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Environmental Applications of Small Unmanned Aircraft Systems in Multi-Service Tactics, Techniques, and Procedures for Chemical, Biological, Radiological, and Nuclear Reconnaissance and Surveillance

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ENVIRONMENTAL APPLICATIONS OF SMALL UNMANNED AIRCRAFT SYSTEMS IN MULTI-SERVICE TACTICS, TECHNIQUES, AND PROCEDURES FOR CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR RECONNAISSANCE AND SURVEILLANCE

THESIS

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Abstract

Small unmanned aircraft systems can be used for a variety of environmental applications. SUAS under 50 kg have the most utility at the tactical level and benefit from the research and development of systems currently being manufactured. Integrating chemical sensors into these systems can enhance Multi-service Tactics, Techniques, and Procedures for Chemical, Biological, Radiological, and Nuclear Reconnaissance and Surveillance. Considering the advantages and disadvantages in the fundamental science of twelve detection technologies, four types of sensors emerged as candidates for SUAS integration. Using specifications from commercial-off-the-shelf sensors, these four detection technologies (Electrochemical, Metal Oxide Semiconductor, Photoionization, and Catalytic Bead) were further evaluated on five parameters (response time, sensitivity, selectivity, power, and weight). Based on this research, MOS detectors are the top detection technology for SUAS employment and integration. In addition to classic chemical warfare agents, toxic industrial chemicals pose a risk to both civilian and military personnel. Eighty-five hazardous chemicals were identified by cross-referencing chemicals detectable using these four technologies with CWA and TIC of interest based on their toxicity and or security issue. Finally, a multi-objective decision model provides a basic decision aid for employing SUAS as a CBRN R&S asset in a tactical environment.

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Brandon B. Barnes

Table of Contents

List of Figures

List of Tables

List of Equations

List of Abbreviations

ACORNS	Array Configurable of Remote Network Sensors
AEGL	Acute Exposure Guideline Levels
AEL	Airborne Exposure Limits
ATD	Advanced Technology Demonstration
ATTP	Army Tactics, Techniques, and Procedures
BLOS	Beyond Line of Sight
BTWC	Biological and Toxin Weapons Convention
CAT	Catalytic
CB	Chemical-Biological
CBRN	Chemical, Biological, Radiological, and Nuclear
CFR	Code of Federal Regulations
COI	Chemicals of Interest
COTS	Commercial off the Shelf
CWA	Chemical Warfare Agent
CWC	Chemical Weapons Convention
DOD	Department of Defense
DOE	Department of Energy
DOJ	Department of Justice
DOT	Department of Transportation
DTRA	Defense Threat Reduction Agency
EC	Electrochemical
ECD	Electron Capture
FID	Flame Ionization Detector
FTIR	Fourier Transform Infrared
GC	Gas Chromatograph
GPS	Global Position System
HALE	High Altitude, Long Endurance
HAPSITE	Hazardous Air Pollutants on Site
IED	Improvised Explosive Device
IMS	Ion Mobility Spectrometry
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
ITF-25	International Task Force 25
JACCS	Joint All-Hazards Common Control Station
JP	Joint Publication
JPEO-CBD	The Joint Program Executive Office for Chemical and Biological Defense

JSTO	Joint Science and Technology Office
JUPITR	Joint U.S. Forces in Korea Portal and Integrated Threat Recognition
LALE	Low Altitude, Long Endurance
LASE	Low Altitude, Short Endurance
LOS	Line of Sight
MALE	Medium Altitude, Long Endurance
MAV	Micro/Miniature Air Vehicle
MAVERECS	Micro-Air Vehicle Enabled Radiological and Environmental Chemical Sensing
MCWP	Marine Corps Warfighting Publication
METT-TC	Mission, Enemy, Terrain and Weather, Troops and Support Available and Civilian Considerations
MOE	Measures of Effectiveness
MOP	Measures of Performance
MOPP	Mission-Oriented Protective Posture
MOS	Metal Oxide Semiconductor
MS	Mass Spectrometry
MTTP	Multi-service Tactics, Techniques, and Procedures
NATO	North Atlantic Treaty Organization
NAV	Nano Air Vehicle
NBC	Nuclear, Biological, and Chemical
NDIR	Nondispersive Infrared
NGCD	Next Generation Chemical Detectors
NTA	Nontraditional Agents
NTTP	Navy Tactics, Techniques, and Procedures
OEM	Original Equipment Manufacturer
OPCW	Organization for the Prohibition of Chemical Weapons
PID	Photoionization Detector
PPE	Personal Protective Equipment
R&S	Reconnaissance and Surveillance
SUAS	Small Unmanned Aircraft System
TIC	Toxic Industrial Chemical
TSCA	Toxic Substance Control Act
TTP	Tactics, Techniques, and Procedures
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System or Unmanned Aerial System
UAV	Unmanned Aircraft Vehicle
UGV	Unmanned Ground Vehicle
UN	United Nations
USEPA	U.S. Environmental Protection Agency

UV	Ultra Vilolet
VOC	Volatile Organic Compound
VTOL	Vertical Take-Off and Landing
WHO	World Health Organization
WMD	Weapons of Mass Destruction
WME	Weapons of Mass Effect

ENVIRONMENTAL APPLICATIONS OF SMALL UNMANNED AIRCRAFT SYSTEMS IN MULTI-SERVICE TACTICS, TECHNIQUES, AND PROCEDURES FOR CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR RECONNAISSANCE AND SURVEILLANCE

I. Introduction

General Issue

Environmental engineering is the study of a dynamic relationship between humans and the environment – how humans impact the environment and how the environment affects humans. Like many other disciplines, environmental engineering has a lot to gain and share from exploring the use of Unmanned Aircraft Systems (UAS). UAS provide a very interesting, and often sophisticated, platform to help scientists, engineers, and operators understand or at least navigate this relationship between man and the environment. The Department of Defense (DOD) has several mission sets, which align with the use of UAS. Most of these missions fall within intelligence, surveillance, and reconnaissance (ISR). The Chemical, Biological, Radiological, and Nuclear (CBRN) community falls within this ISR framework. However, there is limited research related to where these three focus areas – environmental engineering, UAS and CBRN reconnaissance and surveillance (R&S) – converge.

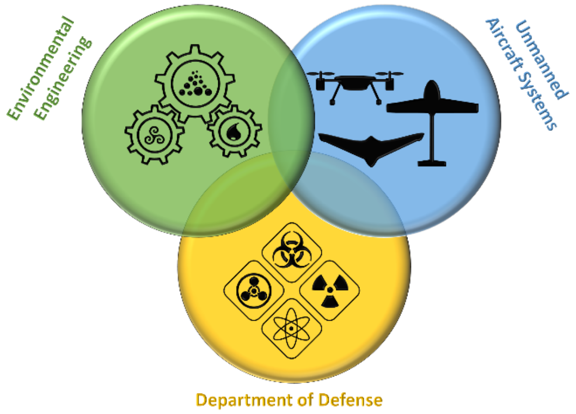

Figure 1: Research Focus Areas

Background

WWI marked the beginning modern chemical weapons use. Although the Geneva Protocol prohibited the use of chemical weapons, nations continued to develop and stockpile weapons of mass destruction (WMD). Despite more recent international efforts by the United Nations' (UN) Organization for the Prohibition of Chemical Weapons (OPCW), there are reports of chlorine gas, sarin, and mustard agents being used in the Middle East (Human Rights Council, 2014). Aggressive state, non-state and terrorist organizations like the Islamic State of Iraq and Syria (ISIS) will not hesitate to use these weapons (Pannell, 2015). The international community, in addition to the U.S. military, needs to be prepared and properly equipped to combat these threats in any environment. However, current CBRN Multi-service Tactics, Techniques, and Procedures (MTTP) are dated and do not account for the use of UAS as a CBRN R&S asset.

The development of UAS has roots in ISR dating back to the 18th Century. The first Unmanned Aircraft Vehicles (UAV) were balloons used for a variety tasks including warfare tactics. With the industrial revolution and advanced warfare, bombs were outfitted with components for propulsion and guidance, which would later be used to create the first Unmanned Aircraft (UA). Aware of the enormous potential of UAS, governments and organizations around the world have designed, developed, and employed UAS in everything from combat to leisure activities.

The terminology, nomenclature, and classification of UAS are convoluted and often disputed. For the purpose of this research a drone is defined as any unmanned aircraft, spacecraft, vehicle, vessel, or submarine designed for re-use. A UAS is a sub-classification of a drone which specifies an aircraft, often called an Unmanned Aircraft

Vehicle (UAV), as one of the primary actors of the system. A typical UAS includes: the UA, sensors, actuators, payload, flight computer, ground control station, and safety pilot. Remotely Piloted Vehicles (RPV) is a unique term, but still considered a UAV. In terms of classifying UAS, there are several conventions with variations between the military, civil, and public arenas; however generally speaking, they all deal with size, flight endurance, and capabilities (Watts, Ambrosia, & Hinkley, 2012). This disjointed nature of terminology and classification is due to the emergence and rapid development of unmanned systems in a wide variety of disciplines across numerous organizations around the world. This is characteristic of how fast the technology is outpacing the language, law and, even in some cases, the application of these systems.

There are several industries fueling the development of UAS including, but not limited to, telecommunications, home security, personal navigation, and hobby. These activities are dominated by an evolution of achieving lower cost and higher reliability with each new generation. This is especially true for Small Unmanned Aircraft Systems (SUAS). In fact, these systems are beginning to saturate the market as the parts become smaller, more durable, and mobile. While there is a healthy supply of UAS, the demand is unrealized because there are still many unexplored applications.

The CBRN community is at the cusp of an opportunity-rich environment and has yet to take full advantage of the improved capabilities inherent with UAS. However, within the last decade, there have been several projects focused on incorporating these state-of-the-art technologies into their architecture. For example, project Joint U.S. Forces in Korea Portal and Integrated Threat Recognition (JUPITR) is a bio-surveillance Advanced Technology Demonstration (ATD) developed by U.S. Army Edgewood

Chemical Biological Center (ECBC) intended for deployment on the Korean Peninsula. The system uses the Joint All-Hazards Common Control Station (JACCS) to integrate an array of sensors into one common operating picture. The military applications in Reconnaissance/Surveillance for Joint Force Protection (MARS JFP) was another project preceding JUPITR, which was also focused on integrating sensors to enhance joint warfighting CBRN defense. UAS provide another platform for integrating sensors into these disparate technologies.

At the heart of these larger projects is the concept of layered sensing (LS), or the integration of disparate technologies. UAS, and the sensors they are equipped with, are only a small component of these larger systems. This systems approach highlights the magnitude of the problem at hand and the need to identify the right platform/sensor combinations for optimal performance. In other words, UAS are not the only answer, but they have the potential to be a significant contributor to environmental applications and future possibilities should be explored.

This research is focused on further investigating the applications of UAS in the MTTP for CBRN R&S (U.S. Army Training and Doctrine Command, 2013). Like many other allied disciplines, environmental engineering has a lot to gain and share from exploring the use of SUAS (Eninger & Johnson, 2015). In addition to analyzing the use of SUAS in CBRN R&S applications, this research explores current and emerging environmental sensors that are small, robust, and capable of being integrated into SUAS. This research provides a framework and decision aid for employing SUAS as a CBRN R&S asset at the tactical level. However, this research will inform and contribute to a larger body of knowledge related to environmental engineering.

Research Objective

The purpose of this research is to determine the feasibility, practicality, and utility of employing small unmanned aircraft systems equipped with chemical sensors in a tactical environment.

Research Aims

SPECIFIC AIM 1: The first aim was to characterize the multi-service tactics, techniques, and procedures for chemical, biological, radiological, and nuclear reconnaissance and surveillance in terms of small unmanned aircraft system applications.

SPECIFIC AIM 2: The second aim was to identify current and emerging environmental sensors optimized for use aboard small unmanned aircraft systems in a tactical environment.

SPECIFIC AIM 3: The third aim was to provide a decision aid for employment of unmanned aircraft systems in a tactical environment.

Scope and Approach

Although this research deals with military doctrine, environmental engineering, systems engineering concepts, the scope is limited to where they converge. Furthermore, within these disciplines, the purview is narrowed to specific areas of interest: CBRN R&S MTTP, chemical detection technologies, and SUAS. However, many of the principles and concepts are measurable, or relatable to other applications outside this research and provide a general platform for further research.

Significance

The most critical aspect of this research is identifying chemical sensor technologies for SUAS employment and integration. There is a significant gap in the literature among the UAS, CBRN, and environmental communities that deal with these specific questions. The other important facet of this research is providing an intellectual basis and decision aid for the use of SUAS in CBRN R&S MTTP.

Methodology

The methods for this research were largely qualitative with the intent to provide a baseline for further research. The first step was to analyze the current MTTP for CBRN R&S from both a theoretical, and a field perspective. This was accomplished by engaging subject matter experts as well as observing CBRN related training and exercises. The second step was to attend academic and industry conferences, in addition to conducting a comprehensive literature review, and to provide an understanding of the state-of-the-art development of UAS. Then, a list of chemical detection technologies for SUAS employment and integration was compiled by reviewing the advantages and disadvantages inherent in the fundamental science of their operation. These detection technologies were then evaluated against parameters relevant to SUAS employment and integration by canvasing, surveying, and consolidating specifications on commercial off the shelf (COTS) chemical sensors from original equipment manufacturers (OEM). The final step, was to use a decision analysis objective hierarchy model to develop a basic decision aid for employment of SUAS for CBRN R&S missions in a tactical environment.

Preview

This thesis is written in the scholarly article format in consideration for submission to the Journal of Hazardous Materials. Chapter II addresses changes to the current CBRN MTTP to include SUAS employment and integration. The article is presented as Chapter III of this thesis and focuses on a survey of various chemical sensor technologies in SUAS applications. Chapter IV presents a basic decision aid for employment of SUAS in a tactical environment developed from a decision analysis objective hierarchy model. Chapter V concludes this thesis and provides a review of findings, limitations, and future research.

II. Tactics, Techniques, and Procedures

Sometimes sophisticated technologies are developed for simple tasks. On the other hand, some very complex activities only require basic technology. Regardless, there is an important link between technology and how it is used. In the military, this relationship is described as acquisitions and doctrine. Where the Defense Acquisition System manages the nation's investments in technology (Brown, 2010) and doctrine provides the fundamental principles and overarching guidance for employment of the Armed Forces (U.S. Joint Chiefs of Staff, 2013). Understanding the intricacies of the Defense Acquisition System was outside the scope of this research. Instead, this research focused on evaluating the current Chemical, Biological, Radiological, and Nuclear (CBRN) Reconnaissance and Surveillance (R&S) Multi-service Tactics, Techniques, and Procedures (MTTP) for Small Unmanned Aircraft Systems (SUAS) integration. By providing an intellectual basis for the integration of SUAS into current CBRN R&S MTTP, this research can be used to make informed acquisition and doctrine recommendations.

The levels of war provide a framework for understanding how doctrine is translated to individual actions. In other words, the leap from doctrine to MTTP is best explained by how they fit into the levels of war. There are three levels of war, strategic, operational, and tactical. Doctrine can be thought of as the warfighting philosophy of the Armed Forces and serves as a bridge between policy and strategy. At the strategic level, doctrine influences relationships between government officials and military commanders. Strategy is then translated into tactics at the operational level; where the focus is on establishing operational objectives. These operational objectives are met through a series of concrete military actions at the tactical level. MTTP form the foundation of concrete military actions and connect individual actions to doctrine. (U.S. Joint Chiefs of Staff, 2013). Therefore, it is important strategically for these MTTP to incorporate relevant available technologies.

One aim of this research was to characterize *Multi-Service Tactics, Techniques, and Procedures for Chemical, Biological, Radiological, and Nuclear Reconnaissance and Surveillance* in relation to SUAS applications. Integration of chemical sensors into mobile aerial platforms is a relatively new area of research (Axisa & DeFelice, 2016; Eninger & Johnson, 2015; Gao et al., 2015; Luo, Meng, Wang, & Ma, 2016; Meng et al., 2015; Puton & Namieśnik, 2016; Rosser et al., 2015; Williams, 2015; Zhang et al., 2016). However, based on this research, there are significant benefits to employing SUAS for chemical detection that are not reflected in the current CBRN MTTP for R&S. The purpose of MTTP publications are to provide a reference for developing tactical level standard operating procedures (SOP) and need to include relevant technologies. This research provides recommendations for changes to CBRN R&S MTTP to include SUAS applications.

CBRN Doctrine

The most recent joint CBRN doctrine was published in 2008 as, Joint Publication 3-11, *Operations in Chemical, Biological, Radiological, and Nuclear (CBRN) Environments*. Prepared by direction of the Chairman of the Joint Chiefs of Staff, this publication provides the overarching guidance to combatant commanders regarding

CBRN operations (U.S. Joint Chiefs of Staff, 2008). However the focus of this research is on tactical level operations. Therefore, the *Multi-Service Tactics, Techniques, and Procedures for Chemical, Biological, Radiological, and Nuclear Reconnaissance and Surveillance* is a more appropriate publication. Published in 2013, this multi-service publication represents the most current MTTP for CBRN R&S. This publication was implemented by each service according to their own publication structure. For instance, the U.S. Army published it as Army Techniques Publication (ATP) No. 3-11.37; the U.S. Marine Corps published it as Marine Corps Warfighting Publication (MCWP) No. 3-37.4; the U.S. Navy published it as Navy Tactics, Techniques, and Procedures (NTTP) 3-11.29 and the U.S. Air Force published it as Air Force Tactics, Techniques, and Procedures (AFTTP) No. 3-2.44. For the purpose of this research, the publication will be referred to as ATP 3-11.37. Regardless of which military service, this publication provides commanders and their staff a standard reference to develop CBRN TTP for R&S associated with site assessment and incorporates doctrine from Joint Publication 3-11. (U.S. Army Training and Doctrine Command, 2013).

The structure of ATP 3-11.37 consists of six chapters and ten appendices. Chapter One presents the fundamentals of intelligence reconnaissance and surveillance (ISR) and how CBRN R&S fits into the larger ISR framework. Chapter Two outlines planning activities which focus on integrating CBRN R&S into the ISR process incorporating all CBRN R&S assets and resources into a single plan. Chapter Three deals with preparation activities intended to improve CBRN R&S mission success. Chapter Four provides an overview of execution activities such as, CBRN ISR forms, modes, methods, tasks, and techniques used to conduct CBRN R&S operations. Chapter Five shifts the focus of the publication from collecting CBRN ISR information to using the four-tier identification levels to make decisions at the tactical, operational and strategic levels. Chapter Six describes tactical level sample management practices. The appendices make up the bulk of the publication and provide much more detailed information regarding planning, preparation and execution activities (U.S. Army Training and Doctrine Command, 2013).

The purpose of this research is to provide an intellectual basis for the use of SUAS for CBRN R&S missions. There is limited reference to unmanned systems in ATP 3-11.37 and primarily refer to UAS as an ISR asset. The only time UAS is referred to as a CBRN asset is in Chapter Four and appendix G when discussing remote CBRN R&S operations. Even then, these references only mention UAS as an emerging technology for operating, or positioning CBRN detectors. In anticipation of SUAS becoming a readily available technology for chemical detection, this research makes recommendations for changes to ATP 3-11.37 that reflect the use of SUAS as a CBRN R&S asset. These changes are most applicable to Chapter Four as well as Appendix F and G which will be discussed in the following section.

Discussion

This section discusses changes to ATP 3-11.37 by providing context and recommendations to specific sections within the publication. By in large, the recommendations are additions to the current text. This section address one overarching change regarding terminology of UAS, identifies three current references in ATP 3-11.37 where UAS is used appropriately, and provides recommendations for changes to Chapter Four, Appendix F and G.

UAS terminology is an area of confusion and should be used deliberately. Unmanned Aircraft Systems (UAS), synonymous with Unmanned Aerial Systems, are a sub classification of drones which primarily operate in the air domain. The aircraft, often called an Unmanned Aircraft Vehicle (UAV), or simply Unmanned Aircraft (UA) only refers to a portion of the system. A typical UAS includes: the UAV, sensors, actuators, payload, flight computer, ground control station, and safety pilot. In general, UAS are classified by size, range, endurance, or capability. For example, the DoD uses Group 1 through 5; increasing by performance, payload, and vehicle size (Department of Defense, 2013). The DHS uses Micro/Miniature Air Vehicle (MAV) or Nano Air Vehicle (NAV); Vertical Take-Off and Landing (VTOL); Low Altitude, Short Endurance (LASE) or Small Unmanned Aircraft Systems (SUAS); Low Altitude, Long Endurance (LALE); Medium Altitude, Long Endurance (MALE); and High Altitude, Long Endurance (HALE) (Watts et al., 2012). International categories include micro, mini, small, tactical, MALE, HALE, and strike or combat UA (Gupta, Ghonge, & Jawandhiya, 2013). Regardless of the specific classification, this research is focused on detecting hazardous chemicals and therefore, primarily interested in smaller, low altitude platforms capable of carrying a sensor payload between 1.2g (single electrochemical sensor) and 20kg (HAPSITE, one of the smallest commercially available gas chromatography, mass spectrometry units) for anywhere between 20 minutes up to 8 hours. Therefore, it is important to distinguish between a CBRN R&S UAV, which may be equipped with CBRN sensors or detectors and an ISR UAV, which may only have multispectral imaging sensors. SUAS are more likely to be used for CBRN R&S than UAS based on their size and utility at the tactical level.

ATP 3-11.37 refers to UAS as a general technology and does not delineate between CBRN R&S and ISR assets. However, these platforms can have drastically different characteristics (e.g., size, weight, endurance, and sensors payloads). There are three instances in ATP 3-11.37 where UAS is referenced as an ISR asset not necessarily equipped with any CBRN detection capabilities. In these cases (see Table 1), UAS is an appropriate term and no change to the current text is necessary.

Table 1: Instances of No Change to the Term, UAS in ATP 3-11.37

Topic (section)	Current Text	Recommendations
Cueing (1-24)	...These assets may cue ground and air reconnaissance assets to investigate specific locations to confirm and amplify information developed by technical assets (for example, aerial capabilities can cover large areas and cue CBRN ground reconnaissance or an **unmanned aircraft system [UAS]** once a CBRN hazard is identified). The commander may dispatch CBRN ground reconnaissance to verify the information and mark the area. Or he may dispatch a **UAS** to verify the information for operational purposes...	No change
CBRN ISR Overlays (2-10)	CBRN ISR overlays are created to graphically depict what is in the CBRN ISR synchronization matrix. Examples of an ISR overlay can be found in appendix B. The CBRN ISR overlay augments the CBRN ISR plan in graphic form. Typical items depicted on the CBRN ISR overlay are: ... -Threat information (known hazard areas, danger areas). -Coverage areas for sensors. -**UAS flight paths**. -Retransmission locations. -Theater laboratory support locations.	No change
Air Environment (G-5)	The operational air environment is the operating medium for fixed- and rotary-wing aircraft, air defense systems, **UAS**, cruise missiles, and some theater ballistic missiles.	No change

There are two sections in Chapter Four where a reference to SUAS for CBRN R&S missions would be necessary and appropriate. The first is section 4-6, where ATP 3-11.37 introduces the aerial mode of CBRN R&S operations. The current text only describes aerial operations conducted from manned aircraft. It also suggests, radiological surveys are the only mission that can be conducted in this mode. However, based on this research, SUAS are also able to conduct aerial CBRN R&S missions and at least locate, survey and detect CBRN hazards. Section 4-7 is the second section in Chapter Four where a reference to SUAS for CBRN R&S is appropriate. This section discusses the methods of CBRN R&S and already mentions UAS. However, in this case it references UAS as an emerging technology along with unmanned ground vehicles (UGV) and robots. In anticipation of these technologies being available for CBRN detection and monitoring this section should be updated. While these recommended changes (see Table 2) may seem minor, they have two very important implications. One, they provide the reader or practitioner with insight into possible applications of available technology and two, keeps the doctrine current.

Table 2: Instances of Changes to the Term, UAS in ATP 3-11.37

Topic (section)	Current Text	Recommendations
Aerial (4-6)	Typically, aerial CBRN R&S operations are conducted during radiological surveys. Aerial R&S operations can cover a much larger area in a shorter period than ground mounted and dismounted operations. It provides added CBRN protection to military personnel by using distance to take readings that can be converted to actual ground readings using an air-ground correlation factor. (See appendix F for more information on aerial CBRN R&S.)	**Aerial CBRN R&S operations may be conducted from both manned and unmanned aircraft.** Aerial R&S operations can cover a much larger area in a shorter period than ground mounted and dismounted operations. It provides added CBRN protection to military personnel by using distance **or remote capabilities to take readings or collect data.** (See appendix F for more information on aerial CBRN R&S.)
Remote (4-7)	Remote CBRN R&S operations are usually performed from a distant location through a communication link to a CBRN detector or monitor. These devices are normally designed to be recoverable. Current remote operations use detectors and monitors at stationary locations. Emerging technologies allow remote CBRN detectors and monitors to be remotely operated on mobile platforms such as **UASs**, unmanned ground vehicles (UGVs), and robots. (See appendix G for more information on remote CBRN R&S.)	Remote CBRN R&S operations are usually performed from a distant location through a communication link to a CBRN detector or monitor. These devices are normally designed to be recoverable. **Remote operations may include detectors and monitors at stationary locations or even use mobile platforms such as Small Unmanned Aircraft Systems (SUAS), unmanned ground vehicles (UGVs), and robots to position CBRN sensors**. (See appendix G for more information on remote CBRN R&S.)

Both sections 4-6 and 4-7 in Chapter Four of ATP 3-11.37 refer the reader to Appendix F and G respectfully. This is because the purpose of Chapter Four is to simply introduce CBRN execution activities by providing an overview of the CBRN ISR forms, modes, methods and techniques (see Figure 2). However, the appendices are meant to provide more detailed information and specifics about the concepts presented in the chapters. In other words, the appendices present the opportunity for improving the quality of information regarding SUAS for CBRN R&S.

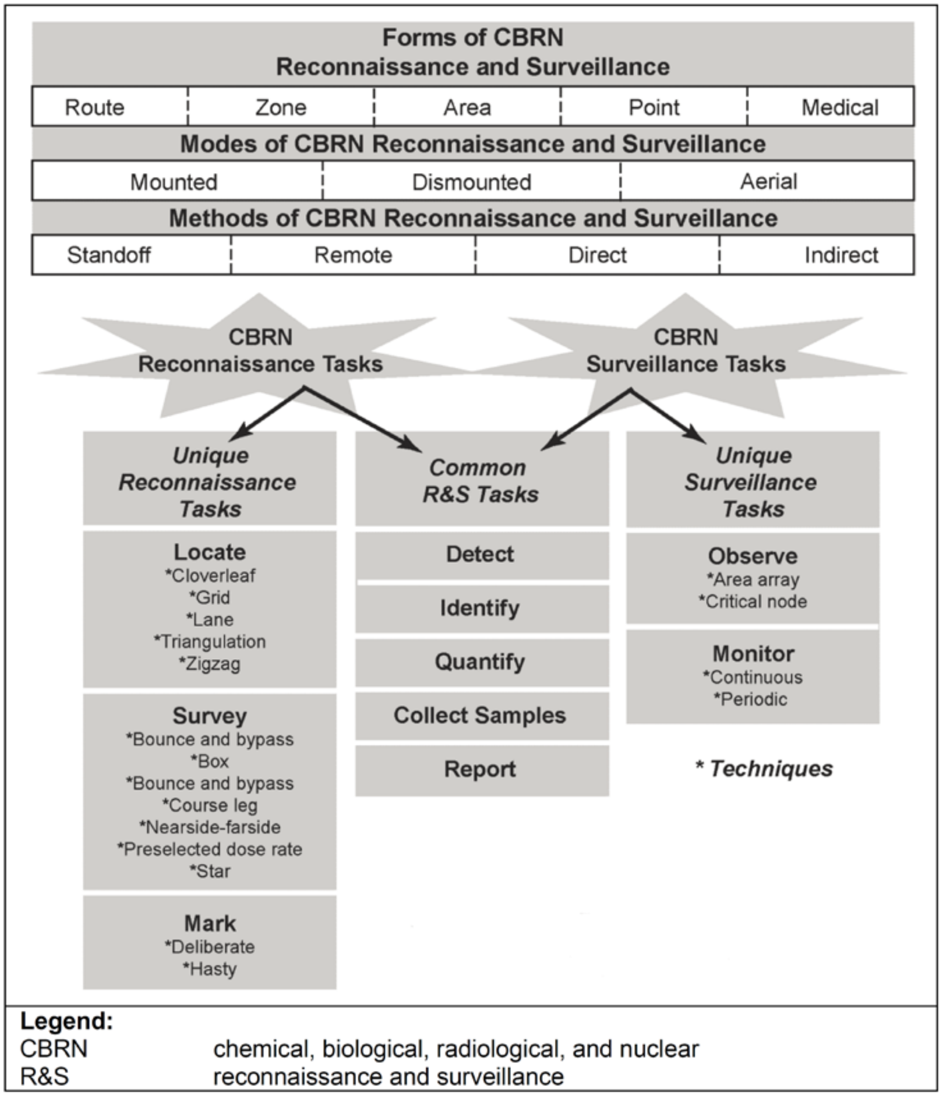

Figure 2: CBRN ISR Task Elements (U.S. Army Training and Doctrine Command, 2013)

Appendix F, deals specifically with aerial CBRN reconnaissance. However, it only recognizes manned aerial CBRN R&S operations. In fact, the document specifically states that UAS with CBRN detection and sampling are currently unavailable. It is reasonable to assume that UAS will be available for CBRN detection before sampling, but eventually both will be achievable. Appendix F, should recognize UAS as an available CBRN R&S asset and add an entire section for unmanned aerial CBRN R&S

operations (see Table 3). A separate section for unmanned aerial operations would provide ATP 3-11 with an opportunity to explain terminology and classification of SUAS. Similar to how Appendix F describes manned aerial operations, unmanned aerial operation will not initially be as robust as dismounted and mounted operations. Instead ATP 3-11.37 should focus on areas where UAS has the greatest potential to improve CBRN R&S operations. Based on their limited endurance and payload capacity, SUAS are more likely to be used for reconnaissance missions because reconnaissance is a more active means of observation. Although, this does not preclude SUAS from being used for surveillance as well. For example, an SUAS equipped with CBRN detectors could be flown to a designated surveillance position, landed and left to collect data for an extended period, then return to its home station. However, this point is captured in Appendix G as a remote detection capability. A section in Appendix F, discussing the advantages and disadvantages of unmanned aerial CBRN reconnaissance, would be appropriate. Since SUAS are more likely to be used for reconnaissance missions, Appendix F should also include a section for both locate and survey techniques.

Table 3: Appendix F Recommendations

Topic (section)	Current Text	Recommendations
Aerial CBRN Reconnaissance (Appendix F)	Currently, manned aerial systems are limited to radiological sensing. Unmanned systems for CBRN sensing and sample collection are currently not available	**Aerial CBRN R&S operations may be conducted from both manned and unmanned aircraft.** **Add an Unmanned Aerial CBRN R&S section to include, but not limited to:** 1. Introduction: discussing UAS terminology and classification 2. Advantages and Disadvantages of Unmanned Aerial CBRN Reconnaissance: 3. Unmanned Aerial CBRN Locate Techniques 4. Unmanned Aerial CBRN Survey Techniques

Appendix G already recognizes UAS as an emerging technology, but similar to the reference in Chapter Four, it should be updated to reflect UAS as an available technology (see Table 4). Beyond this, the points made in appendix G are relevant to unmanned aerial CBRN R&S and require no change.

Table 4: Appendix G Recommendations

Topic (section)	Current Text	Recommendations
Remote Detection Capabilities (G-16)	Remote detection systems are usually operated from a distant location through a communication link to a CBRN detector or monitor. The tripod-mounted variant is intended to operate in the operational field environment at static, designated locations and fixed-site locations near or around airbases and ports. These devices are normally designed to be recoverable. Emerging technologies allow remote CBRN detectors and monitors to be remotely operated on mobile platforms such as **UAS**, UGVs, and robots. With integration into a mobile R&S platform, detectors can also be positioned in a covered and concealed location with maximum LOS to designated key terrain.	Remote detection systems are usually operated from a distant location through a communication link to a CBRN detector or monitor. The tripod-mounted variant is intended to operate in the operational field environment at static, designated locations and fixed-site locations near or around airbases and ports. These devices are normally designed to be recoverable. **Remote operations may include detectors and monitors at stationary locations or even use mobile platforms such as Small Unmanned Aircraft Systems (SUAS), unmanned ground vehicles (UGVs), and robots to position CBRN sensors.** With integration into a mobile R&S platform, detectors can also be positioned in a covered and concealed location with maximum LOS to designated key terrain.

Conclusions

The current MTTP for CBRN R&S are dated because they do not fully address the use of SUAS for chemical detection. As previously mentioned, UAS are a rapidly developing technology. By integrating chemical and other detection technologies with SUAS, these platforms have the potential to greatly enhance CBRN R&S capabilities. The recommended changes are minor, but serve as a stepping stone for further integration and employment. By recognizing SUAS as an available technology, the MTTP for CBRN R&S would provide reason and justification for the acquisition of these types of systems.

III. Scholarly Article

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SURVEY OF CHEMICAL SENSOR TECHNOLOGIES FOR SMALL UNMANNED AIRCRAFT SYSTEM APPLICATIONS

Abstract

This paper describes environmental applications of Unmanned Aircraft Systems (UAS). Specifically, this paper addresses small unmanned aircraft system (SUAS) classification, chemicals of interest, and the capabilities and limitations of current chemical detection technologies for SUAS employment and integration. This review and assessment of chemical sensors provides a framework to inform hazard-to-sensor selection as well as sensor-to-platform considerations. Although focused on classic chemical warfare agents (CWA) and toxic industrial chemicals (TIC), these same principles have boarder applications within environmental engineering and related disciplines.

