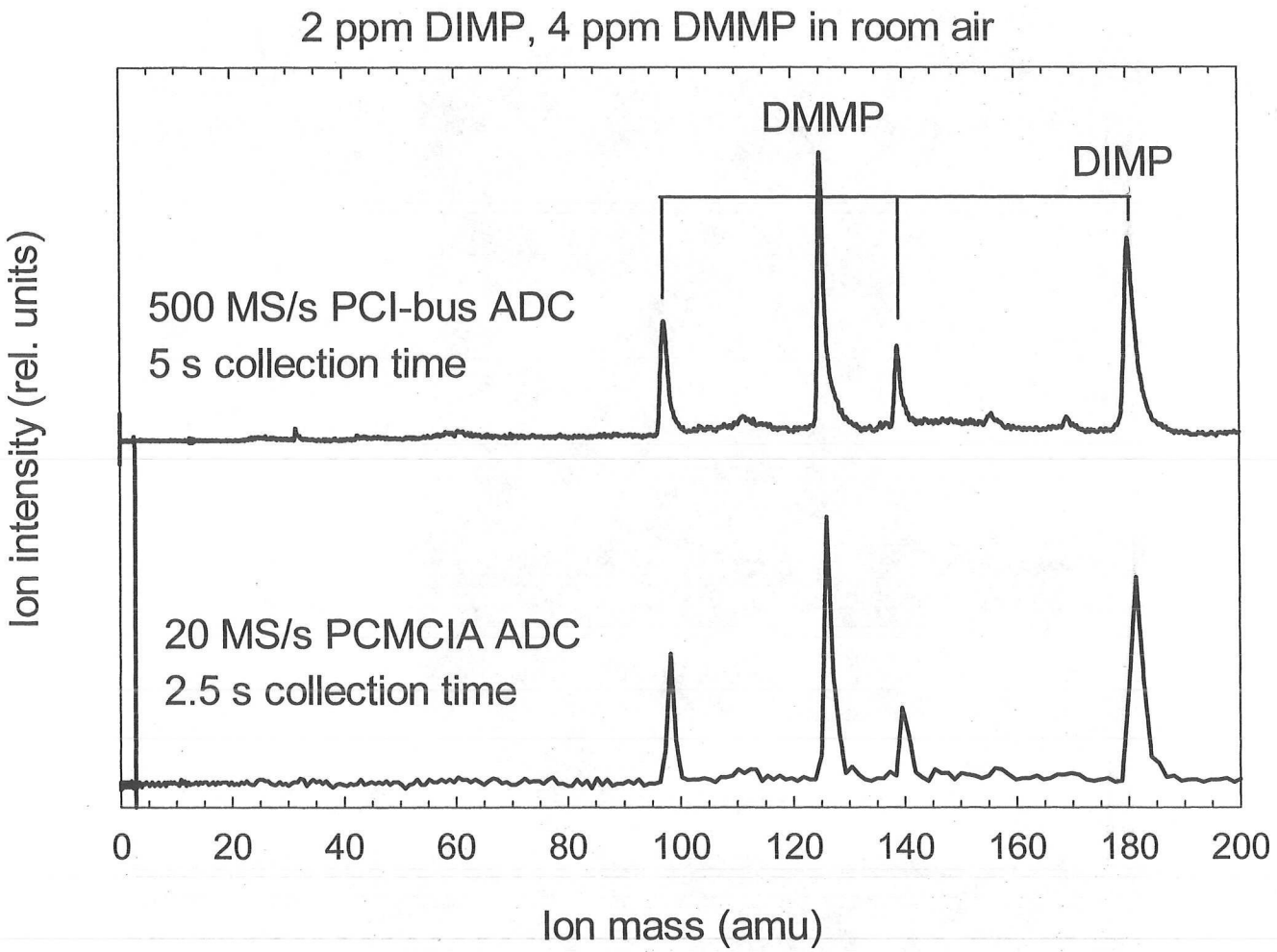

FIG. 6. Comparison of PI/QitTof mass spectra recorded on the lab demonstration instrument with the use of a 500 MS/s PC-based digitizer (Gage CompuScope 8500/PCI) versus a 20-MS/s PCMCIA notebook PC card (National Instruments NI 5102 for PCMCIA) showing the utility of the latter device for recording TOF mass spectra.

