

Testing of Screening Technologies for Detection of Toxic Industrial Chemicals in All Hazards Receipt Facilities

TECHNOLOGY EVALUATION REPORT

Technology Evaluation Report

Testing of Screening Technologies for Detection of Toxic Industrial Chemicals in All Hazards Receipt Facilities

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Preface

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's air, water, and land resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, the EPA's Office of Research and Development (ORD) provides data and science support that can be used to solve environmental problems and to build the scientific knowledge base needed to manage our ecological resources wisely, to understand how pollutants affect our health, and to prevent or reduce environmental risks.

In September 2002, EPA announced the formation of the National Homeland Security Research Center (NHSRC). The NHSRC is part of the ORD; it manages, coordinates, and supports a variety of research and technical assistance efforts. These efforts are designed to provide appropriate, affordable, effective, and validated technologies and methods for addressing risks posed by chemical, biological, and radiological terrorist attacks. Research focuses on enhancing our ability to detect, contain, and clean up in the event of such attacks.

NHSRC's team of world-renowned scientists and engineers is dedicated to understanding the terrorist threat,

communicating the risks, and mitigating the results of attacks. Guided by the roadmap set forth in EPA's Strategic Plan for Homeland Security, the NHSRC ensures rapid production and distribution of security-related products.

The NHSRC has created the Technology Testing and Evaluation Program (TTEP) in an effort to provide reliable information regarding the performance of homeland security-related technologies. TTEP provides independent, quality-assured performance information that is useful to decision makers in purchasing or applying the tested technologies. It provides potential users with unbiased, third-party information that can supplement vendor-provided information. Stakeholder involvement ensures that users' needs and perspectives are incorporated into the test design so that useful performance information is produced for each of the tested technologies. The technology categories of interest include detection and monitoring, water treatment, air purification, decontamination, and computer modeling tools for use by those responsible for protecting buildings, drinking water supplies, and infrastructure and for decontaminating structures and the outdoor environment.

The evaluation reported herein was conducted by Battelle as part of the TTEP program. Information on NHSRC and TTEP can be found at <http://www.epa.gov/ordnhsrc/index.htm>.

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List of Acronyms

AC	hydrogen cyanide (HCN)
ACS	American Chemical Society
AEGL	Acute Exposure Guideline Level
AHRF	All Hazards Receipt Facilities
ATSDR	U.S. Agency for Toxic Substances and Disease Registry
C	celsius
CG	phosgene (COCl ₂)
CGI	combustible gas indicator
CK	cyanogen chloride (CICN)
Cl ₂	chlorine
CN ⁻	cyanide
CWA	chemical warfare agent
DHS	U.S. Department of Homeland Security
DI H ₂ O	deionized water
DoD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
F ⁻	fluoride
FBI	Federal Bureau of Investigation
FID	flame ionization detection
FSP	flame spectrophotometer
G/V	phosphorous compounds
GC	gas chromatography
H ₂ O ₂	hydrogen peroxide
H ₂ S	hydrogen sulfide
HD/HL	sulfur compounds
HN/AC	nitrogen compounds
IMS	ion mobility spectrometer
Int	interferent
L/SA	arsenic compounds
LD ₅₀	lethal dose to half the population
m	meter
MF	mass flow meter
MFC	mass flow controller
mg	milligram
min	minute
mL	milliLiter
MSD	mass selective detection
MV	metering valve
MW	molecular weight
NHSRC	National Homeland Security Research Center
PE	performance evaluation
PID	photoionization detector
ppm	parts per million
QA	quality assurance
QC	quality control
QMP	Quality Management Plan
RH	relative humidity
RSD	relative standard deviation
SA	arsine (AsH ₃)
sec	second
St. Dev.	standard deviation
TEEL	Temporary Emergency Exposure Limit
T	temperature
TIC	toxic industrial chemicals
TSA	technical systems audit
TTEP	Technology Testing and Evaluation Program
UV	ultraviolet
WMD	weapons of mass destruction

Executive Summary

This document is the final report on an evaluation of commercially available screening technologies designed to rapidly detect, and in some cases indicate the concentration of, toxic industrial chemicals (TICs) in air or in water samples. The technology evaluations described in this report were performed by Battelle under the direction of the U.S. Environmental Protection Agency's (EPA) National Homeland Security Research Center (NHSRC) through the Technology Testing and Evaluation Program (TTEP). The technologies evaluated were identified as possible candidates for use in EPA's All Hazards Receipt Facilities (AHRF). The EPA, U.S. Department of Homeland Security (DHS), and U.S. Department of Defense (DoD) have teamed to develop, construct, and implement the AHRF for prescreening unknown and potentially hazardous samples collected during suspected terrorist events. The AHRF are intended for screening of samples for chemical, explosive, and radiological hazards to protect laboratory workers from injury and facilities from contamination and to ensure the integrity of collected samples. These facilities are not intended to provide detailed or quantitative analytical results, but instead to provide initial screening of samples prior to full laboratory analysis, for the safety of laboratory personnel. Screening technologies used in the AHRF are intended to be rapid and qualitative, and may be "low tech" in design and of relatively low cost, but must provide accurate identification of hazardous samples.

The procedures and target TICs used in this evaluation were chosen to represent likely conditions of use in the AHRF. In performing this technology evaluation, Battelle followed the procedures specified in a peer-reviewed test/QA plan established prior to the start of the evaluation and complied with all the quality requirements in the Quality Management Plan for the TTEP program. The screening technologies tested ranged from simple test papers, kits, and color-indicating tubes to hand-held electronic detectors based on photoionization detection (PID), electrochemical (EC) sensors, and flame spectrophotometry (FSP). The screening technologies were challenged with the TICs hydrogen cyanide (designated AC), cyanogen chloride (CK), phosgene (CG), arsine (SA), hydrogen sulfide (H_2S), and chlorine (Cl_2) in air at concentrations that would be seriously hazardous to personnel within a few minutes exposure. Those vapor-phase challenges were delivered at room temperature and normal (50%) relative humidity (RH), both with and without a volatile exhaust hydrocarbon mixture added as an interferent, and at relatively high (30 °C, 80% RH) and low (10 °C, 20% RH) temperature and humidity conditions without the interferent. Water samples used in challenging the screening technologies consisted of cyanide, hydrogen peroxide, or fluoride, each made up in deionized water, and in tap water and salt water as interferents. The water sample testing used TIC concentrations that would be hazardous upon physical contact with the water sample.

Most of the screening technologies showed 100% accuracy, or nearly so, in detecting TICs in air. Several of those technologies accurately detected TICs even though the TIC vapor challenge concentrations were lower than the nominal detection limits stated by the technology vendor. However, none of the tested technologies was designed to detect all six of the target TICs. The Sensidyne Gas Tubes and Draeger Civil Defense Kit color tubes exhibited 100% detection accuracy, or nearly so, for five TICs, and the Draeger CMS Analyzer, an automated color tube sampler and reader, showed 100% detection accuracy for four. The HazMat Smart Strip was 100% accurate in detecting hydrogen peroxide in water, as was the Truetech M272 Water Kit in detecting cyanide.

For the three technologies that provided a quantitative indication of the TIC vapor concentration during testing (i.e., the Draeger CMS Analyzer, MultiRAE Plus PID [with EC sensor for H_2S], and Sensidyne Gas Tubes), the percent relative standard deviation (%RSD) of triplicate responses was within 15% in 32 of the 40 challenge sets with these technologies and was within 10% in 22 of those 40 tests. Test conditions had no apparent effect on the %RSD values. Thus, close precision of responses can be obtained in screening with these technologies but cannot be assumed in all tests. None of the tested technologies produced any false positive responses in testing with either vapor-phase TICs or water samples. False negatives mainly occurred as the inability of a technology to detect a TIC at the challenge concentration even under the normal room conditions. The Anachemia C2 color tubes, MultiRAE Plus PID, Proengin AP2C FSP detector, Truetech M18A3 color tubes, and HazMat Smart Strip all exhibited false negatives for one or more TICs in vapor testing. The HazMat Smart Strip exhibited false negatives for CN^- and F^- , and the Proengin AP2C FSP for CN^- , at the challenge concentrations in water sample testing. No effect of interferents was seen in either vapor- or liquid-phase testing. Temperature and RH effects in TIC vapor testing were also minimal.

The speed and simplicity of the screening process varied widely among the tested technologies. All of the color-indicating tubes for vapor detection were simple to use in principle but differed in the time and difficulty of obtaining the sample. The number of manual pump strokes required to draw the air sample ranged from 1 to 60, and the manual effort needed for those technologies requiring 30 or more pump strokes was excessive even when screening small numbers of samples as in this test. Electric air sampling pumps, whether internal to the technology (as in the automated Draeger CMS Analyzer) or external (as in the Nexteq Civil Defense Kit) greatly reduced the physical effort needed but still required several minutes to draw the required volume. Color-indicating tubes that require the minimum volume would be preferable for use in the AHRF because they enable rapid sample analysis and data generation. The

use of an electrical sampling pump would be valuable if large numbers of samples are to be screened. The two hand-held analyzers tested (MultiRAE Plus PID with EC sensor and Proengin AP2C FSP) provided easy and rapid sample screening. However, although the MultiRAE Plus was easy to use, it was not effective, as only the electrochemical H₂S sensor in the MultiRAE Plus provided a response in these tests. The screening of water samples with the Proengin AP2C FSP was also relatively rapid because of the simplicity of wetting that detector's "scraper" attachment and desorbing collected samples into the AP2C's inlet. The HazMat Smart Strip was the simplest technology to use, requiring only removal of a protective film to expose the indicating patches on the card. However, this technology did not respond to AC. For vapor detection in the AHRF, the HazMat Smart Strip is best suited to be enclosed within a container or attached to a surface, rather than used as a hand-held sampling tool. The Anachemia CM256A1 multifunction card was much more difficult to use, requiring hand manipulation to heat and direct reagents to sections of the card but provided accurate detection of the two TICs for which it was designed (AC and CK).

In terms of the speed and simplicity of liquid sample screening, the Truetech M272 Water Kit was found to be deficient. The multiple detection tubes and reagent tablets needed, and the requirement for 60 mL of water sample, make it unlikely that this technology would be suitable for the AHRF.

The applicability of a technology to screen for multiple TICs at once is an important component of the speed of analysis. Technologies using multiple color-indicating tubes at once (e.g., the Draeger Civil Defense Kit and Nextteq Civil Defense Kit) can provide this capability. Two other technologies of widely different complexity also provide multi-TIC capability: the simple HazMat Smart Strip card and the Proengin AP2C FSP detector.

The initial cost of the tested technologies varied substantially, with most technology purchase costs ranging from a few hundred to a few thousand dollars. The Proengin AP2C FSP detector was the exception at a discounted cost of nearly \$16,000. However, when considering long-term use of the technologies in the AHRF, the per-sample screening costs were generally similar across technologies, i.e., typically less than \$10 per sample.

