



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

THESIS

Brandon B. Barnes, Captain, USMC

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**DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY**

***AIR FORCE INSTITUTE OF TECHNOLOGY***

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**Wright-Patterson Air Force Base, Ohio**

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RECONNAISSANCE AND SURVEILLANCE

THESIS

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Brandon B. Barnes, BS

Captain, USMC

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Brandon B. Barnes, BS  
Captain, USMC

Committee Membership:

Robert M. Eninger, Lt Col, USAF, PhD  
Chair

Alan C. Samuels, PhD  
Member

Clay M. Koschnick, Lt Col, USAF, PhD  
Member

Michael Von Fahnstock, PhD  
Member

### **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

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## **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 Violet                  |
| 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.

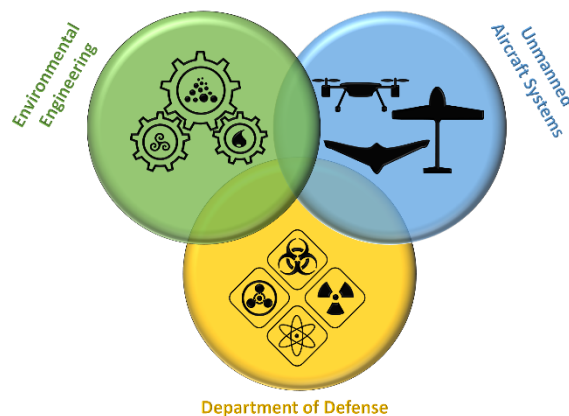


**Figure 1: Research Focus Areas**

## **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 canvassing, 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**

| <u>Topic (section)</u>         | <u>Current Text</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | <u>Recommendations</u> |
|--------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|
| Cueing<br>(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 <b>unmanned aircraft system [UAS]</b> 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 <b>UAS</b> to verify the information for operational purposes... | No change              |
| CBRN ISR<br>Overlays<br>(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:<br>...<br>-Threat information (known hazard areas, danger areas).<br>-Coverage areas for sensors.<br>- <b>UAS flight paths.</b><br>-Retransmission locations.<br>-Theater laboratory support locations.                                            | No change              |
| Air<br>Environment<br>(G-5)    | The operational air environment is the operating medium for fixed- and rotary-wing aircraft, air defense systems, <b>UAS</b> , 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**

| <u>Topic (section)</u> | <u>Current Text</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | <u>Recommendations</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Aerial<br>(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.)                                                       | <b>Aerial CBRN R&amp;S operations may be conducted from both manned and unmanned aircraft.</b> 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 <b>or remote capabilities to take readings or collect data.</b> (See appendix F for more information on aerial CBRN R&S.)                                                                     |
| Remote<br>(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. <b>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.</b> (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.