TABLE 2. Chemical weapons convention treaty relevant compounds detected as molecular ions by PI MS.

Chemical and riot agents	CWC Schedule 2 precursors	CWC Schedule 3 precursors	Decomposition products
GB (Sarin)	Diisopropyl methylphosphonate	Phosphorus oxychloride	Methyl phosphonic acid
GD (Soman)	Diethyl methylphosphonate	Dimethyl phosphite	Ethyl methyl phosphonic acid
	Dimethyl methylphosphonate	Trimethylphosphite	2-chloro diethylsulfide
HD (sulfur mustard)	Diethyl ethylphosphonate	Diethyl phosphite	
HN-1 (nitrogen mustard)	Diethyl methylphosphonothioate	Triethyl phosphite	
	Isopropyl methylphosphonic acid	Triethanolamine	
CR	Cyclohexyl methylphosphonic acid	N-ethyl diethanol amine	
CS	Pinacolyl methylphosphonic acid	N-methyl diethanolamine	
	Methyl phosphonyl dichloride		
	3-quinuclidinol		
	Benzilic acid		
	Pinacolyl alcohol		
	Thiodiglycol		
	N,N-diethylethanolamine		
	1,4 dithiane		
	Thiodiglycol sulfoxide		
	Methylamine		
	Isopropylamine		

the compact, low-power electronics were still being fabricated and a larger set of electronics was used to test the instrument in Figure 5. Subsequently, the low-power electronics were developed and tested successfully on a benchtop instrument.

Inlet System and Throughput

Air and vapor samples were introduced into the subatmospheric pressure ionizer with a leak valve. Typical throughputs were about 5 atm/cm^3/min as determined from the pumping speed of the first differentially pumped region (16 l/s) and the measured pressure (4 mtorr). The pressure in the TOF region was pumped at 40 l/s and typically measured 50 μtorr for a throughput of 0.16 atm/cm^3/min. This corresponds to a differential split ratio of about 25 between the first region pumping and the throughput through the QIT into the TOF region.

The internal volume of the inlet was about 0.25 cm^3, which accounted for a typical residence time of sample of about 3–4 s. In order to reduce this time, a bypass flow was tested by connecting the sample inlet line to the turbomolecular backing pump with a leak valve. This brought the air sampling-time response down to about 2 s, but pushed the limits of what the backing pump could handle. This inlet was fairly crude, but worked adequately for the relatively volatile compounds reported here. In later work (not shown here) the inlet was redesigned with lower internal volume (about <0.1 cm^3), inert surfaces (coated with Silcosteel), and higher temperature (up to 300 °C), which eliminated the need for a bypass flow. If bypass flow is needed, it is probably better done with the use of a small, atmospheric pressure fan or blower.

The inlet system was also capable of accepting liquid injections. This was introduced directly into the 1/16-in.-ID inlet tube normally used to sample air. More recently, we have developed a GC-like inlet system that gave rapid response to the CW-relevant compounds reported here.

Results and Discussion

Near-Universal Detection Efficiency

Chemical-Weapons-Related Compounds. PI MS was tested and found to be an effective near-universal detector for chemical agent and chemical weapons convention (CWC) treaty relevant compounds. Table 2 lists all compounds that have been efficiently detected. A 35-compound CWC-relevant compound library was tested, and strong molecular ion signal was obtained for 34 compounds (97% detection rate). The one miss was benzilic acid, which loses an –OH group to give a strong signal at $[M\text{-}17]^+$. This compound is therefore detectable, but not as a molecular ion. Efficient sample delivery and detection was observed for phosphonic acids (including methylphosphonic and ethylmethylphosphonic acid) as well as alkylethanolamines and alkyl phosphites that are normally difficult to deliver and detect by other MS methods.