1.0 Introduction

This document is the final report on an evaluation of commercially available screening technologies designed to detect the presence, and in some cases indicate the concentration, of toxic industrial chemicals (TICs) in air or in liquid samples. The technology evaluations described in this report were performed by Battelle under the direction of the U.S. Environmental Protection Agency's (EPA) National Homeland Security Research Center (NHSRC) through the Technology Testing and Evaluation Program (TTEP) (Contract GS-23F-0011L-3), and specifically under Task Order 1119 of the TTEP program. The technologies evaluated were identified as possible candidates for use in EPA's All Hazards Receipt Facilities (AHRF), and the testing was designed to evaluate their performance relative to the needs of the AHRF as currently defined in the draft sample screening protocol developed for the AHRF.^{1,2}

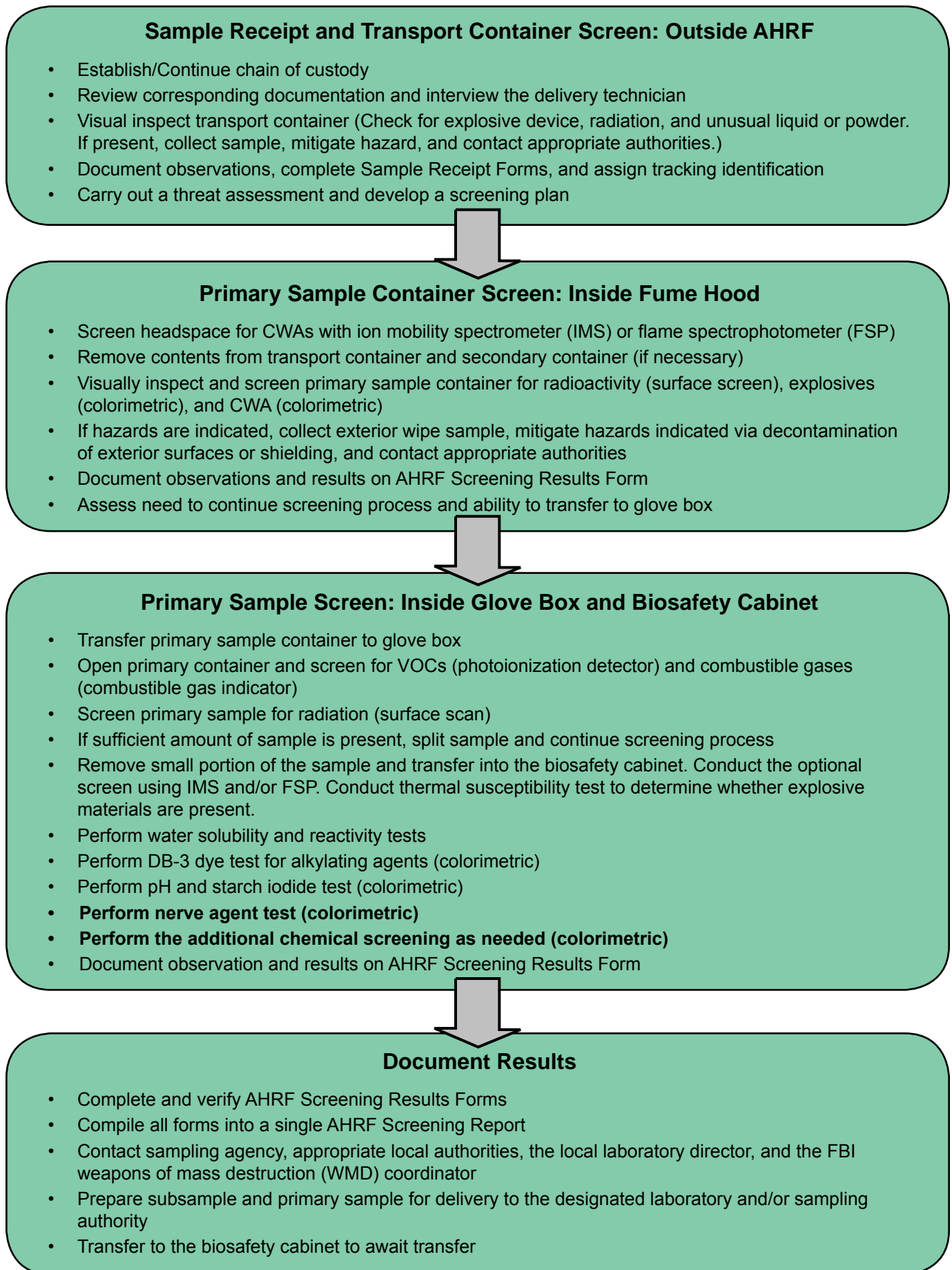
The EPA, U.S. Department of Homeland Security (DHS), and U.S. Department of Defense (DoD) have combined efforts to develop, construct, and implement AHRF capabilities for prescreening unknown and potentially hazardous samples collected during suspected terrorist events. AHRF development was initiated in response to requests from states and federal agencies, particularly public health laboratories, for standardized guidance on screening samples to protect laboratory staff and ensure sample integrity and the validity of analytical results. The AHRF are intended for in-process screening of unknown samples for chemical, explosive, and radiological hazards to protect laboratory workers and

facilities from contamination and injury. The AHRF are intended to serve as a front-end assessment that can be used on an "as needed" basis. These facilities are not intended to provide detailed or quantitative analytical results, but instead to provide initial screening of samples prior to full laboratory analysis, for the safety of all laboratory personnel. Screening technologies used in the AHRF are intended to be rapid and qualitative, and may be "low tech" in design and of relatively low cost, but must ensure meaningful qualitative results.

This report presents the results of the evaluation of commercially available screening devices for rapid detection of TICs in samples and on sample containers entering an AHRF. A separate report³ presents the results of testing such technologies for detection of chemical warfare agents (CWAs). The procedures, target chemicals, and sample types used in this evaluation were chosen to represent conditions of use likely to be present in the AHRF.^{1,2} Figure 1-1 is excerpted from the AHRF Draft Protocol¹ and illustrates the sample screening process to be implemented through the AHRF. As this figure shows, screening of an incoming sample or sample container for chemical contamination occurs in multiple steps of the process and may use multiple screening technologies.

In performing this technology evaluation, Battelle followed the procedures specified in a peer-reviewed test/quality assurance (QA) plan established prior to the start of the evaluation⁴ and complied with all the quality requirements in the Quality Management Plan (QMP)⁵ for the TTEP program.

Figure 1-1. Summary of All Hazards Receipt Facility Sample Screening Process



2.0

Technologies Tested

The screening technologies tested were identified based on a review of commercially available detection devices for the TICs and CWAs of interest. That review was wide ranging in that information on detection devices was initially obtained without concern about the applicability of each device to the AHRF sample screening process. Screening technologies were then selected for testing based on criteria specific to the intended use in the AHRF:

- Applicability to multiple target TICs and CWAs
- Applicability as a qualitative screening tool
- Applicability to multiple sample types (vapor, liquid, surface)
- Speed and simplicity of use
- Cost of use and consumables

The technologies selected for testing were predominantly relatively inexpensive, simple test kits, color tubes, and test strips, but also included a few hand-held electronic instruments employing various detection principles. The reason for inclusion of the latter technologies was their applicability to a wide range of TICs and/or CWAs, and their rapid response, which made them attractive as potential screening devices despite their relatively high initial cost.

Table 2-1 lists the vendor and name of each technology selected for testing with TICs in this program, the detection principle, and the TICs for which each technology was tested in the vapor and liquid sample matrices. The target TICs were all volatile compounds, so a surface sample matrix was not applicable to this evaluation. As Table 2-1 shows, the TICs hydrogen cyanide (HCN; designated AC), cyanogen chloride (ClCN; CK), phosgene (COCl₂; CG), arsine (AsH₃; SA), chlorine (Cl₂), and hydrogen sulfide (H₂S) were used in the vapor-phase, and cyanide (CN⁻), hydrogen peroxide (H₂O₂), and fluoride (F⁻) were used in the liquid phase. Brief descriptions of each TIC screening technology are provided below, along with Web addresses where pictures and more information can be found.

Anachemia C2. This technology consists of color-indicating tubes and a hand pump for drawing the required sample volume through one tube at a time. With this technology ten compressions of the pump provide the required sample volume. <http://www.anachemia.com/defequip/product.html>

Anachemia CM256A1. This device is a multifunction card that employs reagents placed in selected locations on the card, with manual manipulation of portions of the card to initiate reactions, produce heat, and observe color changes in the reagents. Each card can indicate the presence of TICs and CWAs by the performance of a series of about 15 sequential steps and manipulations. <http://www.anachemia.com/defequip/product.html>

Draeger CMS Analyzer. This technology is based on color-indicating tubes, but rather than using individual tubes, the CMS Analyzer uses chips, or cards, on which are mounted ten identical miniature color tubes. The card is inserted into the CMS Analyzer and positioned so that an internal pump draws sample air through one of the tubes. Any resulting color change is read by an electronic colorimeter and displayed as a quantitative indication of the chemical concentration. The card may then be advanced to position the next tube, readying the CMS Analyzer for the next measurement. The cards are indexed so that tubes are positioned accurately and cannot be reused by mistake. http://www.draeger.com/ST/internet/US/en/Products/Detection/ChipMeasurementSystem/CMSAnalyzer/pd_cms_analyzer.jsp

Draeger Civil Defense Kit. This technology uses a hand pump to draw air through five different color-indicating tubes simultaneously, with each tube providing an indication of one TIC or CWA. All five tubes must be in place in the five-port sampling holder for proper sampling to occur. Fifty compressions of the hand pump provide the required sample volumes to all five tubes. http://www.draeger.com/ST/internet/US/en/Products/Detection/Drager-Tubes/DragerTubesSets/DragerCDSSet/pd_cds_set.jsp

MSA Single CWA Sampler Kit. This device also uses color-indicating tubes, with a hand pump to draw sample air through a single indicating tube at a time. Thirty compressions of the hand pump provide the required sample volume. <http://www.msanorthamerica.com/catalog/product679.html>

Nextteq Civil Defense Kit. This technology uses an electric pump (or optional hand pump) to draw air through five different color-indicating tubes simultaneously, with each tube providing an indication of one TIC or CWA. All five tubes must be in place in the five-port sampling holder for proper sampling to occur. The electric pump is preset to draw the required 3.5 L of air through the five sampling tubes within a sampling period of 3.5 minutes. <http://www.nextteq.com/Products.aspx?category=3&subcat=16>

Proengin AP2C. The Proengin AP2C is a hand-held flame spectrophotometer (FSP) that detects characteristic emissions from hazardous chemicals as they are consumed in a flame. The device burns hydrogen, supplied from a compact low-pressure cylinder inside the instrument, with sample air drawn continuously by an internal pump. Detection of a target chemical triggers an alarm from the AP2C, and the instrument provides identification and semi-quantitative readings for the detected chemical. Such readings take the form of a series of five bars that successively turn orange depending on the intensity of response, with separate sets of bars for sulfur compounds (HD/HL), nitrogen compounds

Table 2-1. Summary of TIC Screening Technologies Tested

Screening Technology			Vapor Samples						Liquid Samples		
Vendor	Name	Detection Principle	Hydrogen cyanide (AC)	Cyanogen chloride (CK)	Phosgene (CG)	Arsine (SA)	Chlorine (Cl ₂)	Hydrogen sulfide (H ₂ S)	Cyanide (CN ⁻)	Hydrogen peroxide (H ₂ O ₂)	Fluoride (F)
Anachemia	C2	color tubes	X	X	X						
	CM256A1	multifunction card	X	X							
Draeger	CMS Analyzer	multicolor tubes on a chip	X		X		X	X			
	Civil Defense Kit	color tubes	X	X	X	X	X				
MSA	Single CWA Sampler Kit	color tubes	X	X	X						
Nextteq	Civil Defense Kit	color tubes	X	X	X						
Proengin	AP2C	flame spectrometer	X	X		X		X	X		
RAE Systems	MultiRae Plus	photoionization detector	X	X	X	X	X	X			
Safety Solutions	HazMat Smart Strip	multifunction card	X				X	X	X	X	X
Sensidyne	Gas Detection Tubes	color tubes	X		X	X	X	X			
Truetech	M272 Water Kit	color tubes							X		
	M18A3	color tubes	X	X	X						

(HN/AC), phosphorous compounds (G/V), and arsenic compounds (L/SA). The AP2C also provides a general indication of the presence of hydrocarbon compounds by means of a single bar “CH” display. The S4PE accessories set allows liquid samples to be picked up on disposable “scraper” tips and vaporized into the inlet of the AP2C by means of a heating circuit in the detachable scraper handle. http://www.proengin.com/fp_ap2c.htm

RAE Systems MultiRAE Plus. The MultiRAE Plus is a hand-held photoionization detector (PID) for volatile organics in air that also can incorporate electrochemical sensors for oxygen, explosive gases, and selected TICs. In the PID, an ultraviolet (UV) light source causes ionization of those molecules in the sample air stream that have an ionization potential less than the energy of the UV light. The MultiRAE Plus unit tested was equipped with an electrochemical sensor for H₂S and was challenged separately with each of the six target TICs. It should be noted that the PID principle of the MultiRAE Plus is not necessarily expected to respond to the TICs, but because the MultiRAE Plus is promoted for use as a general toxic compound detector, it was tested with all six TICs. http://www.raesystems.com/products/multi_gas