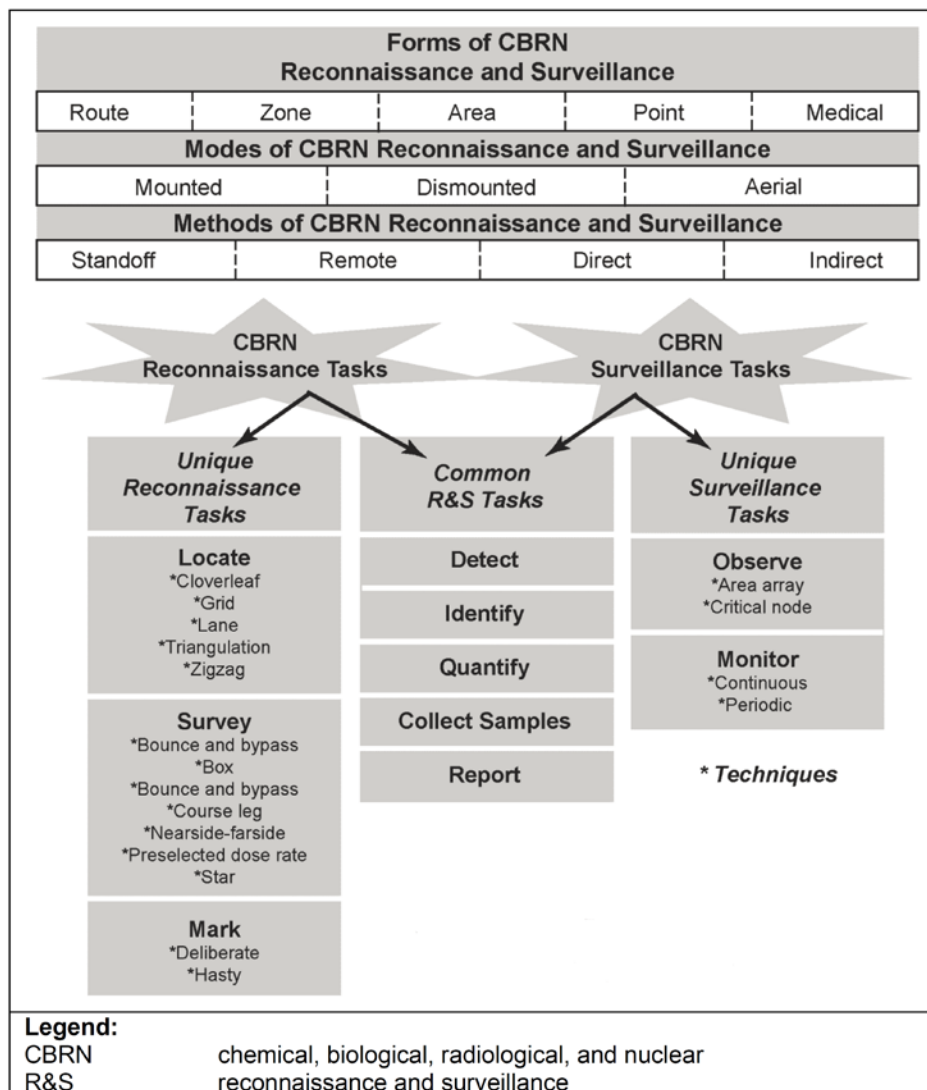


**Figure 2: CBRN ISR Task Elements (U.S. Army Training and Doctrine Command, 2013)**

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**

| <u>Topic (section)</u>                  | <u>Current Text</u>                                                                                                                                       | <u>Recommendations</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 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 | <p><b>Aerial CBRN R&amp;S operations may be conducted from both manned and unmanned aircraft.</b></p> <p><b>Add an Unmanned Aerial CBRN R&amp;S section to include, but not limited to:</b></p> <ol style="list-style-type: none"> <li>1. Introduction: discussing UAS terminology and classification</li> <li>2. Advantages and Disadvantages of Unmanned Aerial CBRN Reconnaissance:</li> <li>3. Unmanned Aerial CBRN Locate Techniques</li> <li>4. Unmanned Aerial CBRN Survey Techniques</li> </ol> |

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**

| <u>Topic (section)</u>               | <u>Current Text</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | <u>Recommendations</u>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 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. <b>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.</b> 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**

Written for consideration of submission to the  
Journal of Hazardous Materials  
([www.journals.elsevier.com/journal-of-hazardous-materials/](http://www.journals.elsevier.com/journal-of-hazardous-materials/))

#### **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 (LC<sub>50</sub>) by inhalation in any mammalian species, of less than 100,000 mg min/m<sup>3</sup> (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<br>Flammable gases<br>flammable aerosols<br>oxidizing gases<br>gasses under pressure<br>flammable liquids<br>flammable solids<br>self-reactive substances and mixtures<br>pyrophoric liquids<br>pyrophoric solids<br>organic peroxides<br>corrosive to metals                                               |
| Health Hazards        | acute toxicity<br>skin corrosion/irritation<br>serious eye damage/eye irritation<br>respiratory or skin sensitization<br>germ cell mutagenicity<br>carcinogenicity<br>reproductive toxicity<br>specific target organ toxicity-single exposure<br>specific target organ toxicity-repeated exposure<br>aspiration hazard |
| Environmental Hazards | hazards to the aquatic environment<br>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)**