1. Introduction

Toxic industrial chemicals (TIC) and chemical warfare agents (CWA) pose a real threat to the health, safety and security of civilians and military personnel around the world (Small, 2002). The most recent international effort to control hazardous materials was the Globally Harmonized System of Classification and Labelling of Chemicals published in 2009. Industrial nations and their regulating bodies are also starting to scrutinize new commercial chemicals. For example, in the United States, the Chemical

Abstracts Service, a division of the American Chemical Society reports more than 118 million unique organic and inorganic chemicals in use today and growing at a rate of 15,000 substances per day. Every industrialized nation uses TIC in manufacturing, agriculture, transportation and many other modern activities. According to the U.S. Environmental Protection Agency (U.S. EPA) there are over 85,000 chemicals listed on the Toxic Substance Control Act of 1976 (TSCA) inventory. As recently as June 22, 2016, President Obama signed the Frank R. Lautenberg Chemical Safety for the 21st Century Act, which amends the TSCA and addresses its shortfalls. Specifically, requirements for the U.S. EPA to evaluate existing chemicals using a new risk-based safety standard in addition to funding, and public transparency improvements. While most TIC are 10-100 times less toxic than classic CW agents, they are more readily available from many different industrial activities (Hincal & Erkekoğlu, 2006). As a result, TIC are more likely the substance of choice aggressive state, non-state and terrorist groups with the intent of staging a chemical attack.

Despite national and international efforts to regulate, prohibit and control the manufacturing, transportation and use of TIC over the past few decades, there are still confirmed reports of chlorine gas, sarin and mustard agents being used as recently as 2014 (Human Rights Council, 2014). As the civil war in Syria continues to unfold, both government and rebel forces are suspected of using chemicals such as chlorine gas (Pannell, 2015). It is clear, even today, certain aggressive states and terrorist groups are capable and willing to use TIC and CWA to their advantage. The most recent international effort to control TIC in conflict was the Chemical Weapons Convention (CWC) of 1993, a multilateral treaty banning chemical weapons and requiring nations to destroy their stockpiles within a specified period. Most industrial nations are aware of the threat and taking actions to safeguard supplies and prepare for a chemical attack or accidental release.

For example, in the United States, the U.S. Army Acquisition Support Center is moving into final prototype testing of Next Generation Chemical Detectors (NGCD), which will detect and identify nontraditional agents (NTA), chemical warfare agents (CWA), toxic industrial chemicals (TIC) and other hazards in the air and on surfaces. The Joint Program Executive Office for Chemical and Biological Defense (JPEO-CBD) is working with the Defense Threat Reduction Agency (DTRA) and Joint Science and Technology Office (JSTO) to identify future chemical detection technologies. In their 30 year roadmap, JPEO-CBD identified one of the top contenders for chemical detection as sensors and component miniaturization for unmanned tactical systems. Future chemical detectors will be smaller, more sophisticated and highly mobile.

SUAS are part of a promising market (Canis, 2015). The Chemical, Biological, Radiological, and Nuclear (CBRN) community has a lot to gain and share from exploring the use of SUAS (Eninger & Johnson, 2015). Although, the development of SUAS has roots in Intelligence, Surveillance, and Reconnaissance (ISR) dating back to the 18th Century (Blom, 2010), these systems are being used for personal, commercial, and civil activities, but not without regulation challenges (Kant et al., 2014). Nonetheless, the future of UAS is promising.

The purpose of this paper is to identify chemical sensor technologies optimal for use aboard SUAS employment and integration by providing a framework to inform hazard-to-sensor selection as well as sensor-to-platform considerations.

2. Small Unmanned Aircraft Systems

There are no universal standards for classifying UAS. The terminology, nomenclature, and classification is convoluted, differing between military, civil and commercial entities. However, in general, UAS are classified by size, range, endurance or capability. For example, the DoD uses Group 1 through 5, which increase by performance, payload, and vehicle size (Department of Defense, 2013). The DHS uses Micro/Miniature Air Vehicle (MAV) or Nano Air Vehicle (NAV); Vertical Take-Off and Landing (VTOL); Low Altitude, Short Endurance (LASE) or Small Unmanned Aircraft Systems (SUAS); Low Altitude, Long Endurance (LALE); Medium Altitude, Long Endurance (MALE); and High Altitude, Long Endurance (HALE) (Watts et al., 2012). International categories include micro, mini, small, tactical, MALE, HALE, and strike or combat UA (Gupta, Ghonge, & Jawandhiya, 2013). Regardless of the specific classification, this research is focused on detecting hazardous chemicals and therefore, primarily interested smaller, low altitude platforms capable of carrying a sensor payload between 1.2g (single electrochemical sensor) and 20kg (HAPSITE, one of the smallest commercially available gas chromatography, mass spectrometry units) for anywhere between 20 minutes up to 8 hours. This type of platform would fall in the Group 1 or 2 category, but definitely below 50 kg. This size of platform is significant for two reasons, (1) these smaller systems have more utility at the tactical level, and (2) they would benefit from the research and development of the majority of UAV being manufactured today.

Terminology is another area of confusion. For the purpose of this research, drone is a universal term describing any unmanned aircraft, spacecraft, vehicle, vessel, or submersible designed for re-use. Unmanned Aircraft Systems (UAS), synonymous with Unmanned Aerial Systems, are a sub classification of drones which primarily operate in the air domain. Within systems engineering, it is important to define a system by identifying actors within system. For example, the aircraft, often called an Unmanned Aircraft Vehicle (UAV), or simply Unmanned Aircraft (UA) is one of the key players of the system. A typical UAS includes: the UA, sensors, actuators, payload, flight computer, ground control station, and safety pilot. It is important to note the sensors described in this research differ from the sensors used for navigation and health of the UAV, which provide input to the basic functionality and operation of system. Instead, they may be considered a payload with independent functions or fully integrated into the system.

3. Chemicals of Interest

Chemicals are classified or categorized in a number of ways. This research is interested in hazardous chemicals which are typically associated with CBRN or first responder efforts. From an international perspective, The Geneva Protocol of 1925, was the first major multilateral effort to control hazardous chemicals, by banning chemical warfare. However, nations continued to develop CWA during WWII and into the 1960s. The chemicals developed during these era were designed to immediately kill, seriously injure, or seriously incapacitate individuals and are considered classic CWA (Pitschmann, 2014). CWA are categorized by the military according to their physiological effects (U.S. Joint Chiefs of Staff, 2008) (see Table 5). Chiefly concerned these classic CWA, the Biological and Toxin Weapons Convention (BTWC) of 1972, prohibits the development, production, acquisition, transfer, stockpiling and use of biological and toxic chemical weapons. The BTWC represents another major effort by the international community to stop the proliferation of hazardous chemicals intended to harm. However, with the widespread use and development of TIC, the international community recognized a need to expand the control of hazardous chemical to include more than the classic CWA. This ideology is culminated in the Chemical Weapons Convention (CWC) of 1993, a multilateral treaty banning chemical weapons and requires nations to destroy their stockpiles within a specified period.

Table 5: Classic Chemical Warfare Agents (CWA) (Sferopoulos, 2009)

Agent Class	Agent Name	Abbreviation
Nerve	Tabun	GA
	Sarin	GB
	Soman	GD
	Ethyl Sarin	GE
	Cyclosarin	GF
	O-ethyl-S-diisopropyl amino methyl methylphosphonothiolate	VX
	S-(Diethyl amino)ethyl O-ethyl ethylphosphonothioate	VE
	Amiton or Tetram	VG
	Phosphonothioic methyl-, S-(2-(diethyl amino)ethyl) O-ethyl ester	VM
Vesicants	Sulfur Mustard	HD
	Nitrogen Mustard	HN-1, HN-2, HN-3
	Lewisite	L
	Mustard-lewisite	HL
	Phenyldichloroarsine	PD
	Phosgene Oxime	CX
Blood	Hydrogen Cyanide	AC
	Cyanogen Chloride	CK
	Arsine	SA
Choking	Chlorine	Cl
	Phosgene	CG
	Diphosgene	DP
	Chloropicrin	PS

The line separating CWA and TIC has more to do with the intention of the user than anything else. In the 1990s the international community recognized that TIC could be used by terrorist, aggressive states or non-states actors to cause mass casualties or mass destruction. In 1994, NATO organized the International Task Force 25 (ITF-25) to assess the potential hazard from TIC. ITF-25 defined TIC as chemicals produced in quantities exceeding 30 tons per year at a single facility and have a concentration required to produce 50% mortality in the exposed population (LCt_{50}) by inhalation in any mammalian species, of less than 100,000 mg min/m3 (Steumpfle, Armour, Howells, & Boulet, 1996). ITF-25 identified 1,164 chemicals meeting this toxicity criteria, which was further reduced to 89 chemicals after applying the production criteria. Using an atmospheric dispersion model for denser- than-air releases developed by Bowman Environmental Engineering called SLAB, ITF-25 categorized 98 chemicals on a hazard index of high, medium, and low (see Table 6).

Table 6: Hazard Index Ranking of TIC (Steumpfle et al., 1996)

HIGH	MEDIUM	LOW
ammonia	acetone cyanohydrin	isothiocyanate
arsine	acrolein	arsenic trichloride
boron trichloride	acrylonitrile	bromine
boron trifluoride	allyl alcohol	bromine chloride
carbon disulfide	allyl amine	bromine pentafluoride
chlorine	allyl chlorocarbonate	bromine trifluoride
diborane	boron tribromide	carbonyl fluoride
ethylene oxide	carbon monoxide	chlorine pentafluoride
fluorine	carbonyl sulfide	chlorine trifluoride
formaldehyde	chloroacetone	chloroacetaldehyde
hydrogen bromide	chloroacetonitrile	chloroacetyl chloride
hydrogen chloride	chlorosulfonic acid	cyanogen
hydrogen cyanide	crotonaldehyde	diphenylmethane-4'-diisocyanate
hydrogen fluoride	diketene	ethyl chloroformate
hydrogen sulfide	1,2-dimethyl hydrazine	ethyl chlorothioformate
nitric acid, fuming	dimethyl sulfate	ethylene imine
phosgene	ethylene dibromide	ethyl phosphonothioicdichloride
phosphorus trichloride	hydrogen selenide	ethyl phosphonous dichloride
sulfur dioxide	iron pentacarbonyl	hexachlorocyclopentadiene
sulfuric acid	methanesulfonyl chloride	hydrogen iodide
tungsten hexafluoride	methyl bromide	isobutyl chloroformate
	methyl chloroformate	isopropyl chloroformate
	methyl chlorosilane	isopropyl isocyanate
	methyl hydrazine	n-butyl chloroformate
	methyl isocyanate	nitric oxide
	methyl mercaptan	n-propyl chloroformate
	n-butyl isocyanate	parathion
	nitrogen dioxide	perchloromethyl mercaptan
	phosphine	sec-butyl chloroformate
	phosphorus oxychloride	sulfuryl fluoride
	phosphorus pentafluoride	tert-butyl isocyanate
	selenium hexafluoride	tetraethyl lead
	silicon tetrafluoride	tetraethyl pyrophosphate
	stibine	tetramethyl lead
	sulfur trioxide	toluene 2,4-diisocyanate
	sulfuryl chloride	toluene 2,6-diisocyanate
	tellurium hexafluoride	
	tert-octyl mercaptan	
	titanium tetrachloride	
	trichloroacetyl chloride	
	trifluoroacetyl chloride	

ITF-25 produced a useful, but limited prioritization based on a hazard index that took into account: toxicity, state, distribution, and production. However, more recently, in 2007, the U.S. Department of Homeland Security published a more comprehensive list of over 300 chemicals of interest (COI) in Appendix A of the Chemical Facility Antiterrorism Standards, 6 CFR Part 27. The list categorizes chemicals based on security issues related to release, theft, or sabotage (see Table 7). This is arguably the most useful list of chemicals related to this research because it includes both CWA, TIC and other hazardous chemicals that could be used to harm people.

Table 7: Hazardous Chemical Security Issues (Department of Homeland Security, 2007)

Release	Toxic, flammable, or explosive chemicals or materials that, if released from a facility, have the potential for significant adverse consequences for human life or health.
Theft	Chemicals or materials that, if stolen or diverted, have the potential to be misused as weapons or easily converted into weapons using simple chemistry, equipment or techniques, in order to create significant adverse consequences for human life or health.
Sabotage	Chemicals or materials that, if mixed with readily available materials, have the potential to create significant adverse consequences for human life or health

There are other ways of classifying harmful chemicals other than CWA and TIC. The most recent international effort to control hazardous materials was the publication of the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), in 2009. The GHS, broadly categorizes chemicals as physical, health, or environmental hazards (see Table 8) and further subcategorizes them based on various chemical properties, negative physiological effects or environmental impacts (Nations, 2009).

Table 8: Categories of Hazardous Chemicals (Nations, 2009)

Physical Hazards	Explosives Flammable gases flammable aerosols oxidizing gases gasses under pressure flammable liquids flammable solids self-reactive substances and mixtures pyrophoric liquids pyrophoric solids organic peroxides corrosive to metals
Health Hazards	acute toxicity skin corrosion/irritation serious eye damage/eye irritation respiratory or skin sensitization germ cell mutagenicity carcinogenicity reproductive toxicity specific target organ toxicity-single exposure specific target organ toxicity-repeated exposure aspiration hazard
Environmental Hazards	hazards to the aquatic environment hazards to the ozone layer

Classifying chemicals based on their chemical properties is very useful when it comes to detection methods. In the next section, this research discusses how different detection technologies can exploit the chemical properties of hazardous chemicals to generate data about the presence and even concentration of a species of interest. The four detection technologies evaluated in this research were: Electrochemical (EC), Metal Oxide Semiconductor (MOS), Photoionization (PID), and Catalytic (CAT). By cross referencing the chemicals that can be detected by these technologies with the COI list and ITF-25's Hazard Index, this research identified 85 chemicals (see Table 9) relevant to this research. This means that, of the 325 chemicals identified by the DHS, approximately, 26% are detectable using commercially available sensors. Of the 85 chemicals identified, 18 are listed as high, 12 medium, and 5 low on ITF-25's Hazard Index; leaving 50 hazardous chemicals unaccounted for. Many of these chemicals can be detected using multiple detection technologies. However, EC can account for 26 chemicals, MOS 58, PID 68, and CAT 8. The next section will discuss the advantages and disadvantages of each.

Table 9: Chemicals of Interest adapted from
(Department of Homeland Security, 2007; Steumpfle et al., 1996)

	DHS Security Issue							ITF-25 Hazard Index			Detection Technology			
Chemicals of Interest	Release - Toxic	Release - Flammables	Release - Explosives	Theft – CWI/CWP	Theft - WME	Theft – EXP/IEDP	Sabotage or Contamination	HIGH	MED	LOW	EC	MOS	PID	CAT
Acetaldehyde		X											X	
Acetyl bromide							X						X	
Acetyl chloride							X						X	
Acetylene		X									X	X	X	X
Acrolein	X								X			X	X	
Acrylonitrile		X							X			X	X	

	DHS Security Issue							ITF-25 Hazard Index			Detection Technology			
Chemicals of Interest	Release - Toxic	Release - Flammables	Release - Explosives	Theft – CWI/CWP	Theft - WME	Theft – EXP/IEDP	Sabotage or Contamination	HIGH	MED	LOW	EC	MOS	PID	CAT
Allyl alcohol	X								X			X	X	
Ammonia	X							X			X	X	X	X
Arsine	X				X			X			X	X	X	
Boron trichloride	X				X			X				X		
Boron trifluoride	X				X			X				X	X	
Bromine	X									X	X	X	X	
1,3-Butadiene		X											X	
Butane		X										X	X	X
Butene		X										X		
1-Butene		X											X	
Carbon disulfide	X							X				X	X	
Chlorine	X				X			X			X	X	X	
Chlorine dioxide	X						X				X	X	X	
Chlorine trifluoride					X					X			X	
Chloroform	X											X	X	
Crotonaldehyde		X							X				X	
Cyanogen		X			X					X			X	
Cyanogen chloride	X				X							X		
Cyclopropane		X											X	
Diborane	X				X			X			X	X	X	
Dichlorosilane		X			X							X		
Difluoroethane		X										X		
1,1-Dimethylhydrazine		X											X	
Dimethylamine		X										X		
Epichlorohydrin	X											X	X	
Ethane		X										X	X	X
Ethyl chloride		X										X	X	
Ethyl ether		X										X	X	
Ethyl mercaptan		X									X		X	
Ethylene		X									X	X	X	X
Ethylene oxide		X						X			X	X	X	
Fluorine	X				X			X			X	X	X	
Furan		X											X	
Germane					X						X	X		
Hydrazine		X									X	X		
Hydrogen		X									X	X		X
Hydrogen bromide					X			X			X	X	X	
Hydrogen chloride	X				X			X			X	X	X	
Hydrogen cyanide					X			X			X	X	X	
Hydrogen fluoride	X				X			X			X	X	X	
Hydrogen iodide					X					X			X	
Hydrogen selenide		X			X				X		X		X	
Hydrogen sulfide	X				X			X			X	X	X	
Isobutane		X										X	X	
Isopentane		X										X	X	
Isoprene		X										X	X	
Methane		X										X	X	X
2-Methyl-1-butene		X											X	

	DHS Security Issue							ITF-25 Hazard Index			Detection Technology			
Chemicals of Interest	Release - Toxic	Release - Flammables	Release - Explosives	Theft – CWI/CWP	Theft - WME	Theft – EXP/IEDP	Sabotage or Contamination	HIGH	MED	LOW	EC	MOS	PID	CAT
3-Methyl-1-butene		X											X	
Methyl chloride		X										X	X	
Methyl formate		X											X	
Methyl hydrazine	X								X			X		
Methyl isocyanate	X								X				X	
Methyl mercaptan		X			X				X		X	X	X	
Methyl thiocyanate	X												X	
Nickel Carbonyl		X											X	
Nitric oxide	X				X					X	X	X	X	
Nitrobenzene						X							X	
Nitromethane						X							X	
Pentane		X										X	X	
Phosgene	X				X			X			X	X	X	
Phosphine		X			X				X		X	X	X	
Phosphorus oxychloride	X			X			X		X			X		
Phosphorus trichloride	X				X		X	X					X	
Propane		X										X	X	X
Propionitrile	X												X	
Propylene		X										X	X	
Propylene oxide		X										X	X	
Propyne		X											X	
Silane		X									X	X		
Silicon tetrachloride							X					X		
Silicon tetrafluoride					X				X			X		
Stibine					X				X				X	
Sulfur dioxide	X				X			X			X	X	X	
Trimethylamine		X										X		
Tungsten hexafluoride					X			X				X		
Vinyl chloride		X										X	X	
Vinyl methyl ether		X											X	
Vinylidene chloride		X										X		

4. Chemical Sensor Technologies:

The focus of this research is to identify chemical detection technologies best suited for SUAS integration. First, this section presents the physical, operational, and performance characteristics important to evaluating direct-reading monitors and further, defines five parameters most relevant to SUAS integration. Secondly, this section explores twelve detection technologies, but comparing only four for SUAS employment and integration. This information can be used by manufacturers to understand which parameters are critical to SUAS integration or by end users to compare different detection technologies. However, this paper is not intended to be an exhaustive list of every detection technology available on the market today. Instead, the specifications from commercial off the shelf (COTS) original equipment manufacturer (OEM) sensors was used to provide data to compare performance parameters. All data presented is based on manufacturer reported specifications. Also, the scope of this research is limited to evaluating different detector technologies and not whole devices, emphasizing the difference between OEM sensors and direct reading monitors. In this research, the term technology is used instead of method to describe different detectors – the portion of a device that actually senses the chemical of interest, or analyte.

4.1 Parameters of interest:

National Institute for Occupational Safety and Health (NIOSH) is one of the world's leading research organizations for establishing standard related analytical equipment. NIOSH, along with over 50 other international organizations, make up the World Health Organization's (WHO) Global Network of Collaborating Centers in Occupational Health representing a majority of the world's occupational health and safety community (The National Institute for Occupational Safety and Health, 2017). NIOSH primarily serves as a research organization responsible for developing recommendations for health and safety standards. Although NIOSH is a U.S. federal agency, it clearly plays a unique and significant role in the larger global occupational health and safety community. In collaboration with the Occupational Safety and Health Administration (OSHA), NIOSH has established criteria for evaluating analytical equipment for chemical detection (National Institute of Occupational Safety and Health, 2012). These technical reports provide guidance on the physical, operational, and performance characteristics for direct-reading monitors on the basis of producing results falling within 25% of the true concentration 95% of the time. NIOSH identified 22 performance characteristics (see Table 10) as well as suggested documentation for physical and operational characteristics (National Institute of Occupational Safety and Health, 2012). However, response time, sensitivity, selectivity, power, and weight are the five parameters most relevant to SUAS integration.

Table 10: Performance Characteristics

(National Institute of Occupational Safety and Health, 2012)

1.	Response Time
2.	Calibration
3.	Linearity
4.	Drift
5.	Range
6.	Environmental Effects
7.	Precision
8.	Bias
9.	Accuracy
10.	Limit of Measurement
11.	Environmental Interferences
12.	Electromagnetic Interference
13.	Drop and Vibration
14.	Remote Sampling
15	Detector Life
16.	Step Change Response and Recovery
17.	Supply Voltage Variation
18.	Long-Term Stability
19.	Monitor Uncertainty
20.	Quality System Requirements (industry standards)
21.	Reliability
22.	Field Evaluation (real world testing)

Response time, sensitivity, and selectivity are key parameters for collecting useful data, while power and weight are essential to SUAS integration. The response time of a given sensor depends on the type of platform chosen, (e.g. rotary, fixed wing, lighter than air) which will affect the amount and character of data that can be collected in a given period. If the response time is relatively quick, there can be more flexibility in the flight characteristics and freedom of movement. Whereas, if the response time is relatively slow, the platform will need to allow longer stationary time. These decisions can have significant implications on the amount of area that can be covered and number of data points that can be collected. For the purpose of this research, response time is reported as the time required for a given sensor to reach 90% of its final response, denoted as T_{90}, and measured in seconds (s).

Sensitivity is crucial when dealing with CWA and TIC because they are harmful at very low concentrations. Many chemicals of concern have health effects in parts per million (ppm) and parts per billion (ppb). However, not all chemical sensors operate based on the same principle of measurement (conductivity, potentiometry, amperometry, etc.) and therefore, sensitivity may be reported slightly different between detector technologies (e.g. nA/ppm or mV/ppm). Nonetheless, within each detection technology, sensitivity is presented in this research using the same units.

Due to cross-sensitivity, selectivity is another important parameter to consider. On one extreme, a detection technology is able to discriminate between nearly every possible chemical (e.g a gas chromatography- mass spectrometry). On the other end of the scale, a detection technology may only be able to detect the presence of a group of chemicals with similar properties. To remain in the scope of this research, selectivity is presented as a qualitative assessment relative to the other detection methods.

Sensor power requirements are most important to the endurance of a SUAS. Propulsion and actuators are typically operated at high voltage, while command and control systems are run at low voltage. Chemical sensors can be integrated as a separate payload with their own power supply, but full integration is preferred, because this allows data to be synchronized with other onboard subsystems such as GPS. Depending on the principle of measurement, each sensors technology consumes power differently and can dependent on the analyte concentration. However, power consumption is expressed as milli-watts (mW).

Weight is critical to both the design and performance of a SUAS. Although shape and dimensions are important, weight is good indicator of the general size of each sensor technology. Since the total size and weight of chemical detection subsystem will depend on other design decisions and how each sensor technology is integrated into the SUAS, the scope of this research is limited to evaluating the weight of individual detectors technologies and not whole devices. Weight is presented as grams (g) or kilo-grams (kg).

The data presented in this research is focused on evaluating smaller chemical detectors intended for portable use. There are a number of manufacturers making portable sensors, but very few if any marketing to SUAS integration. Although NIOSH defines four classifications of portability (personal, portable, transportable, and stationary), these refer to the monitors and not necessarily the detectors. Therefore, this research took the liberty of surveying and compiling data on several small to miniature sized detectors (see Appendix A). Since this data is in survey format, the information presented is intended to be a representative sample of typical specifications for each type of detector and not a statistical analysis. Each of the five parameters are presented on a scale from least optimal (red) to most optimal (green) (see Figure 3) for SUAS employment and integration. Note, for each parameter, larger values are on the left, while smaller values on the right end of the scale.

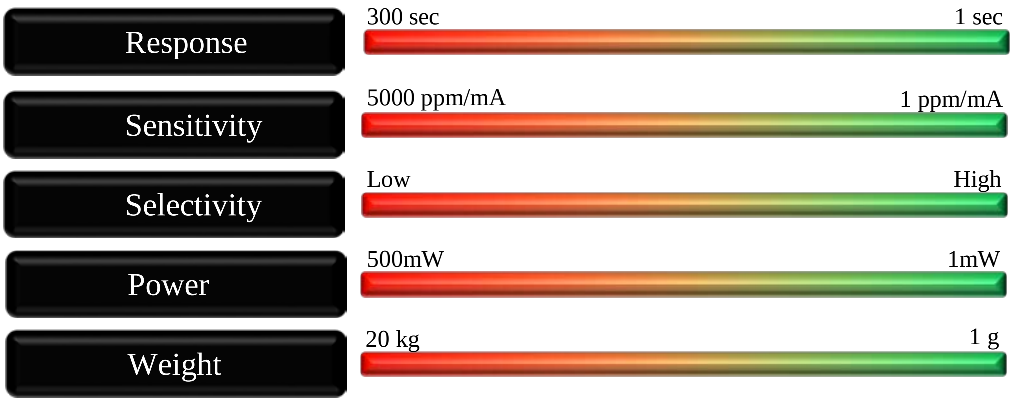

Figure 3: Example Parameter Scale

4.2 Detection Technologies:

Chemical sensors are generally classified based on the operating principle of the transducer (see Table 11), but can also be classified by mode or function such as the phase of the analyte (Hulanicki, Glab, & Ingman, 1991; Sekhar, Brosha, Mukundan, & C, 2010). The scope of this research is focused on gas sensors specifically designed to detect TIC and CWA. Use of chemical sensors for environmental applications or homeland security is not a new concept (Sekhar et al., 2010). However, integration into UAS is a relatively new area of research (Axisa & DeFelice, 2016; Eninger & Johnson, 2015; Gao et al., 2015; Luo et al., 2016; Meng et al., 2015; Puton & Namieśnik, 2016; Rosser et al., 2015; Williams, 2015; Zhang et al., 2016). Therefore this research focused on evaluating chemical detection technologies from the perspective of use aboard a SUAS.

Table 11: Classification of Detection Technologies

(National Institute of Occupational Safety and Health, 2012)

1.	Electrochemical	Conductivity, Potentiometry, Coulometry, Amperometry
2.	Ionization	Flame Ionization, Photoionization, Electron Capture, Ion Mobility
3.	Thermochemical	Thermal Conductivity, Heat of Combustion
4.	Spectrochemical	Infrared, Ultraviolet and Visible Light Photometers, Chemiluminescence, Photometric
5.	Gas Chromatography	
6.	Mass Spectrometry	

This research compares four chemical detection technologies while discussing the advantages and disadvantages of each operating principle pertaining to SUAS employment and integration. While there are a number of other detection technologies available (see Table 12) (MRIGlobal, 2013), the four presented in this research are relatively compact direct-reading gas or vapor sensors. The criteria for selecting these technologies was: commercially available, chemical gas or vapor sensors, which could be integrated into SUAS as a sensor and not as a device. The line between analyzer (device) and detector types (sensor) continues to change as more sophisticated equipment is miniaturized (e.g. Ion Mobility Spectrometry, Gas Chromatography, and Mass Spectrometry). Therefore some attention is given to these technologies in this section even though they are outside the scope of this research.

Table 12: Detection Technologies (MRIGlobal, 2013)

1.	Catalytic/Pellistor	CAT
2.	Electrochemical	EC
3.	Flame Ionization	FID
4.	Ion Mobility Spectrometry	IMS
5.	Metal Oxide Semiconductor	MOS
6.	Micro-electro-mechanical Systems	MEMS
7.	Nanotechnology	NANO
8.	Optical Spectroscopy	OS
9.	Paramagnetic	PM
10.	Photoacoustic Infrared Detection	PA
11.	Photoionization Detection	PID
12.	Surface Acoustic Wave	SAW

Electrochemical: Electrochemical sensors are among the most versatile direct-reading interments for portable chemical detection on the market today (MRIGlobal, 2013) because of their relatively small size, fast response time, sensitivity, selectivity, and low power consumption (Chou, 2000). The overall specifications of electrochemical sensors depended on their intended purpose and design decisions balancing certain performance parameters. The fundamental science behind electrochemical sensors are chemical reactions, typically an oxidation/reduction (redox) reaction. Electrochemical sensors produce an electrical signal proportional to the concentration of a target gas, the analyte. This signal is generally linear at low concentrations, which are expected for monitoring TIC and CWA. The key components of electrochemical sensors are a gas permeable membrane, electrodes, an electrolyte, and in some cases a filter (Chou, 2000).

There are four methods of measuring changes in the electrical signal, (1) conductivity (measuring changes in resistance), (2) potentiometry (measuring changes in voltage), (3) coulometry (measuring electrolysis), and (4) amperometry (measuring changes in current) (National Institute of Occupational Safety and Health, 2012). The fundamental equation governing conductivity is

Equation 1

$$G = \frac{\Lambda C}{1000K} \tag{1}$$

Where:
G = the conductance in siemens (s)
Λ = the equivalent conductance in siemens square centimeter per equivalet (S cm^2 eqivalent^{-1})
C = the concentration in equivalent per liter (equivalent L^{-1})
K = is the cell constant in cm^{-1}
(National Institute of Occupational Safety and Health, 2012)

However, resistance is a more fundamental electrical property than conductivity. Therefore, resistance is more commonly measured. Since resistance is the reciprocal of conductance, the equation can be written as:

Equation 2

$$R = 1/G \qquad (2)$$

Where:
R = resistance in ohms (Ω)
G = the conductance in siemens (s)
(National Institute of Occupational Safety and Health, 2012)

Chemicals measured using this method must be a charged species (ions) or produce ions when in contact with other materials. To produce a change in conductivity the analyte does not necessarily need to be ionized, but can be gaseous or a vapor that will react with other components housed in the sensor, causing a change in conductance between electrodes. Because ions conduct electricity, the presence of an analyte will produce a change in this conductance. Since reactions are temperature dependent, the sensors are as well. The Arrhenius equation can be used to electronically compensate for effects of temperature (National Institute of Occupational Safety and Health, 2012). This is a key limitation to the use of electrochemical sensors on SUAS, because of changes in temperature with altitude, but not prohibitive.

Another method of measuring the signal of an electrochemical sensors is potentiometry. Potentiometry, relies on the effect of an analyte on the potential difference between two electrodes, the cathode and anode in an electrochemical cell. For a given reaction such as, $aA + bB \rightarrow yY + zZ$, the effect of an analyte is governed by the fundamental equation:

,

$$E_{cell} = E_{cell}^{0} - \frac{RT}{nF} \ln \frac{[Y]^{y}[Z]^{z}}{[A]^{a}[B]^{b}}$$

Equation 3

(3)

Where:
E_{cell} = the cell potential
E_{cell}^{0} = the standard cell potential
R = molar gas constant
T = temperature
n = number of electrons involved in the electrode reaction
F = Faraday constant
(National Institute of Occupational Safety and Health, 2012)

Selectivity using this method is achieved by choosing analyte specific membranes, different reagents, potential ranges, and types of electrodes to isolate the analyte of interest. (National Institute of Occupational Safety and Health, 2012).

Coulometry is another way of using an electrochemical sensor to measure the concentration of an analyte. In this case the analyte, or chemical which the analyte reacts with, is electrolyzed according to the Faraday equation:

Equation 4

$$W = \frac{qM}{nF}$$

(4)

Where:
W = the mass of substance that is electrolyzed
q = the charge, in coulombs required to completely electrolyze the substance
M = formula weight
n = number of electrons per molegue required for electrolysis
F = Faraday constant
(National Institute of Occupational Safety and Health, 2012)

In coulometry based sensors, the concentration of the analyte is proportional to the amount of electricity required to electrolyze the substance. This is achieved directly, by integrating the charge required or indirectly, by capturing the time required to electrolyze the substance under a constant current (National Institute of Occupational Safety and Health, 2012).

Amperometry based sensors rely on the electroactive properties of an analyte to produce a current while controlling the potential between electrodes. The resulting current is proportional to the concentration of the analyte. Unlike the other methods of measurement, amperometry requires a reference electrode in order to operate properly.

In summary, there is a wide range of electrochemical sensors making them a very versatile choice for chemical detection. Although selectivity and temperature dependence are common weaknesses of electrochemical sensors (see Table 13), these disadvantages can be overcome with careful selection of various membrane filters, thermostats, and other practical solutions to component selection and construction. Furthermore, if these sensors are integrated into an array of sensors with appropriate algorithms to determine a sequence of exposure, their strengths could be aggregated and prove to be very effective in mixed chemical environments. However, another limiting factor for electrochemical sensors are their dependence on humidity. The condition of the electrolyte is critical to ensure proper operation. The electrolyte can leak in high humidity or dry up in low humidity, rendering the device ineffective or greatly reducing the operating life.

Table 13: Summary of Electrochemical Measurement Principle, Advantages and Disadvantages

Electrochemical	Advantages	Disadvantages
Conductivity (S, Ω)	Uncharged analyte (gas or vapor) Corrosive gasses: (NH_3, H_2S, SO_2)	Non-specific Sensitive to interference Temperature dependent
Potentiometry (V)	pH, CO, Cl_2, CH_2O, H_2S, NO_x, SO_x, O_2, O_3	Non-specific Temperature dependent
Coulometry (C)	Not temperature dependent Very accurate (O_2, CO, Cl_2, HCN, H_2S, NO_x, O_3, SO_2)	Non-specific
Amperometry (A)	Linear over 3 orders of magnitude CO, H_2S, O_2, Cl_2, NO	Non-specific Temperature dependent Reference electrode
Overall	Diffusive monitors Accuracy	Non-specific

Metal oxide semiconductors (MOS), also referred to as solid-state or Taguchi Gas Sensors, are another type of detection technology relying on electrochemical properties, specifically, the conductivity of metal oxides. A signal proportional to the concentration is produced when the analyte adsorbs to the metal oxide changing its conductivity (National Institute of Occupational Safety and Health, 2012). The change in conductivity can be a direct result of the adsorbed analyte or the displacement of surface oxygen. There are two common designs, bead- and chip-type. In both cases transition metals are used to imbed a pair of biased electrodes. A heating element is also required to regulate the temperature of the sensing element (Chou, 2000).