Safety Solutions HazMat Smart Strip. This device is a card that may be attached to a surface, such as a person’s clothing, by means of its adhesive backing. The front surface of the card has eight squares of colorimetric reagents that produce qualitative indications of the presence of several respective contaminants, including chlorine, acids or caustics

(pH indication), fluoride, nerve agents, oxidizers, arsenic, hydrogen sulfide, and cyanide. Removal of a protective film exposes the reagent squares and allows any indicating reactions to take place. <http://www.smart-strip.com/>

Sensidyne Gas Detection Tubes. These are single-use glass tubes containing reagents that change color when a suitable volume of air containing the appropriate target chemical is drawn through the tube. A hand pump is used to draw the correct amount of air sample through one tube at a time. One compression of the hand pump provides the 100-mL volume of sample air required by the vendor’s instructions. The number of compressions may be increased if detection of lower concentrations of the target chemical is needed. <http://www.sensidyne.com/prodcat.php?ID=1>

Truetech M272 Water Kit. This kit for water analysis includes two separate detection technologies, one for TICs and one for CWAs. The TIC technology requires 60 mL of sample and uses reagent tablets, color tubes, and heating provided by lighted matches to obtain a qualitative indication of the presence of chemicals in the sample. This technology was tested with cyanide in aqueous samples. http://www.tradewaysusa.com/eng/products/if_detection.htm

Truetech M18A3. This technology uses color-indicating tubes to detect the presence of TICs and CWAs in air. A hand pump draws air through the tubes, with 60 compressions of the pump providing the required sample volume. http://www.tradewaysusa.com/eng/products/if_detection.htm

3.0 Testing Procedures

3.1 Performance Parameters

The key performance parameters evaluated for the TIC screening technologies were:

- Accuracy of identifying hazardous samples
- False positive/false negative rates
- Analysis time

In addition, technologies providing more than a simple yes/no response were evaluated for the following performance parameter, using the responses displayed by these devices:

- Repeatability

These performance parameters are defined below, and general test procedures are described in Section 3.2. The TIC evaluation was performed according to the requirements of the test/QA plan⁴ and the TTEP QMP.⁵

In addition to these key performance parameters, operational characteristics of the screening technologies were evaluated based on operator observations. These operational characteristics included:

- Ease of use
- Data output
- Cost

3.1.1 Accuracy of Hazard Identification

Accuracy is the ability of a screening technology to identify hazardous samples so that they can be properly handled to minimize risk to laboratory personnel. Accuracy was measured in terms of the percentage of prepared hazardous samples that were correctly identified as hazardous by the screening technology in question.

3.1.2 False Positive/False Negative Rates

A false positive screening result occurs when a technology incorrectly identifies a safe sample as being hazardous. A false negative screening result occurs when a technology incorrectly identifies a hazardous sample as being safe. Responses that identified samples as hazardous when they contained none of the target TICs were denoted as false positives. The absence of a hazard indication with a sample containing a target TIC was denoted as a false negative.

3.1.3 Analysis Time

Analysis time is the time needed to screen a single sample or group of samples with an individual technology. Analysis time is driven by the response time of a technology in indicating a hazard upon presentation of a sample and takes different forms for different screening technologies. For

continuous monitors (e.g., the MultiRAE Plus or Proengin AP2C) analysis time is dependent on instrument response and recovery time. For colorimetric papers the speed of analysis is limited by the color development time after the start of exposure, whereas for colorimetric gas sampling tubes, the time required to draw the required volume of sample gas through the tube is likely to be the limiting factor. For all technologies tested, the appropriate response time was noted to provide a consistent comparison of analysis times.

3.1.4 Repeatability

The responses provided by some sample screening instruments include quantitative readings. Such readings were recorded and the repeatability of such indications was calculated in terms of a percent relative standard deviation (% RSD) of the triplicate challenges at different test conditions.

3.1.5 Operational Characteristics

Ease of use was assessed by operator observations, with particular attention to the conditions of use during screening. This assessment was done in the course of evaluating other performance parameters with TICs, i.e., no additional test procedures were designed specifically to address only the operational characteristics.

For each screening technology, the type of indication or data output was noted (e.g., color change, intensity of color change, low/med/high indication, audio or visual alarm, quantitative measure of concentration), and the clarity of the indication was assessed.

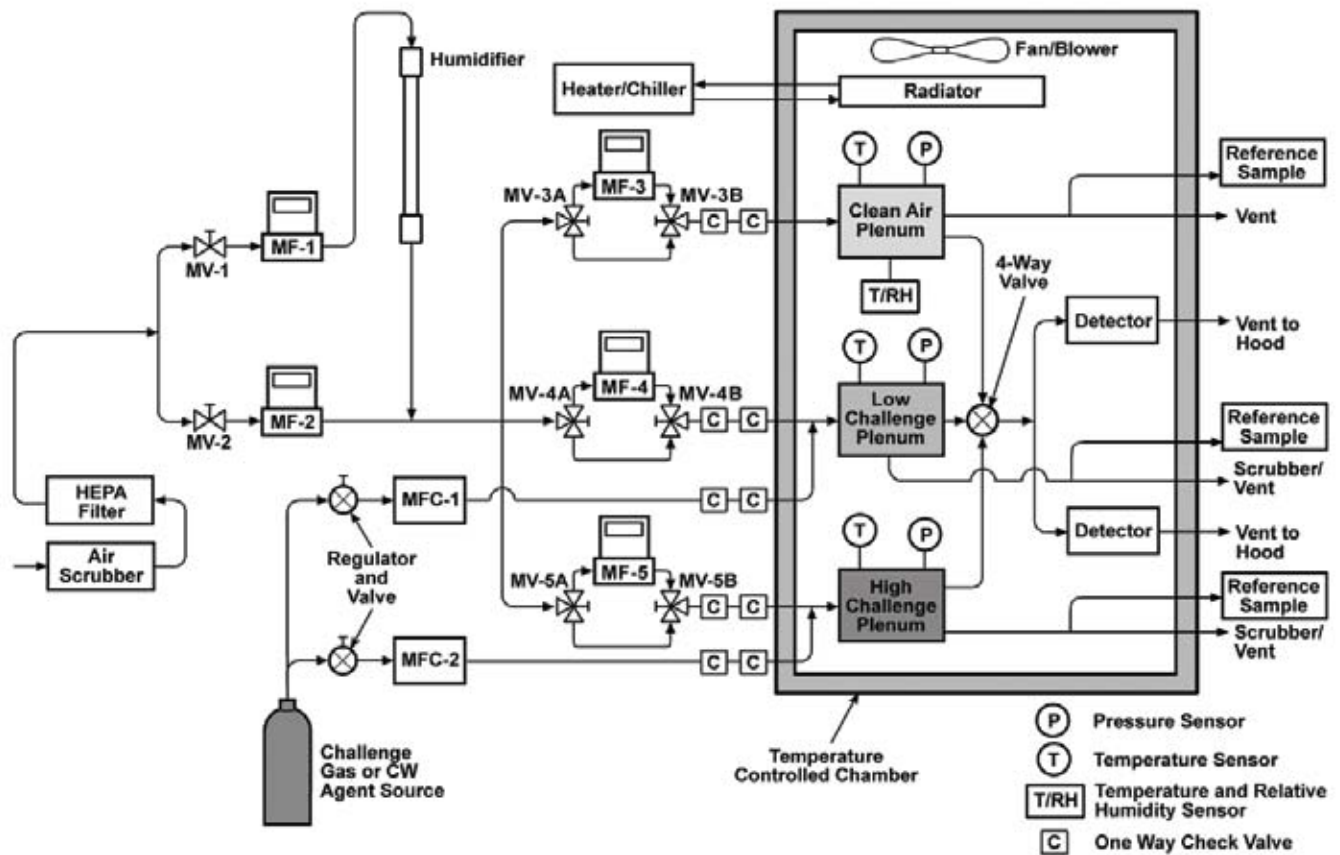
Costs for each technology were assessed based on the purchase and operational costs of the technologies as tested. This technology evaluation was not of sufficient duration to test long-term maintenance or operational costs of the technologies. Estimates for key maintenance items were requested from the vendors as necessary.

3.2 Test Procedures

3.2.1 Vapor-Phase Testing

Screening technologies were evaluated based on their ability to respond to TICs in the vapor-phase, using a test apparatus represented schematically in Figure 3-1. The test system consists of a vapor generation system, a Nafion® humidifier, two challenge plenums, a clean air plenum, metering valves (MVs), RH sensors, thermocouples, and mass flow meters (MFs) and controllers (MFCs). Only one of the two challenge plenums was used in this evaluation. The challenge gas was generated by diluting a commercially obtained compressed gas standard of the target TIC.

Figure 3-1. Test System Schematic



Testing was conducted with one TIC at a time, and on one screening technology at a time, using this apparatus. As illustrated in Figure 3-1, the test apparatus allows the temperature and relative humidity (RH) of the challenge gases to be adjusted. To evaluate a screening technology, a flow of clean air passed through the clean air plenum (Figure 3-1), and an equal flow of air containing a constant concentration of the target TIC passed through one of the other plenums. Each screening technology was connected to the four-way valve shown in the figure, through which the clean air or TIC challenge gas flowed before being vented into a chemical laboratory hood. For technologies that draw their own sample flow, such as the color-indicating tubes, PID, or FSP, an appropriate direct connection was made to allow the instrument to sample from the air flow without pressurization by the flow. Color-indicating cards were placed within a second enclosure through which the clean air or challenge mixture was directed from the four-way valve.

Each screening technology was first sampled (or was exposed to) the clean air flow, and any response or indication from the screening technology was noted. After this background measurement, the four-way valve was switched to the challenge plenum to deliver the TIC challenge gas to the subject technology. Switching between the clean air and TIC challenge gas flows was rapid, and the residence time of gas in the test system was short, so that the analysis time determined for each screening technology was not biased by the limitations of the test apparatus. The sequence of

exposure to clean air followed by exposure to the TIC challenge gas was carried out three successive times for each screening technology with each TIC. For some of the screening technologies tested, this required using a new color-indicating card or tube for each clean air or TIC challenge. For other technologies, a color-indicating tube that showed no response on the clean air challenge was used for the subsequent TIC challenge.

Table 3-1 shows the target TICs used in vapor-phase testing, the challenge concentrations used, and the basis for the chosen concentrations. Except in the case of cyanogen chloride (CK), the target concentrations shown are all Acute Exposure Guideline Level (AEGL) values, and specifically AEGL-2 values for a 10-minute exposure.⁶ The AEGL-2 value is defined as the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. AEGL values are established specifically for the protection of personnel and thus are appropriate target values for AHRF screening. For CK, no AEGL values have been established, so the target value is based on the Temporary Emergency Exposure Limit (TEEL) for that chemical, and specifically the TEEL-2 value for a 15-minute exposure.⁷ The TEEL-2 value is defined as the maximum concentration in air below which it is believed nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or

symptoms that could impair their abilities to take protective action. Delivery of the vapor-phase challenges was deemed acceptable if the TIC concentration determined by the reference methods was within $\pm 20\%$ of the respective target value shown in Table 3-1.

For each screening technology, the test sequence of three clean air blanks interspersed with three TIC challenges was conducted with one TIC at a time at four different conditions: at a base temperature and RH, at relatively high temperature and RH, at relatively low temperature and RH, and at the base temperature and RH with an interferent (a mixture of hydrocarbons characteristic of polluted urban air) added to both the blank and challenge mixtures. However, testing at the base temperature and RH was conducted first, and if a technology failed to respond in all three TIC challenges at

that test condition, then no tests were conducted at the other three test conditions with that TIC. Table 3-2 summarizes the TIC vapor-phase test conditions. The interferent was a mixture of about 40 volatile organic compounds, characteristic of gasoline engine emissions in urban air, in a compressed gas standard in nitrogen. This mixture was added to the blank or TIC challenge air flows at a ratio of 1:100 interferent mix to air flow.