Drug Compounds. The PI source on a benchtop QitTof system was tested for a large variety of drug and nondrug compounds. A collection of 20 drug compounds were chosen at random from a Radian catalog of pharmaceutical compounds to test the universality of the ionization source for a wide variety of drug and druglike compounds. All compounds, but one were detected with strong parent ion signal, generally with minimal fragmentation, and with relatively uniform detection sensitivity. Examples of PI MS data are shown in Figure 7. In addition to these compounds, we tested over a dozen aromatic compounds, 20 aliphatic amines, and about 20 phenol compounds, in addition to the CWC-relevant compounds described above. The molecular ion detection rate was about 95%. There are two caveats to be mentioned:

1. The drug compounds were introduced in protic solvents (e.g., MeOH and H_2O) and tended to give MH^+ rather than M^+ signal.
2. Some steroid compounds were detected by a solvent stripping inlet system.

We are currently testing the universality of PI MS on pharmaceutical combinatorial library samples.

Sensitivity and Specificity

Detection limits have been measured on a benchtop PI/QitTof system including real agent testing at the Edgewood Chemical and Biological Center Surety Lab at Edgewood, MD. Values for a library of about 35 CWC-relevant compounds range from about 10–100 ppb (2–20 pg consumed) for 5-s sampling times (based on the linear extrapolation of signal to the 3σ background variance). Other classes of compounds, such as drugs and aromatics, give similar detection limits. The 30-lb feasibility study field-portable system generally gave a factor of 4–5 poorer detection limit (live agents were not tested). About half of this performance compromise can be attributed to the low 20-MS/s digitizing speed of the field-portable system, which may be upgradeable in a next-generation instrument.

Air Sampling. A sample containing 50-ppb DIMP and 90-ppb DMMP in room air was made in a 5-gal plastic jug. The resultant spectrum is given in Figure 8. The detection limits for DMMP and DIMP, respectively, were measured for a 5-s sampling time and gave values of 28 and 25 ppb. The DIMP detection limit was based on the stronger 97 amu peak; that of the molecular ion was about a factor of 2 poorer.

Liquid sampling. GC-like samples, or other liquid solutions, were analyzed by syringe injection into the air/liquid sampling system. Samples of DIMP and DMMP in methanol were prepared (about 10 ppm by volume, corresponding to about 10 and 12 μg/ml, respectively) and sample volumes of 0.1 μl were injected. S/N ratios of 30 and 80, respectively, leading to solution detection limits of about 1000 ng/ml and 450 ng/ml, respectively, were observed.

Specificity was tested by detecting target compounds in a dirty air sample and the ability to distinctly resolve a mul-

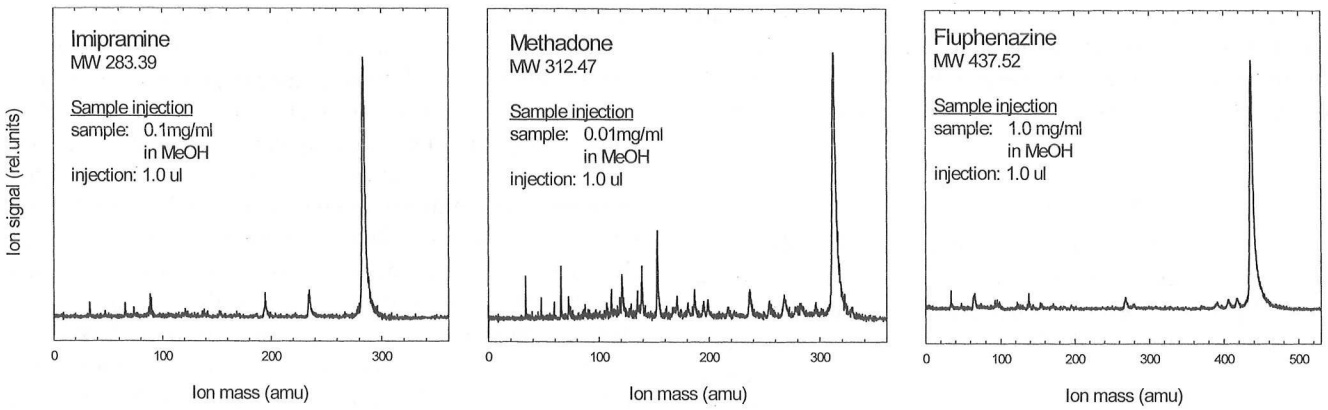

FIG. 7. PI/QitTof mass spectra of drug standards recorded with the use of the 1½-lb PI/QitTof ion optics assembly, but on a benchtop vacuum system.