Solid-state sensors are another one of the most versatile chemical detection technologies available. Solid-state sensors are able to detect gas concentrations across several orders of magnitude by varying the operating temperature and careful selection of component materials. This is one of the advantages of MOS over other sensor technologies. However, similar to electrochemical sensors, they are sensitive to interfering gases and non-selective without the use of filters. Another distinct disadvantage is a slow recovery time (Chou, 2000).

Ionization: Ionization sensors are one of the few detection technologies where there is a significant amount of variability in the miniaturization and portability between different types of detectors. There are four types of ionization detectors: (1) photoionization (PID), (2) flame ionization (FID), (3) electron capture (ECD), and (4) ion-mobility spectrometry (IMS). The fundamental science behind these detectors is the ionization of chemicals which are then collected by an electrode, which induces a current proportional to the concentration. Depending on the type of sensor, the analyte is ionized by an ultraviolet (UV) lamp, flame, or radioactive source (National Institute of Occupational Safety and Health, 2012). The way these sources are generated and operated are the limiting factors in the miniaturization and portability of these sensors. Photoionization sensors are the most compact among the four types and falls within the scope of this research. However, there is potential for these other types of sensors to be used aboard SUAS and are therefore discussed briefly.

The principle operation of a PID is the frequency and intensity of an UV light source to ionize gas or vapor molecules, making them ideal for VOC. The radiation energy required is typically reported as electron volts (eV), but is related to wavelength through Planck’s Constant. Only molecules with lower ionization potential than energy output of the UV lamp are ionized. Ionization occurs when a photon is absorbed by the analyte (Chou, 2000). As an analyte enters the ionization chamber, the UV light will cause the molecules to lose an electron through photon adsorption and become positively charged.

Equation 5

$$R + hv \rightarrow R^{+} + e^{-} \tag{5}$$

Where:
R = the molecule to be ionized
hv = photon having energy greater than the ionization potential of R
R^{+} = ionized molecule
e^{-} = electron
(National Institute of Occupational Safety and Health, 2012)

Once ionized, the positively charged molecules are propelled by an anode toward the collecting cathode where a signal is generated proportional to the concentration (Chou, 2000). This is a nondestructive process and one of the advantages of PID.

There are several inherent advantages and disadvantages to using photoionization for SUAS employment based on the principles of operation. As previously mentioned, photoionization is a nondestructive process, which is an advantage for SUAS employment because it does not require a fuel source, such as hydrogen gas, which is commonly used in FID. Instead, most portable PID use a high-voltage, low-current charge to excite a low-pressure inert gas, isolated by a lamp wall. The most common inert gas used, is krypton, because it emits 10.6 eV, which is greater or equal to most VOC. Other gasses used are argon and xenon. The most disadvantageous component to SUAS employment is the lamp window. To allow UV radiation to pass through the lamp window crystals made of magnesium fluoride or lithium fluoride are used. These windows are fragile and require regular cleaning using a fine solid aluminum oxide powder. Another disadvantage to PID, is the effect of humidity, which scatters the UV light and can lead to calibration errors and faulty readings (Chou, 2000).

Flame ionization detectors (FID) use a hydrogen-air mixture to burn organic compounds, which produce ions through chemical ionization. This is a non-selective process. Whereas, with photoionization there is a level of selectivity achieved using different energy lamps. Most portable FID tend to be much larger than PID, because they require a hydrogen fuel source. Another significant disadvantage to FID is they are not safe for use in atmospheres containing flammable or combustible compounds. Electron capture detectors (EDC) use a radioactive beta particle emitter to ionize a carrier gas inside the ECD cell. The free electrons react with electronegative compounds and induce a change in the current between the electrodes of the detector. Ion-mobility Spectrometry (IMS) detectors use an ionization source such as ^{63}Ni foil to generate background ions. These ions react with the analyte molecules in series of ionization reactions before being accelerated through a weak electrical field in a drift tube, toward a flat conducing plate where a signal is generated proportional to the concentration of the analyte (National Institute of Occupational Safety and Health, 2012). All four types of ionization detectors are associated with analytical lab equipment such as a gas chromatographic system. However, PID are the most compact ionization sensors available. There are a number of portable IMS sensors available on the market today for on-site chemical monitoring, but tend to be more complex than PID. In 2013 the DHS did a market survey of portable IMS devices and found several capable of detecting CWA and TICs (National Urban Security Technology Laboratory, 2013).

Ionization	Advantages	Disadvantages
Photoionization (PID)	Compact Non-destructive Some selectivity	Fragile components
Flame Ionization (FID)		Non-selective Destructive Hydrogen source required
Electron capture (ECD)		Radiation source
Ion-mobility Spectrometry (IMS)	Selective	

Thermochemical: In comparison to other detection technologies, thermochemical sensors are relatively simple detectors. They are commonly used to detect combustible gases and vapors. Thermal conductivity and heat of combustion are the two thermal properties exploited by these devices to detect an analyte concentration. Thermal conductivity sensors are universal detectors and not ideal for SUAS employment. Whereas heat of combustion sensors have a degree of selectivity based on different component materials and operating temperatures. Therefore, only heat of combustion sensors are considered in this research for SUAS integration.

When chemicals burn they release a characteristic amount of energy. This thermal property can be used to measure the concentration of a combustible analyte. The most common heat of combustion sensors use catalytically heated filaments or oxidation catalysts to ignite the contaminant of interest (National Institute of Occupational Safety and Health, 2012). Catalytic bead sensors (CAT) evolved from a rudimentary platinum wire detector, and were first used in coal mines over fifty years ago. The sensors used today incorporate catalysts such as metal oxides, platinum, palladium and thoria. These catalysts allow the sensor to burn the analyte at temperatures lower than the heat of combustion. Relying on the coefficient of temperature for platinum, these sensors use a

Wheatstone-bridge to balance an electrical circuit and measure changes in voltage proportional to the concentration of the analyte (Chou, 2000).

There are several advantages and disadvantages associated with the application of CAT sensors for SUAS applications. While these sensors are relatively easy to manufacture, there is a significant amount of variability inherent in the quality of materials used. Calibration is important and dependent on the specific application of these sensors. For example, most CAT sensors are calibrated by the manufacturer using methane, because of its availability and chemical properties, but will require correction factors or complete recalibration for other applications. One of the most critical factors affecting the performance of CAT sensors is catalyst poisoning, where certain chemicals will deactivate the sensor. The most concerning chemicals for applications related to this research are, silicon sulfur compounds, chlorine, and heavy metals. Other chemicals can also cause temporary malfunctions. These include halogen compounds and Freon. Another important factor to consider is the effects of heat. These sensors operate at very high temperatures.

Spectrochemical: The majority of spectrochemical sensors are relativity more complex than the other detection technologies considered in this research. However, there are some types of spectrochemical sensors suitable for SUAS employment. Spectrochemical sensors include four general types of analyzers, (1) infrared (IR), (2) UV and visible photometers, (3) chemiluminescent, and (4) photometric. The fundamental science behind these detection technologies is how spectrum is emitted, absorbed, or scattered by an analyte. The most common type used in portable devices is IR and more specifically, nondispersive infrared (NDIR), which is a subcategory. Another subcategory of IR is Fourier transform (FTIR), which is more common in analytical equipment. Infrared sensors can be used to detect many similar hydrocarbons as solid-state and catalytic bead sensors. However, there are some significant advantages to IR sensors. Therefore, this detection technology is discussed, but was not evaluated in this research.

Infrared sensors exploit wavelengths in electromagnetic spectrum between 770 to 1000 nanometers. Most molecules absorb IR radiation through vibrational or rotational transitions specific to each compound. The fundamental equation for absorbance, is Beer’s Law.

Equation 6

$$A = \varepsilon b c \tag{6}$$

Where:
A = absorbance
ε = molar absorptivity
b = path length
c = the concentration

(National Institute of Occupational Safety and Health, 2012)

Portable IR sensors are limited by the relationship between absorbance (A) and the path length. This is a great example of how the fundamental science introduces physical limitations on the portability and miniaturization of a detection technology. Most portable devices balance precision with selectivity and throughput. IR sensors consist of an IR radiation source, optical filters (to select wavelengths), and a detector. The key differences between IR, NDIR and FTIR have to do with the selection and position of the optical filters. Traditional IR sensors place the optical filter between the IR source and sample to interrogate the analyte with only one wavelength. NDIR sensors place the optical filter between the sample and the detector to detect only one wavelength. FTIR sensors, on the other hand, use an interferometer to interrogate the sample with phased IR beam (National Institute of Occupational Safety and Health, 2012). There are also a number of different detectors that can be used to generate a usable electrical signal proportional to the concentration of the analyte. The most common fall into one of the following categories: thermoelectric, thermistor bolometer, pyroelectric detector, photon detector, Luft detector, or photoacoustic detector (Chou, 2000). Raman spectroscopy is another closely related vibrational spectrometry, worth mentioning because of its application in portable devices. However, this technology is outside, the scope of this research.

The most significant advantage to IR sensors is that they can interrogate the analyte without coming into direct contact with the sample. In comparison to Catalytic sensors, IR sensors are not affected by poisoning or burnout, because of this characteristic. However, IR sensors are significantly more complex than catalytic and solid-state detectors. Another major disadvantage to IR sensors, is that they are significantly affected by humidity, due to the effects of water scattering and absorbing the IR beam.

Gas Chromatography and Mass Spectrometry: Gas chromatographs (GC) and mass spectrometers (MS) help provide context to the other detection technologies already discussed. GC/MS represent the gold standard in laboratory analytical equipment for vapor and gas detection. In fact, there are several portable, direct-reading, GC/MS commercially available (National Institute of Occupational Safety and Health, 2012). The

Hazardous Air Pollutants on Site (HAPSITE), by INFICON, is one of the most notable field portable GC/MS on the market today. However, in terms of complexity, these types of detectors boarder on the line between laboratory and field equipment and are a long way from being considered for SUAS employment.

In summary, there are a number of technologies available to detect gases or vapors, each with unique fundamental capabilities and limitation, and advantages and disadvantages associated with SUAS employment. The goal of any chemical detector is to separate, identify, and quantify a species of interest. For each detection technology, the ability to separate, identify, and quantify a species of interest is a function of the science and how the actual sensor performs. Of the detection technologies discussed above, four were selected for further evaluation based on their performance. Graphical representations of these four detection technologies can be found in Figure 4, but are not intended to be detailed technical drawings. The four detection technologies that were evaluated were: Electrochemical (EC), Metal Oxide Semiconductor (MOS), Photoionization (PID), and Catalytic (CAT).

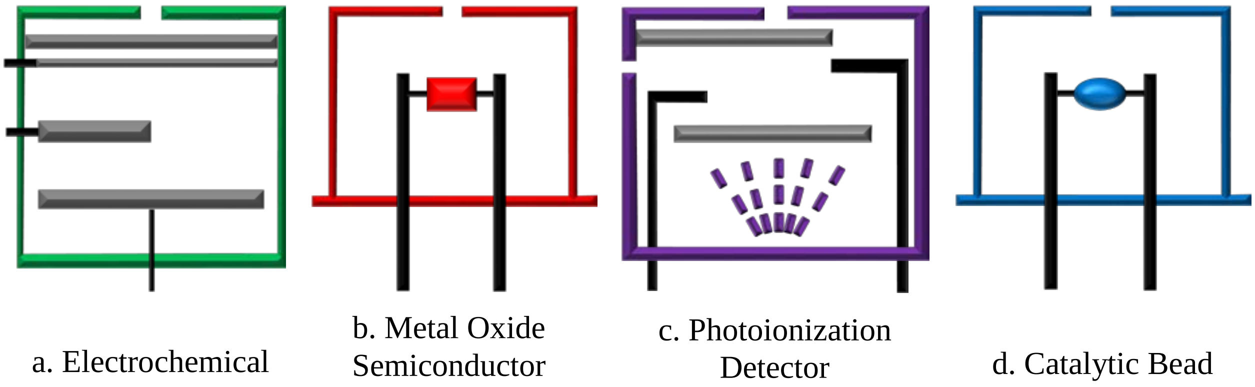
a. Electrochemical
b. Metal Oxide Semiconductor
c. Photoionization Detector
d. Catalytic Bead

Figure 4: Graphical Representations of Detection Technologies inspired by (Chou, 2000)

5. Discussion

Currently, the most suitable chemical detection technologies for SUAS employment are, Electrochemical (EC), Metal Oxide Semiconductor (MOS), Photoionization (PID), and Catalytic (CAT). These four detection technologies were compared using five performance parameters, response time, sensitivity, selectivity, power, and weight (see Figure 6). Of the 85 hazardous chemicals identified, 18 were listed as high on ITF-25's Hazard Index, of which only 13 were detectible with at least three of the four these detection technologies. Ammonia was the only chemical detectable by all four technologies and happens to be a very common TIC. For comparison, Arsine (a blood agent) and Chlorine (a choking agent) were selected because they are classic CWA.

A relative scale was developed to assess the overall potential for SUAS employment and integration (see Figure 5). The scale ranks each detection technology based on the number of most optimal parameters minus the number of least optimal parameters and eliminates parameters with significant variability.

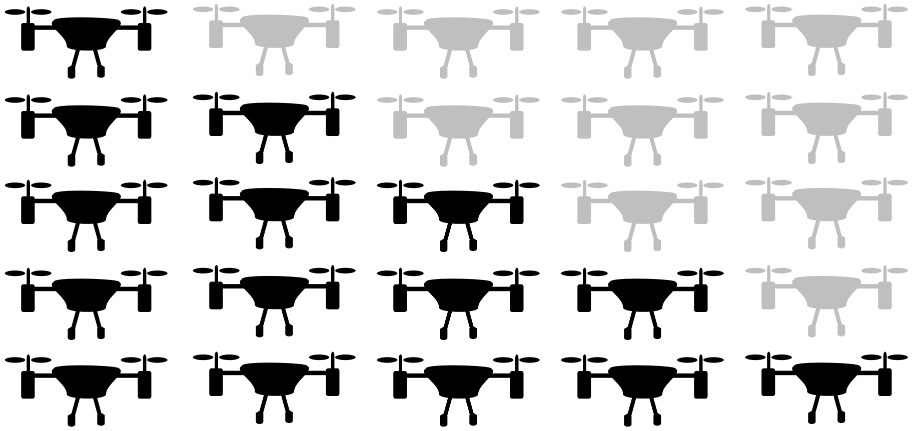

Figure 5: SUAS Employment and Integration Scale for Chemical Detection Technologies

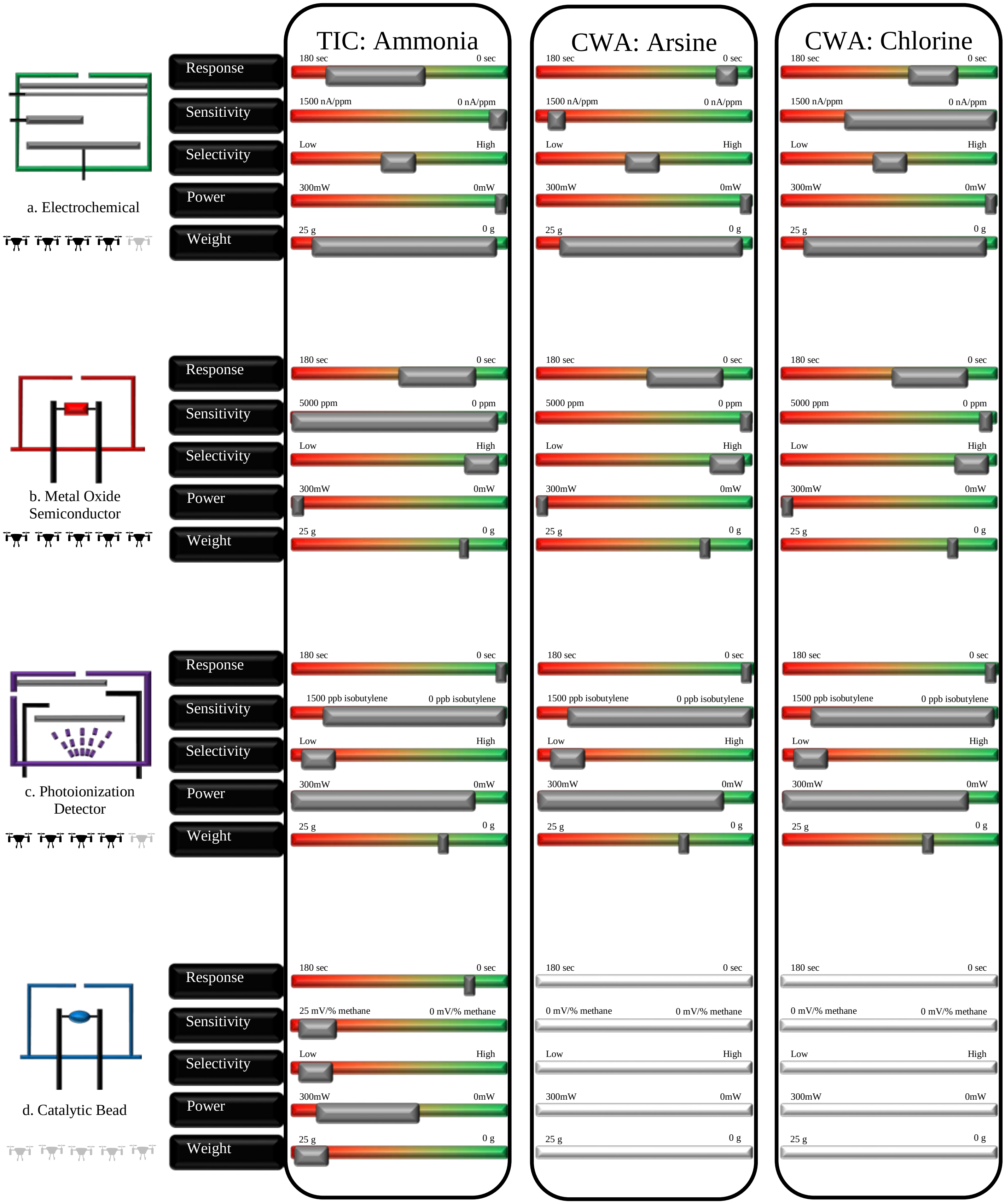

Figure 6: Comparison of Detection Technologies

6. Conclusion

Four detection technologies were evaluated for SUAS employment and integration: Electrochemical (EC), Metal Oxide Semiconductor (MOS), Photoionization (PID), and Catalytic (CAT). These four detection technologies were compared using five performance parameters, response time, sensitivity, selectivity, power, and weight and assessed for overall SUAS employment and integration. MOS, EC and PID sensors are capable of detecting 85 hazardous chemicals of interest and suitable for SUAS employment and integration. Based on this research and of these four detection technologies, MOS detectors are the top detection technology for SUAS employment and integration. Furthermore, an array of sensors configured using a sophisticated algorithm could provide the necessary level of selectivity needed in multiple gases or mixed gas scenarios. In fact, this research suggests that multiple detection technologies can be used together on a single platform to counteract or balance the weakness of one detection technology with another. This paper provides information on SUAS classification, chemicals of interest, and the capabilities and limitations of current chemical detection technologies. The review and assessment of chemical sensors provides a framework to inform hazard-to-sensor selection as well as sensor-to-platform considerations. Although focused on classic chemical warfare agents (CWA) and toxic industrial chemicals (TIC), these same principles have boarder applications within environmental engineering and related disciplines.

IV. Multi-Objective Decision Analysis

Introduction

Decision analysis is the study of how decisions are made and then utilized to create decision aids (Morris, 1977). One aim of this research was to develop a basic decision aid for the employment of Small Unmanned Aircraft Systems (SUAS) intended for tactical CBRN R&S missions. The intention of a decision aid is not to replace the decision making process, but instead give the decision maker context for their choices. In the case of this research, a decision aid was used to demonstrate how decision analysis could be used to explore outcomes of a basic model and make recommendations for the future use of a technology. This research takes a more general academic, yet practical approach to developing a decision model; rather than present a comprehensive decision aid for a specific SUAS platform configuration. Commanders will always have to make decisions about which assets to employ, but if scientists, researchers, and engineers also take the time consider how those decisions are made, they will design equipment better suited for its intended purpose.

The capabilities and limitations of a military unit are defined by their equipment and personnel assets. It is important to consider the benefit of a new technology against the potential displacement of other assets, and namely to avoid inadvertently degrading a unit's overall ability to perform. In other words, although a new technology may be more effective in certain situations, if it requires additional resources and is redundant, then it may not be a wise investment. However, if this technology can be successfully integrated into a multi-purpose platform, or architecture, it could serve as a force multiplier.

While the U.S. Army plays the largest role in CBRN operations, the U.S. Marine Corps has a unique perspective on tactical level operations. Therefore, the decision model was tailored for a Marine Corps commander, but could easily be adjusted to meet the needs of any service. After determining what is important to a battalion commander, an objective hierarchy model deemed to be the most compatible because the decision to employ an asset is based on multiple competing objectives. Input from subject matter experts was gathered via an online questionnaire to inform the criteria used in the model. Afterward, the model was used to evaluate two scenarios with three alternatives.

Objective Hierarchy Model

A basic objective hierarchy model (see Appendix F) was developed with three levels: (1) the overall objective, (2) decision categories, and (3) key measures. The overall objective answers the question, which CBRN R&S asset to employ? The decision categories were chosen based on how military commanders commonly think about how their decisions will affect their unit's ability to shoot, move, communicate, and survive. These categories are further broken down into the leaf nodes, or measures of effectiveness (MOE): number of response personnel required for a given mission, how long it takes to get to the contamination area, the amount of area that can be covered in a given period, the quality of data, loss of life, and loss of equipment (see Figure 7). The weights were assigned according the author's preferences. Although, every decision maker is unique and would assign weights to each node according to their own priorities.

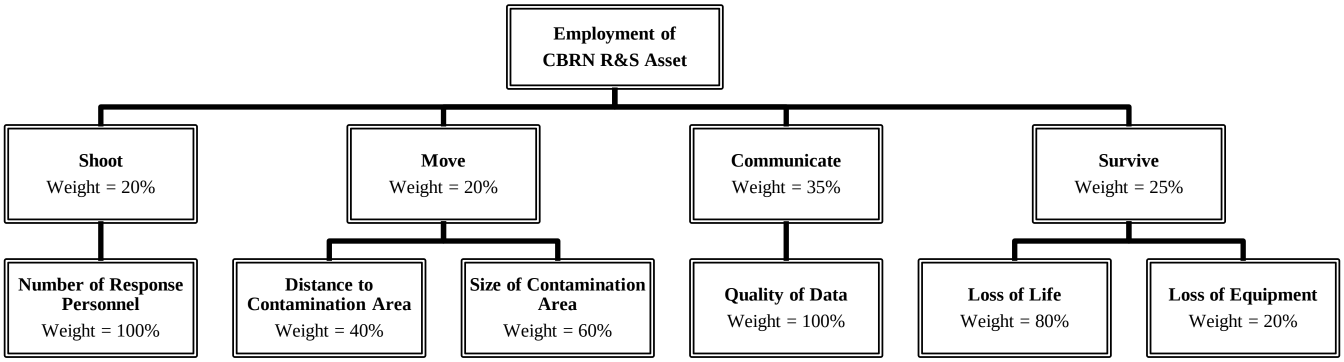

Figure 7: Objective Hierarchy Model

A unit's ability to shoot goes beyond sending rounds down range and also includes locating the enemy, and relying on each person to competently and proficiently do their job. Every unit deals with limited personnel, especially in units with highly specialized personnel. Thus, each additional response person will theoretically displace one member of the unit from their primary duty. In the most simplistic terms, an infantryman would be replaced with a CBRN specialist. Therefore, the number of response personnel is directly tied to a unit's ability to shoot.

Movement is rather straight forward concept and a unit's freedom of movement is a function of the enemy and other obstacles. A chemical hazard can be a significant obstacle. So, the time it takes to travel to the hazard and cover a specified area is directly related to a unit's ability to move beyond the obstacle.

Communication boils down to getting information to those who need it. The continuum of turning data into information, information into knowledge, and knowledge into wisdom begins with collecting quality data. Therefore, the quality of data is a measure of a unit’s ability to communicate.

Survival is not limited to an individual’s actions, but is broadly applied to a unit’s level of security. While there are many ways to evaluate a unit’s level of security, the two most apparent measures are loss of life and loss of equipment. Therefore, it is important to assess the risk of losing either given different alternatives.

Thresholds and Objectives

The following thresholds and objectives (see Figure 8) were chosen based on input from subject matter experts. A questionnaire was sent to various CBRN professionals to gather their input. The objective and threshold represent the gamut from the best to worst case for each MOE.

MOE	Threshold	Objective
Number of Response Personnel	40	1
Distance to contamination area (time, s)	60	0
Area Covered (time, hr.)	8	0
Quality of Data	0	1
Loss of Life (USD)	$400,000	0
Loss of Equipment (USD)	$20,000	0

Figure 8: Thresholds and Objectives

The number of personnel was set between 1 to 40 personnel based on the size of a platoon in a battalion. Each scenario defines the distance to and size of the contamination area. Since speed is a function of distance and time, these two MOE are actually measured in time, where assumptions are made about the speed of each asset. The quality of data is measured on a scale of 0 to 1. Loss of life was set at a threshold of $400,000 based on the life insurance coverage for one individual. Similarly, loss of equipment was set at $20,000 based on the average cost of a SUAS plus an estimated value of the additional detection equipment on board. These are reasonable assumptions, but further refinement of these MOE is an area for future research.

Utility functions

This research focused on three general utility functions which describe behaviors expected of decision makers: risk neutral, risk averse, and risk taking. However, they can also be explained as having direct, increasing, or decreasing returns. These three curves are defined over the range [0,1] and the input variables are normalized to the domain [0,1] (see Figure 9). A risk neutral utility or direct return function was chosen for the quality of data, loss of life, loss of equipment, because the utility for each of the MOE is directly proportional to the input variable. A risk averse or increasing return utility function was chosen for the number of response personnel and size of the contamination area. With both of these MOE there is an effect of increasing return as you go from threshold to objective. In the case of distance to the contamination area, there is an effect of diminishing returns as you go from threshold to objective, so a risk taking curve was selected.

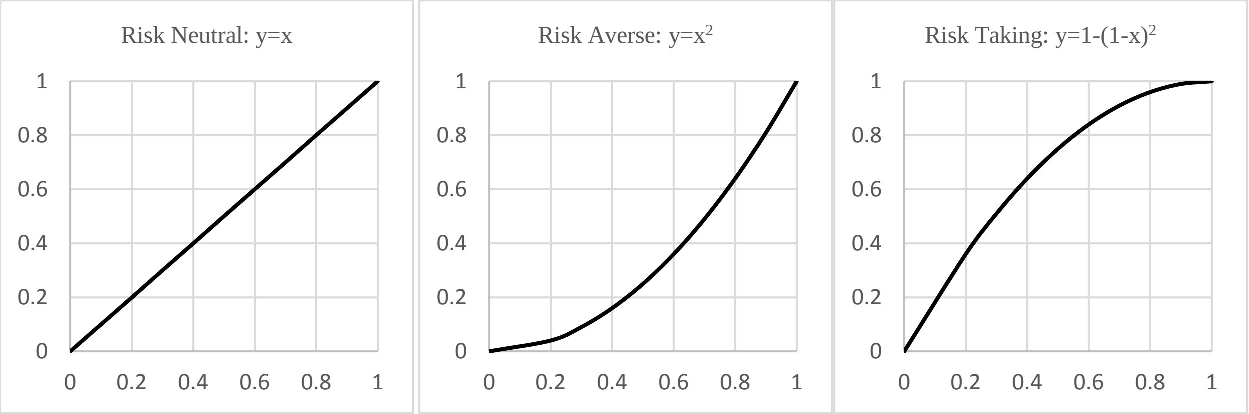

Figure 9: Utility Functions

Scenarios and Alternatives

This research considered two scenarios: friendly and hostile. However, the general situation of the hazard was same for both. A CWA or TIC, such as chlorine or ammonia, was released in a small city center about 1 square kilometer (247.105 acres) in size, and 3.5 km (2.1748 mi) away from the response personnel. Again, the key difference between each scenario has to do with the potential risk of conflict during the mission. Three alternatives were selected to capture the differences between manned, unmanned and a combination team. The following section will describe how parameters were selected for each alternative given the two scenarios.

Friendly scenario parameters:

An SUAS team may consist of 3-5 personnel: a couple of CBRN specialists, a safety pilot, and a technician. Therefore, in the friendly scenario, the SUAS team was set at 4 personnel. A typical CBRN response team consists of a squad (12 personnel) to platoon (40 personnel) size element. For the purpose of this scenario, the conventional team was set at 26 personnel. The combination would require more than the SUAS team and fewer than the conventional team and was therefore set at 15 personnel for this scenario.

The average maximum airspeed of commercially available SUAS is about 90 kph (55.92 mph). Common SUAS practice is to transit at about 60-80% throttle to extend endurance. Therefore a cruising speed of 65 kph (40.39 mph) was chosen based on 70% throttle; resulting in a transit time to the contamination area for the SUAS of 3.23 minutes. Transportation of the conventional team to the contamination area would require a small convoy. Given the distance to the contamination area, an average speed of 40 kilometers per hour was chosen; resulting in a transit time of 5.25 minutes. The limiting factor for the combination team to travel to the contamination area would be transportation of personnel. Therefore the same time was chosen for the conventional team as well.

Depending on the specific techniques used, the time it takes to survey the contamination area will vary. However, in general, a SUAS will be able to cover more area in a shorter period of time than a manned team. To survey, locate or detect a hazard in a small city center may take a conventional team a many hours. For the purpose of this scenario, this task was set at 5 hours for the conventional team and a conservative factor of 60% of the same time was set for the SUAS team; resulting in 3 hours to complete the task. Since the combination team would be able to augment their efforts with the SUAS, having the advantage of both assets, they could complete the given task in a much shorter time. Therefore, a conservative factor of 50% was set for the combination team; resulting in a 2.5 hour mission.

The quality of data in this scenario was set between presumptive and field confirmatory on a relative scale. A manned team will have more sophisticated equipment and therefore collect higher quality data. However, an SUAS may have better remote communication abilities to transmit data. Therefore, the quality of data for the combination team was set at the highest value, 1; the conventional and SUAS team at 80% and 60% of that value respectfully (see Table 14).

In a friendly environment, safety takes priority and the risk of injuring personnel or damaging equipment is reduced in both severity and probability. Minor damage to an SUAS is only going to cost a fraction of its total value. In this scenario, damage to the

SUAS was set at 1% of its total value, resulting in $200 of damage. Damage to equipment by the conventional team was set at $50 to account for lost, broken, or damaged parts. Minor cuts and bruises to personnel were assumed negligible and set at zero across the board.

Table 14: Friendly Parameters

MOE	SUAS	Conventional	Combination
Number of Response Personnel	4	26	15
Distance to contamination area (minutes)	3.23	5.25	5.25
Area Covered (hours)	3	5	2.5
Quality of Data	.6	1	.8
Loss of Life (USD)	0	0	0
Loss of Equipment (USD)	$200	$50	$250

Hostile scenario:

In a hostile scenario, additional personnel would be required to provide security resulting in redundancy. Therefore, the SUAS, conventional and combination teams were increased by 20%; resulting in 5, 31, and 18 personnel respectfully. Transit times would be more aggressive in a hostile environment. Therefore, time to the contamination area was adjusted. At 80% throttle, a cruising speed of 72 kph (44.74 mph) the SUAS team would be onsite in 2.92 minutes. The conventional team, traveling at an average speed of 60 kph (37.28 mph), would arrive at the contamination area in 3.5 minutes. Due to friction in war, tasks in hostile environment generally take longer. Therefore, a 10% increase in time from the friendly scenario was allocated to each team in order to account for these extra precautions (see Table 15). Similarly, a degraded value in the quality of data collected by each team decreased by a factor of 10%. The risk of death or injury is much higher in a hostile environment. The SUAS is able to maintain greater distance from the contamination area and away from hostile forces. Therefore loss of life was set at $4,000 for the SUAS team using a 1% factor while the conventional team was set at $40,000 using a 10% factor. The Combination team has fewer people, so the loss of life parameter was set at $20,000 using a 5% factor. More serious loss of equipment is likely in a hostile environment, so these parameters were set for the SUAS team at $10,000 using a 50% factor. Since the conventional team has more people and more equipment, this parameter was set at $12,000 using a 60% factor and the combination team was set at $15,000 because they are utilizing both manned and unmanned equipment.

Table 15: Hostile Parameters

MOE	SUAS	Conventional	Combination
Number of Response Personnel	5	31	18
Distance to contamination area (minutes)	2.92	3.5	3.5
Area Covered (hours)	3.3	5.5	2.75
Quality of Data	.18	.9	.72
Loss of Life (USD)	$4,000	$40,000	$20,000
Loss of Equipment (USD)	$10,000	$12,000	$15,000

Assumptions:

Many of the assumptions were discussed in the previous section, but there are few overall assumptions. Since SUAS are relatively inexpensive, this research deduced that these systems are available to the military at a considerably lower cost, or at most equal to the value of a conventional CBRN team, for that reason cost was not considered as a factor. Although additional training would be required, there would be presumably fewer personnel needed to complete a given mission. Only transit times were considered because setup and launch times are comparable to preparing and loading a team for a given mission.