Reference analysis methods were used to quantify the TIC concentrations in the clean air and the challenge mixtures to confirm that the concentrations delivered were within the acceptable tolerance of $\pm 20\%$ from the target value. Table 3-3 lists the reference methods used for each of the TICs in the vapor-phase testing. References to the methods used are footnoted in Table 3-3.

Table 3-1. Challenge Concentrations for TIC Vapor Testing

TIC/CW Agent	Concentration ^a	Basis for Concentration ^b
Hydrogen cyanide (AC)	17 ppm (18.7 mg/m ³)	AEGL-2 value
Cyanogen chloride (CK)	0.4 ppm (1 mg/m ³)	TEEL-2 value
Phosgene (CG)	0.6 ppm (2.4 mg/m ³)	AEGL- 2 value
Chlorine (Cl ₂)	2.8 ppm (8.4 mg/m ³)	AEGL- 2 value
Arsine (SA)	0.3 ppm (1 mg/m ³)	AEGL- 2 value
Hydrogen sulfide (H ₂ S)	41 ppm (57.4 mg/m ³)	AEGL- 2 value

^a At normal temperature and pressure, 1 ppm = (MW)(0.0409) milligrams per cubic meter (mg/m³), where MW is the molecular weight of the compound

^b AEGL = Acute Exposure Guideline Level; TEEL = Temporary Emergency Exposure Limit

Table 3-2. Test Conditions Used in TIC Vapor Testing

Condition	Temperature (°C)	Relative Humidity (%)	Interferent ^a
Base	20	50	None
High T/RH	30	80	None
Low T/RH	10	20	None
Interferent Test	20	50	hydrocarbon mix

^a See text for description.

Table 3-3. Reference Methods for Vapor-Phase TICs

TIC	Sampling Method	Analysis Method
Hydrogen cyanide (AC)	Air sample injected directly into GC	GC/FID ^a
Cyanogen chloride (CK)	Air sample injected directly into GC	GC/FID ^b
Phosgene (CG)	Continuous portable monitor	Electrochemical detection ^c
Chlorine (Cl ₂)	Continuous portable monitor	Electrochemical detection ^c
Arsine (SA)	Collection in gas sampling bag for GC injection and Continuous portable monitor	GC/MSD ^d and Electrochemical detection ^c
Hydrogen sulfide	Continuous electrochemical detector	Electrochemical detection ^c

^a Reference 8

^b Reference 9

^c Commercially available detectors used: Draeger MiniWarn for chlorine, Jerome Model 860 for hydrogen sulfide, Draeger Pac III for phosgene and arsine

^d Reference 10

Table 3-4. TIC Concentrations Used in Liquid Testing

TIC	Concentration	Solvent ^a	Basis for Concentration
Cyanide	0.7 mg/mL	Water	0.1 x Oral LD ₅₀
Fluoride	0.7 mg/mL	Water	0.1 x Acute Toxic Dose
Hydrogen peroxide	10% (100 mg/mL)	Water	ATSDR Guidelines

^a Solvents used for each TIC included DI water, municipal tap water, and DI water with 3% NaCl by weight.

For the TICs hydrogen cyanide and cyanogen chloride, air samples delivered from the test apparatus were injected directly for detection by gas chromatography (GC) with flame ionization detection (FID).^{8,9} Phosgene was determined using a portable electrochemical detector, the Draeger Pac III[®]. Chlorine was also determined by a commercially available continuous electrochemical analyzer, the Draeger MiniWarn. Arsine was determined initially by a gas chromatographic method with a capillary column and mass selective detection (MSD), using samples collected in gas sampling bags from the test apparatus.¹⁰ Approximately at the midway point of testing with arsine, a comparison was made between arsine measurements made by the GC method and simultaneous measurements from the Draeger Pac III instrument. That comparison showed equivalent results from the two methods, so for greater convenience the Pac III was used for the remainder of the arsine testing. Hydrogen sulfide was determined with the Jerome Model 860, a commercial continuous electrochemical monitor.

3.2.2 Liquid Sample Testing

The testing with TICs in liquid samples used water as the solvent because the target TICs (CN⁻, F⁻, and H₂O₂) are water-soluble species. However, to simulate potential interfering sample matrices that might be encountered, samples were prepared not only in deionized (DI) water (produced by a Labconco WaterPro PS water purification system in Battelle's laboratory), but also in municipal tap water and in DI water containing 3.0% by weight NaCl. Each of the TICs was prepared at a single concentration in each of these three aqueous solvents, and each of these liquid challenge samples contained a single TIC, i.e., no mixed samples were prepared. Each screening technology was tested with three blank samples of the aqueous matrix and with three samples of the same matrix containing the TIC. However, if a technology failed to detect a TIC in all three challenge samples with the DI water sample matrix, then no tests were conducted with that TIC in the tap water or salt water matrices. Table 3-4 lists the TICs tested in liquid samples, the concentrations used in the evaluation of liquid screening technologies, and the basis for the concentrations used.

Because the purpose of the AHRF screening protocol is to protect analytical personnel from toxic exposures in handling and analyzing samples, the use of challenge concentrations taken from drinking water standards was not appropriate,

i.e., it is unrealistic to assume that an analyst would ever deliberately ingest a sample provided for analysis. Furthermore, drinking water standards assume the ingestion of several liters of water per day. As a result, the aqueous challenge concentrations for cyanide, fluoride, and hydrogen peroxide in Table 3-4 were based on reasonable assumptions and/or the interpretation of information on toxic effects. The concentration shown for cyanide was based on the assumption that a water sample of 50-mL volume, containing an amount of the target chemical equal to one-tenth of the oral dose that would be lethal to half the population (LD₅₀), is spilled on the skin and that all of the chemical is then absorbed into the body through the skin. For cyanide, with an LD₅₀ of 5 mg/kg of body weight, and an assumed body weight of 70 kg, the total mass of cyanide would be 35 mg, and the concentration in a 50-mL sample would be 0.7 mg/mL, as shown in Table 3-4. Similarly, the acute toxic dose of fluoride is generally reported as 3 to 5 mg/kg. Taking the higher number, and making the same one-tenth adjustment and assumptions as above for cyanide, results in the 0.7 mg/mL concentration shown in Table 3-4. For hydrogen peroxide, the concentration of 10% (by weight) in Table 3-4 was identified by the U.S. Agency for Toxic Substances and Disease Registry (ATSDR) as being strongly irritating and potentially corrosive to skin.

The liquid challenge samples were made up gravimetrically (for CN⁻ and F⁻) or volumetrically (for H₂O₂) from high-purity (American Chemical Society [ACS] Reagent Grade or better) chemicals. Laboratory volumetric glassware was used for all dilutions, and the challenge samples were made up to the required TIC concentration immediately before testing took place. As a result, it was deemed unnecessary to conduct reference analyses on the liquid challenge samples. This choice to forego the reference analyses was documented by preparation of a formal deviation from the test/QA plan.

3.3 Data Recording

Because of the qualitative nature of the technologies being tested, the test observations were recorded manually by the testing personnel on hard copy data sheets prepared for this purpose. Upon completion of testing, the data sheets were reviewed and signed by a Battelle staff member not conducting the testing but familiar with the test procedures. The data were then entered from the hard copy data sheets into an Access[®] electronic database.

Quality Assurance/Quality Control

Quality assurance/quality control (QA/QC) procedures were performed in accordance with the QMP for the TTEP program⁵ and the test/QA plan for this verification test.⁴ QA/QC procedures and results are described below for the vapor- and liquid-phase TIC testing. The only deviation from the test/QA plan was the absence of reference analyses on the liquid samples. As noted in Section 3.2.2, a deviation form was prepared to document this difference.

4.1 Vapor-Phase Samples

4.1.1 Blank Challenges

As described in Section 3.2.1, challenges with TIC vapors were interspersed with corresponding blank (i.e., clean air) challenges. In all cases, blank challenges were at the same temperature and of the same relative humidity as the interspersed TIC challenge mixtures. In addition, the reference methods described in Section 3.2.1 and referred to in Section 4.1.2 were used to determine the TIC concentrations in the blank challenges. At no time was a detectable level of a target TIC found in any of the blank challenges.

4.1.2 Reference Analyses

As described in Section 3.2.1, reference measurements were made to document that the concentrations of vapor-phase TICs in the challenge mixtures were within $\pm 20\%$ of the target concentrations listed in Table 3-1, as required in the test/QA plan.⁴ At all times, those reference methods were operated and calibrated according to the instructions provided by the manufacturer or an applicable Battelle Standard Operating Procedure. Table 4-1 summarizes the results of the vapor-phase TIC reference measurements, showing the target concentrations and acceptable ranges, and the mean, standard deviation, and range of the reference results. All reference results for AC, CK, CG, Cl₂, and H₂S were within

the required 20% tolerance. For SA, a few reference results were slightly below the lower acceptable concentration limit of 0.24 ppm. However, those reference results were obtained at the end of a test in which the technology being tested responded clearly and positively to the presence of the TIC. As a result, it was concluded that the slightly low SA concentration did not handicap the technology's performance, so the test was not repeated, and the reference results were flagged but kept in the data set.

4.1.3 TIC Vapor-Phase Testing Audits

Three types of audits were performed during the TIC testing: a performance evaluation (PE) audit of the TIC vapor delivery system using the reference analysis methods, a technical systems audit (TSA) of the test procedures, and a data quality audit of the recorded test data. Audit procedures and results are described below.

4.1.3.1 Performance Evaluation Audit

PE audits of the TIC vapor delivery system were carried out using a commercial gas standard of each TIC that was independent of the TIC source gas used in testing. The PE audit involved preparing two separate TIC challenge mixtures by diluting the source gas that was used throughout testing and by similarly diluting the independent gas standard. Both TIC mixtures were then analyzed using the relevant reference method, and the agreement of the reference results indicated the overall agreement of the two TIC standards, as well as the accuracy of the dilution system. The dilution of the source gas and independent audit standards was done in such a way that identical final TIC concentrations were targeted. Agreement of the concentrations was required to be within 20% relative to the independent standard result.⁴ All TIC mixtures for the PE audit were prepared at approximately 20 °C and 50% RH.

Table 4-1. Summary of Reference Results from TIC Vapor Testing

TIC	Target Concentration (ppm)	Acceptable Range (ppm)	Reference Results	
			Mean (\pm St. Dev.) (ppm)	Range (ppm)
AC	17	13.6 to 20.4	17.5 (0.9)	14.5 to 19.1
CK	0.4	0.32 to 0.48	0.40 (0.03)	0.34 to 0.46
CG	0.6	0.48 to 0.72	0.55 (0.05)	0.48 to 0.70
Cl ₂	2.8	2.24 to 3.36	2.78 (0.40)	2.25 to 3.35
SA	0.3	0.24 to 0.36	0.28 (0.05)	0.21 ^a to 0.36
H ₂ S	41	32.8 to 49.1	44.4 (2.9)	39 to 49

^a SA reference results below the lower acceptable limit were observed in two tests in which the tested technology responded clearly and positively to all challenges; test results retained.

Table 4-2. Summary of TIC PE Audit Results

TIC	Audit Date	TIC Gas Cylinder Numbers ^a	TIC Cylinder Concentration, ppm ^a	Reference Method Results, ppm ^a	Agreement %
AC	10/17/06	XA3572 A016366	10,000 9,990	23.0 20.9	10.0
CK	10/2/06	NA025680 NA025981	10,400 1,020	0.38 0.44	13.6
CG	10/2/06	NA025205 NA025927	1,070 1,080	0.64 0.61	4.9
SA	10/17/06	N1A013216 NA025688	9,190 986	0.84 0.88	4.5
Cl2	10/17/06	A023136 1A1013	10,000 10,000	15.1 14.5	4.1
H2S	10/17/06	ALM022686 CLM010314	20,200 2,010	30.0 34.0	11.8

^a First listing is source gas used in TIC testing, second gas listed is independent PE audit standard.