| Chemicals of Interest | DHS Security Issue |                      |                      |                 |             |                  |                           | ITF-25 Hazard Index |     |     | Detection Technology |     |     |     |
|-----------------------|--------------------|----------------------|----------------------|-----------------|-------------|------------------|---------------------------|---------------------|-----|-----|----------------------|-----|-----|-----|
|                       | 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   |     |

| Chemicals of Interest | DHS Security Issue |                      |                      |                 |             |                  |                           | ITF-25 Hazard Index |     |     | Detection Technology |     |     |     |
|-----------------------|--------------------|----------------------|----------------------|-----------------|-------------|------------------|---------------------------|---------------------|-----|-----|----------------------|-----|-----|-----|
|                       | 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   |     |

| Chemicals of Interest  | DHS Security Issue |                      |                      |                 |             |                  |                           | ITF-25 Hazard Index |     |     | Detection Technology |     |     |     |
|------------------------|--------------------|----------------------|----------------------|-----------------|-------------|------------------|---------------------------|---------------------|-----|-----|----------------------|-----|-----|-----|
|                        | 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.

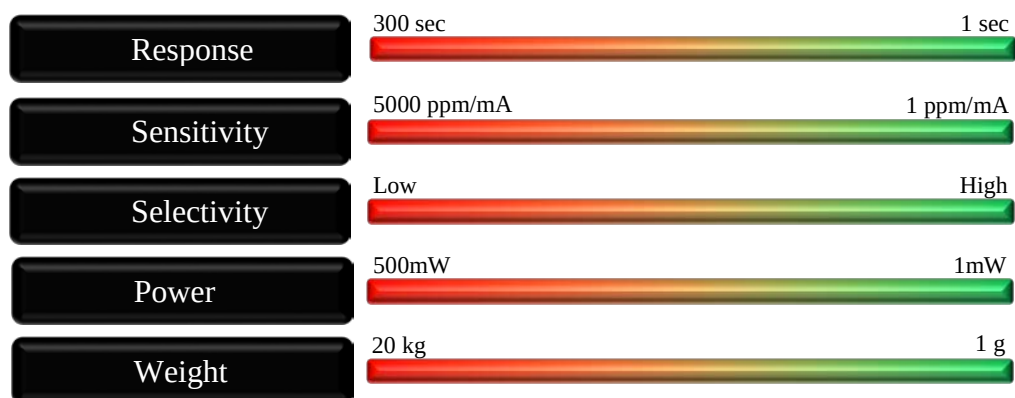


**Figure 3: Example Parameter Scale**

#### **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

$$G = \frac{\Lambda C}{1000K} \quad \text{Equation 1} \quad (1)$$

Where:

$G$  = the conductance in siemens (s)

$\Lambda$  = the equivalent conductance in siemens square centimeter per equivalent ( $\text{S cm}^2 \text{ equivalent}^{-1}$ )

$C$  = the concentration in equivalent per liter (equivalent  $\text{L}^{-1}$ )

$K$  = is the cell constant in  $\text{cm}^{-1}$

(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:

$$R = 1/G$$

Equation 2

(2)

Where:

$R$  = resistance in ohms ( $\Omega$ )

$G$  = 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:

,

$$E_{cell} = E_{cell}^0 - \frac{RT}{nF} \ln \frac{[Y]^y [Z]^z}{[A]^a [B]^b} \quad \text{Equation 3} \quad (3)$$

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:

$$W = \frac{qM}{nF} \quad \text{Equation 4} \quad (4)$$

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 mole 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, $\Omega$ ) | Uncharged analyte (gas or vapor)<br>Corrosive gasses: (NH <sub>3</sub> , H <sub>2</sub> S, SO <sub>2</sub> )                                                         | Non-specific<br>Sensitive to interference<br>Temperature dependent |
| Potentiometry (V)           | pH, CO, Cl <sub>2</sub> , CH <sub>2</sub> O, H <sub>2</sub> S, NO <sub>x</sub> ,<br>SO <sub>x</sub> , O <sub>2</sub> , O <sub>3</sub>                                | Non-specific<br>Temperature dependent                              |
| Coulometry (C)              | Not temperature dependent<br>Very accurate<br>(O <sub>2</sub> , CO, Cl <sub>2</sub> , HCN, H <sub>2</sub> S, NO <sub>x</sub> , O <sub>3</sub> ,<br>SO <sub>2</sub> ) | Non-specific                                                       |
| Amperometry (A)             | Linear over 3 orders of magnitude<br>CO, H <sub>2</sub> S, O <sub>2</sub> , Cl <sub>2</sub> , NO                                                                     | Non-specific<br>Temperature dependent<br>Reference electrode       |
| Overall                     | Diffusive monitors<br>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.