Results

The overall utility for each alternative in both scenarios was generated (see Figure 10) using the same objective hierarchy model without adjusting the assigned weights. These values represent the kind of data a decision maker can expect from this type of model. As previously stated, these numbers are not meant to be a substitute for decision making, but provide context to aid in the process. The true value of a decision aid is the deliberate process of identifying MOE, assigning weights to each decision category, and setting the thresholds and objectives. In the friendly scenario, both the SUAS and combination teams had a similar overall utility value. This is a great example of how the model is intended as a supportive tool. In this case, the model helped the decision maker eliminate at least one option, but will still need to account for other factors when making a final decision between the remaining choices. Each commander will have to asses wat is most important, assign the appropriate weights to each node and could have very different outcomes. The ability of this type of model to discriminate has a lot to do with the accuracy of the inputs and the tolerance of the weights on each MOE. A 2-5% difference may not be significant enough for a decision maker to discriminate between two choices. The model is only as good as the inputs. The results presented here are based on very conservative parameters. For example, the loss of life MOE allow only accounted for the life insurance policy of one service member and the risk was minimized in both scenarios. Accounting for every service member using a more robust measure for the loss of life, this model would have produced very different results. Again, the point of this model is to provide a baseline for having a discussion about the use of SUAS for CBRN operations. Each parameter deserves attention and careful consideration.

Table 16: Objective Hierarchy Results

	SUAS	Conventional	Combination
Friendly	.76	.72	.75
Hostile	.69	.62	.65

Conclusion

An objective hierarchy model was created as a basic decision aid for the employment of SUAS as a possible CBRN R&S asset. Thresholds and objectives were based on research and input from subject matter experts, while the emphasis of the model was specific to the decision maker. The utility functions were based on risk neutral, risk averse, and risk taking behaviors. This research considered two scenarios: friendly and hostile. For each scenario there were three alternatives: a SUAS, conventional and combination team. This model and approach provides a basic decision aid for the employment of SUAS in CBRN R&S. Further refinement of this model may provide more insight into the benefit of SUAS integration, however this tool can be used to drive the conversation about using these systems for CBRN detection by providing quantifiable data for comparison.

V. Conclusions

Overview

Chapter I provided an introduction and background to the major concepts of relevant to this research: environmental engineering, UAS, and CBRN. Chapter II focused on Specific Aim I; addressing changes to the current CBRN MTTP for CBRN R&S include SUAS employment and integration. The most significant change recommended in this chapter, included a UAS section to appendix F, which dealt with the aerial mode of CBRN R&S. Chapter III was written as a scholarly article in consideration for submission to the *Journal of Hazardous Materials*. This chapter explored topics related to Specific Aim II, and chemical detection technologies. Moreover, this chapter discussed information about UAS classification and terminology, hazardous chemicals of interest, and details about capabilities and limitations of different detection technologies. In addition, this chapter supplied a template for comparing various detection technologies for SUAS employment and integration. Chapter IV addressed Specific Aim III. The intention of this chapter was to develop a basic decision aid for employment of SUAS in a tactical environment decision analysis objective hierarchy model.

Review of Findings

Integrating chemical sensors into SUAS has the potential to significantly enhance CBRN R&S operations as well as many other closely related fields. This simple action could thrust CBRN R&S MTTP into the forefront of 21st century state-of-the-art detection capabilities. Consequently, this research recommends incremental changes to the current MTTP. The most significant recommendation, based on Specific Aim I, is to include an unmanned section to the current publication dealing with the aerial mode of CBRN R&S. Overall, the most crucial aspect of this research is related to Specific Aim II. The integration of chemical sensor into SUAS requires answers to three fundamental questions, which are dependent on each other: (1) Which platform? (2) Which chemical? and (3) Which sensor? Chapter III laid down the foundation for answering these questions with information about the classification of UAS, a prioritization of hazardous chemicals, and comparison of different detection technologies.

Twelve detection technologies were identified and classified into six categories based on the operating principle of the transducer. Considering the advantages and disadvantages of the fundamental science for each category, four detection technologies emerged as candidates for SUAS integration. Using specifications from commercial off the shelf (COTS) original equipment manufacturer (OEM) sensors, these four detection technologies (Electrochemical Detection (EC), Metal Oxide Semiconductor (MOS), Photoionization Detection (PID), Catalytic Bead Sensor (CAT)) were further evaluated on five parameters (response time, sensitivity, selectivity, power, and weight) relevant to SUAS employment and integration. Based on this research and of these four detection technologies, MOS detectors are the top detection technology for SUAS employment and integration. Furthermore, an array of sensors configured using a sophisticated algorithm could provide the necessary level of selectivity needed in multiple gases or mixed gas scenarios. In fact, this research suggests that multiple detection technologies can be used together on a single platform to counteract or balance the weakness of one detection technology with another. Eighty-five hazardous chemicals were identified by cross-referencing detectable chemicals using these four technologies with CWA and TIC of interest based on their toxicity and or availability.

Chapter IV is significant because how assets are employed at the tactical level is thoroughly examined and discussed. Commanders have to balance capabilities and limitations of their units by making decisions about which assets to employ. The decision aid developed in response to Specific Aim III addresses one way to explore this dilemma.

Limitations

The limitations of this research are affiliated with its scope. However, the methods and approach conducted provide a template for future research. The extent of this research was limited to tactical level MTTP, SUAS, and direct reading chemical detection technologies. This research balanced a theoretical, technical, and practical approach to answer specific aims and the overall research objective. Applications suggest experimentation using real SUAS and sensors. However, this research was limited by scope, funding and time for this type application based research. This is addressed further in the next section regarding future research.

Future Research

There are opportunities for future research associated with each specific aim. Specific Aim I and Chapter II, serve as a baseline for addressing changes to the current MTTP for CBRN R&S. Although, further research is required to explore and develop the tasks and techniques for SUAS employment and integration. The particular techniques for SUAS CBRN R&S will need to be developed based on real world testing and evaluation. For example, a comparison study between a SUAS team and a traditional manned CBRN team conducting a locate task using various techniques, could be used to determine which techniques are best performed using a SUAS. This type of research, along with lessons learned from the operating forces using these technologies will only improve the MTTP for CBRN R&S.

Future research associated with Specific Aim II can be divided into three thrust areas: (1) SUAS design and integration, (2) testing and development of chemical sensors, (3) prioritization of hazardous chemicals. Testing and development of chemical sensors for SUAS employment and integration has the greatest potential because there are almost no chemical sensors designed specifically for this application.

Specific aim III was limited as an academic theoretical exercise. However, Chapter IV serves as a baseline for future research in this area. The basic decision aid presented in this chapter could be used in future research by refining the input parameters with real world data or be used only as method for developing other decision aids.

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Appendix A

Table 17: Chemical to Hazard Table, adapted from (Department of Homeland Security, 2007)

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Acetaldehyde	75-07-0	1.00	10,000						X						X			X						
Acetone cyanohydrin	75-86-5					ACG	APA							X						X		X		
Acetyl bromide	506-96-7					ACG	APA							X	X			X						
Acetyl chloride	75-36-5					ACG	APA							X	X			X						
Acetyl iodine	507-02-8					ACG	APA							X										
Acetylene	74-86-2	1.00	10,000						X						X	X	X	X	X					
Acrolein	107-02-8	1.00	5,000					X							X		X	X		X		X		
Acrylonitrile	107-13-1	1.00	10,000						X						X		X	X		X		X		
Acrylyl chloride	814-68-6	1.00	10,000						X															
Allyl alcohol	107-18-6	1.00	15,000					X							X		X	X		X		X		
Allylamine	107-11-9	1.00	10,000						X															

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Allyltrichlorosilane	107-37-9					ACG	APA							X										
Aluminum	7429-90-5			ACG	100								X											
Aluminum bromide	7727-15-3					ACG	APA							X										
Aluminum chloride	7446-70-0					ACG	APA							X										
Aluminum phosphide	20859-73-8					ACG	APA							X										
Ammonia (anhydrous)	7664-41-7	1.00	10,000					X																
Ammonia	7664-41-7	20.00	20,000					X							X	X	X	X	X	X	X			
Ammonium nitrate	6484-52-2	ACG	5,000	ACG	400					X			X											
Ammonium nitrate, solid [nitrogen concentration of 23% nitrogen or greater]	6484-52-2			33.00	2000								X											
Ammonium perchlorate	7790-98-9	ACG	5,000	ACG	400					X			X											
Ammonium picrate	131-74-8	ACG	5,000	ACG	400					X			X											
Amyltrichlorosilane	107-72-2					ACG	APA							X										

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Antimony pentafluoride	7783-70-2					ACG	APA							X										
Arsenic trichloride	7784-34-1	1.00	15,000	30.00	2.2			X			X									X			X	
Arsine	7784-42-1	1.00	1,000	0.67	15			X				X			X	X	X	X		X	X			X
Barium azide	18810-58-7	ACG	5,000	ACG	400					X			X											
1,4-Bis(2-chloroethylthio)-n-butane	142868-93-7			CUM 100g							X													
Bis(2-chloroethylthio)methane	63869-13-6			CUM 100g							X													
Bis(2-chloroethylthiomethyl)ether	63918-90-1			CUM 100g							X													
1,5-Bis(2-chloroethylthio)-n-pentane	142868-94-8			CUM 100g							X													
1,3-Bis(2-chloroethylthio)-n-propane	63905-10-2			CUM 100g							X													
Boron tribromide	10294-33-4			12.67	45	ACG	APA					X		X						X		X		
Boron trichloride	10294-34-5	1.00	5,000	84.70	45			X				X			X		X			X	X			
Boron trifluoride	7637-07-2	1.00	5,000	26.87	45			X				X			X		X	X		X	X			

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Boron trifluoride compound with methyl ether (1:1)	353-42-4	1.00	15,000					X																
Bromine	7726-95-6	1.00	10,000					X							X	X	X	X		X			X	
Bromine chloride	13863-41-7			9.67	45							X								X			X	
Bromine pentafluoride	7789-30-2					ACG	APA							X						X			X	
Bromine trifluoride	7787-71-5			6.00	45	ACG	APA					X		X						X			X	
Bromotrifluorethylene	598-73-2	1.00	10,000						X															
1,3-Butadiene	106-99-0	1.00	10,000						X						X			X						
Butane	106-97-8	1.00	10,000						X						X		X	X	X					
Butene	25167-67-3	1.00	10,000						X						X		X							
1-Butene	106-98-9	1.00	10,000						X						X			X						
2-Butene	107-01-7	1.00	10,000						X															
2-Butene-cis	590-18-1	1.00	10,000						X															
2-Butene-trans	624-64-6	1.00	10,000						X															
Butyltrichlorosilane	7521-80-4					ACG	APA							X										

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Calcium hydrosulfite	15512-36-4					ACG	APA							X										
Calcium phosphide	1305-99-3					ACG	APA							X										
Carbon disulfide	75-15-0	1.00	20,000					X							X		X	X		X	X			
Carbon oxysulfide	463-58-1	1.00	10,000						X															
Carbonyl fluoride	353-50-4			12.00	45							X								X			X	
Carbonyl sulfide	463-58-1			56.67	500							X								X		X		
Chlorine	7782-50-5	1.00	2,500	9.77	500			X				X			X	X	X	X		X	X			X
Chlorine dioxide	10049-04-4	1.00	1,000			ACG	APA	X						X	X	X	X	X						
Chlorine monoxide	7791-21-1	1.00	10,000						X															
Chlorine pentafluoride	13637-63-3			4.07	15							X								X			X	
Chlorine trifluoride	7790-91-2			9.97	45							X			X			X		X			X	
Chloroacetyl chloride	79-04-9					ACG	APA							X						X			X	
2-Chloroethylchloro-methylsulfide	2625-76-5			CUM 100g							X													
Chloroform	67-66-3	1.00	20,000					X							X		X	X						

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Chloromethyl ether	542-88-1	1.00	1,000					X																
Chloromethyl methyl ether	107-30-2	1.00	5,000					X																
1-Chloropropylene	590-21-6	1.00	10,000						X															
2-Chloropropylene	557-98-2	1.00	10,000						X															
Chlorosarin	1445-76-7			CUM 100g							X													
Chlorosoman	7040-57-5			CUM 100g							X													
Chlorosulfonic acid	7790-94-5					ACG	APA							X						X		X		
Chromium oxychloride	14977-61-8					ACG	APA							X										
Crotonaldehyde	4170-30-3	1.00	10,000						X						X			X		X		X		
Crotonaldehyde, (E)-	123-73-9	1.00	10,000						X															
Cyanogen	460-19-5	1.00	10,000	11.67	45				X			X			X			X		X			X	
Cyanogen chloride	506-77-4	1.00	10,000	2.67	15			X				X			X		X							X
Cyclohexylamine	108-91-8	1.00	15,000					X																
Cyclohexyltrichlorosilane	98-12-4					ACG	APA							X										
Cyclopropane	75-19-4	1.00	10,000						X						X			X						

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
DF	676-99-3			CUM 100g							X													
Diazodinitrophenol	87-31-0	ACG	5,000	ACG	400					X			X											
Diborane	19287-45-7	1.00	2,500	2.67	15			X				X			X	X	X	X		X	X			
Dichlorosilane	4109-96-0	1.00	10,000	10.47	45				X			X			X		X							
N,N-(2-diethylamino)ethanethiol	100-38-9			30.00	2.2						X													
Diethyldichlorosilane	1719-53-5					ACG	APA							X										
o,o-Diethyl S-[2-(diethylamino)ethyl] phosphorothiolate	78-53-5			30.00	2.2						X													
Diethyleneglycol dinitrate	693-21-0	ACG	5,000	ACG	400					X			X											
Diethyl methylphosphonite	15715-41-0			30.00	2.2						X													
N,N-Diethyl phosphoramidic dichloride	1498-54-0			30.00	2.2						X													
N,N-(2-diisopropylamino)-ethanethiol	5842-07-9			30.00	2.2						X													
Difluoroethane	75-37-6	1.00	10,000						X						X		X							

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
N,N-Diisopropyl phosphoramidic dichloride	23306-80-1			30.00	2.2						X													
1,1-Dimethylhydrazine	57-14-7	1.00	10,000						X						X			X						
Dimethylamine	124-40-3	1.00	10,000						X						X		X							
N,N-(2-dimethylamino)ethanethiol	108-02-1			30.00	2.2						X													
Dimethyldichlorosilane	75-78-5	1.00	10,000			ACG	APA		X					X										
N,N-Dimethyl phosphoramidic dichloride	677-43-0			30.00	2.2						X													
2,2-Dimethylpropane	463-82-1	1.00	10,000						X															
Dingu	55510-04-8	ACG	5,000	ACG	400					X			X											
Dinitrogen tetroxide	10544-72-6			3.80	15							X												
Dinitrophenol	25550-58-7	ACG	5,000	ACG	400					X			X											
Dinitroresorcinol	519-44-8	ACG	5,000	ACG	400					X			X											
Diphenyldichlorosilane	80-10-4					ACG	APA							X										
Dipicryl sulfide	2217-06-3	ACG	5,000	ACG	400					X			X											
Dipicrylamine [or] Hexyl	131-73-7	ACG	5,000	ACG	400					X			X											

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
N,N-(2-dipropylamino)ethanethiol	5842-06-8			30.00	2.2						X													
N,N-Dipropyl phosphoramidic dichloride	40881-98-9			30.00	2.2						X													
Dodecyltrichlorosilane	4484-72-4					ACG	APA							X										
Epichlorohydrin	106-89-8	1.00	20,000					X							X		X	X						
Ethane	74-84-0	1.00	10,000						X						X		X	X	X					
Ethyl acetylene	107-00-6	1.00	10,000						X															
Ethyl chloride	75-00-3	1.00	10,000						X						X		X	X						
Ethyl ether	60-29-7	1.00	10,000						X						X		X	X						
Ethyl mercaptan	75-08-1	1.00	10,000						X						X	X		X						
Ethyl nitrite	109-95-5	1.00	10,000						X															
Ethyl phosphonyl difluoride	753-98-0			CUM 100g							X													
Ethylamine	75-04-7	1.00	10,000						X															
Ethyldiethanolamine	139-87-7			80.00	220						X													
Ethylene	74-85-1	1.00	10,000						X						X	X	X	X	X					
Ethylene oxide	75-21-8	1.00	10,000						X						X	X	X	X		X	X			

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Ethylenediamine	107-15-3	1.00	20,000					X																
Ethyleneimine	151-56-4	1.00	10,000						X															
Ethylphosphonothioic dichloride	993-43-1			30.00	2.2						X													
Ethyltrichlorosilane	115-21-9					ACG	APA							X										
Fluorine	7782-41-4	1.00	1,000	6.17	15			X				X			X	X	X	X		X	X			
Fluorosulfonic acid	7789-21-1					ACG	APA							X										
Formaldehyde (solution)	50-00-0	1.00	15,000					X																
Furan	110-00-9	1.00	10,000						X						X			X						
Germane	7782-65-2			20.73	45							X			X	X	X							
Germanium tetrafluoride	7783-58-6			2.11	15							X												
Guanyl nitrosaminoguanylidene hydrazine		ACG	5,000	ACG	400					X			X											
Hexaethyl tetraphosphate and compressed gas mixtures	757-58-4			33.37	500							X												
Hexafluoroacetone	684-16-2			15.67	45							X												

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Hexanitrostilbene	20062-22-0	ACG	5,000	ACG	400					X			X											
Hexolite	121-82-4	ACG	5,000	ACG	400					X			X											
Hexyltrichlorosilane	928-65-4					ACG	APA							X										
HMX	2691-41-0	ACG	5,000	ACG	400					X			X											
HN1 (nitrogen mustard-1)	538-07-8			CUM 100g							X													X
HN2 (nitrogen mustard-2)	51-75-2			CUM 100g							X													X
HN3 (nitrogen mustard-3)	555-77-1			CUM 100g							X													X
Hydrazine	302-01-2	1.00	10,000						X						X	X	X							
Hydrochloric acid	7647-01-0	37.00	15,000					X																
Hydrocyanic acid	74-90-8	1.00	2,500					X																
Hydrofluoric acid	7664-39-3	50.00	1,000					X																
Hydrogen	1333-74-0	1.00	10,000						X						X	X	X		X					
Hydrogen bromide	10035-10-6			95.33	500							X			X	X	X	X		X	X			

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Hydrogen chloride	7647-01-0	1.00	5,000	ACG	500			X				X			X	X	X	X		X	X			
Hydrogen cyanide	74-90-8			4.67	15							X			X	X	X	X		X	X			X
Hydrogen fluoride	7664-39-3	1.00	1,000	42.53	45			X				X			X	X	X	X		X	X			
Hydrogen iodide	10034-85-2			95.33	500							X			X			X		X			X	
Hydrogen peroxide	7722-84-1			35	400								X											
Hydrogen selenide	7783-07-5	1.00	10,000	0.07	15				X			X			X	X		X		X		X		
Hydrogen sulfide	7783-06-4	1.00	10,000	23.73	45			X				X			X	X	X	X		X	X			
Iodine pentafluoride	7783-66-6					ACG	APA							X										
Iron, pentacarbonyl-	13463-40-6	1.00	10,000						X															
Isobutane	75-28-5	1.00	10,000						X						X		X	X						
Isobutyronitrile	78-82-0	1.00	20,000					X																
Isopentane	78-78-4	1.00	10,000						X						X		X	X						

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Isoprene	78-79-5	1.00	10,000						X						X		X	X						
Isopropyl chloride	75-29-6	1.00	10,000						X															
Isopropyl chloroformate	108-23-6	1.00	15,000					X												X			X	
Isopropylamine	75-31-0	1.00	10,000						X															
Isopropylphosphonothioic dichloride	1498-60-8			30.00	2.2						X													
Isopropylphosphonyl difluoride	677-42-9			CUM 100g							X													
Lead azide	13424-46-9	ACG	5,000	ACG	400					X			X											
Lead styphnate	15245-44-0	ACG	5,000	ACG	400					X			X											
Lewisite 1	541-25-3			CUM 100g							X													X
Lewisite 2	40334-69-8			CUM 100g							X													X
Lewisite 3	40334-70-1			CUM 100g							X													X
Lithium amide	7782-89-0					ACG	APA							X										
Lithium nitride	26134-62-3					ACG	APA							X										

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Magnesium (powder)	7439-95-4			ACG	100								X											
Magnesium diamide	7803-54-5					ACG	APA							X										
Magnesium phosphide	12057-74-8					ACG	APA							X										
MDEA	105-59-9			80.00	220						X													
Mercury fulminate	628-86-4	ACG	5,000	ACG	400					X			X											
Methacrylonitrile	126-98-7	1.00	10,000					X																
Methane	74-82-8	1.00	10,000						X						X		X	X	X					
2-Methyl-1-butene	563-46-2	1.00	10,000						X						X			X						
3-Methyl-1-butene	563-45-1	1.00	10,000						X						X			X						
Methyl chloride	74-87-3	1.00	10,000						X						X		X	X						
Methyl chloroformate	79-22-1	1.00	10,000						X											X		X		
Methyl ether	115-10-6	1.00	10,000						X															
Methyl formate	107-31-3	1.00	10,000						X						X			X						
Methyl hydrazine	60-34-4	1.00	15,000					X							X		X			X		X		
Methyl isocyanate	624-83-9	1.00	10,000					X							X			X		X		X		

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Methyl mercaptan	74-93-1	1.00	10,000	45.00	500				X			X			X	X	X	X		X		X		
Methyl thiocyanate	556-64-9	1.00	20,000					X							X			X						
Methylamine	74-89-5	1.00	10,000						X															
Methylchlorosilane	993-00-0			20.00	45							X												
Methyldichlorosilane	75-54-7					ACG	APA							X										
Methylphenyldichlorosilane	149-74-6					ACG	APA							X										
Methylphosphonothioic dichloride	676-98-2			30.00	2.2						X													
2-Methylpropene	115-11-7	1.00	10,000						X															
Methyltrichlorosilane	75-79-6	1.00	10,000			ACG	APA		X					X										
Sulfur mustard (Mustard gas (H))	505-60-2			CUM 100g							X													
O-Mustard (T)	63918-89-8			CUM 100g							X													
Nickel Carbonyl	13463-39-3	1.00	10,000						X						X			X						
Nitric acid	7697-37-2	80.00	15,000	68.00	400			X					X											
Nitric oxide	10102-43-9	1.00	10,000	3.83	15			X				X			X	X	X	X		X			X	

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Nitrobenzene	98-95-3			ACG	100								X		X			X						
5-Nitrobenzotriazol	2338-12-7	ACG	5,000	ACG	400					X			X											
Nitrocellulose	9004-70-0	ACG	5,000	ACG	400					X			X											
Nitrogen mustard hydrochloride	55-86-7			30.00	2.2						X													
Nitrogen trioxide	10544-73-7			3.83	15							X												
Nitroglycerine	55-63-0	ACG	5,000	ACG	400					X			X											
Nitromannite	15825-70-4	ACG	5,000	ACG	400					X			X											
Nitromethane	75-52-5			ACG	400								X		X			X						
Nitrostarch	9056-38-6	ACG	5,000	ACG	400					X			X											
Nitrosyl chloride	2696-92-6			1.17	15							X												
Nitrotriazolone	932-64-9	ACG	5,000	ACG	400					X			X											
Nonyltrichlorosilane	5283-67-0					ACG	APA							X										
Octadecyltrichlorosilane	112-04-9					ACG	APA							X										
Octolite	57607-37-1	ACG	5,000	ACG	400					X			X											

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Octonal	78413-87-3	ACG	5,000	ACG	400					X			X											
Octyltrichlorosilane	5283-66-9					ACG	APA							X										
Oleum (Fuming Sulfuric acid)	8014-95-7	1.00	10,000					X																
Oxygen difluoride	7783-41-7			0.09	15							X												
1,3-Pentadiene	504-60-9	1.00	10,000						X															
Pentane	109-66-0	1.00	10,000						X						X		X	X						
1- Pentene	109-67-1	1.00	10,000						X															
2-Pentene, (E)-	646-04-8	1.00	10,000						X															
2-Pentene, (Z)-	627-20-3	1.00	10,000						X															
Pentolite	8066-33-9	ACG	5,000	ACG	400					X			X											
Peracetic acid	79-21-0	1.00	10,000						X															
Perchloromethylmercaptan	594-42-3	1.00	10,000					X																
Perchloryl fluoride	7616-94-6			25.67	45							X												
PETN	78-11-5	ACG	5,000	ACG	400					X			X											

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Phenyltrichlorosilane	98-13-5					ACG	APA							X										
Phosgene	75-44-5	1.00	500	0.17	15			X				X			X	X	X	X		X	X			X
Phosphine	7803-51-2	1.00	10,000	0.67	15				X			X			X	X	X	X		X		X		
Phosphorus	7723-14-0			ACG	400								X											
Phosphorus oxychloride	10025-87-3	1.00	5,000	80.00	220	ACG	APA	X			X			X	X		X			X		X		
Phosphorus pentabromide	7789-69-7					ACG	APA							X										
Phosphorus pentachloride	10026-13-8					ACG	APA							X										
Phosphorus pentasulfide	1314-80-3					ACG	APA							X										
Phosphorus trichloride	7719-12-2	1.00	15,000	3.48	45	ACG	APA	X				X		X	X			X		X	X			
Picrite	556-88-7	ACG	5,000	ACG	400					X			X											
Piperidine	110-89-4	1.00	10,000						X															
Potassium chlorate	3811-04-9			ACG	400								X											
Potassium cyanide	151-50-8					ACG	APA							X										
Potassium nitrate	7757-79-1			ACG	400								X											

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Potassium perchlorate	7778-74-7			ACG	400								X											
Potassium permanganate	7722-64-7			ACG	400								X											
Potassium phosphide	20770-41-6					ACG	APA							X										
Propadiene	463-49-0	1.00	10,000						X															
Propane	74-98-6	1.00	60,000						X						X		X	X	X					
Propionitrile	107-12-0	1.00	10,000					X							X			X						
Propyl chloroformate	109-61-5	1.00	10,000						X															
Propylene	115-07-1	1.00	10,000						X						X		X	X						
Propylene oxide	75-56-9	1.00	10,000						X						X		X	X						
Propyleneimine	75-55-8	1.00	10,000					X																
Propylphosphonothioic dichloride	2524-01-8			30.00	2.2						X													
Propylphosphonyl difluoride	690-14-2			CUM 100g							X													
Propyltrichlorosilane	141-57-1					ACG	APA							X										
Propyne	74-99-7	1.00	10,000						X						X			X						

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
QL	57856-11-8			CUM 100g							X													
RDX	121-82-4	ACG	5,000	ACG	400					X			X											
RDX and HMX mixtures	121-82-4	ACG	5,000	ACG	400					X			X											
Sarin	107-44-8			CUM 100g							X													X
Selenium hexafluoride	7783-79-1			1.67	15							X								X		X		
Sesquimustard	3563-36-8			CUM 100g							X													
Silane	7803-62-5	1.00	10,000						X						X	X	X							
Silicon tetrachloride	10026-04-7					ACG	APA							X	X		X							
Silicon tetrafluoride	7783-61-1			15.00	45							X			X		X			X		X		
Sodium azide	26628-22-8			ACG	400								X											
Sodium chlorate	7775-09-9			ACG	400								X											
Sodium cyanide	143-33-9					ACG	APA							X										

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Sodium hydrosulfite	7775-14-6					ACG	APA							X										
Sodium nitrate	7631-99-4			ACG	400								X											
Sodium phosphide	12058-85-4					ACG	APA							X										
Soman	96-64-0			CUM 100g							X													X
Stibine	7803-52-3			0.67	15							X			X			X		X		X		
Strontium phosphide	12504-16-4					ACG	APA							X										
Sulfur dioxide	7446-09-5	1.00	5,000	84.00	500			X				X			X	X	X	X		X	X			
Sulfur tetrafluoride	7783-60-0	1.00	2,500	1.33	15			X				X												
Sulfur trioxide	7446-11-9	1.00	10,000					X												X		X		
Sulfuryl chloride	7791-25-5					ACG	APA							X						X		X		
Tabun	77-81-6			CUM 100g							X													X
Tellurium hexafluoride	7783-80-4			0.83	15							X								X		X		

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Tetrafluoroethylene	116-14-3	1.00	10,000						X															
Tetramethyllead	75-74-1	1.00	10,000					X																
Tetramethylsilane	75-76-3	1.00	10,000						X															
Tetranitroaniline	53014-37-2	ACG	5,000	ACG	400					X			X											
Tetranitromethane	509-14-8	1.00	10,000						X															
Tetrazene	109-27-3	ACG	5,000	ACG	400					X			X											
1H-Tetrazole	288-94-8	ACG	5,000	ACG	400					X			X											
Thiodiglycol	111-48-8			30.00	2.2						X													
Thionyl chloride	7719-09-7					ACG	APA							X										
Titanium tetrachloride	7550-45-0	1.00	2,500	13.33	45	ACG	APA	X				X		X						X		X		
TNT	118-96-7	ACG	5,000	ACG	400					X			X											
Torpex	67713-16-0	ACG	5,000	ACG	400					X			X											
Trichlorosilane	10025-78-2	1.00	10,000			ACG	APA		X					X										
Triethanolamine	102-71-6			80.00	220						X													

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Triethanolamine hydrochloride	637-39-8			80.00	220						X													
Triethyl phosphite	122-52-1			80.00	220						X													
Trifluoroacetyl chloride	354-32-5			6.93	45							X								X		X		
Trifluorochloroethylene	79-38-9	1.00	10,000	66.67	500				X			X												
Trimethylamine	75-50-3	1.00	10,000						X						X		X							
Trimethylchlorosilane	75-77-4	1.00	10,000			ACG	APA		X					X										
Trimethyl phosphite	121-45-9			80.00	220						X													
Trinitroaniline	26952-42-1	ACG	5,000	ACG	400					X			X											
Trinitroanisole	606-35-9	ACG	5,000	ACG	400					X			X											
Trinitrobenzene	99-35-4	ACG	5,000	ACG	400					X			X											
Trinitrobenzenesulfonic acid	2508-19-2	ACG	5,000	ACG	400					X			X											
Trinitrobenzoic acid	129-66-8	ACG	5,000	ACG	400					X			X											
Trinitrochlorobenzene	88-88-0	ACG	5,000	ACG	400					X			X											
Trinitrofluorenone	129-79-3	ACG	5,000	ACG	400					X			X											
Trinitro-meta-cresol	602-99-3	ACG	5,000	ACG	400					X			X											

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
Trinitronaphthalene	55810-17-8	ACG	5,000	ACG	400					X			X											
Trinitrophenetole	4732-14-3	ACG	5,000	ACG	400					X			X											
Trinitrophenol	88-89-1	ACG	5,000	ACG	400					X			X											
Trinitroresorcinol	82-71-3	ACG	5,000	ACG	400					X			X											
Tritonal	54413-15-9	ACG	5,000	ACG	400					X			X											
Tungsten hexafluoride	7783-82-6			7.10	45							X			X		X			X	X			
Vinyl acetate monomer	108-05-4	1.00	10,000						X															
Vinyl acetylene	689-97-4	1.00	10,000						X															
Vinyl chloride	75-01-4	1.00	10,000						X						X		X	X						
Vinyl ethyl ether	109-92-2	1.00	10,000						X															
Vinyl fluoride	75-02-5	1.00	10,000						X															
Vinyl methyl ether	107-25-5	1.00	10,000						X						X			X						
Vinylidene chloride	75-35-4	1.00	10,000						X						X		X							
Vinylidene fluoride	75-38-7	1.00	10,000						X															
Vinyltrichlorosilane	75-94-5					ACG	APA							X										

Chemicals of Interest (COI)	Chemical Abstract Service (CAS) #	Release: Minimum Concentration (%)	Release: Screening Threshold Quantities (in pounds)	Theft: Minimum Concentration (%)	Theft: Screening Threshold Quantities (in pounds unless otherwise noted)	Sabotage: Minimum Concentration (%)	Sabotage: Screening Threshold Quantities	Security Issue: Release - Toxic	Security Issue: Release - Flammables	Security Issue: Release - Explosives	Security Issue: Theft – CWI/CWP	Security Issue: Theft - WME	Security Issue: Theft – EXP/IEDP	Security Issue: Sabotage/Contamination	Detect?	Detect? EC	Detect? MOS	Detect? PID	Detect? CAT	ITF-25?	ITF-25? HIGH	ITF-25? MED	ITF-25? LOW	Classic CWA?
VX	50782-69-9			CUM 100g							X													X
Zinc hydrosulfite	7779-86-4					ACG	APA							X										