Table 4-2 summarizes the TIC PE audits, showing the target TIC, the date of the PE audit, identification of the source and independent standards used, the reference method results for the delivered TIC concentration from each standard, and the percent agreement. Table 4-2 shows that all the PE audit results were well within the 20% target tolerance set in the test/QA plan.⁴

4.1.3.2 Technical Systems Audit

A Battelle Quality Management representative conducted a TSA of the TIC vapor testing on September 8, 2006, to ensure that the test was being conducted in accordance with the test/QA plan⁴ and the TTEP QMP.⁵ In the TSA, the test procedures were compared to those specified in the test/QA plan,⁴ and data acquisition and handling procedures, as well as the reference standards and methods, were reviewed. Observations and findings from the TSA were documented and submitted to the Battelle Task Order Leader for response. None of the findings of the TSA required corrective action. Records from the TSA are permanently stored with the Battelle Quality Manager.

4.1.3.3 Data Quality Audit

At least 10% of the data acquired during the TIC vapor testing were audited. Battelle's Quality Manager traced the data from the initial handwritten data record through to final reporting, to ensure the integrity of the reported results. All summaries and calculations performed on the data undergoing the audit were checked.

4.2 Liquid-Phase Samples

4.2.1 Blank Challenges

As described in Section 3, the aqueous challenge samples containing TICs were interspersed with corresponding blank challenge samples. These blank samples consisted of the same water used for the challenge samples. None of the

blank samples elicited any positive response from any of the technologies being tested.

4.2.2 Reference Analyses

As noted in Section 3.2.2, the liquid challenge sample solutions were made up gravimetrically or volumetrically from high-purity chemicals and used immediately after preparation. As a result, with the concurrence of the Battelle Quality Manager, reference analyses were not conducted on the liquid challenge samples.

4.2.3 TIC Liquid-Phase Testing Audits

Auditing of the liquid-phase testing was limited to a data quality audit. No PE audit was performed on the liquid samples because the high quality of the reagents and the reliability of the preparation methods made reference analyses unnecessary. No TSA was performed on the liquid sample testing because of the short duration and simple nature of that testing.

All of the data acquired during the TIC liquid sample testing were audited. Battelle's Quality Manager traced the data from the initial handwritten data record through to final reporting, to ensure the integrity of the reported results. All summaries and calculations performed on the data undergoing the audit were checked.

4.3 QA/QC Reporting

Each audit was documented in accordance with the TTEP QMP.⁵ Once the audit report was prepared, the Battelle Verification Test Coordinator ensured that a response was provided for each adverse finding or potential problem and implemented any necessary follow-up corrective action. The Battelle Quality Manager ensured that follow-up corrective action was taken. The results of the TSA were submitted to EPA.

4.4 Data Review

Records generated in the verification test received a one-over-one review before these records were used to calculate, evaluate, or report verification results. Data were reviewed by

a Battelle technical staff member involved in the verification test. The person performing the review added his/her initials and the date of review to a hard copy of the record being reviewed.

5.0 Test Results

The primary results of this evaluation of potential AHRF sample screening technologies consist of the observed responses to the TIC challenges, which establish the accuracy of each technology for sample screening. Those responses were also reviewed to determine false positive and negative rates for each technology and to establish the repeatability of responses for those few technologies tested that provide more than a qualitative (yes/no) response. Analysis time and operational factors were also evaluated based on operator observations and test records.

5.1 Accuracy

The test results for each technology were compiled into databases that list the technology name, each target TIC and its test concentration, reference method results confirming the delivered TIC concentration, the test conditions (T, RH, presence/absence of interferent), and the technology's response to the triplicate blank and challenge runs. The database of test results for the vapor-phase TICs is included in this report as Appendix A, and the database of test results for liquid-phase TICs is included as Appendix B. To make these test results immediately understandable, a condensed version of the database has been prepared, in which color coding of the test results is used to provide a visual indication of screening technology performance. In this format, a technology that provides a positive response to all three challenges in a single test condition with a TIC is indicated with the color green; positive responses in only one or two of the three challenges are shown by the color yellow; and the absence of a positive response in all three challenges is shown by the color red. This condensed summary of screening technology performance is shown in Table 5-1 for those technologies tested with vapor-phase TICs and in Table 5-2 for those technologies tested with TICs in liquid samples.

Table 5-1 shows that several of the technologies tested for screening vapor-phase TICs correctly responded to the presence of the TICs under all four test conditions, resulting in an accuracy of 100%. The Anachemia CM256A1 card, the two Draeger color tube technologies, the MSA and Nextteq kits, and the Sensidyne color tubes all showed high accuracy

in detecting the target TICs with which they were challenged. Among this group, only a single instance of failure to indicate was noted, for the Draeger Civil Defense Kit in one of the three trials with CK at the base condition. This technology responded correctly to all other challenges with CK, at the base condition and at all other test conditions, resulting in 92% accuracy (i.e., 11 out of 12 correct responses) for this technology with CK. No single technology was applicable to all six of the target TICs, but the Draeger Civil Defense Kit and Sensidyne tubes were the two technologies that had high accuracy for five of the six TICs and between them can detect all six.

Table 5-1 also shows that the Anachemia C2 tubes were unable to detect the three TICs tested, at the target concentrations used. The RAE MultiRAE Plus was challenged with all six TICs and showed 100% accuracy only to H₂S and 0% accuracy for the other TICs. These results show that the electrochemical sensor was effective for H₂S detection but that the PID is ineffective for detecting the TICs. The Proengin AP2C and Truetech M18A3 tubes did not show response to CK, and the HazMat Smart Strip did not respond to AC. Also, an unusual response was seen from the Proengin AP2C instrument in testing at low T and low RH with AC. In all other tests with AC, the instrument responded with a reading of one bar for HN/AC and with a simultaneous reading of one bar for L/SA, suggesting an arsenic compound. However, at the low T/low RH condition, only the L/SA response was seen, i.e., the correct response to hydrogen cyanide was not observed. Although the one-bar reading for L/SA would provide some measure of protection for laboratory staff, the Proengin readings at this test condition were judged incorrect because of the absence of the indication of cyanide observed at the other test conditions. An overall accuracy of 75% resulted for the Proengin instrument in detecting AC.

Table 5-2 shows that the Truetech M272 Water Kit correctly indicated the presence of cyanide in all three water matrices, and the Safety Solutions HazMat Smart Strip did the same for hydrogen peroxide. No other positive responses were found with the liquid samples.

Table 5-1. Summary Results of TIC Vapor Testing

Technology	TIC	Test Condition ^{a, b}			
		Base	Base + Int	Low	High
Anachemia C2 Tubes	AC				
	CG				
	CK				
Anachemia CM256A1	AC				
	CK				
Draeger Civil Defense Kit	AC				
	CG				
	Cl ₂				
	CK				
	SA				
Draeger CMS Analyzer	AC				
	CG				
	Cl ₂				
	H ₂ S				
MSA Single CWA Kit	AC				
	CG				
	CK				
Nextteq Civil Defense Kit	AC				
	CG				
	CK				
Proengin AP2C	AC			C	
	CK				
	H ₂ S				
	SA				
RAE MultiRAE Plus	AC				
	CG				
	Cl ₂				
	CK				
	H ₂ S				
	SA				
S. S. HazMat Smart Strip	AC				
	Cl ₂				
	H ₂ S				

Table 5-1. (Continued)

Technology	TIC	Test Condition ^{a, b}			
		Base	Base + Int	Low	High
Sensidyne Gas Tubes	AC				
	CG				
	Cl ₂				
	H ₂ S				
	SA				
Truetech M18A3 Tubes	AC				
	CG				
	CK				

^a Base = room T and 50% RH; Base + Interferent (Int) = room T, 50% RH, and gas exhaust mixture at 1% of total flow; Low = 10 °C and 20% RH; High = 30 °C and 80% RH.

^b Green = proper response in all three challenges; Yellow = proper response in 1 or 2 of the 3 challenges; Red = no responses in the 3 challenges. Absence of color indicates test not conducted.

^c The response of the instrument under these conditions is described on page 13.

Table 5-2. Summary Results of TIC Liquid Testing

Technology	TIC	Test Solvent		
		DI H ₂ O	Tap H ₂ O	DI + NaCl
Proengin AP2C	CN ⁻			
S. S. HazMat Smart Strip	CN ⁻			
	H ₂ O ₂			
	F ⁻			
Truetech M272 Water Kit	CN ⁻			

^a Green = proper response in all three challenges; Yellow = proper response in 1 or 2 of the 3 challenges; Red = no responses in the 3 challenges. Absence of color means test not conducted.

5.2 False Positive/False Negatives

5.2.1 False Positives

Testing for false positive responses was done through challenges with a completely blank sample (i.e., clean air in the TIC vapor testing or DI water in the liquid testing) and through challenges with interferent in the absence of a target TIC (i.e., the hydrocarbon mixture in the vapor testing or the tap water and salt water matrices in the liquid testing). No response was observed from any of the tested technologies when challenged with blank samples or the interferent matrices in either vapor or liquid testing. Thus, no false positives were observed from any of the tested screening technologies.

5.2.2 False Negatives

False negatives are shown by the red or yellow cells in Tables 5-1 and 5-2, which indicate the absence of a response in all three challenges or the absence of a response in one or two challenges, respectively. For clarity, Table 5-3 draws information from Tables 5-1 and 5-2 to list the false negative

responses observed in the vapor and liquid TIC testing. None of the false negatives was attributable to the hydrocarbon mixture used as an interferent in the vapor testing or to the tap water or salt water matrices used in the liquid testing. The great majority of false negatives were simply the inability of the technology to detect the target TIC at the challenge concentration under the base test condition.

In vapor testing, for the Draeger Civil Defense Kit, a false negative rate of 8% for CK (i.e., 1 out of 12 negative responses) is calculated. False negative rates of 25% resulted for the Proengin AP2C for AC and for the Truetech M18A3 tubes for CG. All other negative responses for both vapor and liquid tests in Table 5-3 equated to false negative rates of 100%, as the target TIC was not detected even under the base test conditions.

False negative responses are of great concern in the AHRF sample screening process, so an assessment was made of how the expected detection capabilities of the screening technologies compare to the actual detection behavior summarized in Tables 5-1 through 5-3. This assessment could be done only for vapor-phase TIC detection, as summarized

in Table 5-1, because no information was available from the technology vendors on the likely detection limits of their technologies for TICs in the liquid phase. Even for vapor-phase TIC detection, stated detection limits were not available from the vendors for all the technologies tested.

Regarding the detection of TIC vapors, this assessment shows that in nearly all cases the screening technologies were able to detect the TIC challenge concentrations, when those concentrations were higher than the stated detection limit of the technology. The inability of the Anachemia C2 tubes to detect AC, of the HazMat Smart Strip to detect AC, and of the RAE MultiRAE Plus to detect AC and SA, are the only examples of a technology failing to detect a TIC present at or above the technology's stated detection limit. On the other hand, there are many examples of technologies accurately detecting the vapor-phase TICs, even though the challenge concentrations were lower than the stated detection limits of the technology. The Anachemia CM256A1, MSA Single CWA Kit, Nextteq Civil Defense Kit, Sensidyne Gas Detection Tubes, and Truetech M18A3 tubes all showed

accurate detection of one or more TICs, even when the challenge concentrations were below their stated detection limits. With this detection capability these technologies offer greater protection in sample screening than would be suggested by their stated detection limits.

5.3 Analysis Time

The time required to screen a sample with each of the screening technologies was determined by the effort required for sample collection (e.g., drawing of air sample with a hand pump) or manipulation (e.g., mixing of reagents, breaking of tubes), as well as by the inherent response time of the detection principle of each technology. Table 5-4 summarizes the analysis time observations for each technology, listing the type of samples (vapor or liquid), the approximate typical analysis time (seconds or minutes) characteristic of each technology, and comments on the time response. It should be noted that these results apply to the target TIC concentrations used in this test. The presence of higher concentrations may produce more rapid responses with some technologies.