titude of compounds in a complex mixture. Figure 9 presents the PI mass spectrum of a mixture consisting of 500-ppb DIMP and 900-ppb DMMP in an air sample saturated with automobile exhaust. The bottom spectrum corresponds to a sample collected from the tailpipe of a car in a 5-gal plastic bottle. The bottle was visibly opaque and saturated with water vapor when the spectrum was recorded. The phosphonates were subsequently added by syringe and the top spectrum recorded. The DIMP signature peaks 97 amu and 181 amu and the DMMP parent peak at 125 amu are clearly visible for a 5-s sampling time.

The minimal fragmentation and uncomplicated spectra typically observed for molecules enables real-time analysis of multicomponent mixtures. These results show the capability to distinctly detect target compounds in complex matrices as a rapid screen.

Dynamic Range

The dynamic range of the PI/QitTof instrument was measured on a benchtop system with the use of the same stack shown in Figure 4. Signal level versus mass quantity of an-

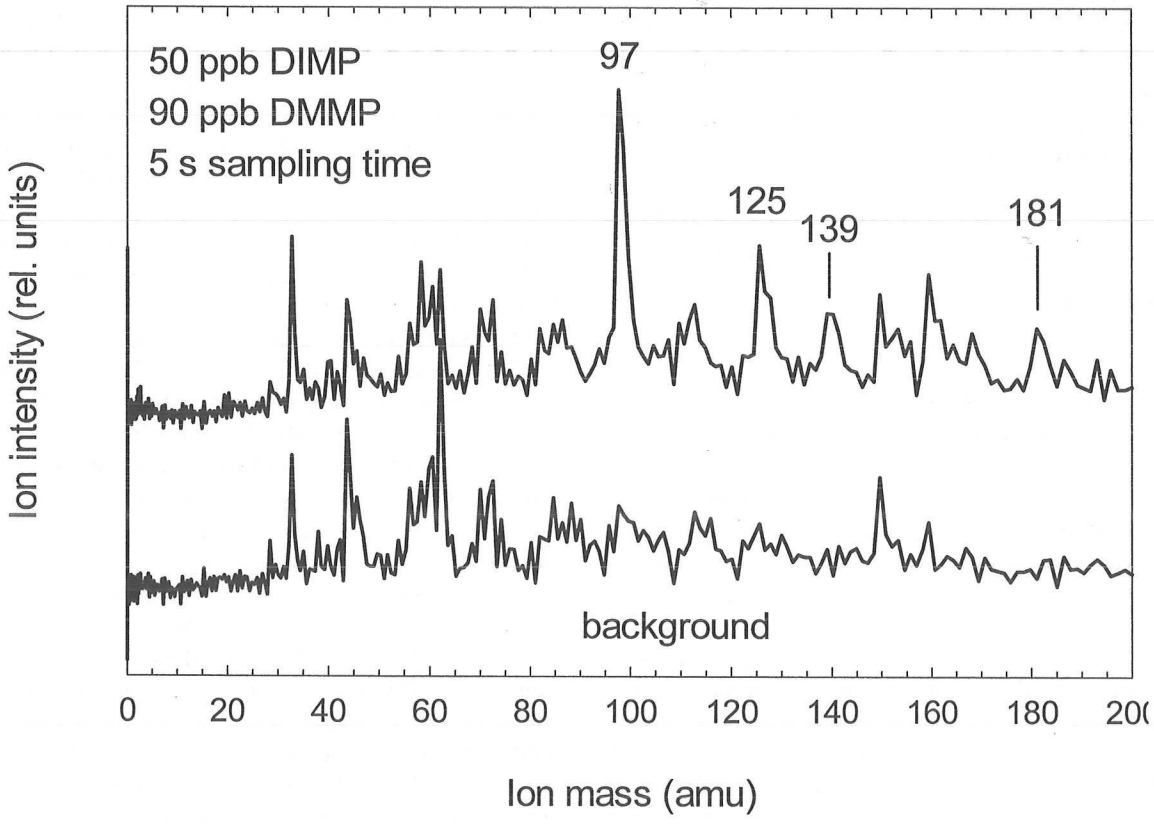

FIG. 8. PI/QitTof mass spectra under 30-lb detector conditions (reduced pumping and notebook 20 MS/s digitizer system) illustrating detectability of low concentrations of phosphonates in room air.