Appendix B

Table 18: Sensor to Chemical

Sensor Type	Detection Technology	Manufacture	Target Chemical
CAT	Catalytic or Pellistor	Alphasense Ltd.	Acetylene
CAT	Catalytic or Pellistor	Alphasense Ltd.	Butane
CAT	Catalytic or Pellistor	Alphasense Ltd.	Carbon Monoxide
CAT	Catalytic or Pellistor	Alphasense Ltd.	Ethane
CAT	Catalytic or Pellistor	Alphasense Ltd.	Ethylene
CAT	Catalytic or Pellistor	Alphasense Ltd.	Heptane
CAT	Catalytic or Pellistor	Alphasense Ltd.	Hexane
CAT	Catalytic or Pellistor	Alphasense Ltd.	Hydrogen
CAT	Catalytic or Pellistor	Alphasense Ltd.	Isobutylene
CAT	Catalytic or Pellistor	Alphasense Ltd.	Nonane
CAT	Catalytic or Pellistor	Alphasense Ltd.	n-Pentane
CAT	Catalytic or Pellistor	Alphasense Ltd.	Octane
CAT	Catalytic or Pellistor	Alphasense Ltd.	Propane
CAT	Catalytic or Pellistor	City Technology Ltd.	Acetone
CAT	Catalytic or Pellistor	City Technology Ltd.	Acetylene
CAT	Catalytic or Pellistor	City Technology Ltd.	Ammonia
CAT	Catalytic or Pellistor	City Technology Ltd.	Carbon Monoxide
CAT	Catalytic or Pellistor	City Technology Ltd.	Combustibles
CAT	Catalytic or Pellistor	City Technology Ltd.	Cyclohexane
CAT	Catalytic or Pellistor	City Technology Ltd.	Ethyl acetate
CAT	Catalytic or Pellistor	City Technology Ltd.	Ethylene
CAT	Catalytic or Pellistor	City Technology Ltd.	Hydrogen
CAT	Catalytic or Pellistor	City Technology Ltd.	Methyl ethyl ketone
CAT	Catalytic or Pellistor	City Technology Ltd.	Toluene
CAT	Catalytic or Pellistor	City Technology Ltd.	Unleaded Petrol
CAT	Catalytic or Pellistor	SGX Sensortech	Ammonia
CAT	Catalytic or Pellistor	SGX Sensortech	Methane
EC	Electrochemical	Alphasense Ltd.	Ammonia
EC	Electrochemical	Alphasense Ltd.	Carbon Monoxide
EC	Electrochemical	Alphasense Ltd.	Chlorine
EC	Electrochemical	Alphasense Ltd.	Ethylene Oxide
EC	Electrochemical	Alphasense Ltd.	Hydrogen
EC	Electrochemical	Alphasense Ltd.	Hydrogen Chloride
EC	Electrochemical	Alphasense Ltd.	Hydrogen Cyanide
EC	Electrochemical	Alphasense Ltd.	Hydrogen Sulfide
EC	Electrochemical	Alphasense Ltd.	Nitrogen Dioxide
EC	Electrochemical	Alphasense Ltd.	Oxygen
EC	Electrochemical	Alphasense Ltd.	Phosphine
EC	Electrochemical	Alphasense Ltd.	Sulfur Dioxide
EC	Electrochemical	Analox Ltd.	Ammonia
EC	Electrochemical	Analox Ltd.	Bromine
EC	Electrochemical	Analox Ltd.	Cabon Monoxide

Sensor Type	Detection Technology	Manufacture	Target Chemical
EC	Electrochemical	Analox Ltd.	Chlorine
EC	Electrochemical	Analox Ltd.	Chlorine Dioxide
EC	Electrochemical	Analox Ltd.	Ethylene Oxide
EC	Electrochemical	Analox Ltd.	Fluorine
EC	Electrochemical	Analox Ltd.	Hydrogen
EC	Electrochemical	Analox Ltd.	Hydrogen Chloride
EC	Electrochemical	Analox Ltd.	Hydrogen Cyanide
EC	Electrochemical	Analox Ltd.	Hydrogen Fluoride
EC	Electrochemical	Analox Ltd.	Hydrogen Sulfide
EC	Electrochemical	Analox Ltd.	Nitric Oxide
EC	Electrochemical	Analox Ltd.	Nitrogen Dioxide
EC	Electrochemical	Analox Ltd.	Oxygen
EC	Electrochemical	Analox Ltd.	Ozone
EC	Electrochemical	Analox Ltd.	Phosphine
EC	Electrochemical	Analox Ltd.	Sulfur Dioxide
EC	Electrochemical	City Technology Ltd.	Ammonia
EC	Electrochemical	City Technology Ltd.	Arsine
EC	Electrochemical	City Technology Ltd.	Carbon Monoxide
EC	Electrochemical	City Technology Ltd.	Chlorine
EC	Electrochemical	City Technology Ltd.	Chlorine Dioxide
EC	Electrochemical	City Technology Ltd.	Diborane
EC	Electrochemical	City Technology Ltd.	Ethylene Oxide
EC	Electrochemical	City Technology Ltd.	Exhaust Gases
EC	Electrochemical	City Technology Ltd.	Fluorine
EC	Electrochemical	City Technology Ltd.	General Air Quality
EC	Electrochemical	City Technology Ltd.	Hydrazine
EC	Electrochemical	City Technology Ltd.	Hydrogen
EC	Electrochemical	City Technology Ltd.	Hydrogen Bromide
EC	Electrochemical	City Technology Ltd.	Hydrogen Chloride
EC	Electrochemical	City Technology Ltd.	Hydrogen Cyanide
EC	Electrochemical	City Technology Ltd.	Hydrogen Fluoride
EC	Electrochemical	City Technology Ltd.	Hydrogen Selenide
EC	Electrochemical	City Technology Ltd.	Hydrogen Sulfide
EC	Electrochemical	City Technology Ltd.	Mercaptan
EC	Electrochemical	City Technology Ltd.	Mercaptane
EC	Electrochemical	City Technology Ltd.	Nitric Oxide
EC	Electrochemical	City Technology Ltd.	Nitrogen Dioxide
EC	Electrochemical	City Technology Ltd.	Oxygen
EC	Electrochemical	City Technology Ltd.	Ozone
EC	Electrochemical	City Technology Ltd.	Phosgene
EC	Electrochemical	City Technology Ltd.	Phosphine
EC	Electrochemical	City Technology Ltd.	Selenium Hydride
EC	Electrochemical	City Technology Ltd.	Silane
EC	Electrochemical	City Technology Ltd.	Sulfur Dioxide
EC	Electrochemical	City Technology Ltd.	Tetrahydrothiophene
EC	Electrochemical	Detcon Inc.	Acetylene
EC	Electrochemical	Detcon Inc.	Ammonia
EC	Electrochemical	Detcon Inc.	Arsine

Sensor Type	Detection Technology	Manufacture	Target Chemical
EC	Electrochemical	Detcon Inc.	Bromine
EC	Electrochemical	Detcon Inc.	Butadiene
EC	Electrochemical	Detcon Inc.	Carbon Monoxide
EC	Electrochemical	Detcon Inc.	Chlorine
EC	Electrochemical	Detcon Inc.	Chlorine Dioxide
EC	Electrochemical	Detcon Inc.	Diborane
EC	Electrochemical	Detcon Inc.	Ethanol
EC	Electrochemical	Detcon Inc.	Ethyl Mercaptan
EC	Electrochemical	Detcon Inc.	Ethylene
EC	Electrochemical	Detcon Inc.	Ethylene Oxide
EC	Electrochemical	Detcon Inc.	Fluorine
EC	Electrochemical	Detcon Inc.	Formaldehyde
EC	Electrochemical	Detcon Inc.	Germane
EC	Electrochemical	Detcon Inc.	Hydrazine
EC	Electrochemical	Detcon Inc.	Hydrogen
EC	Electrochemical	Detcon Inc.	Hydrogen
EC	Electrochemical	Detcon Inc.	Hydrogen
EC	Electrochemical	Detcon Inc.	Hydrogen Bromide
EC	Electrochemical	Detcon Inc.	Hydrogen Chloride
EC	Electrochemical	Detcon Inc.	Hydrogen Cyanide
EC	Electrochemical	Detcon Inc.	Hydrogen Fluoride
EC	Electrochemical	Detcon Inc.	Hydrogen Sulfide
EC	Electrochemical	Detcon Inc.	Methanol
EC	Electrochemical	Detcon Inc.	Methyl Mercaptan
EC	Electrochemical	Detcon Inc.	Nitric Oxide
EC	Electrochemical	Detcon Inc.	Nitrogen Dioxide
EC	Electrochemical	Detcon Inc.	Ozone
EC	Electrochemical	Detcon Inc.	Phosphine
EC	Electrochemical	Detcon Inc.	Silane
EC	Electrochemical	Detcon Inc.	Sulfur Dioxide
MOS	Metal-Oxide Semiconductor	Alphasense Ltd.	Carbon Monoxide
MOS	Metal-Oxide Semiconductor	Alphasense Ltd.	Hydrogen Sulfide
MOS	Metal-Oxide Semiconductor	Alphasense Ltd.	VOC
MOS	Metal-Oxide Semiconductor	Detcon Inc.	Hydrogen Sulfide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Acetic Acid
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Acetone
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Acetonitrile
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Acetylene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Acrolein
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Acrylic Acid
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Acrylonitrile
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Allyl Alcohol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Allyl Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ammonia
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Anisole
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Arsenic Pentafluoride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Arsine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Benzene

Sensor Type	Detection Technology	Manufacture	Target Chemical
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Biphenyl
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Boron Trichloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Boron Trifluoride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Bromine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Butadiene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Butane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Butanol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Butene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Butyl Acetate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Carbon Disulfide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Carbon Monoxide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Carbon Tetrachloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Cellosolve Acetate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Chlorine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Chlorine Dioxide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Chlorobutadiene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Chloroethanol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Chloroform
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Chlorotrifluoroethylene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Cumene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Cyanogen Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Cyclohexane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Cyclopentane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Deuterium
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Diborane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dibromoethane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dibutylamine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dichlorobutene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dichloroethane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dichlorofluoroethane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dichloropentadiene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dichlorosilane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Diesel Fuel
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Diethyl Benzene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Diethyl Sulfide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Difluorochloroethane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Difluoroethane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dimethyl Ether
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Dimethylamine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Epichlorohydrin
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethanol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethyl Acetate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethyl Benzene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethyl Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethyl Chlorocarbonate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethyl Ether
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethylene

Sensor Type	Detection Technology	Manufacture	Target Chemical
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Ethylene Oxide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Fluorine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Formaldehyde
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Freon-11
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Freon-113
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Freon-114
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Freon-12
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Freon-123
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Freon-22
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Fuel Oil or Kerosene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Gasoline
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Germane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Heptane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hexane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hexene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hydrazine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hydrogen
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hydrogen Bromide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hydrogen Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hydrogen Cyanide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hydrogen Fluoride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Hydrogen Sulfide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Isobutane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Isobutylene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Isopentane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Isoprene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Isopropanol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	JP4
MOS	Metal-Oxide Semiconductor	International Sensor Technology	JP5
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methanol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Acetate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Acrylate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Bromide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Butanol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Cellosolve
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Ethyl
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Hydrazine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Isobutyl
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Mercaptan
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl Methacrylate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methylene Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Methyl-Tert Butyl
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Mineral Spirits
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Monochlorobenzene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Monoethylamine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Morpholine

Sensor Type	Detection Technology	Manufacture	Target Chemical
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Naptha
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Natural Gas
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Nitric Oxide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Nitrogen Dioxide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Nitrogen Trifluoride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Nonane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Pentane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Perchloroethylene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Phenol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Phosgene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Phosphine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Phosphorus Oxychloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Picoline
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Propane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Propylene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Propylene Oxide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Silane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Silicon Tetrachloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Silicon Tetrafluoride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Styrene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Sulfur Dioxide
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Tetrahydrofuran
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Tetraline
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Toluene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Toluene Diisocyanate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Trichloroethane
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Trichloroethylene
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Triethylamine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Trifluoroethanol
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Trimethylamine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Tungsten Hexafluoride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Turpentine
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Vinyl Acetate
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Vinyl Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Vinylidene Chloride
MOS	Metal-Oxide Semiconductor	International Sensor Technology	Xylene
NDIR	Non-Dispersive Infra-Red	Alphasense Ltd.	Carbon Dioxide
NDIR	Non-Dispersive Infra-Red	Alphasense Ltd.	Methane
NDIR	Non-Dispersive Infra-Red	City Technology Ltd.	Carbon Dioxide
NDIR	Non-Dispersive Infra-Red	City Technology Ltd.	Combustibles
NDIR	Non-Dispersive Infra-Red	Detcon Inc.	Carbon Dioxide
NDIR	Non-Dispersive Infra-Red	Detcon Inc.	Combustible Hydrocarbons
PID	Photoionization Detector	Alphasense Ltd.	VOC
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1,1-Trichloroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1,2,2-Tetrachloro-1,2-difluoroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1,2,2-tetrachloro-1,2-difluoroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1,2-Trichloro-1,2,2-trifluoroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1,2-trichloro-1,2,2-trifluororethane

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1-Dibromoethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1-Dichloroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1-Dimethoxyethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,1-Dimethylhydrazine
PID	Photoionization Detector	Baseline-Mocon Inc.	1,2-Dibromoethene
PID	Photoionization Detector	Baseline-Mocon Inc.	1,2-Dichloro-1,1,2,2-tetrafluoroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,2-dichloro-1,1,2,2-tetrafluoroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,2-Dichloroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,2-Dichloropropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,3-Butadiene
PID	Photoionization Detector	Baseline-Mocon Inc.	1,3-Dibromopropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1,3-Dichloropropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Bromo-2-chloroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Bromo-2-methylpropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Bromo-4-fluorobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Bromobutane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Bromopentane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Bromopropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Bromopropene
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Butanethiol
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Butene
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Butyne
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Chloro-2-methylpropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Chloro-3-fluorobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Chlorobutane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Chloropropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Hexene
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Iodo-2-methylpropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Iodobutane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Iodopentane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Iodopropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Methyl napthalene
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Nitropropane
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Pentene
PID	Photoionization Detector	Baseline-Mocon Inc.	1-Propanethiol
PID	Photoionization Detector	Baseline-Mocon Inc.	2,2,4-Trimethyl pentane
PID	Photoionization Detector	Baseline-Mocon Inc.	2,2-Dimethyl butane
PID	Photoionization Detector	Baseline-Mocon Inc.	2,2-Dimethyl propane
PID	Photoionization Detector	Baseline-Mocon Inc.	2,3-Butadione
PID	Photoionization Detector	Baseline-Mocon Inc.	2,3-Dichloropropene
PID	Photoionization Detector	Baseline-Mocon Inc.	2,3-Dimethyl butane
PID	Photoionization Detector	Baseline-Mocon Inc.	2,3-Lutidine
PID	Photoionization Detector	Baseline-Mocon Inc.	2,4-Lutidine
PID	Photoionization Detector	Baseline-Mocon Inc.	2,4-Pentanedione
PID	Photoionization Detector	Baseline-Mocon Inc.	2,4-Xylidine
PID	Photoionization Detector	Baseline-Mocon Inc.	2,6-Lutidine
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Amino pyridine
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Bromo-2-methylpropane

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Bromobutane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Bromopropane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Bromothiophene
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Butanone
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Chloro-2-methylpropane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Chlorobutane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Chloropropane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Chlorothiophene
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Furaldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Heptanone
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Hexanone
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Iodobutane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Iodopropane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Methyl furan
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Methyl napthalene
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Methyl-1-butene
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Methylpentane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Nitropropane
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Pentanone
PID	Photoionization Detector	Baseline-Mocon Inc.	2-Picoline
PID	Photoionization Detector	Baseline-Mocon Inc.	3,3-Dimethyl butanone
PID	Photoionization Detector	Baseline-Mocon Inc.	3-Bromopropene
PID	Photoionization Detector	Baseline-Mocon Inc.	3-Butene nitrile
PID	Photoionization Detector	Baseline-Mocon Inc.	3-Chloropropene
PID	Photoionization Detector	Baseline-Mocon Inc.	3-Methyl-1-butene
PID	Photoionization Detector	Baseline-Mocon Inc.	3-Methyl-2-butene
PID	Photoionization Detector	Baseline-Mocon Inc.	3-Methylpentane
PID	Photoionization Detector	Baseline-Mocon Inc.	3-Picoline
PID	Photoionization Detector	Baseline-Mocon Inc.	4-Methylcyclohexene
PID	Photoionization Detector	Baseline-Mocon Inc.	4-Picoline
PID	Photoionization Detector	Baseline-Mocon Inc.	a -Chloroacetophenone
PID	Photoionization Detector	Baseline-Mocon Inc.	a -Methyl styrene
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetaldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetamide
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetic acid
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetic anhydride
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetone
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetonitrile
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetophenone
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetyl bromide
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetyl chloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Acetylene
PID	Photoionization Detector	Baseline-Mocon Inc.	Acrolein
PID	Photoionization Detector	Baseline-Mocon Inc.	Acrylamide
PID	Photoionization Detector	Baseline-Mocon Inc.	Acrylonitrile
PID	Photoionization Detector	Baseline-Mocon Inc.	Allyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	Allyl chloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Ammonia

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	Aniline
PID	Photoionization Detector	Baseline-Mocon Inc.	Anisidine
PID	Photoionization Detector	Baseline-Mocon Inc.	Anisole
PID	Photoionization Detector	Baseline-Mocon Inc.	Arsine
PID	Photoionization Detector	Baseline-Mocon Inc.	Benzaldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Benzenethiol
PID	Photoionization Detector	Baseline-Mocon Inc.	Benzonitrile
PID	Photoionization Detector	Baseline-Mocon Inc.	Benzotrifluoride
PID	Photoionization Detector	Baseline-Mocon Inc.	Biphenyl
PID	Photoionization Detector	Baseline-Mocon Inc.	Boron oxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Boron trifluoride
PID	Photoionization Detector	Baseline-Mocon Inc.	Bromine
PID	Photoionization Detector	Baseline-Mocon Inc.	Bromobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Bromochloromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Bromoform
PID	Photoionization Detector	Baseline-Mocon Inc.	Butane
PID	Photoionization Detector	Baseline-Mocon Inc.	Butyl mercaptan
PID	Photoionization Detector	Baseline-Mocon Inc.	Camphor
PID	Photoionization Detector	Baseline-Mocon Inc.	Carbon dioxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Carbon disulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Carbon monoxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Carbon tetrachloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Chlorine
PID	Photoionization Detector	Baseline-Mocon Inc.	Chlorine dioxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Chlorine trifluoride
PID	Photoionization Detector	Baseline-Mocon Inc.	Chloroacetaldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Chlorobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Chlorobromomethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Chlorofluoromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Chloroform
PID	Photoionization Detector	Baseline-Mocon Inc.	Chlorotrifluoromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Chrysene
PID	Photoionization Detector	Baseline-Mocon Inc.	cis-2-Butene
PID	Photoionization Detector	Baseline-Mocon Inc.	cis-Dichloroethene Decaborane
PID	Photoionization Detector	Baseline-Mocon Inc.	Cresol
PID	Photoionization Detector	Baseline-Mocon Inc.	Crotonaldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Cumene
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyanogen
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclohexane
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclohexanol
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclohexanone
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclohexene
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclo-octatetraene
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclopentadiene
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclopentane
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclopentanone
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclopentene

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	Cyclopropane
PID	Photoionization Detector	Baseline-Mocon Inc.	Decaborane
PID	Photoionization Detector	Baseline-Mocon Inc.	Diazomethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Diborane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dibromochloromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dibromodifluoromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dibromomethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dibutylamine
PID	Photoionization Detector	Baseline-Mocon Inc.	Dichlorodifluoromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	dichlorodifluoromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dichlorofluoromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dichloromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Diethoxymethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Diethyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Diethyl ether
PID	Photoionization Detector	Baseline-Mocon Inc.	Diethyl ketone
PID	Photoionization Detector	Baseline-Mocon Inc.	Diethyl sulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Diethyl sulfite
PID	Photoionization Detector	Baseline-Mocon Inc.	Difluorodibromomethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dihydropyran
PID	Photoionization Detector	Baseline-Mocon Inc.	Diiodomethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Diisopropylamine
PID	Photoionization Detector	Baseline-Mocon Inc.	Dimethoxymethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Dimethyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Dimethyl ether
PID	Photoionization Detector	Baseline-Mocon Inc.	Dimethyl sulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Dimethylaniline
PID	Photoionization Detector	Baseline-Mocon Inc.	Dimethylformamide
PID	Photoionization Detector	Baseline-Mocon Inc.	Dimethylphthalate
PID	Photoionization Detector	Baseline-Mocon Inc.	Dinitrobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Dioxane
PID	Photoionization Detector	Baseline-Mocon Inc.	Diphenyl
PID	Photoionization Detector	Baseline-Mocon Inc.	Dipropyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Dipropyl sulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Durene
PID	Photoionization Detector	Baseline-Mocon Inc.	Epichlorohydrin
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethanethiol (ethyl mercaptan)
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethanolamine Ethene
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethene
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl bromide
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl chloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl disulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl ether

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl formate
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl iodide
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl isothiocyanate
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl mercaptan
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl methyl sulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl nitrate
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl propionate
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethyl thiocyanate
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethylene
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethylene chlorohydrin
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethylene diamine
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethylene dibromide
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethylene dichloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethylene oxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethylenelmine
PID	Photoionization Detector	Baseline-Mocon Inc.	Ethynylbenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Fluorine
PID	Photoionization Detector	Baseline-Mocon Inc.	Fluorobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Formaldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Formamide
PID	Photoionization Detector	Baseline-Mocon Inc.	Formic acid
PID	Photoionization Detector	Baseline-Mocon Inc.	Furan
PID	Photoionization Detector	Baseline-Mocon Inc.	Furfural
PID	Photoionization Detector	Baseline-Mocon Inc.	Heptane
PID	Photoionization Detector	Baseline-Mocon Inc.	Hexachloroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Hexane
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrazine Hydrogen
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen bromide
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen chloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen cyanide
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen fluoride
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen iodide
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen selenide
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen sulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydrogen telluride
PID	Photoionization Detector	Baseline-Mocon Inc.	Hydroquinone
PID	Photoionization Detector	Baseline-Mocon Inc.	Iodine
PID	Photoionization Detector	Baseline-Mocon Inc.	Iodobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Isobutane
PID	Photoionization Detector	Baseline-Mocon Inc.	Isobutyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	Isobutyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	Isobutyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Isobutyl formate
PID	Photoionization Detector	Baseline-Mocon Inc.	Isobutyraldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Isobutyric acid
PID	Photoionization Detector	Baseline-Mocon Inc.	Isopentane
PID	Photoionization Detector	Baseline-Mocon Inc.	Isophorone
PID	Photoionization Detector	Baseline-Mocon Inc.	Isoprene

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	Isopropyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	Isopropyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	Isopropyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Isopropyl benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Isopropyl ether
PID	Photoionization Detector	Baseline-Mocon Inc.	Isovaleraldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Ketene
PID	Photoionization Detector	Baseline-Mocon Inc.	Maleic anhydride
PID	Photoionization Detector	Baseline-Mocon Inc.	m-Bromotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	m-Chlorotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	m-Dichlorobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Mesityl oxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Mesitylene
PID	Photoionization Detector	Baseline-Mocon Inc.	Methane
PID	Photoionization Detector	Baseline-Mocon Inc.	Methanethiol
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl acetylene
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl acrylate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl bromide
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl butyl ketone
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl butyrate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl cellosolve
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl chloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl chloroform
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl disulfide
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl ethyl ketone
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl formate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl iodide
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl isobutyl ketone
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl isobutyrate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl isocyanate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl isopropyl ketone
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl isothiocyanate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl mercaptan
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl methacrylate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl propionate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl propyl ketone
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl thiocyanate
PID	Photoionization Detector	Baseline-Mocon Inc.	Methylal
PID	Photoionization Detector	Baseline-Mocon Inc.	Methylcyclohexane
PID	Photoionization Detector	Baseline-Mocon Inc.	Methylene chloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Methyl-n-amyl ketone
PID	Photoionization Detector	Baseline-Mocon Inc.	m-Fluorotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	m-Iodotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	Monomethyl aniline
PID	Photoionization Detector	Baseline-Mocon Inc.	Monomethyl hydrazine

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	Morpholine
PID	Photoionization Detector	Baseline-Mocon Inc.	m-Xylene
PID	Photoionization Detector	Baseline-Mocon Inc.	N,N-Diethyl acetamide
PID	Photoionization Detector	Baseline-Mocon Inc.	N,N-Diethyl formamide
PID	Photoionization Detector	Baseline-Mocon Inc.	N,N-Dimethyl acetamide
PID	Photoionization Detector	Baseline-Mocon Inc.	N,N-Dimethyl formamide
PID	Photoionization Detector	Baseline-Mocon Inc.	Naphthalene
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyl benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyl formate
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyraldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyric acid
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Butyronitrile
PID	Photoionization Detector	Baseline-Mocon Inc.	Nickel carbonyl
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitric oxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitrobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitrogen
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitrogen dioxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitrogen trifluoride
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Nitrotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Methyl acetamide
PID	Photoionization Detector	Baseline-Mocon Inc.	n-Propyl nitrate
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Bromotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Chlorotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	Octane
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Dichlorobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Fluorophenol
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Fluorotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Iodotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Terphenyls
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Toluidine
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Vinyl toluene
PID	Photoionization Detector	Baseline-Mocon Inc.	Oxygen
PID	Photoionization Detector	Baseline-Mocon Inc.	o-Xylene
PID	Photoionization Detector	Baseline-Mocon Inc.	Ozone
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Bromotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Chlorotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Dichlorobenzene
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Dioxane
PID	Photoionization Detector	Baseline-Mocon Inc.	Pentaborane
PID	Photoionization Detector	Baseline-Mocon Inc.	Pentane
PID	Photoionization Detector	Baseline-Mocon Inc.	Perchloroethylene
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Fluorotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	Pheneloic

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	Phenol
PID	Photoionization Detector	Baseline-Mocon Inc.	Phenyl ether
PID	Photoionization Detector	Baseline-Mocon Inc.	Phenyl hydrazine
PID	Photoionization Detector	Baseline-Mocon Inc.	Phenyl isocyanate
PID	Photoionization Detector	Baseline-Mocon Inc.	Phenyl isothiocyanate
PID	Photoionization Detector	Baseline-Mocon Inc.	Phenylene diamine
PID	Photoionization Detector	Baseline-Mocon Inc.	Phosgene
PID	Photoionization Detector	Baseline-Mocon Inc.	Phosphine
PID	Photoionization Detector	Baseline-Mocon Inc.	Phosphorus trichloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Phthalic anhydride
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Iodotoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Nitrochloro benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Propane
PID	Photoionization Detector	Baseline-Mocon Inc.	Propargyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	Propiolactone
PID	Photoionization Detector	Baseline-Mocon Inc.	Propionaldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Propionic acid
PID	Photoionization Detector	Baseline-Mocon Inc.	Propionitrile
PID	Photoionization Detector	Baseline-Mocon Inc.	Propyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	Propyl alcohol
PID	Photoionization Detector	Baseline-Mocon Inc.	Propyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	Propyl benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Propyl ether
PID	Photoionization Detector	Baseline-Mocon Inc.	Propyl formate
PID	Photoionization Detector	Baseline-Mocon Inc.	Propylene
PID	Photoionization Detector	Baseline-Mocon Inc.	Propylene dichloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Propylene imine
PID	Photoionization Detector	Baseline-Mocon Inc.	Propylene oxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Propyne
PID	Photoionization Detector	Baseline-Mocon Inc.	p-tert-Butyltoluene
PID	Photoionization Detector	Baseline-Mocon Inc.	p-Xylene
PID	Photoionization Detector	Baseline-Mocon Inc.	Pyridine
PID	Photoionization Detector	Baseline-Mocon Inc.	Pyrrole
PID	Photoionization Detector	Baseline-Mocon Inc.	Quinone
PID	Photoionization Detector	Baseline-Mocon Inc.	s-Butyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	s-Butyl benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	sec-Butyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	Stibine
PID	Photoionization Detector	Baseline-Mocon Inc.	Styrene
PID	Photoionization Detector	Baseline-Mocon Inc.	Sulfur dioxide
PID	Photoionization Detector	Baseline-Mocon Inc.	Sulfur hexafluoride
PID	Photoionization Detector	Baseline-Mocon Inc.	Sulfur monochloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Sulfuryl fluoride
PID	Photoionization Detector	Baseline-Mocon Inc.	t-Butyl amine
PID	Photoionization Detector	Baseline-Mocon Inc.	t-Butyl benzene
PID	Photoionization Detector	Baseline-Mocon Inc.	Tetrachloroethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Tetrachloroethene
PID	Photoionization Detector	Baseline-Mocon Inc.	Tetrachloromethane

Sensor Type	Detection Technology	Manufacture	Target Chemical
PID	Photoionization Detector	Baseline-Mocon Inc.	Tetrahydrofuran
PID	Photoionization Detector	Baseline-Mocon Inc.	Tetrahydropyran
PID	Photoionization Detector	Baseline-Mocon Inc.	Thiolacetic acid
PID	Photoionization Detector	Baseline-Mocon Inc.	Thiophene
PID	Photoionization Detector	Baseline-Mocon Inc.	Toluene
PID	Photoionization Detector	Baseline-Mocon Inc.	trans-2-Butene
PID	Photoionization Detector	Baseline-Mocon Inc.	trans-Dichloroethene
PID	Photoionization Detector	Baseline-Mocon Inc.	Tribromoethene
PID	Photoionization Detector	Baseline-Mocon Inc.	trichlorofluoromethane
PID	Photoionization Detector	Baseline-Mocon Inc.	Valeraldehyde
PID	Photoionization Detector	Baseline-Mocon Inc.	Valeric acid
PID	Photoionization Detector	Baseline-Mocon Inc.	Vinyl acetate
PID	Photoionization Detector	Baseline-Mocon Inc.	Vinyl bromide
PID	Photoionization Detector	Baseline-Mocon Inc.	Vinyl chloride
PID	Photoionization Detector	Baseline-Mocon Inc.	Vinyl methyl ether
PID	Photoionization Detector	Baseline-Mocon Inc.	Water
PID	Photoionization Detector	Detcon Inc.	VOC

Appendix C

Table 19: Electrochemical Detection Survey

Manufacture	Sensor Name	Target Chemical	Weight (g)	Sensitivity (nA/ppm)	Range (ppm)	Response time t90 (s)	Load resistor (Ω)
Alphasense Ltd.	NH3-B1 Ammonia Sensor	Ammonia	< 13	25 to 45	100	< 60	10 to 47
Alphasense Ltd.	CL2-A1 Chlorine Sensor	Chlorine	< 6	-350 to -750	20	< 60	33
Alphasense Ltd.	CL2-D4 Chlorine Sensor Miniature Size	Chlorine	< 2	-200 to -450	20	< 35	33
Alphasense Ltd.	CL2-B1 Chlorine Sensor	Chlorine	< 13	-600 to -1150	20	< 60	33
Alphasense Ltd.	HCL-A1 Hydrogen Chloride Sensor	Hydrogen Chloride	< 6	80 to 130	100	< 300	10 to 33
Alphasense Ltd.	HCL-B1 Hydrogen Chloride Sensor	Hydrogen Chloride	< 13	150 to 250	100	< 200	10 to 33
Alphasense Ltd.	HCN-A1 Hydrogen Cyanide Sensor	Hydrogen Cyanide	< 6	55 to 85	100	< 70	10 to 33
Alphasense Ltd.	HCN-B1 Hydrogen Cyanide Sensor	Hydrogen Cyanide	< 6	80 to 140	100	< 120	10 to 33
Alphasense Ltd.	HCN-D4 Hydrogen Cyanide Sensor	Hydrogen Cyanide	< 2	30 to 50	50	< 50	10 to 47
Alphasense Ltd.	H2S-A1 Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 6	550 to 875	100	< 35	10 to 47
Alphasense Ltd.	H2S-A4 Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 6	1200 to 1650	50	< 45	33 to 100
Alphasense Ltd.	H2S-AE Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 6	65 to 105	2,000	< 25	10 to 47
Alphasense Ltd.	H2S-AH Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 6	950 to 1450	50	< 30	10 to 47
Alphasense Ltd.	H2S-B1 Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 13	300 to 450	200	< 55	10 to 47
Alphasense Ltd.	H2S-B4 Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 13	1450 to 2050	100	< 55	33 to 100
Alphasense Ltd.	H2S-BE Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 13	80 to 115	2,000	< 50	10 to 47
Alphasense Ltd.	H2S-BH Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 13	1400 to 2100	50	< 55	10 to 47
Alphasense Ltd.	H2S-D4 Hydrogen Sulfide Sensor	Hydrogen Sulfide	< 2	110 to 170	100	< 25	10 to 47
Alphasense Ltd.	SO2-A4 Sulfur Dioxide Sensor	Sulfur Dioxide	< 6	320 to 480	50	< 20	33 to 100
Alphasense Ltd.	SO2-AE Sulfur Dioxide Sensor	Sulfur Dioxide	< 6	55 to 80	2,000	< 30	10 to 47
Alphasense Ltd.	SO2-AF Sulfur Dioxide Sensor	Sulfur Dioxide	< 6	300 to 550	50	< 35	10 to 47
Alphasense Ltd.	SO2-B4 Sulfur Dioxide Sensor	Sulfur Dioxide	< 13	275 to 475	100	< 30	33 to 100
Alphasense Ltd.	SO2-BE Sulfur Dioxide Sensor	Sulfur Dioxide	< 13	70 to 100	2,000	< 30	10 to 47
Alphasense Ltd.	SO2-BF Sulfur Dioxide Sensor	Sulfur Dioxide	< 13	300 to 480	100	< 40	10 to 47
Alphasense Ltd.	SO2-D4 Sulfur Dioxide Sensor	Sulfur Dioxide	< 2	180 to 420	20	< 15	22