Table 5-3. Summary of False Negative Responses

Technology	TIC	Number of False Negatives	Test Condition
Vapor			
Anachemia C2 Tubes	AC, CG, CK	3 each	Base
Draeger Civil Defense Kit	CK	1	Base
Proengin AP2C	AC	3 ^a	Low T/Low RH
	CK	3	Base
RAE MultiRAE Plus	AC, CG, Cl ₂ , CK, SA	3 each	Base
S.S. HazMat Smart Strip	AC	3	Base
Truetech M18A3 Tubes	CG	3	High T/High RH
	CK	3	Base
Liquid			
Proengin AP2C	CN ⁻	3	DI H ₂ O
S.S. HazMat Smart Strip	CN ⁻	3	DI H ₂ O
	F ⁻	3	DI H ₂ O

^a At this test condition the Proengin AP2C indicated only L/SA (arsenic compound) and not HN/AC (cyanide compound), although both indications were given with AC at the other three test conditions.

Table 5-4. Summary of Sample Analysis Times

Technology	Sample Type	Response Time ^a	Comments
Anachemia C2 Tubes	Vapor	min	Requires a few minutes to complete recommended ten pump strokes
Anachemia CM256A1	Vapor	sec	Color occurs within several seconds after exposure; manipulation of card takes up to one minute
Draeger Civil Defense Kit	Vapor	sec	Color change begins to occur in several seconds, however recommended 50 pump strokes take a couple minutes to complete
Draeger CMS Analyzer	Vapor	min	Automated color tube sampler and reader, takes several minutes for a reading
MSA Single CWA Kit	Vapor	min	Time for noticeable color change depends on concentration of analyte; recommended 30 pump strokes take a couple minutes to complete
Nextteq Civil Defense Kit	Vapor	min	Time for noticeable color change depends on concentration of analyte; required sample volume takes several minutes with electric pump
Proengin AP2C	Vapor	sec	Response typically occurs within a few seconds
	Liquid	sec	Less than one minute to install scraper, wet scraper with sample, desorb scraper into inlet, and obtain instrument response
RAE MultiRae Plus	Vapor	sec	Response within approximately 15 seconds
S. S. HazMat Smart Strip	Vapor	sec	Color change within several seconds
	Liquid	sec	Color change within a few seconds
Sensidyne Gas Tubes	Vapor	sec	Color change almost immediate (within a few seconds); one minute needed per pump stroke; for test concentrations only one pump stroke was needed
Truetech M18A3	Vapor	min	Recommended 60 pump strokes take several minutes to complete; color change begins in a fraction of that time
Truetech M272 Water Kit	Liquid	min	Several minutes due to complexity of procedure required

^a Indication of whether typical time to response occurs in minutes (Min) or seconds (Sec).

5.4 Repeatability

For the three screening technologies that provided quantitative readings (the Draeger CMS Analyzer, MultiRAE Plus, and Sensidyne gas tubes), the repeatability of the

readings at each test condition was determined. Table 5-5 summarizes the responses obtained from these two technologies, showing for each TIC and test condition the nominal TIC concentration and the mean, standard deviation, and %RSD of the screening technology readings.

Table 5-5. Repeatability of Technology Readings

Technology	TIC	Condition	Nominal TIC Conc.	Readings			
				Mean	Std. Dev	%RSD	
Draeger CMS	AC	Base+Int	17 ppm	12.4	2.8	22.3	
		Low T/RH		16.9	4.0	23.7	
		High T/RH		9.7	1.4	14.0	
	CG	Base	0.6 ppm	0.52	0.06	11.5	
		Base+Int		0.51	0.07	13.7	
		Low T/RH		0.52	0.06	11.5	
		High T/RH		0.59	0.05	8.5	
	Cl2	Base	2.8 ppm	2.9	0.8	27.2	
		Base+Int		3.3	0.2	6.4	
		Low T/RH		2.9	0.5	16.0	
		High T/RH		2.1	0.5	24.2	
	H2S	Base	41 ppm	41.7	2.1	5.0	
		Base+Int		44.7	1.5	3.4	
		Low T/RH		41.0	1.0	2.4	
		High T/RH		42.3	2.1	4.9	
MultiRAE Plus	H2S	Base	41 ppm	8.0	0.7	8.2	
		Base+Int		5.9	0.8	13.6	
		Low T/RH		10.9	1.0	8.7	
		High T/RH		9.7	1.4	14.1	
Sensidyne Tubes	AC	Base	17 ppm	23.0	1.4	6.1	
		Base+Int		27.0	1.7	6.4	
		Low T/RH		24.3	3.2	13.2	
		High T/RH		17.0	0.0	0	
		CG	Base	0.6 ppm	1.0	0.0	0
			Base+Int		1.0	0.0	0
			Low T/RH		1.3	0.3	21.8
			High T/RH		1.0	0.0	0
		Cl2	Base	2.8 ppm	2.0	0.0	0
			Base+Int		2.4	0.4	15.0
			Low T/RH		3.0	0.2	5.7
			High T/RH		2.4	0.5	21.0
		H2S	Base	41 pm	55.3	1.2	2.1
			Base+Int		58.0	2.0	3.4
			Low T/RH		53.3	1.2	2.2
			High T/RH		52.0	2.0	3.8
	SA	Base	0.3 ppm	0.42	0.03	7.1	
		Base+Int		0.40	0.0	0	
		Low T/RH		0.45	0.05	11.1	
		High T/RH		0.43	0.06	14.0	

Table 5-5 shows that most of the %RSD values (32 of 40 results) are less than 15% and over half (22 of 40) are less than 10%, indicating that these screening technologies can provide precise quantitative responses. However, several %RSD values exceed 20%, most commonly with the Draeger CMS for AC and CI2. There does not appear to be any clear dependence of the %RSD values on the test condition for any of these three technologies. The overall result of this evaluation is that close precision of readings can occur with these quantitative screening technologies, but it cannot be assumed under all circumstances.

5.5 Operational Factors

Operational factors were assessed based on the observations of the test operator and are summarized in Table 5-6, which for each TIC technology describes the general ease of use, any problems noted in using the technology, and the physical effort required for use. The latter issue was included because several of the vapor sampling technologies rely on drawing sample air through a colorimetric tube using a hand pump, and such effort can become tedious if performed repetitively.

Table 5-6. Summary of Observations on Operational Factors of the Technologies

Technology	General Ease of Use	Problems with Use	Physical Effort Needed
Anachemia C2 Tubes	Relatively complex procedure (with some analytes) of breaking tube, inserting into pump, drawing sample through, then adding reagent to tube	Sample tube packets say not to use after September 10 with no specific year indicated — distributor says 2010; pump difficult to use, and could not tell if working properly	Arm/hand strength needed for pump
Anachemia CM256A1	Simple procedure of breaking ampoules on a card to wet/activate test patches and exposing patches to sample; easily distinguishable color changes	Breakage of two green ampoules at one time causes rapid exothermic reaction — creates fumes and sprays green liquid	Minimal
Draeger Civil Defense Kit	Simple procedure of breaking tubes, inserting into manifold, and drawing sample through tubes; easily distinguishable color changes; five compounds can be tested for at one time	Prolonged use can cause fatigue to hands; Draeger sells five-tube sets to be used with kit, which are approximately five times more expensive on a per-tube basis compared to single tubes purchased separately	Hand strength needed for pump
Draeger CMS Analyzer	Simple procedure of sliding chip back and forth inside electronic device with a slide switch; 10 sequential analyses of a chemical per chip; gives a digital reading	Gears for slide switch easily become misaligned; if misalignment occurs chip can become unusable	Minimal effort needed to move sliding switch back and forth
MSA Single CWA Kit	Simple procedure of breaking tube and inserting into pump; most tubes test for more than one compound	Some color changes not very distinguishable; prolonged use can cause hand fatigue; squeeze counter on pump broke after a couple uses	Hand strength needed for pump operation
Nextteq Civil Defense Kit,	Simple procedure of breaking tubes, inserting into manifold, and drawing sample through tubes; five compounds can be tested for at one time	Impregnating adsorbent layer by breaking liquid ampoules sometimes difficult; electric pump flow was easily disrupted causing pump to stop; some color changes difficult to distinguish	Minimal effort with electric pump; manual pump also available

Table 5-6. (Continued)

Technology	General Ease of Use	Problems with Use	Physical Effort Needed
Proengin AP2C	Simple procedure of starting device and waiting for reading (for vapors) or taking sample with scraper tip, heating scraper tip inline with device and waiting for reading (for liquids)	No significant problems; low-pressure hydrogen supplies will need replacement periodically in regular use (12-hour supply life easily maximized by turning instrument on and off)	None
RAE MultiRAE Plus	Simple procedure of starting device and waiting for electronic reading	Device uses PID for general detection, with electrochemical sensors for specific compounds; PID sensor nonresponsive to TICs, only electrochemical sensor for H ₂ S gave response	None
S. S. HazMat Smart Strip	Peel off protective cover for immediate use	Some color changes almost imperceptible; instructions say mainly used for aerosols making reliability of vapor and liquid tests uncertain	None
Sensidyne Gas Tubes	Simple procedure of breaking tube, inserting into pump, and drawing sample through; easily distinguishable color changes; tubes graduated to estimate concentration	Only one TIC can be tested for at a time	Number of pump strokes needed depends on suspected concentration; only one stroke required for distinguishable color change at tested concentrations
Truetech M18A3 Tubes	Relatively complex procedure (with some analytes) of breaking tube, inserting into bulb, drawing sample through, then adding reagent to tube	Some tubes not scored making breaking difficult; repeated use causes ends of tubes to shred bulb orifice causing blockage and potential leak problem; some color changes not very distinguishable; repetitive use caused hand soreness	Hand strength needed
Truetech M272 Water Kit	Relatively complex procedure involving wet chemistry and adsorbent tubes	Requires 60 mL of sample and multiple steps for detection	Minimal effort but time consuming

5.6 Screening Technology Costs

In choosing technologies for screening large numbers of samples in an AHRF, both the initial cost of a TIC screening technology and the cost per sample of the technology in extended use are important. Table 5-7 summarizes the cost information for each technology tested, showing the identity of each technology, the purchase price of the technology as tested, and the per-sample cost of consumable items.

Table 5-7 shows that the purchase costs of most of the screening technologies were approximately \$3,000 or less, with the Proengin AP2C the exception at nearly \$16,000. (As noted in the table, the Proengin AP2C purchase price was a discount from the vendor because of the nature of this program; the normal purchase price is likely to be approximately 30% higher.) However, comparison of the purchase prices of different technologies can be misleading because many of the technologies as purchased can screen relatively few samples with the original materials. For

example, for most of the technologies in Table 5-7 that rely on color-indicating tubes, the purchased technology typically allows screening of only about 10 to 40 samples. Testing larger numbers of samples requires obtaining additional tubes, and indeed numerous purchases of additional consumable items were needed to complete the testing reported here. On the other hand, for the two Truetech technologies in Table 5-7, the consumable sampling tubes are not available except as part of the original kit, i.e., obtaining more screening capability means buying another kit. The lowest extreme in terms of original purchase price is the Safety Solutions HazMat Smart Strip at \$20, however this indicator card technology is purchased one at a time, so only a single sample screening is obtained for that price. At the other extreme, the relatively expensive MultiRAE Plus and Proengin AP2C detectors are capable of screening large numbers of samples without frequent replacement of consumables.

AHRF operations may call for screening of large numbers of samples, and therefore the cost of extended use of each technology is important. Table 5-7 shows that for most of the TIC screening technologies tested, per-sample costs in long-term use are typically \$5 to \$10, with some variation depending on the TIC in question. Per-sample costs for the HazMat Smart Strip and the Truetech M18A3 kit are \$20 and about \$15, respectively. The purchase cost of each Anachemia CM256A1 indicator card is about \$17, but because each card can detect three different TICs/CWAs, the per-sample cost is estimated at about \$5. Long-term per-sample costs of the MultiRAE Plus and the Proengin AP2C are lower but also less well defined. For the MultiRAE Plus, the primary expendable cost will be replacement of batteries; however, battery life was not assessed in this test. This cost would probably equate to pennies per sample in continuous use. The Proengin AP2C uses low-pressure hydrogen supplies that are designed to last for 12 hours of continuous use; supply life was not tested in this program but

this life seems reasonable based on the experience in testing the instrument. The Proengin AP2C is designed to be turned off whenever sample screening is not in progress, so the 12-hour supply life can equate to substantially longer periods of use depending on the frequency of sample screening. An indicator on the instrument shows the status of the hydrogen supply. Two fully charged hydrogen supplies are provided in the Proengin AP2C package. These supplies can be refilled by Proengin at a cost of \$25 each, plus a charge of \$225 for shipping of 1 to 10 supplies at a time to and from Proengin's office in Fort Lauderdale, Florida. Purchase of single, new, fully charged hydrogen supplies, separate from purchase of the detector, costs \$488 each. A refilling bench that allows the user to recharge the supplies from a high pressure cylinder of hydrogen is also available for approximately \$65,000. The Proengin AP2C also uses batteries; however, the cost of battery replacement is likely trivial compared to the cost of replacing the hydrogen supply.