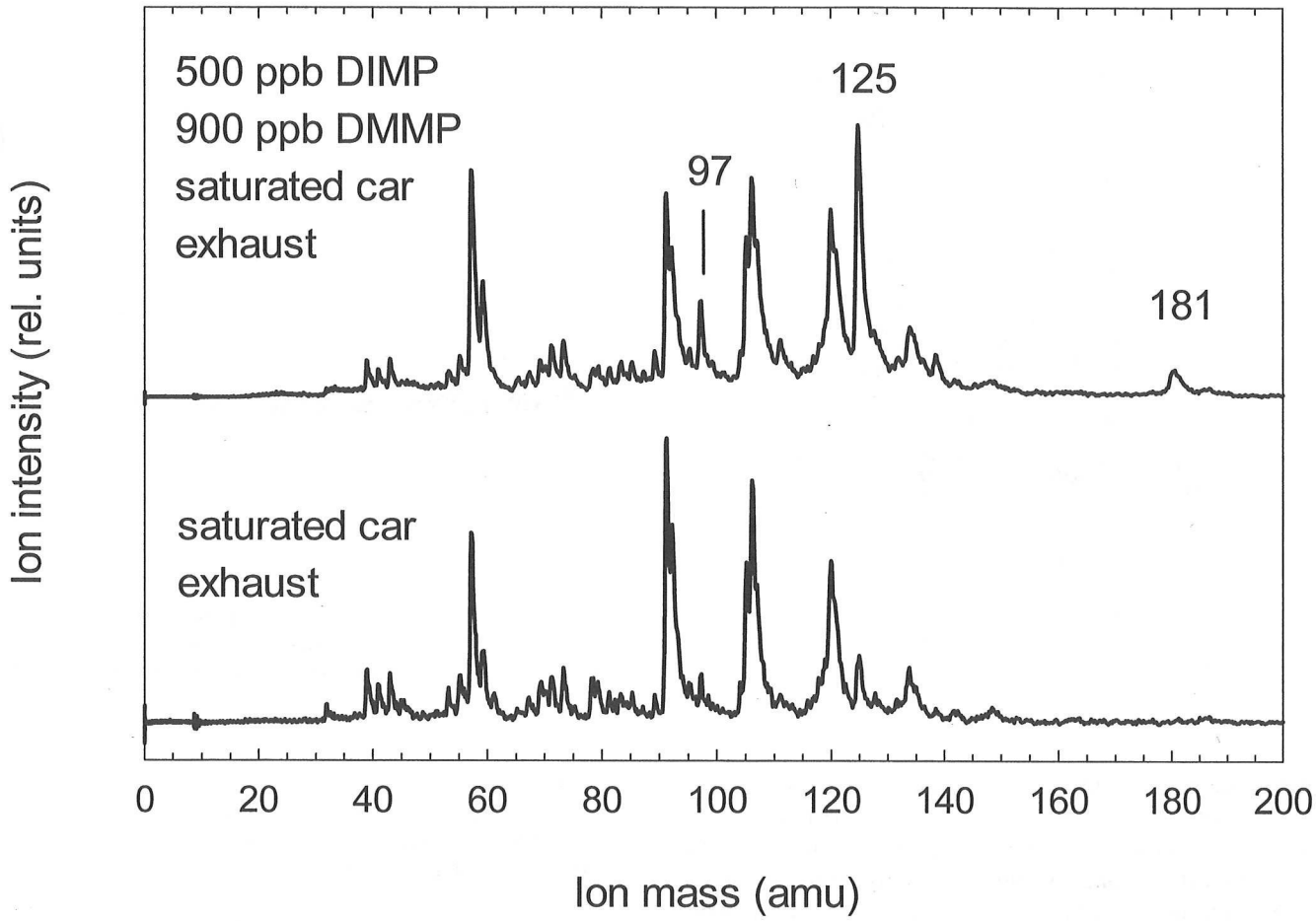

FIG. 9. PI/QitTof mass spectra (recorded on lab instrument under 30-lb operating conditions) of phosphonate sample in saturated car exhaust (recorded with desktop 500 MS/s digitizer system).