Manufacture	Sensor Name	Target Chemical	Weight (g)	Sensitivity (nA/ppm)	Range (ppm)	Response time t90 (s)	Load resistor (Ω)
Analox Ltd.	3008 SI	Ammonia	< 600		10	< 150	50-500
Analox Ltd.	3008 SI	Ammonia	< 600		50	< 150	50-500
Analox Ltd.	3008 SI	Ammonia	< 600		100	< 150	50-500
Analox Ltd.	3015 SI	Bromine	< 600		10	< 60	50-500
Analox Ltd.	3000 SI	Cabon Monoxide	< 600		100	< 30	50-500
Analox Ltd.	3000 SI	Cabon Monoxide	< 600		200	< 30	50-500
Analox Ltd.	3000 SI	Cabon Monoxide	< 600		300	< 30	50-500
Analox Ltd.	3000 SI	Cabon Monoxide	< 600		500	< 30	50-500
Analox Ltd.	3000 SI	Cabon Monoxide	< 600		1000	< 30	50-500
Analox Ltd.	3006 SI	Chlorine	< 600		10	< 60	50-500
Analox Ltd.	3006 SI	Chlorine	< 600		100	< 60	50-500
Analox Ltd.	3011 SI	Chlorine Dioxide	< 600		10	< 120	50-500
Analox Ltd.	3017 SI	Ethylene Oxide	< 600		20	< 140	50-500
Analox Ltd.	3013 SI	Fluorine	< 600		10	< 60	50-500
Analox Ltd.	3003 SI	Hydrogen	< 600		1000	< 50	50-500
Analox Ltd.	3003 SI	Hydrogen	< 600		2000	< 50	50-500
Analox Ltd.	3010 SI	Hydrogen Chloride	< 600		10	< 150	50-500
Analox Ltd.	3007 SI	Hydrogen Cyanide	< 600		10	< 150	50-500
Analox Ltd.	3007 SI	Hydrogen Cyanide	< 600		50	< 150	50-500
Analox Ltd.	3007 SI	Hydrogen Cyanide	< 600		100	< 150	50-500
Analox Ltd.	3016 SI	Hydrogen Fluoride	< 600		10	< 120	50-500
Analox Ltd.	3001 SI	Hydrogen Sulfide	< 600		50	< 30	50-500
Analox Ltd.	3001 SI	Hydrogen Sulfide	< 600		100	< 30	50-500
Analox Ltd.	3001 SI	Hydrogen Sulfide	< 600		500	< 30	50-500
Analox Ltd.	3005 SI	Nitric Oxide	< 600		100	< 15	50-500
Analox Ltd.	3005 SI	Nitric Oxide	< 600		1000	< 15	50-500
Analox Ltd.	3004 SI	Nitrogen Dioxide	< 600		10	< 40	50-500
Analox Ltd.	3004 SI	Nitrogen Dioxide	< 600		100	< 40	50-500
Analox Ltd.	3012 SI	Oxygen	< 600		25	< 20	50-500
Analox Ltd.	3009 SI	Ozone	< 600		2	< 150	50-500
Analox Ltd.	3009 SI	Ozone	< 600		5	< 150	50-500

Manufacture	Sensor Name	Target Chemical	Weight (g)	Sensitivity (nA/ppm)	Range (ppm)	Response time t90 (s)	Load resistor (Ω)
Analox Ltd.	3014 SI	Phosphine	< 600		10	< 60	50-500
Analox Ltd.	3002 SI	Sulfur Dioxide	< 600		20	< 15	50-500
Analox Ltd.	3002 SI	Sulfur Dioxide	< 600		100	< 15	50-500
City Technology Ltd.	SensoriC NH3 3E 100 MINI	Ammonia	1.2- 17	90	100	<120	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 100 SENSORIC CLASSIC	Ammonia	1.2- 17	90	100	<120	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 100 CTL 4 series adaptation	Ammonia	1.2- 17	90	100	<120	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 100 CTL 7 series adaptation	Ammonia	1.2- 17	90	100	<120	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 100 SE MINI	Ammonia	1.2- 17	130	100	< 60	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 100 SE SENSORIC CLASSIC	Ammonia	1.2- 17	130	100	< 60	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 100 SE CTL 4 series adaptation	Ammonia	1.2- 17	130	100	< 60	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 100 SE CTL 7 series adaptation	Ammonia	1.2- 17	130	100	< 60	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 1000 SENSORIC CLASSIC	Ammonia	1.2- 17	6	1000	< 120	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 1000 CTL 4 series adaptation	Ammonia	1.2- 17	6	1000	< 120	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 1000 CTL 7 series adaptation	Ammonia	1.2- 17	6	1000	< 120	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 1000 SE MINI	Ammonia	1.2- 17	8	1000	< 90	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 1000 SE SENSORIC CLASSIC	Ammonia	1.2- 17	8	1000	< 90	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 1000 SE CTL 4 series adaptation	Ammonia	1.2- 17	8	1000	< 90	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 1000 SE CTL 7 series adaptation	Ammonia	1.2- 17	8	1000	< 90	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 5000 SE MINI	Ammonia	1.2- 17	4	5000	< 90	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 5000 SE SENSORIC CLASSIC	Ammonia	1.2- 17	4	5000	< 90	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 5000 SE CTL4 series adaptation	Ammonia	1.2- 17	4	5000	< 90	1.5 to 33
City Technology Ltd.	SensoriC NH3 3E 5000 SE CTL 7 series adaptation	Ammonia	1.2- 17	4	5000	< 90	1.5 to 33
City Technology Ltd.	SensoriC AsH3 3E 1 MINI	Arsine	1.2- 17	1400	1	< 30	1.5 to 33
City Technology Ltd.	SensoriC AsH3 3E 1 SENSORIC CLASSIC	Arsine	1.2- 17	1400	1	< 30	1.5 to 33
City Technology Ltd.	SensoriC AsH3 3E 1 CTL 4 series adaptation	Arsine	1.2- 17	1400	1	< 30	1.5 to 33
City Technology Ltd.	SensoriC AsH3 3E 1 CTL 7 series adaptation	Arsine	1.2- 17	1400	1	< 30	1.5 to 33
City Technology Ltd.	3CLH CiTiceL	Chlorine	22	1000	20	≤60	33
City Technology Ltd.	SensoriC Cl2 3E 10 MINI	Chlorine	1.2- 17	450	10	< 60	1.5 to 33
City Technology Ltd.	SensoriC Cl2 3E 10 SENSORIC CLASSIC	Chlorine	1.2- 17	450	10	< 60	1.5 to 33
City Technology Ltd.	SensoriC Cl2 3E 10 CTL 4 series adaptation	Chlorine	1.2- 17	450	10	< 60	1.5 to 33
City Technology Ltd.	SensoriC Cl2 3E 10 CTL 7 series adaptation	Chlorine	1.2- 17	450	10	< 60	1.5 to 33

Manufacture	Sensor Name	Target Chemical	Weight (g)	Sensitivity (nA/ppm)	Range (ppm)	Response time t90 (s)	Load resistor (Ω)
City Technology Ltd.	3MCLH mV Output CiTiceL	Chlorine	38		100	< 60	
City Technology Ltd.	Chlorine_Shawcity_Cl23E50 MINI	Chlorine	1.2- 17	450	50	< 30	
City Technology Ltd.	Chlorine_Shawcity_Cl23E50 SENSORIC CLASSIC	Chlorine	1.2- 17	450	50	< 30	
City Technology Ltd.	Chlorine_Shawcity_Cl23E50 CTL 4 series adaptation	Chlorine	1.2- 17	450	50	< 30	
City Technology Ltd.	Chlorine_Shawcity_Cl23E50 CTL 7 series adaptation	Chlorine	1.2- 17	450	50	< 30	
City Technology Ltd.	T3CLH 4-20mA Transmitter TH3A-1A	Chlorine	58		5	< 60	
City Technology Ltd.	T3CLH 4-20mA Transmitter TH3B-1A	Chlorine	58		10	< 60	
City Technology Ltd.	T3CLH 4-20mA Transmitter TH3C-1A	Chlorine	58		20	< 60	
City Technology Ltd.	T3CLH 4-20mA Transmitter TH3D-1A	Chlorine	58		30	< 60	
City Technology Ltd.	T3CLH 4-20mA Transmitter TH3E-1A	Chlorine	58		50	< 60	
City Technology Ltd.	T3CLH 4-20mA Transmitter TH3F-1A	Chlorine	58		100	< 60	
City Technology Ltd.	T3CLH 4-20mA Transmitter TH3G-1A	Chlorine	58		200	< 60	
City Technology Ltd.	7CLH CiTiceL	Chlorine	17	1	20	< 60	33
City Technology Ltd.	SensoriC HF 3E 10 SE MINI	Hydrogen Fluoride	1.2- 17	300	10	< 90	
City Technology Ltd.	SensoriC HF 3E 10 SE SENSORIC CLASSIC	Hydrogen Fluoride	1.2- 17	300	10	< 90	
City Technology Ltd.	SensoriC HF 3E 10 SE CTL4 series adaptation	Hydrogen Fluoride	1.2- 17	300	10	< 90	
City Technology Ltd.	SensoriC HF 3E 10 SE CTL 7 series adaptation	Hydrogen Fluoride	1.2- 17	300	10	< 90	
City Technology Ltd.	SensoriC COCl2 3E 1 SENSORIC CLASSIC	Phosgene	1.2- 17	650	1	< 120	
City Technology Ltd.	SensoriC COCl2 3E 1 CTL 4 series adaptation	Phosgene	1.2- 17	650	1	< 120	
City Technology Ltd.	SensoriC COCl2 3E 1 CTL 7 series adaptation	Phosgene	1.2- 17	650	1	< 120	

Table 20: Metal Oxide Semiconductor Detection Survey

Manufacture	Sensor Name	Target Chemical	Weight (g)	Range (ppm)	%LEL or % by Volume	Response time t80 (s)	Power (mW)
Figaro Engineering Inc.	TGS 8100	Air Contaminants		1 to 30			
International Sensor Technology	Solid State Sensor	Acetic Acid	5	100, 200		20 to 90	300
International Sensor Technology	Solid State Sensor	Acetone	5	100, 200, 500, 1000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Acetonitrile	5	100		20 to 90	300
International Sensor Technology	Solid State Sensor	Acetylene	5	50	LEL	20 to 90	300

Manufacture	Sensor Name	Target Chemical	Weight (g)	Range (ppm)	%LEL or % by Volume	Response time t80 (s)	Power (mW)
International Sensor Technology	Solid State Sensor	Acrolein (Acrylaldehyde)	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Acrylic Acid	5	100		20 to 90	300
International Sensor Technology	Solid State Sensor	Acrylonitrile	5	50, 60, 80, 100, 200, 500	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Allyl Alcohol	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Allyl Chloride	5	200		20 to 90	300
International Sensor Technology	Solid State Sensor	Ammonia	5	50, 70, 75, 100, 150, 200, 300, 400, 500,1000, 2000, 2500, 4000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Anisole	5	100		20 to 90	300
International Sensor Technology	Solid State Sensor	Arsenic Pentafluoride	5	5		20 to 90	300
International Sensor Technology	Solid State Sensor	Arsine	5	1, 10		20 to 90	300
International Sensor Technology	Solid State Sensor	Benzene	5	50, 75, 100, 1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Biphenyl	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Boron Trichloride	5	500		20 to 90	300
International Sensor Technology	Solid State Sensor	Boron Trifluoride	5	500		20 to 90	300
International Sensor Technology	Solid State Sensor	Bromine	5	20		20 to 90	300
International Sensor Technology	Solid State Sensor	Butadiene	5	50, 100, 3000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Butane	5	400, 1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Butanol	5	1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Butene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Butyl Acetate	5	100	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Carbon Disulfide	5	50, 60, 100		20 to 90	300
International Sensor Technology	Solid State Sensor	Carbon Monoxide	5	50, 100, 150, 200, 250, 300, 500, 1000,3000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Carbon Tetrachloride	5	50, 100, 10000		20 to 90	300
International Sensor Technology	Solid State Sensor	Cellosolve Acetate	5	100		20 to 90	300
International Sensor Technology	Solid State Sensor	Chlorine	5	10, 20, 50, 100, 200		20 to 90	300
International Sensor Technology	Solid State Sensor	Chlorine Dioxide	5	10, 20		20 to 90	300
International Sensor Technology	Solid State Sensor	Chlorobutadiene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Chloroethanol	5	200		20 to 90	300

Manufacture	Sensor Name	Target Chemical	Weight (g)	Range (ppm)	%LEL or % by Volume	Response time t80 (s)	Power (mW)
International Sensor Technology	Solid State Sensor	Chloroform	5	50, 100, 200		20 to 90	300
International Sensor Technology	Solid State Sensor	Chlorotrifluoroethylene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Cumene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Cyanogen Chloride	5	20		20 to 90	300
International Sensor Technology	Solid State Sensor	Cyclohexane	5	100	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Cyclopentane	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Deuterium	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Diborane	5	10, 50		20 to 90	300
International Sensor Technology	Solid State Sensor	Dibromoethane	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Dibutylamine	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Dichlorobutene	5		1% by Volume	20 to 90	300
International Sensor Technology	Solid State Sensor	Dichloroethane (EDC)	5	50, 100	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Dichlorofluoroethane	5	100, 1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Dichloropentadiene	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Dichlorosilane	5	50, 100		20 to 90	300
International Sensor Technology	Solid State Sensor	Diesel Fuel	5	50	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Diethyl Benzene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Diethyl Sulfide	5	10		20 to 90	300
International Sensor Technology	Solid State Sensor	Difluorochloroethane	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Difluoroethane (152A)	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Dimethyl Ether	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Dimethylamine (DMA)	5	30, 50		20 to 90	300
International Sensor Technology	Solid State Sensor	Epichlorohydrin	5	50, 100, 500, 1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Ethane	5	1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Ethanol	5	200, 1000, 2000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Ethyl Acetate	5	200, 1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Ethyl Benzene	5	200	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Ethyl Chloride	5	100	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Ethyl Chlorocarbonate	5		1% by Volume	20 to 90	300
International Sensor Technology	Solid State Sensor	Ethyl Ether	5	100, 800, 1000	LEL	20 to 90	300

Manufacture	Sensor Name	Target Chemical	Weight (g)	Range (ppm)	%LEL or % by Volume	Response time t80 (s)	Power (mW)
International Sensor Technology	Solid State Sensor	Ethylene	5	100, 1000, 1200	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Ethylene Oxide	5	5, 10, 20, 30, 50, 75, 100, 150, 200, 300,1000, 1500, 2000, 3000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Fluorine	5	20, 100		20 to 90	300
International Sensor Technology	Solid State Sensor	Formaldehyde	5	15, 50, 100, 500, 1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Freon-11	5	1000, 2000, 5000		20 to 90	300
International Sensor Technology	Solid State Sensor	Freon-113	5	100, 200, 500, 1000, 2000	1% by Vol.	20 to 90	300
International Sensor Technology	Solid State Sensor	Freon-114	5	1000, 2000, 20000		20 to 90	300
International Sensor Technology	Solid State Sensor	Freon-12	5	1000, 2000, 3000		20 to 90	300
International Sensor Technology	Solid State Sensor	Freon-123	5	1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Freon-22	5	100, 200, 500, 1000, 2000		20 to 90	300
International Sensor Technology	Solid State Sensor	Fuel Oil or Kerosene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Gasoline	5	100, 1000, 2000, 20000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Germane	5	10, 50		20 to 90	300
International Sensor Technology	Solid State Sensor	Heptane	5	1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Hexane	5	50, 100, 200, 2000, 2500, 3000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Hexene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Hydrazine	5	5, 10, 20, 100, 1000	1% by Volume	20 to 90	300
International Sensor Technology	Solid State Sensor	Hydrogen	5	50, 100, 200, 500, 1000, 2000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Hydrogen Bromide	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Hydrogen Chloride	5	50, 100, 200, 400, 500, 1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Hydrogen Cyanide	5	20, 30, 50, 100, 200, 1000, 10000		20 to 90	300
International Sensor Technology	Solid State Sensor	Hydrogen Fluoride	5	20, 50, 100, 200		20 to 90	300
International Sensor Technology	Solid State Sensor	Hydrogen Sulfide	5	5, 10, 20, 30, 50, 100, 300, 1000	LEL	20 to 90	300

Manufacture	Sensor Name	Target Chemical	Weight (g)	Range (ppm)	%LEL or % by Volume	Response time t80 (s)	Power (mW)
International Sensor Technology	Solid State Sensor	Isobutane	5	1000, 3000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Isobutylene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Isopentane	5	1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Isoprene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Isopropanol	5	200, 400, 500, 1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	JP4	5	1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	JP5	5	1000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methane	5	100, 200, 1000, 1500, 2000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methanol	5	200, 300, 400, 500, 1000, 2000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Acetate	5	30		20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Acrylate	5	60		20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Bromide	5	20, 50, 60, 100, 500, 1000, 10000, 40,000		20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Butanol	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Cellosolve	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Chloride	5	100, 200, 300, 2000, 10000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Ethyl Ketone	5	100, 500, 1000, 4000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Hydrazine	5	5		20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Isobutyl Ketone	5	200, 500, 2000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Mercaptan	5	30		20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl Methacrylate	5	100	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methylene Chloride	5	20, 100, 200, 300, 400, 500, 600, 1000, 2000, 3000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Methyl-Tert Butyl Ether	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Mineral Spirits	5	200, 3000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Monochlorobenzene	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Monoethylamine	5	30, 100, 1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Morpholine	5	500		20 to 90	300

Manufacture	Sensor Name	Target Chemical	Weight (g)	Range (ppm)	%LEL or % by Volume	Response time t80 (s)	Power (mW)
International Sensor Technology	Solid State Sensor	Naptha	5	1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Natural Gas	5	1000, 2000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Nitric Oxide	5	20, 50		20 to 90	300
International Sensor Technology	Solid State Sensor	Nitrogen Dioxide	5	20, 50, 100		20 to 90	300
International Sensor Technology	Solid State Sensor	Nitrogen Trifluoride	5	50, 500, 1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Nonane	5	2000		20 to 90	300
International Sensor Technology	Solid State Sensor	Pentane	5	200, 1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Perchloroethylene	5	200, 1000, 2000, 20000		20 to 90	300
International Sensor Technology	Solid State Sensor	Phenol	5	100		20 to 90	300
International Sensor Technology	Solid State Sensor	Phosgene	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Phosphine	5	3, 5, 10, 20, 30, 50		20 to 90	300
International Sensor Technology	Solid State Sensor	Phosphorus Oxychloride	5	200		20 to 90	300
International Sensor Technology	Solid State Sensor	Picoline	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Propane	5	100, 1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Propylene	5	100, 200, 1000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Propylene Oxide	5	100	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Silane	5	10, 20, 50		20 to 90	300
International Sensor Technology	Solid State Sensor	Silicon Tetrachloride	5	1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Silicon Tetrafluoride	5	1000		20 to 90	300
International Sensor Technology	Solid State Sensor	Styrene	5	200, 300	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Sulfur Dioxide	5	50, 100		20 to 90	300
International Sensor Technology	Solid State Sensor	Tetrahydrofuran	5	200, 300, 1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Tetraline	5	100		20 to 90	300
International Sensor Technology	Solid State Sensor	Toluene	5	50, 100, 200, 500, 2000, 5000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Toluene Diisocyanate	5	15		20 to 90	300
International Sensor Technology	Solid State Sensor	Trichloroethane	5	50, 100, 500, 1000 ,	1% by Volume	20 to 90	300
International Sensor Technology	Solid State Sensor	Trichloroethylene	5	50, 100, 200, 300, 500, 1000, 2000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Triethylamine (TEA)	5	100		20 to 90	300

Manufacture	Sensor Name	Target Chemical	Weight (g)	Range (ppm)	%LEL or % by Volume	Response time t80 (s)	Power (mW)
International Sensor Technology	Solid State Sensor	Trifluoroethanol	5	25, 100		20 to 90	300
International Sensor Technology	Solid State Sensor	Trimethylamine (TMA)	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Tungsten Hexafluoride	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Turpentine	5		LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Vinyl Acetate	5	1000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Vinyl Chloride	5	20, 50, 100, 200, 400, 500, 1000, 4000, 10000	LEL	20 to 90	300
International Sensor Technology	Solid State Sensor	Vinylidene Chloride	5	50		20 to 90	300
International Sensor Technology	Solid State Sensor	Xylene	5	100, 200, 300, 1000	1% by Volume	20 to 90	300

Table 21: Photoionization Detection Survey

Manufacture	Sensor Name	Target Chemical	Weight (g)	Minimum Resolution (ppb isobutylene)	Linear Range (ppm)	Response time t90 (s)	Power Consumption (mW)
Alphasense Ltd.	PID-A1 Photo Ionisation Detector	VOC	< 8	< 100	300	< 3	70
Alphasense Ltd.	PID-AH Photo Ionisation Detector	VOC	< 8	1	50	< 3	110
Baseline-MOCON, Inc.	piD-TECH eVx 10.6 eV Green	VOC	< 8	1,000	10,000	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH eVx 10.6 eV Purple	VOC	< 8	500	2,000	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH eVx 10.6 eV Red	VOC	< 8	50	200	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH eVx 10.6 eV Yellow	VOC	< 8	5	20	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH eVx 10.6 eV Blue	VOC	< 8	0.5	2	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH eVx 10.0 Purple	VOC	< 8	1500	6,000	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH eVx 10.0 Red	VOC	< 8	150	600	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH eVx 10.0 Yellow	VOC	< 8	15	60	<3	80 to 200
Baseline-MOCON, Inc.	piD-TECH plus 10.6 eV Black Extended	VOC	<8	100	10,000	<3	64 to 300
Baseline-MOCON, Inc.	piD-TECH plus 10.6 eV Black	VOC	<8	50	2,000	<3	64 to 300
Baseline-MOCON, Inc.	piD-TECH plus 10.6 eV Bronze	VOC	<8	25	200	<3	64 to 300
Baseline-MOCON, Inc.	piD-TECH plus 10.6 eV Silver	VOC	<8	5	20	<5	64 to 300
Baseline-MOCON, Inc.	piD-TECH plus 10.0 eV Black	VOC	<8	150	6,000	<3	64 to 300
Baseline-MOCON, Inc.	piD-TECH plus 10.0 eV Bronze	VOC	<8	75	600	<3	64 to 300

Manufacture	Sensor Name	Target Chemical	Weight (g)	Minimum Resolution (ppb isobutylene)	Linear Range (ppm)	Response time t90 (s)	Power Consumption (mW)
Baseline-MOCON, Inc.	piD-TECH plus 10.0 eV Silver	VOC	<8	15	60	<5	64 to 300
Baseline-MOCON, Inc.	piD-TECH plus 9.6 eV Bronze	VOC	<8	1,250	10,000	<3	64 to 300
Baseline-MOCON, Inc.	piD-TECH plus 9.6 eV Silver	VOC	<8	250	1,000	<5	64 to 300

Table 22: Catalytic Detection Survey

Manufacture	Sensor Name	Target Chemical	Weight (g)	Sensitivity (mV/% methane)	Range % LEL Methane	Response time t90 (s)	Power Consumption (mW)
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Acetylene	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Acetylene	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Butane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Butane	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Carbon Monoxide	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Ethane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Ethylene	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Ethylene	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Heptane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Hexane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Hydrogen	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Hydrogen	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Isobutylene	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Isobutylene	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Nonane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Nonane	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	n-Pentane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	n-Pentane	< 26	15 to 22	0 to 100	< 15	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Octane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-D3 Combustible Gas Pellistor	Propane	< 10	10 to 17	0 to 100	< 12	190
Alphasense Ltd.	CH-A3 Combustible Gas Pellistor	Propane	< 26	15 to 22	0 to 100	< 15	190

Manufacture	Sensor Name	Target Chemical	Weight (g)	Sensitivity (mV/% methane)	Range % LEL Methane	Response time t90 (s)	Power Consumption (mW)
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Acetone		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Acetylene	24	24	0 to 100	<20	263
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	Acetylene	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Acetylene		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Ammonia	24	24	0 to 100	<20	263
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Ammonia		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Carbon Monoxide	24	24	0 to 100	<20	263
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Carbon Monoxide		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Cyclohexane	24	24	0 to 100	<20	263
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Cyclohexane		28	0 to 100	<20	
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Ethanol		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Ethlene	24	24	0 to 100	<20	263
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Ethyl acetate		28	0 to 100	<20	
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	Ethylene	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Ethylene		28	0 to 100	<20	
City Technology Ltd.	4P50M CiTipeL Combustible Gas Sensor	Hydrogen	24	37	0 to 100	<20	276
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Hydrogen	24	24	0 to 100	<20	263
City Technology Ltd.	4P75M CiTipeL Combustible Gas Sensor	Hydrogen	24	24	0 to 100	<20	263
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	Hydrogen	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Hydrogen		28	0 to 100	<20	
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Iso-propyl alcohol		28	0 to 100	<20	
City Technology Ltd.	4P50M CiTipeL Combustible Gas Sensor	Methane	24	37	0 to 100	<20	276
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Methane	24	24	0 to 100	<20	263
City Technology Ltd.	4P75M CiTipeL Combustible Gas Sensor	Methane	24	24	0 to 100	<20	263
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	Methane	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Methane		28	0 to 100	<20	
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Methanol		28	0 to 100	<20	
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Methyl ethyl ketone		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	n-Butane	24	24	0 to 100	<20	263

Manufacture	Sensor Name	Target Chemical	Weight (g)	Sensitivity (mV/% methane)	Range % LEL Methane	Response time t90 (s)	Power Consumption (mW)
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	n-Butane	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	n-Butane		28	0 to 100	<20	
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	n-Heptane	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	n-Heptane		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	n-Hexane	24	24	0 to 100	<20	263
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	n-Hexane		28	0 to 100	<20	
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	n-Octane		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	n-Pentane	24	24	0 to 100	<20	263
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	n-Pentane	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	n-Pentane		28	0 to 100	<20	
City Technology Ltd.	4P75C T4 CiTipeL Combustible Gas Sensor	Propane	24	24	0 to 100	<20	263
City Technology Ltd.	MICROpeL 75C Combustible Gas Sensor	Propane	2	31	0 to 100	<5	295
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Propane		28	0 to 100	<20	
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Toluene		28	0 to 100	<20	
City Technology Ltd.	P90E CiTipeL Combustible Gas Sensor	Unleaded Petrol		28	0 to 100	<20	
SGX Sensortech	VQ547TS	Ammonia	22	21	0 to 100	< 20	135 to 230
SGX Sensortech	VQ546M	Methane	22	-4	0 to 100	< 20	135 to 230
SGX Sensortech	VQ546MR	Methane	22	4	0 to 100	< 20	135 to 230
SGX Sensortech	VQ548ZD	Methane	22	20	0 to 100	< 20	135 to 230
SGX Sensortech	VQ548ZD/W	Methane	22	20	0 to 100	< 20	135 to 230
SGX Sensortech	VQ548ZD-S	Methane	22	20	0 to 100	< 20	135 to 230
SGX Sensortech	VQ549ZD	Methane	22	30	0 to 100	< 20	135 to 230
SGX Sensortech	VQ549ZD/W	Methane	22	30	0 to 100	< 20	135 to 230

Appendix D

Exercise Research Data Collection Form

This form is intended for research purposes only. The data collected will be used to inform research in environmental applications of unmanned aerial systems in multi-service tactics, techniques, and procedures for chemical, biological, radiological, and nuclear reconnaissance and surveillance. This effort is part of a Master of Science program thesis at the Air Force Institute of Technology. For questions or concerns, please contact Brandon Barnes, Captain, USMC (graduate student) at Brandon.Barnes@afit.edu or Robert Eninger, Lt Col USAF (thesis advisor) at Robert.Eninger@afit.edu

If you think an unmanned aerial system (UAS) could provide additional capability, what specific tasks, techniques or procedures do you think could gain the most from the employment of a UAS?

Instructions: Pick a real world or training scenario you were involved with and believe an Unmanned Aircraft Vehicle (UAV) could have been a useful asset if available. Then, answer the following questions. However, your answers should reflect NOT having a UAV at your disposal. The intent here is to characterize CBRN operations WITHOUT the use of a UAV. For questions about terminology please reference: ATP 3-11.37.

A. Administrative Information

Exercise:

Event:

Location:

Date of Event: mm/dd/yyyy format

Scenario:

Observer's Unit:

Observer Name:

Observer Title:

Observer Rank:

○ E1 through E4
○ E5 through E6
○ E7 or above
○ O1 through O3
○ O4 through O6

o O7 or above

Observer Service:

o Marine Corps
o Air Force
o Army
o Navy
o Other

B. Execution

Number of Response Personnel:

o 1-5
o 6-12
o 13-40
o >40
o Unknown

Mission identification level

o Presumptive: The employment of technologies with limited specificity and sensitivity by general- purpose forces in a field environment to determine the presence of a CBRN hazards with a low level of confidence and the degree of certainty necessary to support immediate tactical decisions.

o Field confirmatory: The employment of technologies with increased specificity and sensitivity by technical forces in a field environment to identify CBRN hazards with a moderate level of confidence and the degree of certainty necessary to support follow-on tactical decisions.

o Other

Mission mode:

o Mounted o Dismounted o Other

Mission Method:

o Standoff o Remote o Direct o Indirect o Other

Mission duration:

o 10 minutes
o 30 minutes
o 1 hour
o 8 hours
o 1 day
o Multiple days

Hazard type:

o Chemical
o Biological
o Radiological
o Nuclear
o Other

Approximate size of contamination zone:

o 1 square meter (10.8 square feet, about the size of a typical dog house)
o 10 square meters (108 square feet, about the size of a typical bedroom)
o 100 square meters (1076 square feet, about the size of a typical house)
o 1 square kilometer (0.386 square miles, about the size of a typical city center)
o 10 square kilometers (3.86 square miles, about the size of a typical town)
o 100 square kilometers (38.6 square miles, about the size of a typical small city)

Approximate distance to contamination zone/area:

o Less than 5 kilometers (less than 3.1 miles)

- Between 5 and 50 kilometers (between 3.1 and 31 miles)
- Greater than 50 kilometers (greater than 31 miles)

Please describe the enemy: (size, activity, location, unit, time, and equipment)

Please describe the hazard:

Terrain:
- Restrictive
- Permissive
- Urban
- Rural
- Jungle
- Mountain
- Desert
- Other

Please describe the terrain:

Weather:
- Wind
- Heavy precipitation
- Extreme temperatures
- Other

Please describe the weather:

Mission intent: Choose one
- Reconnaissance
- Surveillance

Reconnaissance Mission task: Choose one
- Detect
- Locate
- Identify
- Survey
- Quantify
- Collect
- Mark
- Report
- Other

Please describe the technique used to detect:

Which technique was used to locate? Choose one.

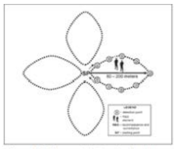

Figure E-9. Dismounted, cloverleaf technique

o Cloverleaf

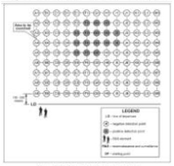

Figure E-10. Dismounted, grid technique

o Grid

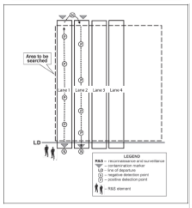

Figure E-8. Dismounted, lane technique

o Lane

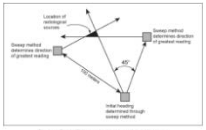

Figure E-11. Triangulation locate technique

o Triangulation

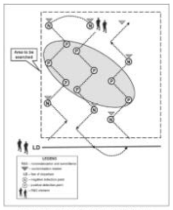

Figure E-7. Dismounted, zigzag technique

o Zigzag

o Other

Please describe the technique used to identify:

Which technique was used to observe? Choose one.

- o Area array
- o Critical node
- o Other

Which technique was used to monitor? Choose one.

- o Continuous
- o Periodic
- o Other

What technique was used to survey? Choose one.

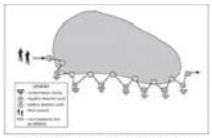

Figure E-13. Dismounted, bounce-and-bypass technique

○ Bounce and bypass

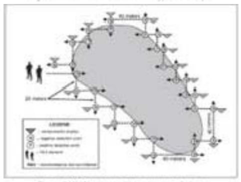

Figure E-16. Dismounted, box survey technique

○ Box

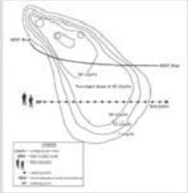

Figure E-14. Dismounted, course leg technique

○ Course leg

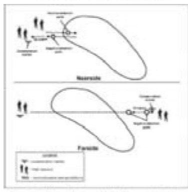

Figure E-12. Dismounted, nearside-farside survey technique

○ Nearside-Farside

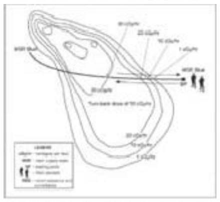

Figure E-15. Sample preselected dose rate technique

○ Preselected dose rate

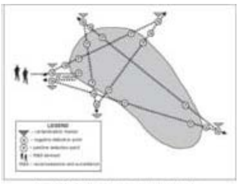

Figure E-18. Dismounted, star survey technique

○ Star

○ Other

Please describe the technique used to quantify:

Please describe the technique used to collect:

Which technique was used to mark? Choose one.

- ○ Deliberate
- ○ Hasty
- ○ Other

Please describe the technique used to report:

Level of PPE - Check all that apply

- ☐ Military MOPP 4 / Civilian Level A
- ☐ Military MOPP 3 / Civilian Level B
- ☐ Military MOPP 2 / Civilian Level C
- ☐ Military MOPP 1 / Civilian Level D
- ☐ Military MOPP 0 / Civilian PPE NONE
- ☐ Military MOPP Ready

List or describe other equipment or devices used. Check all that apply.

- ☐ AN/URD-13 Radiac Set
- ☐ AN/VDR-2 Radiac Set
- ☐ AN/PDR-77 Radiac Set
- ☐ Identifinder Radiac Set
- ☐ M8 CWA Detector Paper
- ☐ pH Detector Paper
- ☐ Potassium Iodide Detector Paper
- ☐ MultiRae Pro
- ☐ M4A1 JCAD Detector
- ☐ First Defender RMX
- ☐ TruDefender FT
- ☐ Other

C. Results

Mission success: on a scale of 1-5 rate the success of the mission, 1 being a failed mission and 5 being a successful mission.

1: Failed Mission	2	3	4	5: Successful Mission

Describe the Mission Success:

Decisions Made:

Findings:

Confidence in results: on a scale of 1-5 rate the confidence in the results, 1 being little to no confidence and 5 being very confident.