Table 5-7. Cost Information on TIC Screening Technologies

Vendor	Technology	Technology Cost	Consumable Items	Cost per Sample ^a
Anachemia	C2	\$684	Tubes (boxes of 5)	\$7
	CM256A1	\$189	Card	~\$5
Draeger	CMS Analyzer	\$1,922	Chips (10 tubes per chip)	AC: \$5 CG: \$7 Cl ₂ : \$4 H ₂ S: \$4
	Civil Defense Kit	\$3,114	Tubes (boxes of 10)	AC: \$6 CK: \$9 CG: \$8 SA: \$8 Cl ₂ : \$7
MSA	Single CWA Sampler Kit	\$1,295	Tubes (boxes of 10)	AC: \$8 CK: \$8 CG: \$8
Nextteq	Civil Defense Kit	\$1,875	Tubes (boxes of 10)	AC: \$5 CK: \$5 CG: \$5
Proengin	AP2C	\$15,708 (discount for testing)	Hydrogen supplies; batteries. Scraper tips for liquid sampling (packs of 10).	<\$3 ^b \$4 (for liquid sampling)
RAE Systems	MultiRae Plus	\$3,290	Batteries	<< \$1
Safety Solutions	HazMat Smart Strip	\$20	Card	\$20
Sensidyne	Gas Detection Tubes	\$532	Tubes (boxes of 10)	AC: \$6 CG: \$6 SA: \$6 Cl ₂ : \$6 H ₂ S: \$6
Truetech	M272 Water Kit	\$386	Tubes (purchased as part of kit)	~\$5 ^c
	M18A3	\$1,189	Tubes (purchased as part of kit)	~\$15 ^c

^a Except as noted otherwise, approximate cost per sample analysis in extended use, based on cost of consumable items (excluding original purchase price of the technology).

^b Per sample cost assumes 100 samples can be screened per hydrogen supply and that refill costs are worst-case \$250 per supply (see text).

^c Cost per sample estimated based on original purchase price and number of analyses provided by original materials (consumables not available except as part of kit).

Performance Summary

The ideal characteristics of a TIC screening technology for use in the AHRF include accurate detection of TICs; absence of false positive and negative responses; absence of temperature, RH, or interferent effects; a rapid and simple sample screening process; and low initial and operating costs. As a secondary characteristic, for a technology that gives a quantitative response, consistency of response is valuable in that the technology may be able to distinguish heavily contaminated from lightly contaminated samples.

The testing reported here was designed to evaluate the screening technologies on each of the characteristics listed above, and that purpose was accomplished. However, the limitations of this evaluation relative to screening samples in the AHRF should also be noted. This evaluation addressed a wide variety of screening technologies and focused on the relative performance of those technologies for use in the AHRF, rather than on in-depth investigation of any single technology. Similarly, testing of vendor performance claims was not an objective of the evaluation. For example, determination of the detection limits of the screening technologies was specifically not a goal of this evaluation. Rather, the challenge TIC concentrations were chosen based on health risk information and the desire to protect AHRF staff, and the ability to detect the presence of TICs at those levels was assessed regardless of vendor claims about detection limits. Also, test conditions in this evaluation were intended to represent those under which the screening technologies might actually be used in the AHRF, but those actual conditions are not completely known at this time. Thus, the sample matrices, temperature and RH ranges, and interferences used may not fully address the reality of AHRF operations. This evaluation also focused on relatively inexpensive technologies suitable for screening large numbers of samples. Other, far more expensive, technologies exist that might prove useful in some aspects of AHRF operations. On the other hand, this evaluation tested each technology in realistic use by a skilled practitioner, in a manner that closely represents how the technology would be used under the AHRF screening protocol (Figure 1-1). As a result, the results summarized below represent a valuable assessment of the usefulness of each technology for AHRF screening.

Regarding accuracy for vapor-phase TICs, most of the tested technologies showed 100% accuracy, or nearly so, in detecting the TICs to which they were applicable. Notable exceptions were the Anachemia C2 tubes, which did not detect any of the three TICs with which they were challenged, and the PID sensor of the MultiRAE Plus detector, which (consistent with the nature of the PID) did not respond to several TICs. However, none of the tested technologies was designed to detect all six of the target TICs; the Sensidyne Gas Tubes and Draeger Civil Defense Kit

exhibited 100% accuracy, or nearly so, for five TICs, and the Draeger CMS Analyzer for four. Regarding accuracy in detecting TICs in water samples, the HazMat Smart Strip was 100% accurate in detecting hydrogen peroxide, as was the Truetech M272 Water Kit in detecting cyanide.

For those technologies that provided a quantitative indication of the TIC vapor concentration during testing (i.e., the Draeger CMS Analyzer, MultiRAE Plus [for H₂S only], and Sensidyne Gas Tubes), the %RSD of triplicate responses was within 15% in 32 of the 40 challenge sets with these technologies and within 10% in 22 of those 40 tests. Test conditions had no apparent effect on the %RSD values. Thus, close precision of responses can be obtained in screening with these technologies but cannot be assumed in all tests.

None of the tested technologies produced any false positive responses in either vapor- or liquid-phase TIC testing. False negatives mainly occurred as the inability of a technology to detect a TIC even under the base test conditions. The Anachemia C2 and MultiRAE Plus results noted above were the prime examples, but false negatives under base conditions also occurred with the Proengin AP2C and Truetech M18A3 tubes for CK and the HazMat Smart Strip for AC in vapor testing, and with the HazMat Smart Strip for CN⁻ and F⁻ and Proengin AP2C for CN⁻ in liquid testing.

No effect of interferences was seen, in either vapor- or liquid-phase testing, with those technologies challenged with the interferences. Temperature and RH effects in vapor testing were also minimal. In fact, results potentially attributable to temperature and RH effects were seen in only two cases. The Truetech M18A3 failed to respond to CG at the high T/high RH condition, and the Proengin AP2C gave an incorrect response to AC at the low T/low RH condition.

The speed and simplicity of the screening process varied widely among the tested technologies. All of the vapor detection technologies based on color-indicating tubes are simple to use in principle but differed in the time and difficulty of obtaining the sample. With such technologies, the number of manual pump strokes required to draw the sample ranged from 1 (Sensidyne Gas Tubes) to 60 (Truetech M18A3), and the manual effort needed for those technologies requiring 30 or more pump strokes was excessive even when screening small numbers of samples as in this test. Electric air sampling pumps, whether internal to the technology (as in the automated Draeger CMS Analyzer) or external (as in the Nextteq Civil Defense Kit) greatly reduce the physical effort needed but still may require several minutes to draw the required volume. Use of color-indicating tubes that require the minimum volume would seem preferable for use in the AHRF, and use of an electrical sampling pump might be helpful even then, if large numbers of samples are to be screened. The two real-time analyzers tested (MultiRAE

Plus and Proengin AP2C) provided easy and rapid sample screening, although only the electrochemical H₂S sensor in the MultiRAE Plus provided response from that instrument in these tests. The speed of screening water samples with the Proengin AP2C was also relatively rapid because of the simplicity of wetting the “scraper” attachment and desorbing into the instrument inlet. The HazMat Smart Strip was the simplest technology to use, requiring only removal of a protective film to expose the indicating patches on the card. However, this technology did not respond to AC. For vapor detection in the AHRF, the HazMat Smart Strip is best suited to being enclosed within a container or attached to a surface, rather than being used as a hand-held sampling tool. The

Anachemia CM256A1 multifunction card was considerably more difficult to use, requiring hand manipulation to heat and direct reagents to sections of the card, but provided accurate detection of the only two TICs for which it was applicable (AC and CK).

In terms of the speed and simplicity of liquid sample screening, the Truetech M272 Water Kit was found to be deficient. The multiple detection tubes and reagent tablets needed, and the requirement for 60 mL of water sample, make it unlikely that this technology would be suitable for the AHRF.

7.0

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Appendix A

Results of Testing with Vapor-Phase Toxic Industrial Chemicals

Vapor Challenge Results Summary: results of all tests with vapor-phase TICs

Vapor Actual ppm vs Nominal ppm: results showing quantitative responses and %RSD values for those technologies listed as providing a “concentration” response in the previous table

Vapor False Positives: results obtained from all technologies when challenged with exhaust gas interferent in the absence of any TICs

Vapor Challenge Results Summary

Technology	Chemical	Temperature	Humidity	Interferent	Result	Count of Result
<i>Anachemia C2</i>						
	AC	Medium	Medium	None	none	3
	CG	Medium	Medium	None	green (no CG present)	3
	CK	Medium	Medium	None	none	3
<i>Anachemia CM256A1</i>						
	AC	Medium	Medium	None	pink/blue	3
	AC	Medium	Medium	Gas Exhaust (1%)	pink	3
	AC	Low	Low	None	pink	3
	AC	High	High	None	pink/blue	3
	CK	Medium	Medium	None	pink/blue	3
	CK	Medium	Medium	Gas Exhaust (1%)	pink/blue	3
	CK	Low	Low	None	pink/blue	3
	CK	High	High	None	pink/blue	3
<i>Draeger CDS</i>						
	AC	Medium	Medium	None	red	3
	AC	Medium	Medium	Gas Exhaust (1%)	red	3
	AC	Low	Low	None	red	3
	AC	High	High	None	red	3
	CG	Medium	Medium	None	green	3
	CG	Medium	Medium	Gas Exhaust (1%)	green	3
	CG	Low	Low	None	strong green	3
	CG	High	High	None	slight green	3
	Chlorine	Medium	Medium	None	brown	3
	Chlorine	Medium	Medium	Gas Exhaust (1%)	brown	3
	Chlorine	Low	Low	None	brown	3
	Chlorine	High	High	None	brown stain	3
	CK	Medium	Medium	None	none	1
	CK	Medium	Medium	None	pink	2
	CK	Medium	Medium	Gas Exhaust (1%)	pink	3
	CK	Low	Low	None	pink	3
	CK	High	High	None	pink	3
	SA	Medium	Medium	None	dark ring	3
	SA	Medium	High	Gas Exhaust (1%)	purple stain	3

Technology	Chemical	Temperature	Humidity	Interferent	Result	Count of Result
Draeger CMS	SA	Low	Low	None	purple stain	3
	SA	High	High	None	purple ring	3
	AC	Medium	Medium	None	concentration ^a	3
	AC	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	AC	Low	Low	None	concentration ^a	3
	AC	High	High	None	concentration ^a	3
	CG	Medium	Medium	None	concentration ^a	3
	CG	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	CG	Low	Low	None	concentration ^a	3
	CG	High	High	None	concentration ^a	3
	Chlorine	Medium	Medium	None	concentration ^a	3
	Chlorine	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	Chlorine	Low	Low	None	concentration ^a	3
	Chlorine	High	High	None	concentration ^a	3
MSA	H ₂ S	Medium	Medium	None	concentration ^a	3
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	H ₂ S	Low	Low	None	concentration ^a	3
	H ₂ S	High	High	None	concentration ^a	3
	AC	Medium	Medium	None	red spots	3
	AC	Medium	Medium	Gas Exhaust (1%)	red spots	3
	AC	Low	Low	None	orange spots	3
	AC	High	High	None	yellow/orange	3
	CG	Medium	Medium	None	red	3
	CG	Medium	Medium	Gas Exhaust (1%)	red	3
	CG	Low	Low	None	slight red	3
	CG	High	High	None	red	3
	CK	Medium	Medium	None	light pink	3
	CK	Medium	Medium	Gas Exhaust (1%)	light pink	3
CK	Low	Low	None	pink	3	
CK	High	High	None	slight pink	3	
Multi RAE Plus	AC	Medium	Medium	None	none	3