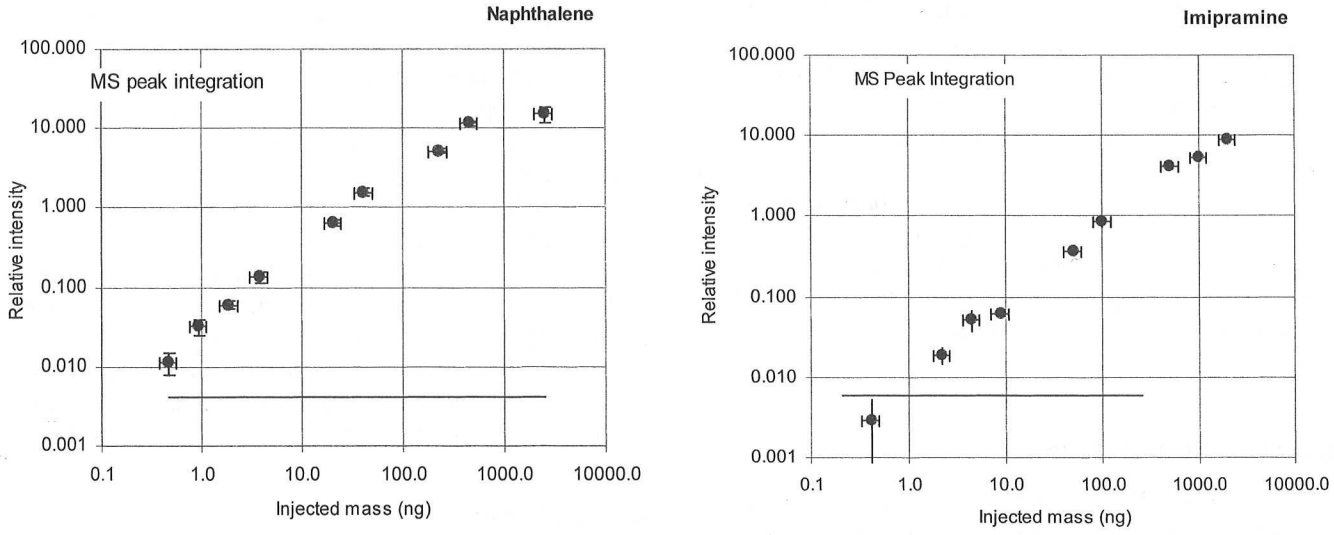

FIG. 10. PI/QitTof measurements of dynamic range measured with the use of the 1½-lb PI/QitTof ion optics assembly, but on a benchtop vacuum system. The horizontal line is the limit of detection corresponding to a signal intensity that is 3σ of the background uncertainty.