1: Little to no confidence	2	3	4	5: very confident

Confidence in Results:

Appendix E

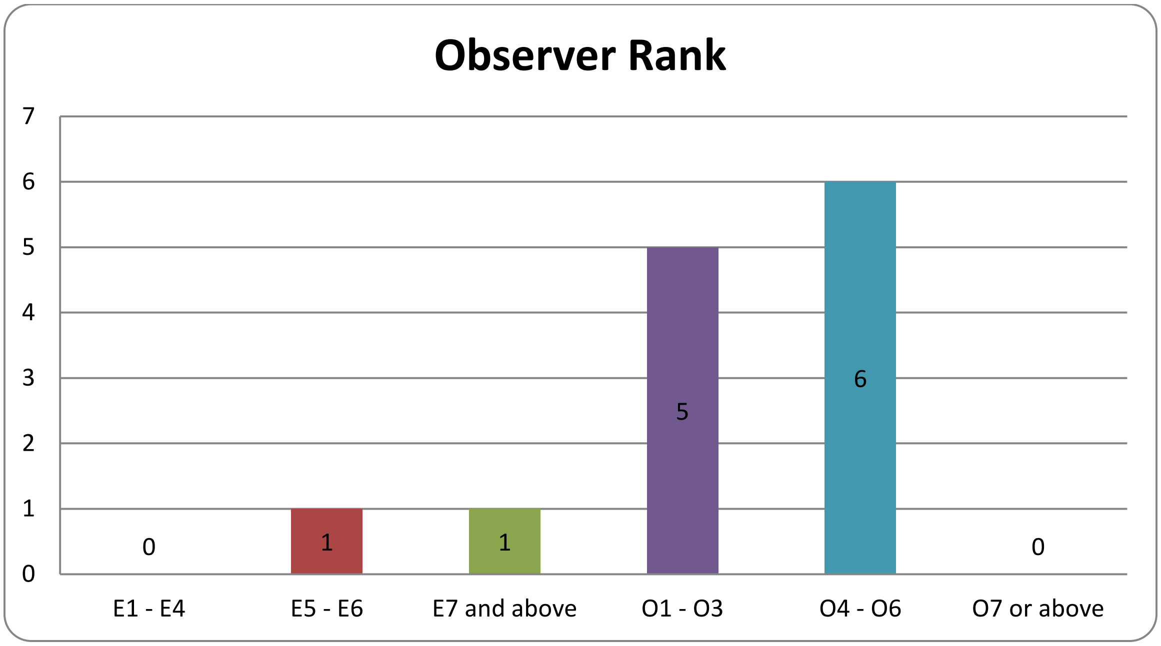

Figure 10: Questionnaire Results: Observer Rank

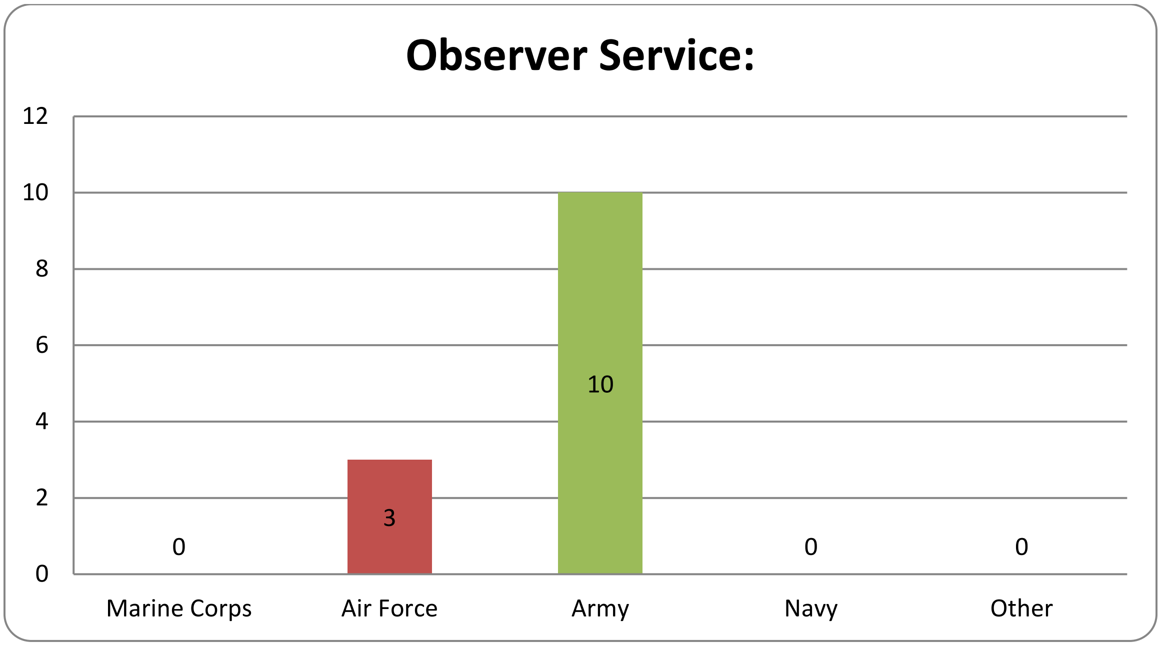

Figure 11: Questionnaire Results: Observer Service

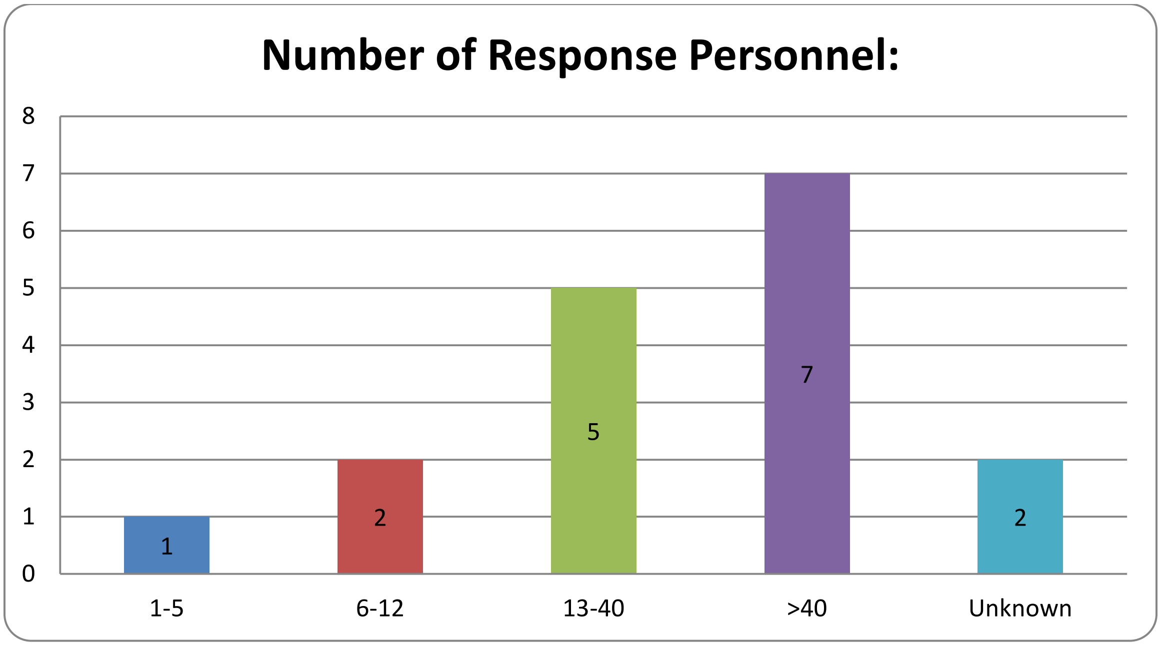

Figure 12: Questionnaire Results: Number of Response Personnel

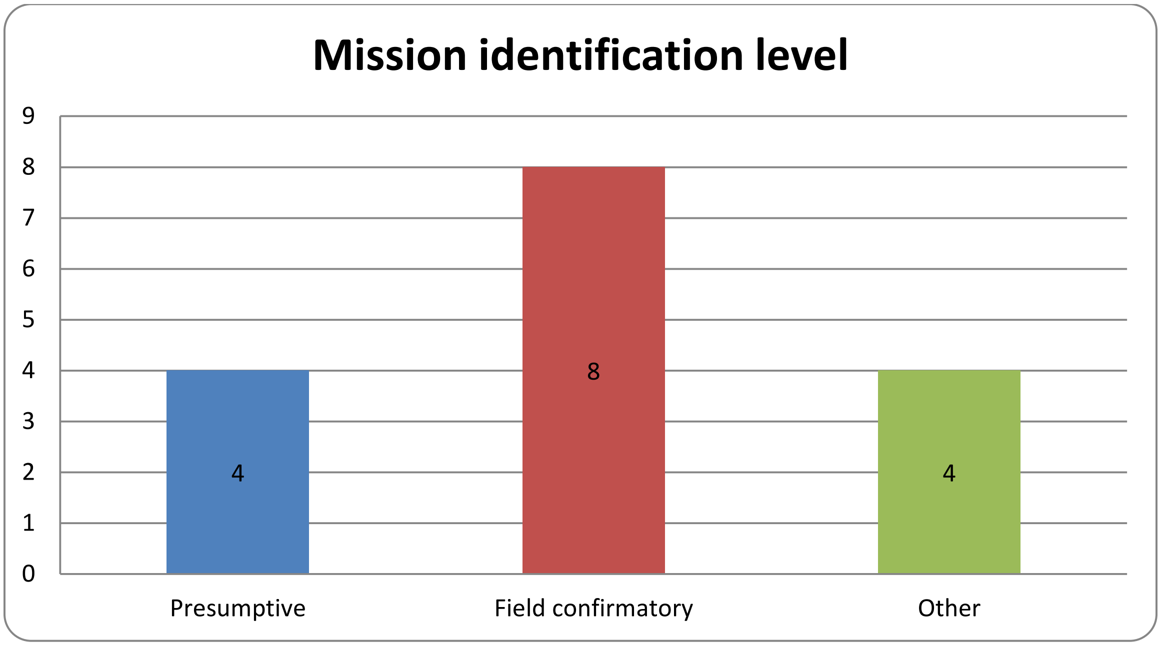

Figure 13: Questionnaire Results: Mission Identification Level

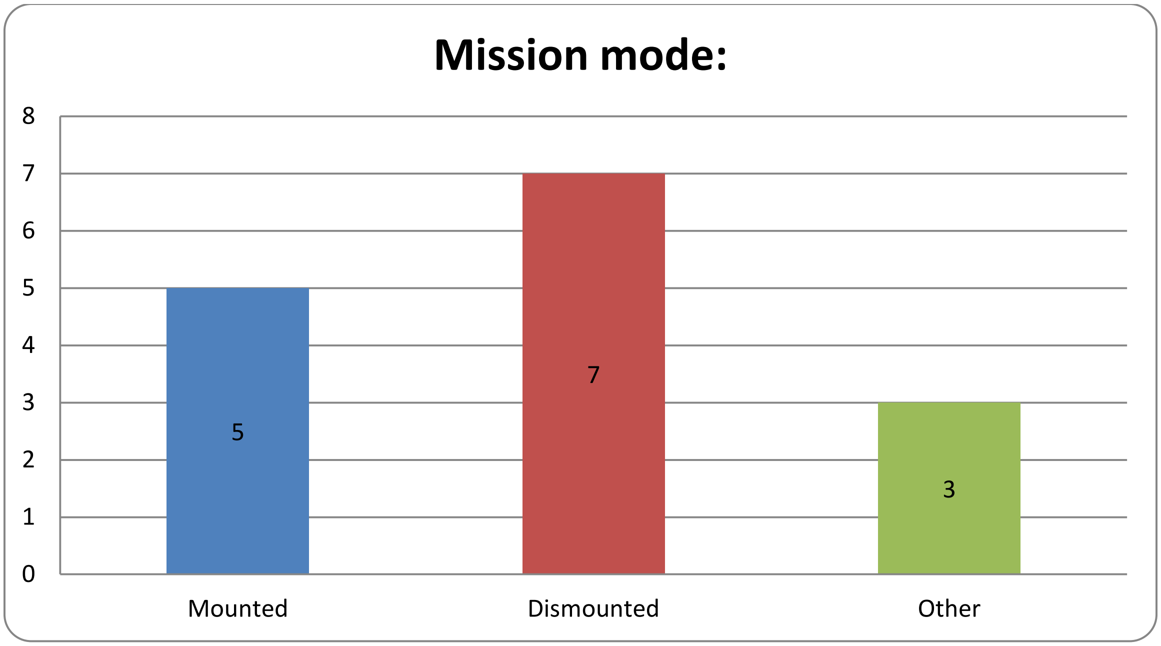

Figure 14: Questionnaire Results: Mission Mode

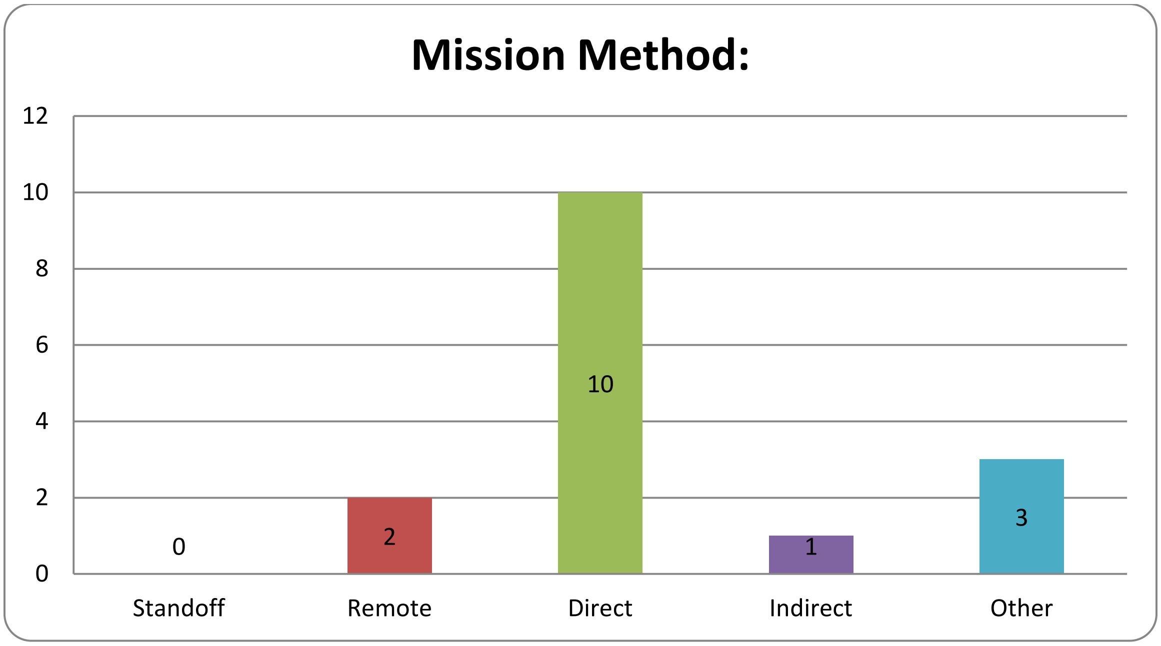

Figure 15: Questionnaire Results: Mission Method

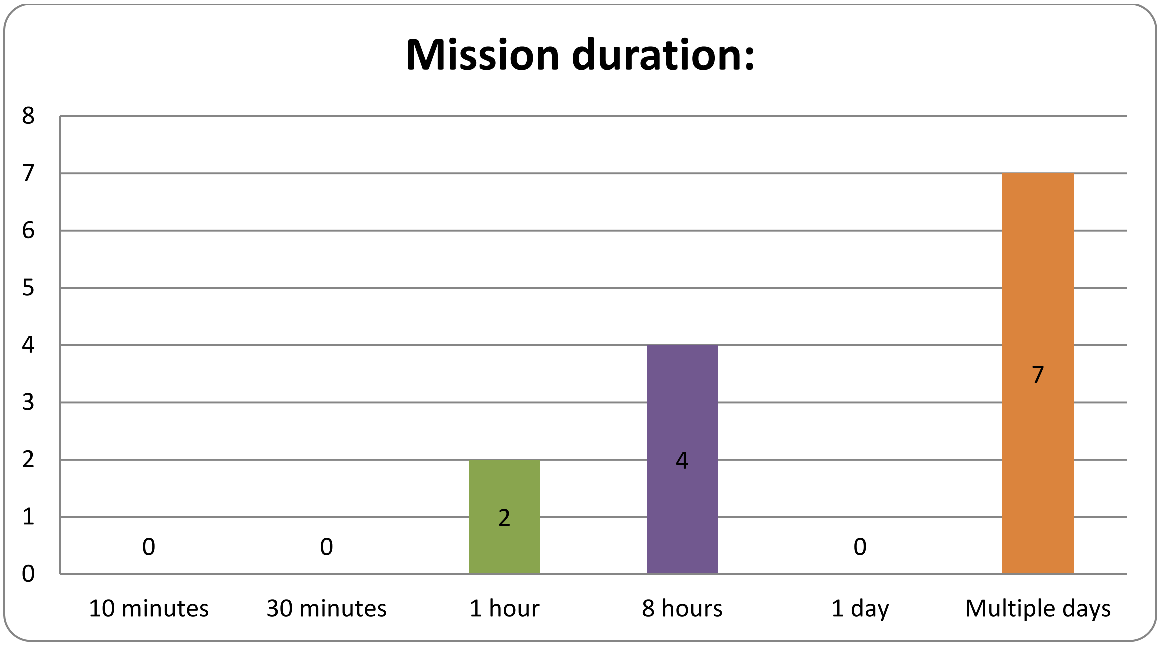

Figure 16: Questionnaire Results: Mission Duration

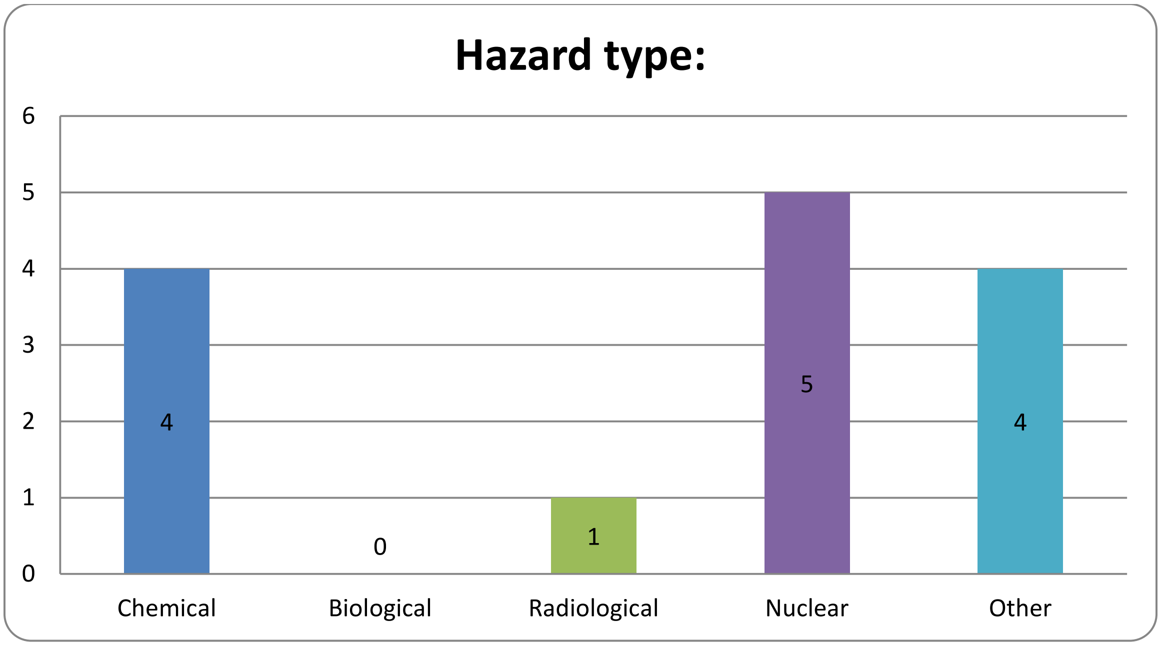

Figure 17: Questionnaire Results: Hazard Type

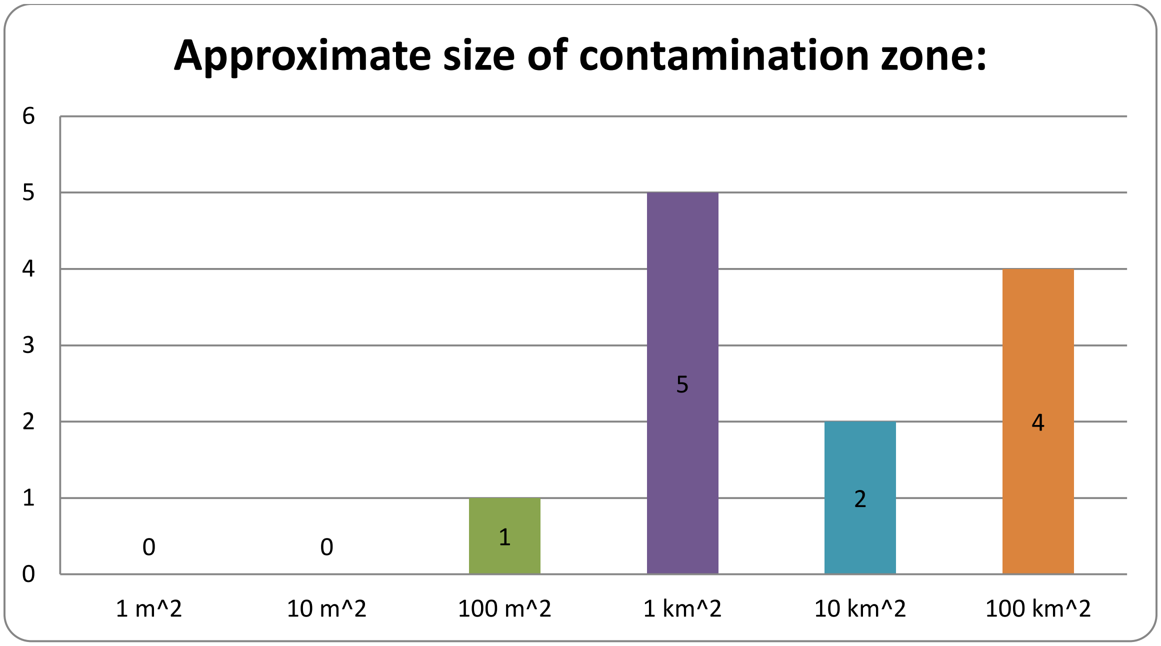

Figure 18: Questionnaire Results: Size of Contamination Zone

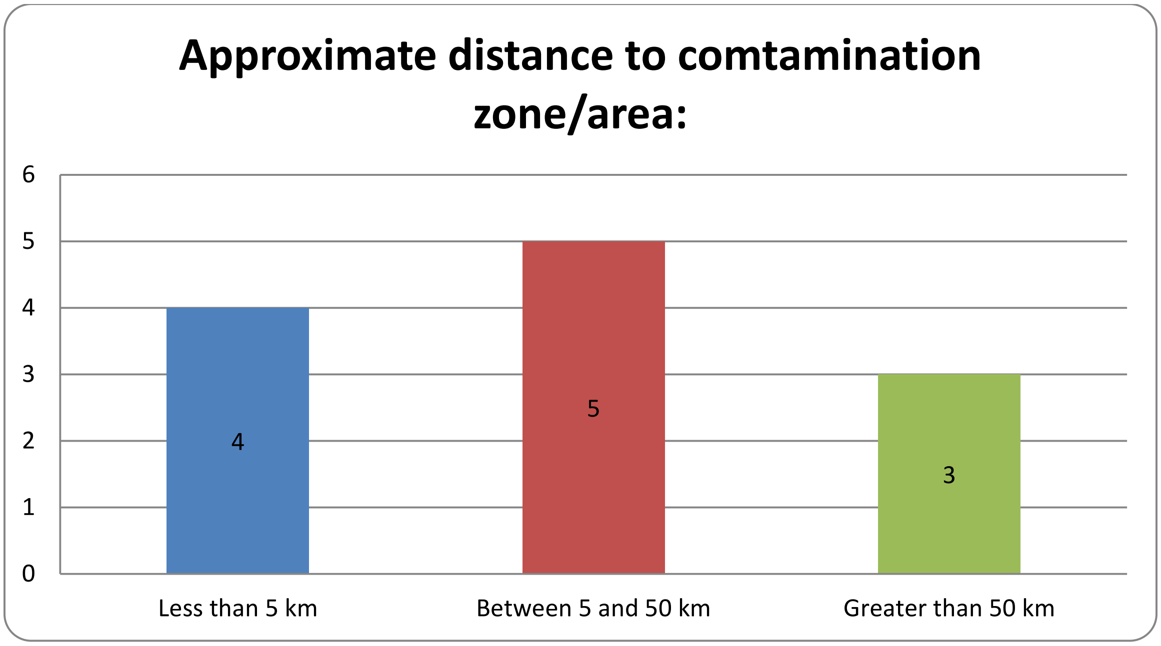

Figure 19: Questionnaire Results: Distance to Contamination Area

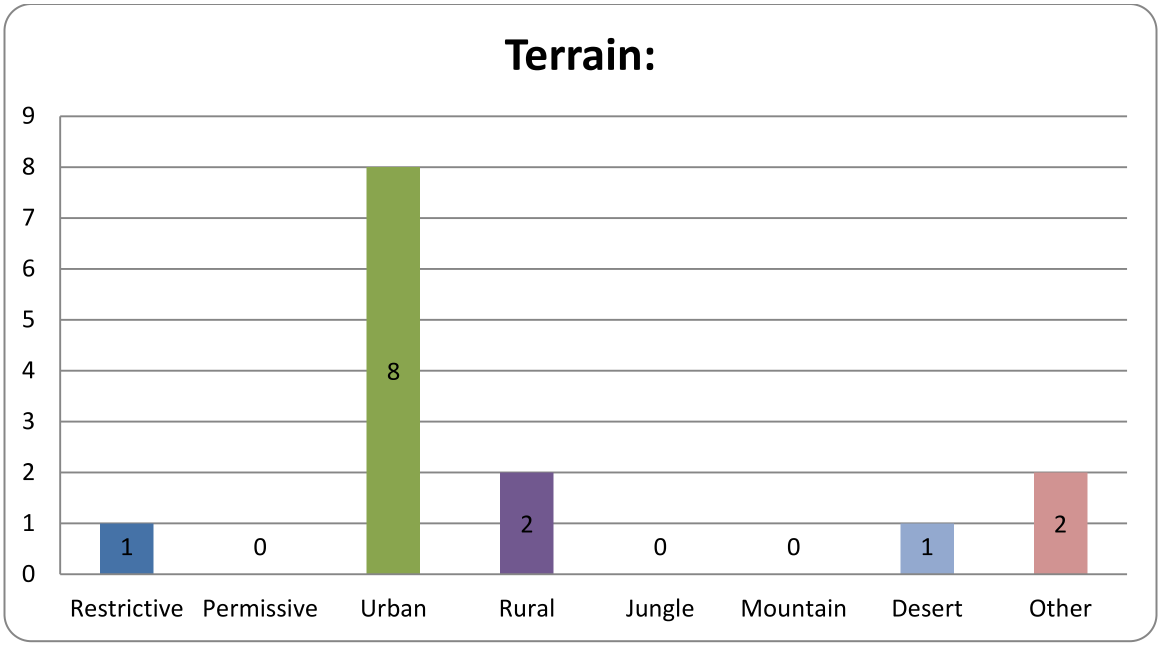

Figure 20: Questionnaire Results: Terrain

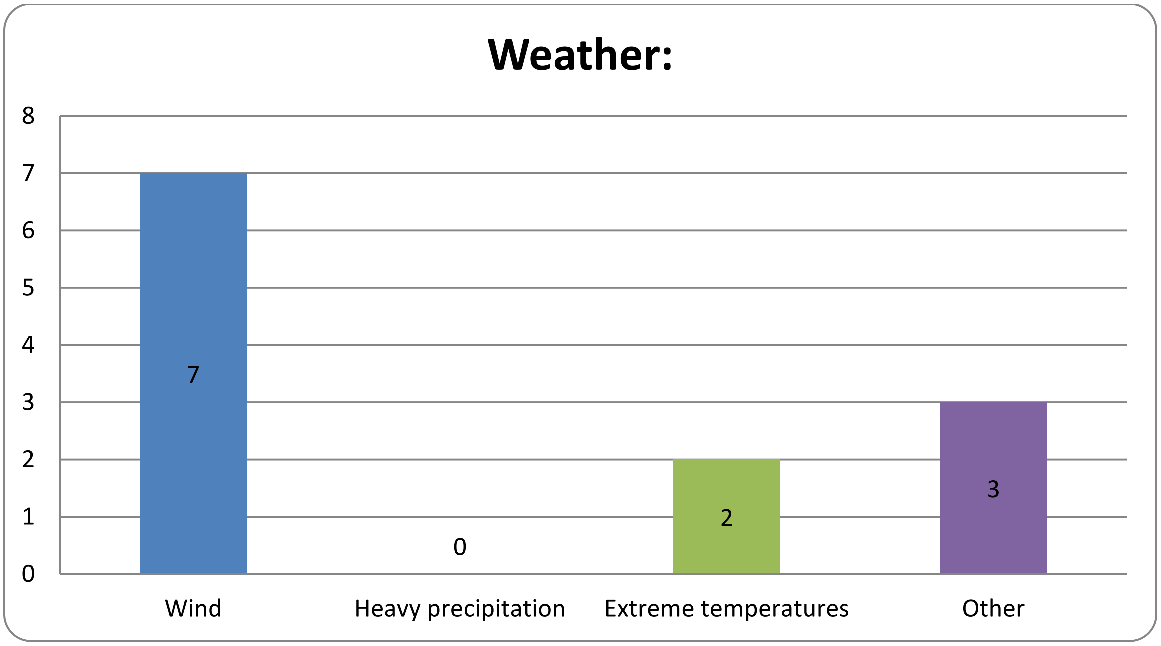

Figure 21: Questionnaire Results: Weather

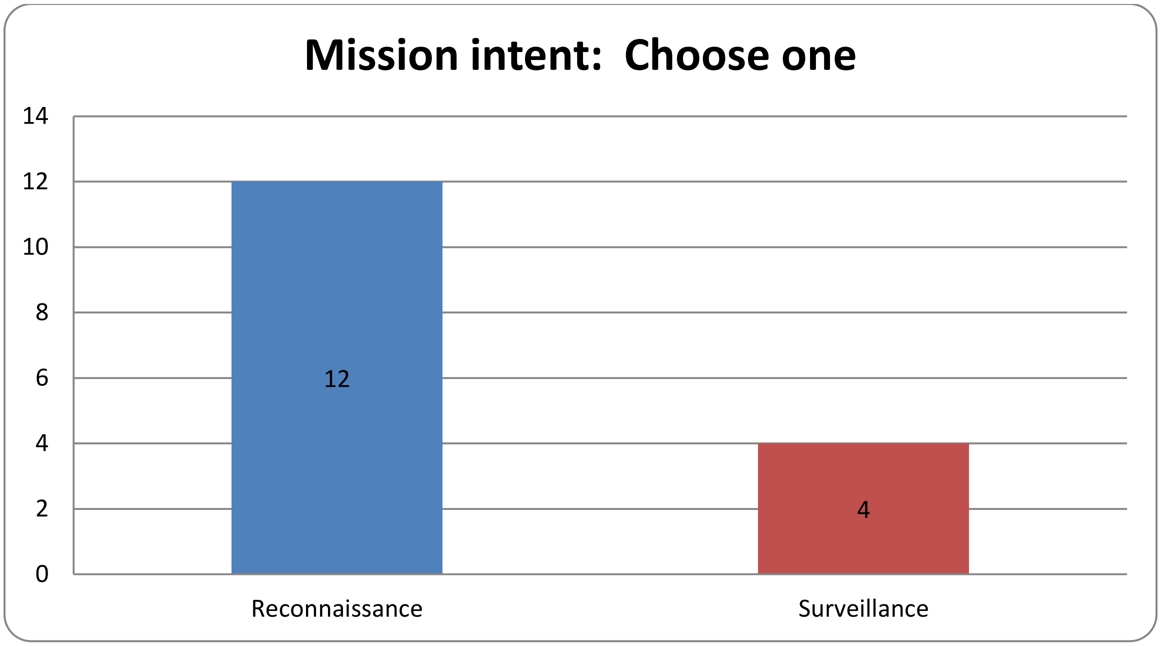

Figure 22: Questionnaire Results: Mission Intent

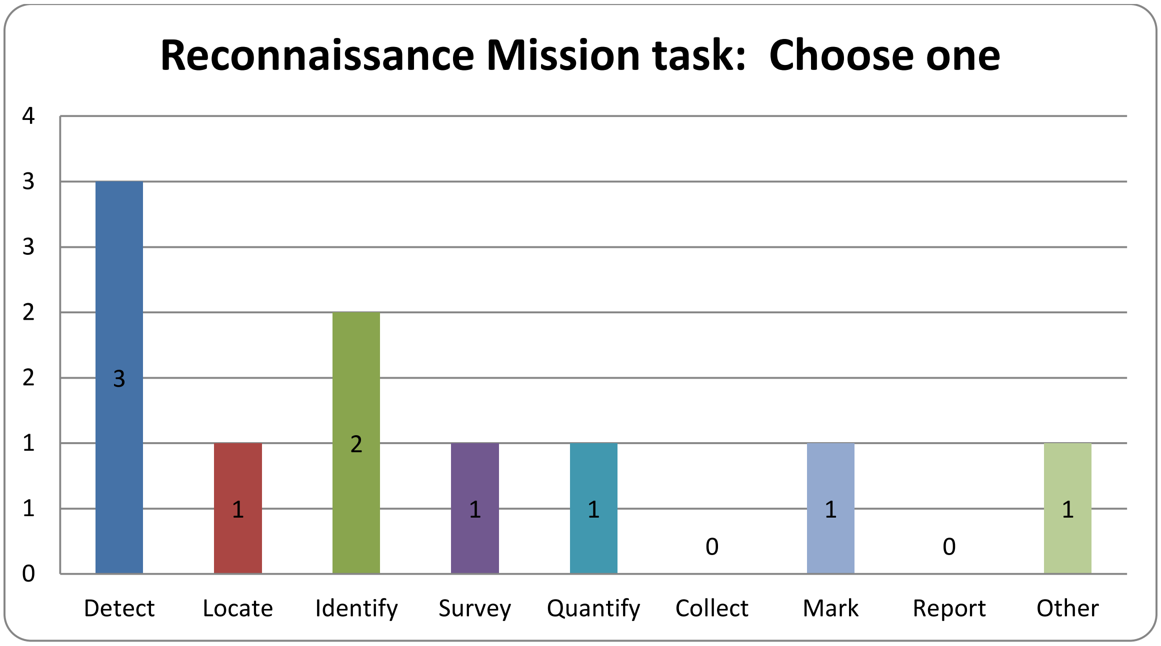

Figure 23: Questionnaire Results: Reconnaissance Task

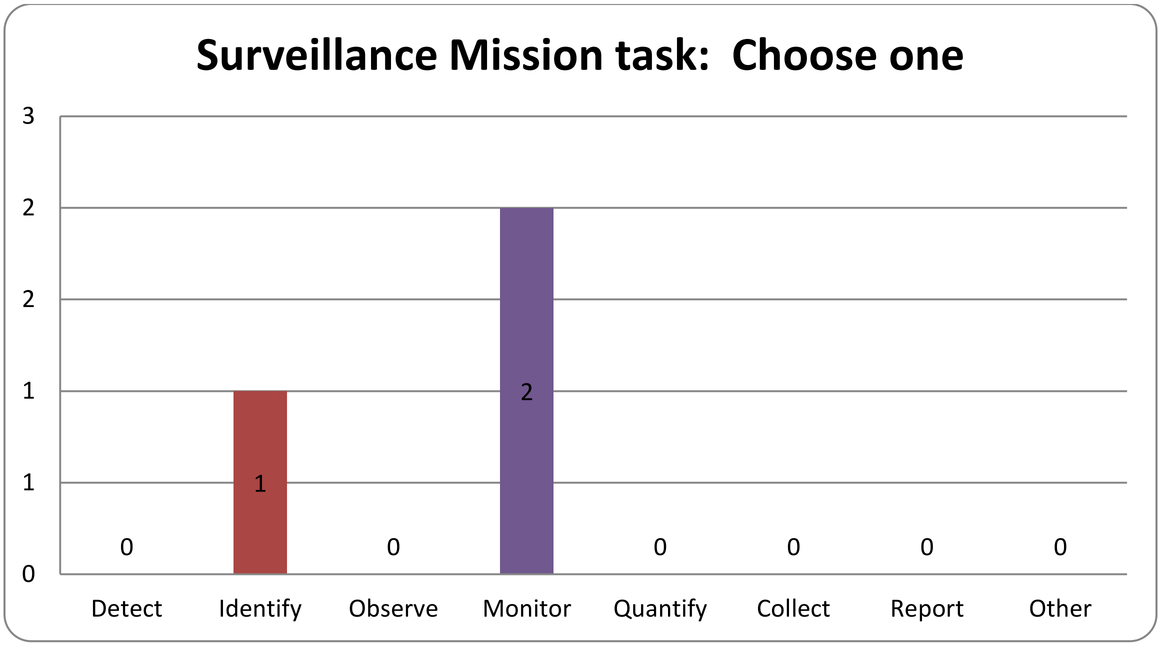

Figure 24: Questionnaire Results: Surveillance Task

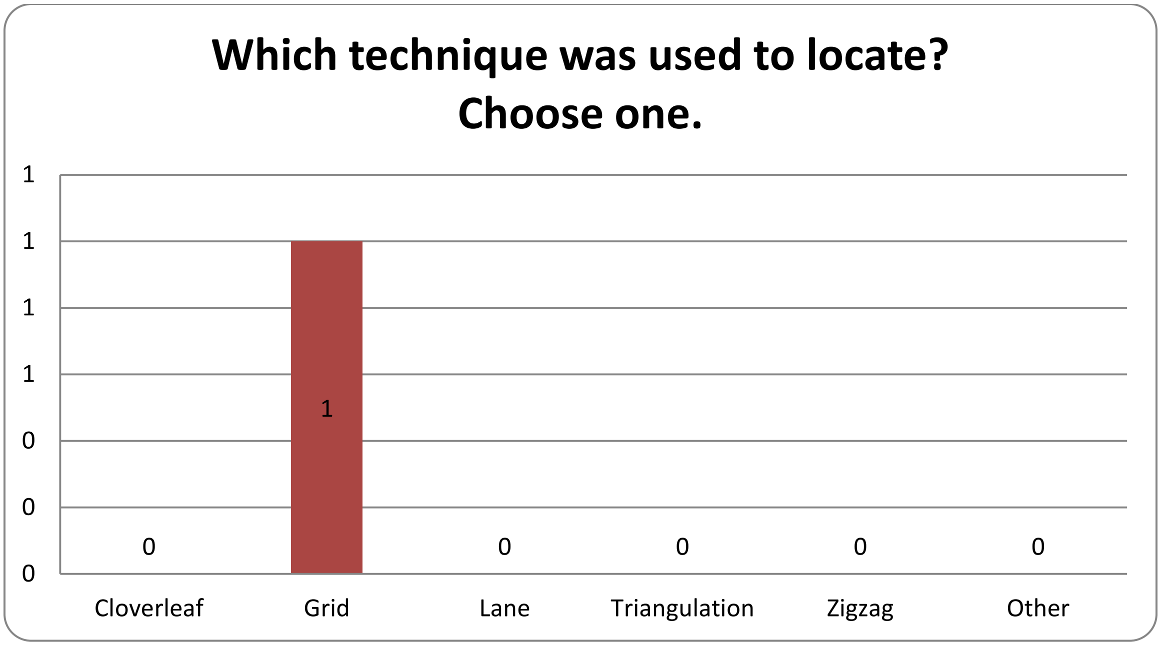

Figure 25: Questionnaire Results: Locate Techniques Used

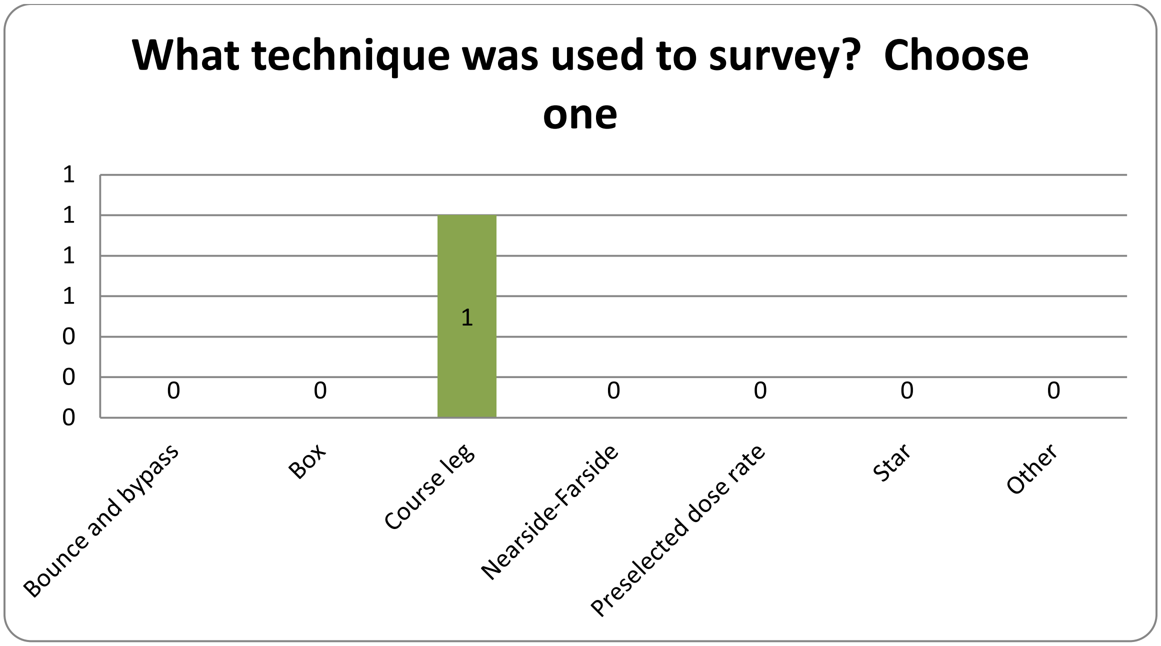

Figure 26: Questionnaire Results: Survey Techniques Used

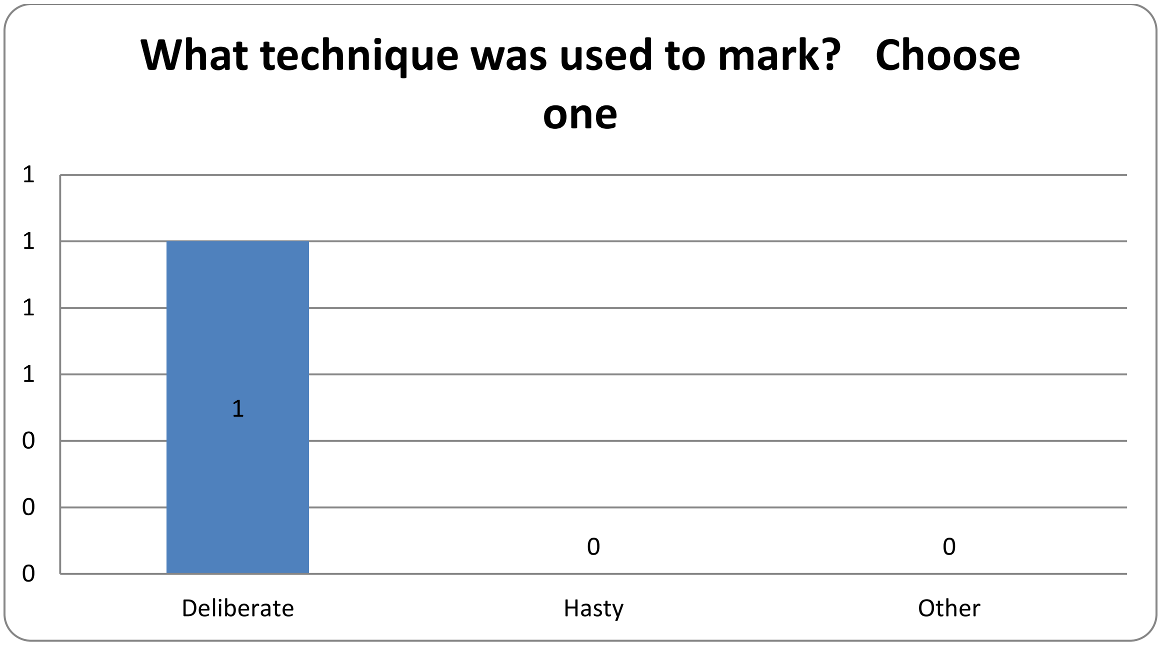

Figure 27: Questionnaire Results: Mark Techniques Used

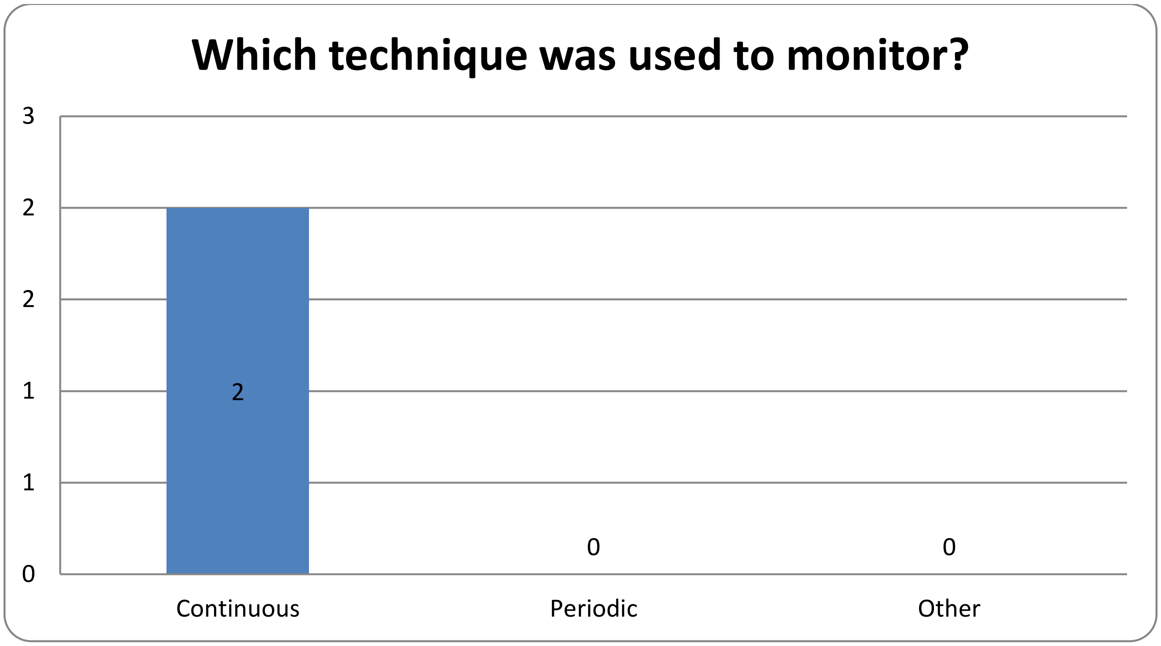

Figure 28: Questionnaire Results: Monitor Techniques Used

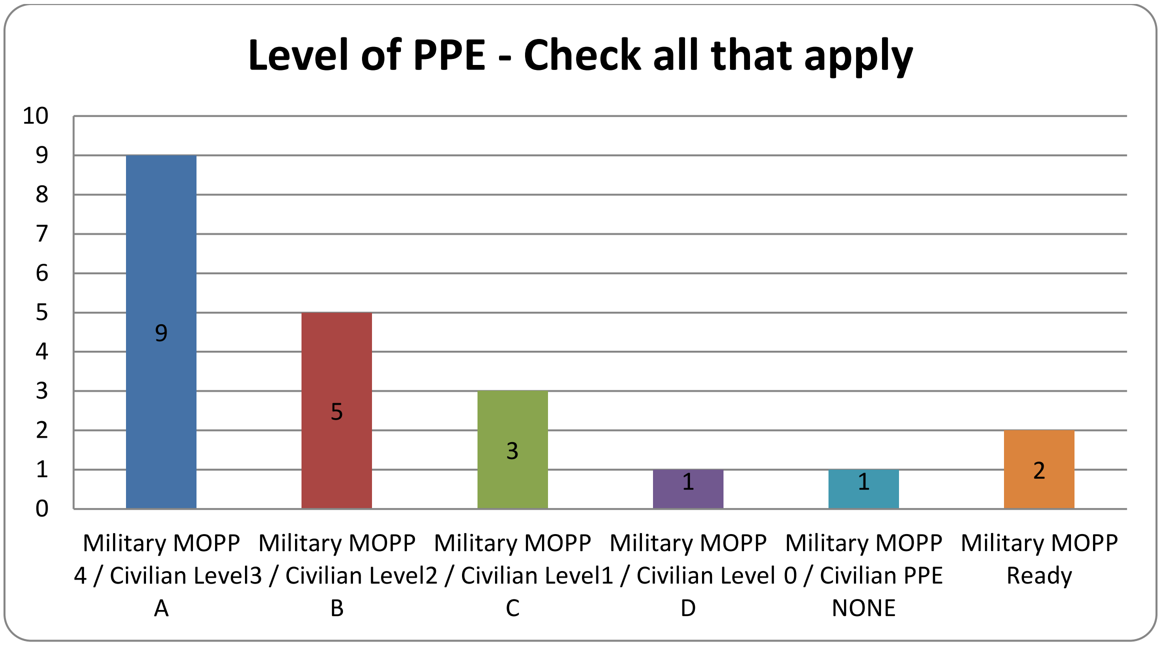

Figure 29: Questionnaire Results: Personal Protective Equipment

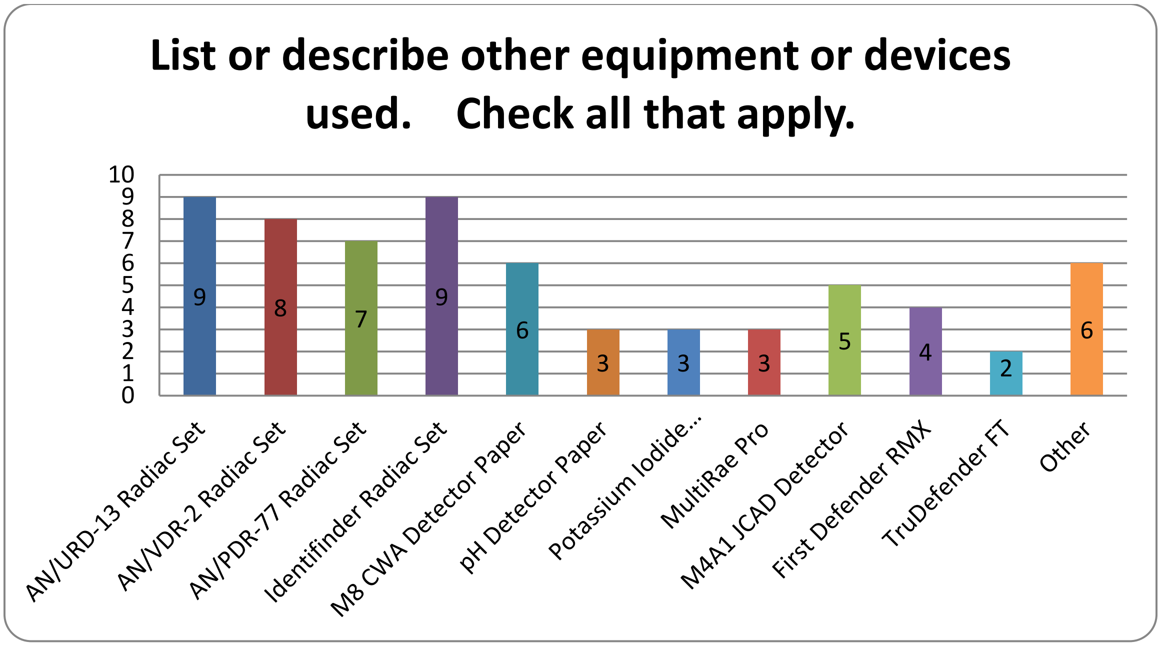

Figure 30: Questionnaire Results: Equipment Used

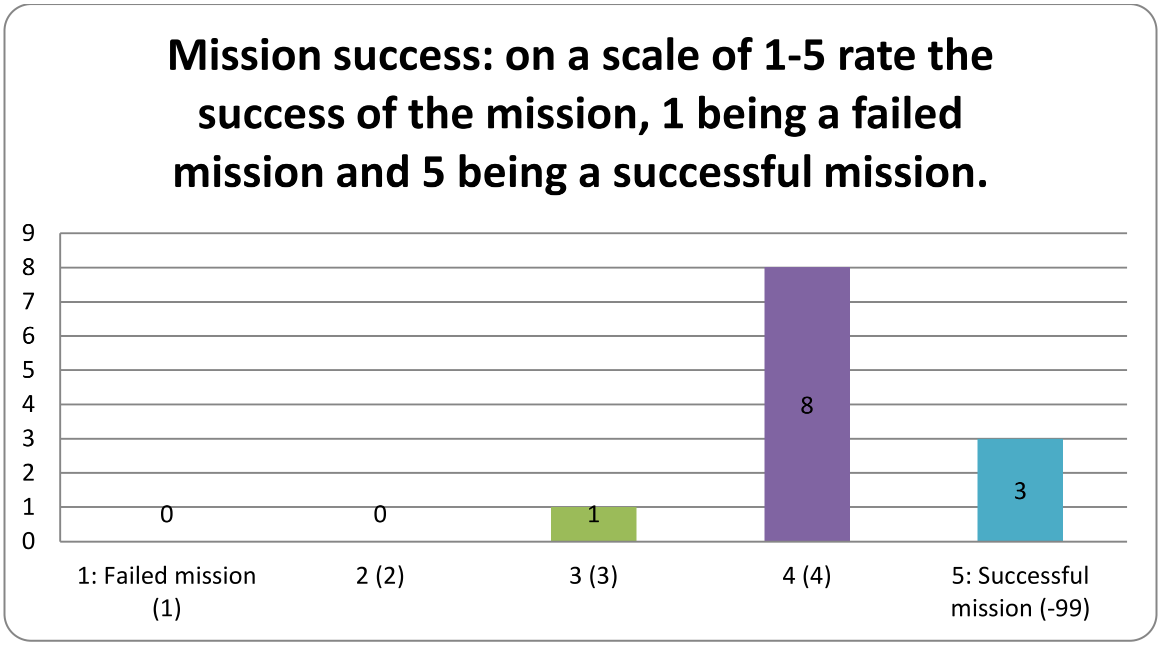

Figure 31: Questionnaire Results: Mission Success

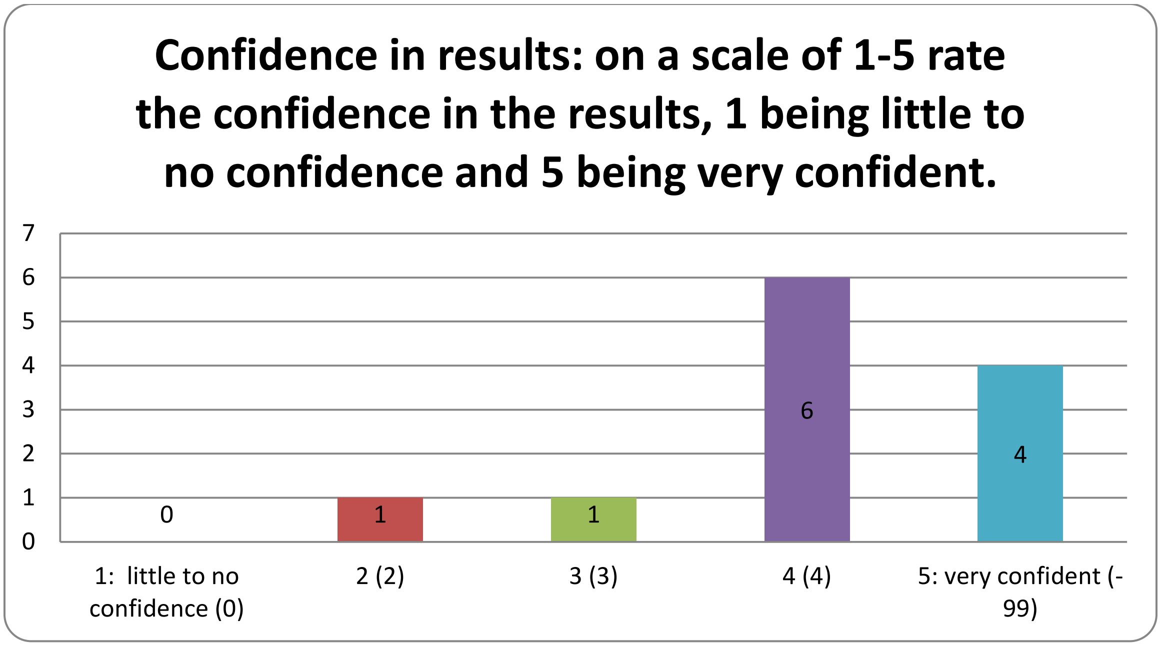

Figure 32: Questionnaire Results: Confidence in Results

Appendix F

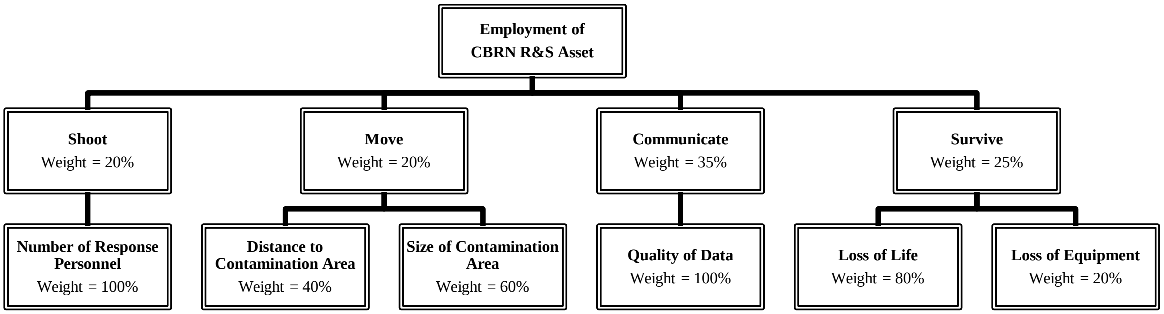

Figure 33: Friendly Scenario Objective Hierarch Decision Tree

Table 23: Friendly Scenario Objective Hierarchy Model

Cell: B18	Thresh	Obj	Weight	SUAS	Utility	Conventional	Utility	Combo	Utility	Utility Function
Number of Response Personnel	40	1	100.0%	4	0.85	26	0.13	15	0.41	U(x) = x^2
Shoot			20.0%		0.85		0.13		0.41	
Distance to Contamination Area (min)	60	0	40.0%	3.23	1.00	5.25	0.99	5.25	0.99	U(x) = 1 - (1 - x)^2
Size of Contamination Area (hr)	8	0	60.0%	3	0.39	5	0.14	2.5	0.47	U(x) = x^2
Move			20.0%		0.63		0.48		0.68	
Quality of Data	0	1	100.0%	0.6	0.60	1	1.00	0.8	0.80	U(x) = x
Communicate			35.0%		0.60		1.00		0.80	
Loss of Life ($)	$400,000	$0	80.0%	$0	1.00	$0	1.00	$0	1.00	U(x) = x
Loss of Equipment ($)	$20,000	$0	20.0%	$200	0.99	$50	1.00	$250	0.99	U(x) = x
Survive			25.0%		1.00		1.00		1.00	
				Total Utility:	0.76		0.72		0.75	

Table 24: Friendly Scenario Objective Hierarchy Model Equations

Utility	Utility	Utility
=(($C19-G19)/($C19-$D19))^2	=(($C19-I19)/($C19-$D19))^2	=(($C19-K19)/($C19-$D19))^2
=E19*H19	=E19*J19	=E19*L19
=1-(1-((C22-G22)/(C22-D22)))^2	=1-(1-((C22-I22)/(C22-D22)))^2	=1-(1-((C22-K22)/(C22-D22)))^2
=((C23-G23)/(C23-D23))^2	=((C23-I23)/(C23-D23))^2	=((C23-K23)/(C23-D23))^2
=(E22*H22)+(E23*H23)	=(E22*J22)+(E23*J23)	=(E22*L22)+(E23*L23)
=(C26-G26)/(C26-D26)	=(C26-I26)/(C26-D26)	=(C26-K26)/(C26-D26)
=E26*H26	=E26*J26	=E26*L26
=(C29-G29)/(C29-D29)	=(C29-I29)/(C29-D29)	=(C29-K29)/(C29-D29)
=(C30-G30)/(C30-D30)	=(C30-I30)/(C30-D30)	=(C30-K30)/(C30-D30)
=(E29*H29)+(E30*H30)	=(E29*J29)+(E30*J30)	=(E29*L29)+(E30*L30)
=H20*$E20+H24*$E24+H27*$E27+H31*E31	=J20*$E20+J24*$E24+J27*$E27+J31*E31	=L20*$E20+L24*$E24+L27*$E27+L31*E31

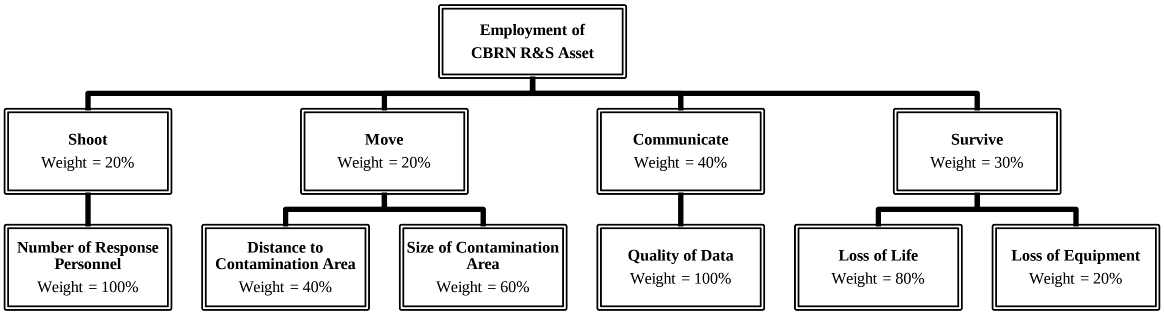

Figure 34: Hostile Scenario Objective Hierarch Decision Tree

Table 25: Hostile Scenario Objective Hierarchy Model

Cell: B18	Thresh	Obj	Weight	SUAS	Utility	Conventional	Utility	Combo	Utility	Utility Function
Number of Response Personnel	40	1	100.0%	5	0.81	31	0.05	18	0.32	U(x) = x^2
Shoot			20.0%		0.81		0.05		0.32	
Distance to Contamination Area (min)	60	0	40.0%	2.92	1.00	3.5	1.00	3.5	1.00	U(x) = 1 - (1 - x)^2
Size of Contamination Area (hr)	8	0	60.0%	3.3	0.35	5.5	0.10	2.75	0.43	U(x) = x^2
Move			20.0%		0.61		0.46		0.66	
Quality of Data	0	1	100.0%	0.54	0.54	0.9	0.90	0.72	0.72	U(x) = x