Technology	Chemical	Temperature	Humidity	Interferent	Result	Count of Result
	CG	Medium	Medium	None	none	3
	Chlorine	Medium	Medium	None	none	3
	CK	Medium	Medium	None	none	3
	H ₂ S	Medium	Medium	None	concentration ^a	3
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	H ₂ S	Low	Low	None	concentration ^a	3
	H ₂ S	High	High	None	concentration ^a	3
	SA	Medium	Medium	None	none	3
<i>Nextteq</i>						
	AC	Medium	Medium	None	dark pink	3
	AC	Medium	Medium	Gas Exhaust (1%)	dark pink	3
	AC	Low	Low	None	red stain	3
	AC	High	High	None	red stain	3
	CG	Medium	Medium	None	red	3
	CG	Medium	Medium	Gas Exhaust (1%)	red	3
	CG	Low	Low	None	red	3
	CG	High	High	None	red	3
	CK	Medium	Medium	None	pink	3
	CK	Medium	Medium	Gas Exhaust (1%)	pink	3
	CK	Low	Low	None	pink	3
	CK	High	High	None	pink	3
<i>Proengin AP2C</i>						
	AC	Medium	Medium	None	HN,AC level 1; L,SA level 1	3
	AC	Medium	Medium	Gas Exhaust (1%)	HN,AC level 1; L,SA level 1	3
	AC	Low	Low	None	L,SA level 1 and 2	3
	AC	High	High	None	HN,AC level 1; L,SA level 1	3
	CK	Medium	Medium	None	none	3
	H ₂ S	Medium	Medium	None	L,SA level 1; HD,HL level 1, 2, and 3	3
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	L,SA level 1; HD,HL level 1 and 2	2
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	L,SA level 1; HD,HL level 1, 2 and 3	1
	H ₂ S	Low	Low	None	L,SA level 1; HD,HL level 1, 2 and 3	3
	H ₂ S	High	High	None	HD,HL level 1, 2, 3, 4 and 5	3
	SA	Medium	Medium	None	L,SA level 1 and 2	3

Technology	Chemical	Temperature	Humidity	Interferent	Result	Count of Result
Safety Solutions	SA	Medium	Medium	Gas Exhaust (1%)	L, SA level 1 and 2	3
	SA	Low	Low	None	L, SA level 1 and 2	3
	SA	High	High	None	L, SA level 1 and 2	1
	SA	High	High	None	L, SA level 1, 2, and 3	2
	AC	Medium	Medium	None	none	3
	Chlorine	Medium	Medium	None	chlorine: grey; oxidizer: yellow	3
	Chlorine	Medium	Medium	Gas Exhaust (1%)	chlorine: grey; oxidizer: yellow	3
	Chlorine	Low	Low	None	chlorine: grey; oxidizer: yellow	3
	Chlorine	High	High	None	chlorine: grey; oxidizer: black	3
	H ₂ S	Medium	Medium	None	beige	3
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	beige	3
	H ₂ S	Low	Low	None	light beige	3
H ₂ S	High	High	None	black	3	
Sensidyne	AC	Medium	Medium	None	concentration ^a	3
	AC	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	AC	Low	Low	None	concentration ^a	3
	AC	High	High	None	concentration ^a	3
	CG	Medium	Medium	None	concentration ^a	3
	CG	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	CG	Low	Low	None	concentration ^a	3
	CG	High	High	None	concentration ^a	3
	Chlorine	Medium	Medium	None	concentration ^a	3
	Chlorine	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	Chlorine	Low	Low	None	concentration ^a	3
	Chlorine	High	High	None	concentration ^a	3
H ₂ S	Medium	Medium	None	concentration ^a	3	
H ₂ S	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3	
H ₂ S	Low	Low	None	concentration ^a	3	
H ₂ S	High	High	None	concentration ^a	3	

Technology	Chemical	Temperature	Humidity	Interferent	Result	Count of Result
	SA	Medium	Medium	None	concentration ^a	3
	SA	Medium	Medium	Gas Exhaust (1%)	concentration ^a	3
	SA	Low	Low	None	concentration ^a	3
	SA	High	High	None	concentration ^a	3
<i>Truetech</i>						
	AC	Medium	Medium	None	blue stain	3
	AC	Medium	Medium	Gas Exhaust (1%)	blue	3
	AC	Low	Low	None	blue	3
	AC	High	High	None	light blue	3
	CG	Medium	Medium	None	slight green	3
	CG	Medium	Medium	Gas Exhaust (1%)	green	3
	CG	Low	Low	None	green	3
	CG	High	High	None	none	3
	CK	Medium	Medium	None	none	4

a: See table starting on page A-7 for summary of quantitative readings.

Vapor Actual ppm vs Nominal ppm

Technology	Chemical	Temperature Range	RH Range	Interferent	Average (ppm)	Std Dev	Nominal Concentration
<i>Draeger CMS</i>							
	AC	Medium	Medium	None	14.77	7.31	AEGL-2 17ppm
	AC	Medium	Medium	Gas Exhaust (1%)	12.37	2.76	AEGL-2 17ppm
	AC	Low	Low	None	16.93	4.01	AEGL-2 17ppm
	AC	High	High	None	9.67	1.35	AEGL-2 17ppm
	CG	Medium	Medium	None	0.52	0.06	AEGL-2 0.6 ppm
	CG	Medium	Medium	Gas Exhaust (1%)	0.51	0.07	AEGL-2 0.6 ppm
	CG	Low	Low	None	0.52	0.06	AEGL-2 0.6ppm
	CG	High	High	None	0.59	0.05	AEGL-2 0.6ppm
	Chlorine	Medium	Medium	None	2.87	0.78	AEGL-2 2.8ppm
	Chlorine	Medium	Medium	Gas Exhaust (1%)	3.29	0.21	AEGL-2 2.8ppm
	Chlorine	Low	Low	None	2.88	0.46	AEGL-2 2.8ppm
	Chlorine	High	High	None	2.07	0.50	AEGL-2 2.8ppm
	H ₂ S	Medium	Medium	None	41.67	2.08	AEGL-2 41 ppm
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	44.67	1.53	AEGL-2 41 ppm
	H ₂ S	Low	Low	None	41.00	1.00	AEGL-2 41 ppm
	H ₂ S	High	High	None	42.33	2.08	AEGL-2 41 ppm
<i>Multi RAE Plus</i>							
	AC	Medium	Medium	None	0.00	0.00	AEGL-2 17ppm
	CG	Medium	Medium	None	0.00	0.00	AEGL-2 0.6ppm
	Chlorine	Medium	Medium	None	0.00	0.00	AEGL-2 2.8ppm
	CK	Medium	Medium	None	0.00	0.00	TEEL-2 0.4 ppm
	H ₂ S	Medium	Medium	None	7.97	0.65	AEGL-2 41ppm
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	5.90	0.80	AEGL-2 41ppm
	H ₂ S	Low	Low	None	10.90	0.95	AEGL-2 41ppm
	H ₂ S	High	High	None	9.70	1.37	AEGL-2 41ppm
<i>Sensidyne</i>							
	AC	Medium	Medium	None	23.00	1.41	AEGL-2 17ppm
	AC	Medium	Medium	Gas Exhaust (1%)	27.00	1.73	AEGL-2 17ppm
	AC	Low	Low	None	24.33	3.21	AEGL-2 17ppm
	AC	High	High	None	17.00	0.00	AEGL-2 17ppm
	CG	Medium	Medium	None	1.00	0.00	AEGL-2 0.6 ppm
	CG	Medium	Medium	Gas Exhaust (1%)	1.00	0.00	AEGL-2 0.6 ppm

<i>Technology</i>	<i>Chemical</i>	<i>Temperature Range</i>	<i>RH Range</i>	<i>Interferent</i>	<i>Average (ppm)</i>	<i>Std Dev</i>	<i>Nominal Concentration</i>
	CG	Low	Low	None	1.33	0.29	AEGL-2 0.6 ppm
	CG	High	High	None	1.00	0.00	AEGL-2 0.6 ppm
	Chlorine	Medium	Medium	None	2.00	0.00	AEGL-2 2.8ppm
	Chlorine	Medium	Medium	Gas Exhaust (1%)	2.40	0.36	AEGL-2 2.8ppm
	Chlorine	Low	Low	None	3.00	0.17	AEGL-2 2.8ppm
	Chlorine	High	High	None	2.43	0.51	AEGL-2 2.8ppm
	H ₂ S	Medium	Medium	None	55.33	1.15	AEGL-2 41 ppm
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	58.00	2.00	AEGL-2 41 ppm
	H ₂ S	Low	Low	None	53.33	1.15	AEGL-2 41 ppm
	H ₂ S	High	High	None	52.00	2.00	AEGL-2 41 ppm
	SA	Medium	Medium	None	0.42	0.03	AEGL-2 0.3 ppm
	SA	Medium	Medium	Gas Exhaust (1%)	0.40	0.00	AEGL-2 0.3ppm
	SA	Low	Low	None	0.45	0.05	AEGL-2 0.3 ppm
	SA	High	High	None	0.43	0.06	AEGL-2 0.3 ppm

Vapor False Positives

Technology	Potential Response	Temperature Range	Relative Humidity Range	Interferent	Blank/Challenge	Response	Result
<i>Anachemia</i>							
	AC or CK	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
<i>Draeger CDS</i>							
	AC, CK, CG, SA, or Chlorine	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
<i>Draeger CMS</i>							
	AC	Medium	Medium	Gas Exhaust (1%)	Challenge	< 2.00 ppm	< 2.00 ppm
	CG	Medium	Medium	Gas Exhaust (1%)	Challenge	< 0.050 ppm	< 0.050 ppm
	Chlorine	Medium	Medium	Gas Exhaust (1%)	Challenge	< 2.00 ppm	< 2.00 ppm
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	Challenge	< 2.00 ppm	< 2.00 ppm
<i>MSA</i>							
	AC, CK, or CG	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
<i>Multi RAE Plus</i>							
	AC, CK, CG, SA, Chlorine, or H ₂ S	Medium	Medium	Gas Exhaust (1%)	Challenge	0.0 ppm	0.0 ppm
<i>Nextteq</i>							
	AC, CK, or CG	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
<i>Proengin AP2C</i>							
	AC, CK, SA, or H ₂ S	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
<i>Safety Solutions</i>							
	AC, H ₂ S, or Chlorine	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
	AC	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
	CG	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
	Chlorine	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
	H ₂ S	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
	SA	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
<i>Truetech</i>							
	AC	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none
	CG	Medium	Medium	Gas Exhaust (1%)	Challenge	none	none

Appendix B

Results of Testing with Toxic Industrial Chemicals in Liquid Samples

Liquid Challenge Results Grouped: results of all tests with liquid-phase TIC solutions

Liquid Challenge Results Grouped

<i>Technology</i>	<i>Chemical</i>	<i>Interferent</i>	<i>Response</i>	<i>Count of Result</i>
<i>Proengin AP2C</i>				
	CN ⁻ /DI H ₂ O	None	none	3
<i>Safety Solutions</i>				
	CN ⁻ /DI H ₂ O	None	none	3
	F ⁻ /DI H ₂ O	None	none	3
	H ₂ O ₂ /DI H ₂ O	None	dark purple	3
	H ₂ O ₂ /DI H ₂ O	Tap Water	dark purple	3
	H ₂ O ₂ /DI H ₂ O	3% NaCl	dark purple	3
<i>Truetech M272 Water Kit</i>				
	CN ⁻ /DI H ₂ O	None	Red tube: blue; blue tube: none	3
	CN ⁻ /DI H ₂ O	Tap Water	Red tube: blue; blue tube: none	3
	CN ⁻ /DI H ₂ O	3% NaCl	Red tube: blue; blue tube: none	3

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