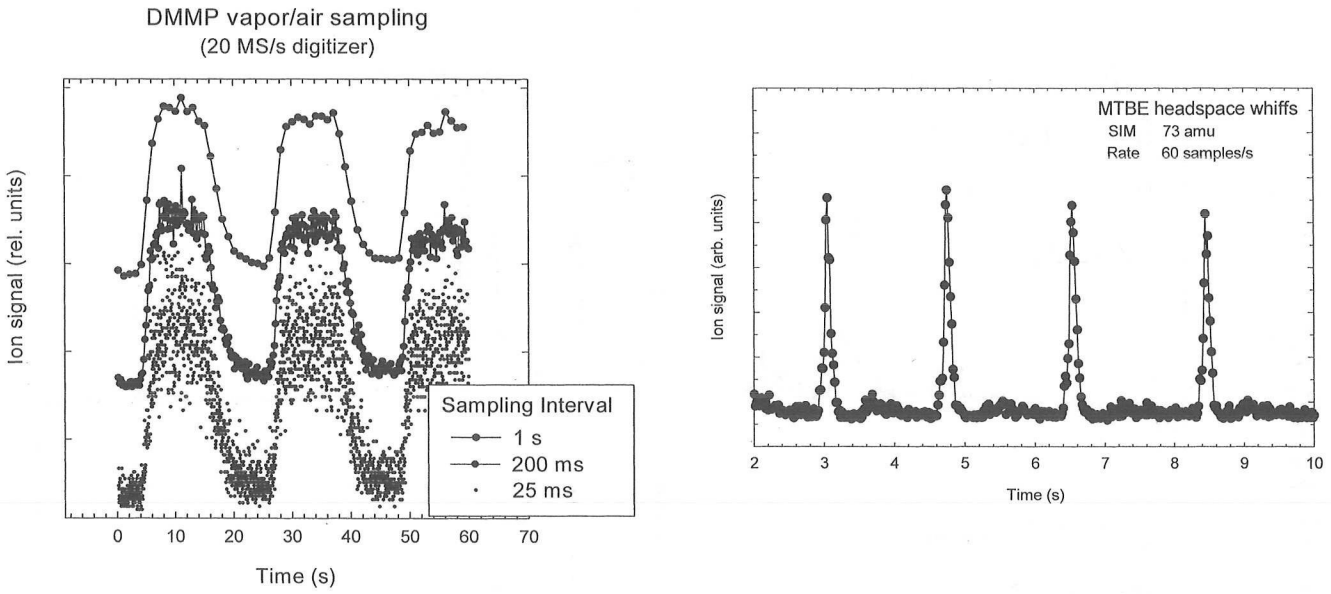

FIG. 11. (Left) Time response for DMMP air sampling for a 10-s on/off exposure cycle. Sampling was conducted at 25-ms intervals (40 Hz, oversampled), and compressed to 200-ms and 1-s intervals to show improvement in signal-to-noise ratio. Results on left were recorded on field-portable prototype instrument. (Right) Example of fast response to sniffs of MTBE in air with new low-internal-volume heated capillary inlet, recorded on benchtop instrument.

alyte is shown in Figure 10 for naphthalene and imipramine. A 4-decade dynamic range and over 3-decade linear range was measured for a single set of instrument conditions. It is expected that this range would decrease by about a factor of 2–5 for the field-portable system, due to the poorer detection limits relative to the benchtop version.

Speed

Results showing response time and signal reproducibility are given in Figure 11. Figure 11(a) shows the response time to an air sample of DMMP under a bypass flow from the sampler of about 300 mtorr/l/s. The rise times shown (1/e times) are 2–5 s. However, this additional load on the diaphragm turbomolecular backing pump pushes the overall pumping system to its limit. A new inlet was designed that minimized internal volume, used silica-coated inert surfaces, and operated at higher temperatures (up to 200 °C). This significantly reduced response time without the need for a bypass flow. These tests were conducted on a benchtop instrument and have not yet been applied to the field-portable system, but the benefits are expected to scale down. Figure 11(b) shows the response of rapid introductions of MTBE vapor to the new inlet. The response time is on the order of 0.1 s.

Conclusions and Outlook

The field-portable feasibility demonstration reported here indicates that compact, high-performance TOFMS is ready for field development. The features that distinguish the current work from previous work include:

- High performance QitTof
- High-throughput sampling from differential pumping
- Novel threshold photoionization source
- High-speed TOF; up to 200 Hz full mass spectra recording rate
- Suitable for direct coupling to fast GC
- 30-lb feasibility

In closing, we note that the current instrument is well suited for use with compact, low-power fast GC. The QitTof instrument can handle GC inlet temperatures up to 350 °C, is compatible with He and air flow, and can handle sample flows up to 6 ml/min, well in excess of the 1–2 ml/min flows required of existing low-power GC columns. We anticipate a demand for a GC/MS that can operate in two modes:

- Rapid screening (10 s) of complex mixtures using PI MS.
- On-demand GC/MS using electron ionization (EI) and library matching for detailed analysis.

This strategy would provide maximum efficiency and sampling rates, particularly if operating on battery power. The integration of a dual EI/PI source has already been developed by Syagen and would be routinely implemented on a field-portable system.

This technology may have a role in biological detection with the use of a pyrolysis front end. Syagen has conducted preliminary tests that demonstrate efficient detection of fatty-acid methyl esters (FAMES), fatty acids and carboxylic acids, and picolinic acid. These compounds are signatures for pyrolysis of gram-positive pathogens, such as anthrax.

Acknowledgments

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