Communicate			35.0%		0.54		0.90		0.72	
Loss of Life ($)	$400,000	$0	80.0%	$4,000	0.99	$40,000	0.90	$20,000	0.95	U(x) = x
Loss of Equipment ($)	$20,000	$0	20.0%	$10,000	0.50	$12,000	0.40	$15,000	0.25	U(x) = x
Survive			25.0%		0.89		0.80		0.81	
				Total Utility:	0.69		0.62		0.65	

Table 26: Hostile Scenario Objective Hierarchy Model Equations

Utility	Utility	Utility
=(($C19-G19)/($C19-$D19))^2	=(($C19-I19)/($C19-$D19))^2	=(($C19-K19)/($C19-$D19))^2
=E19*H19	=E19*J19	=E19*L19
=1-(1-((C22-G22)/(C22-D22)))^2	=1-(1-((C22-I22)/(C22-D22)))^2	=1-(1-((C22-K22)/(C22-D22)))^2
=((C23-G23)/(C23-D23))^2	=((C23-I23)/(C23-D23))^2	=((C23-K23)/(C23-D23))^2
=(E22*H22)+(E23*H23)	=(E22*J22)+(E23*J23)	=(E22*L22)+(E23*L23)
=(C26-G26)/(C26-D26)	=(C26-I26)/(C26-D26)	=(C26-K26)/(C26-D26)
=E26*H26	=E26*J26	=E26*L26
=(C29-G29)/(C29-D29)	=(C29-I29)/(C29-D29)	=(C29-K29)/(C29-D29)
=(C30-G30)/(C30-D30)	=(C30-I30)/(C30-D30)	=(C30-K30)/(C30-D30)
=(E29*H29)+(E30*H30)	=(E29*J29)+(E30*J30)	=(E29*L29)+(E30*L30)
=H20*$E20+H24*$E24+H27*$E27+H31*E31	=J20*$E20+J24*$E24+J27*$E27+J31*E31	=L20*$E20+L24*$E24+L27*$E27+L31*E31

Vita.

Captain Brandon B. Barnes is from Corrales, New Mexico. In 2011 he graduated from the United States Naval Academy, with a Bachelor's of Science in Systems Engineering and was commissioned as a Marine Corps Ground Officer. After attending The Basic Officer Corps, and being selected as Logistics Officer, he was assigned to 1st Marine Regiment, 1st Marine Division, Camp Pendleton California to serve as the Maintenance Management Officer (MMO) and oversee facilities aboard Camp Horno.

After attending Logistics Officer Course at Camp Johnson, North Carolina, Captain Barnes was assigned to 1st Battalion, 4th Marines (V14) where he served as the MMO and Arm, Ammunitions and Explosives (AA&E) Officer. In 2012 V14 stood up as the Battalion Landing Team (BLT) for the 13th Marine Expeditionary Unit and deployed in 2013. During this time, in addition to his duties as the MMO and AA&E Officer, he assumed the role as the Team Embarkation Officer (TEO) for the USS BOXER. After deploying, he took charge as the Motor Transport Platoon Commander for the battalion.

In 2015 Captain Barnes was selected to attend the Air Force Institute of Technology at Wight Patterson Air Force Base, Dayton Ohio as part of the Commandant's Career Level Education Program and earn his Master's Degree in Environmental Engineering. After graduation he will become the Deputy Director for the Environmental Branch at Marine Corps Recruit Depot, Parris Island in South Carolina.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Small unmanned aircraft systems can be used for a variety of environmental applications. SUAS under 50 kg have the most utility at the tactical level and benefit from the research and development of systems currently being manufactured. Integrating chemical sensors into these systems can enhance Multi-service Tactics, Techniques, and Procedures for Chemical, Biological, Radiological, and Nuclear Reconnaissance and Surveillance. Considering the advantages and disadvantages in the fundamental science of twelve detection technologies, four types of sensors emerged as candidates for SUAS integration. Using specifications from commercial-off-the-shelf sensors, these four detection technologies (Electrochemical, Metal Oxide Semiconductor, Photoionization, and Catalytic Bead) were further evaluated on five parameters (response time, sensitivity, selectivity, power, and weight). Based on this research, MOS detectors are the top detection technology for SUAS employment and integration. In addition to classic chemical warfare agents, toxic industrial chemicals pose a risk to both civilian and military personnel. Eighty-five hazardous chemicals were identified by cross-referencing chemicals detectable using these four technologies with CWA and TIC of interest based on their toxicity and or security issue. Finally, a multi-objective decision model provides a basic decision aid for employing SUAS as a CBRN R&S asset in a tactical environment.

15. SUBJECT TERMS

Unmanned Aircraft Systems (UAS), Chemical, Biological, Radiological, and Nuclear Reconnaissance (CBRN), Tactics, Techniques, and Procedures (TTP), chemical detection, Electrochemical, Metal Oxide Semiconductor, Photoionization, and Catalytic Bead chemical warfare agents CWA, toxic industrial chemicals (TIC)

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a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	161	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565, x 4511 (Robert.Eninger@afit.edu)

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