Where:

$R$  = the molecule to be ionized

$h\nu$  = 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  $^{63}\text{Ni}$  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 conducting 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<br>Non-destructive<br>Some selectivity | Fragile components                                       |
| Flame Ionization (FID)          |                                                | Non-selective<br>Destructive<br>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 relatively 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.

$$A = \epsilon bc$$

Equation 6

(6)

Where:

$A$  = absorbance

$\epsilon$  = 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).

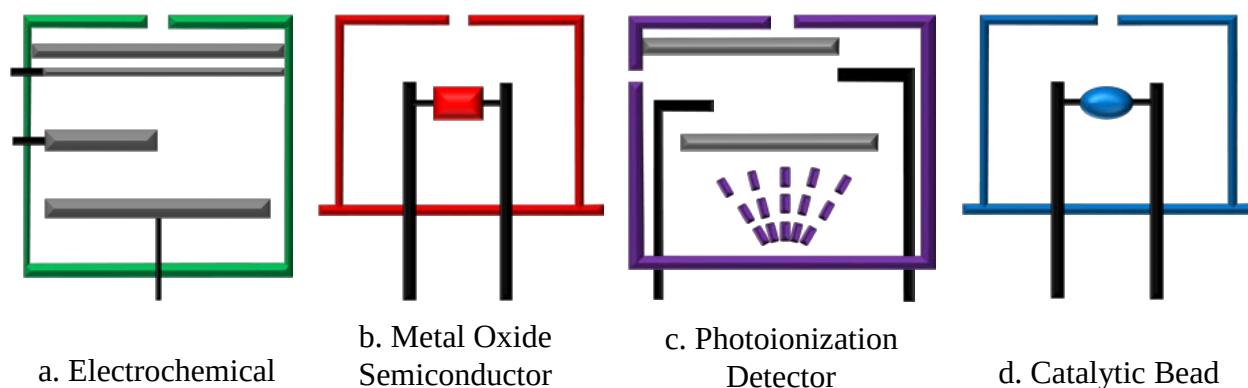


**Figure 4: Graphical Representations of Detection Technologies inspired by (Chou, 2000)**

## 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 detectable 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.

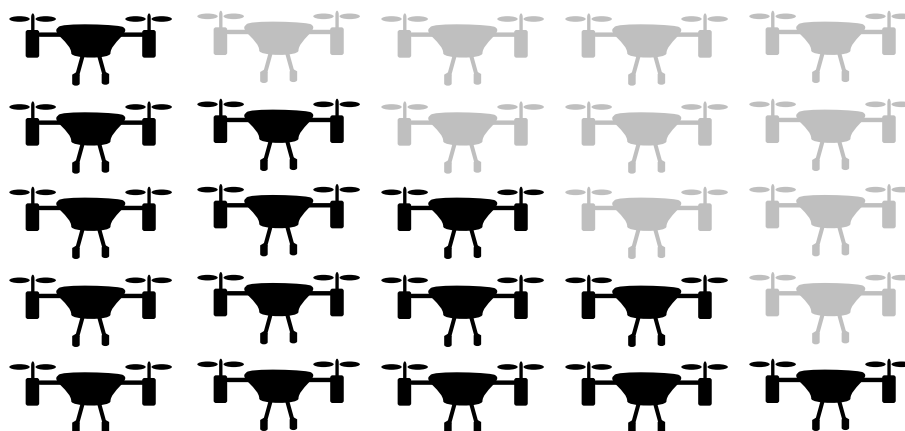


**Figure 5: SUAS Employment and Integration Scale for Chemical Detection Technologies**

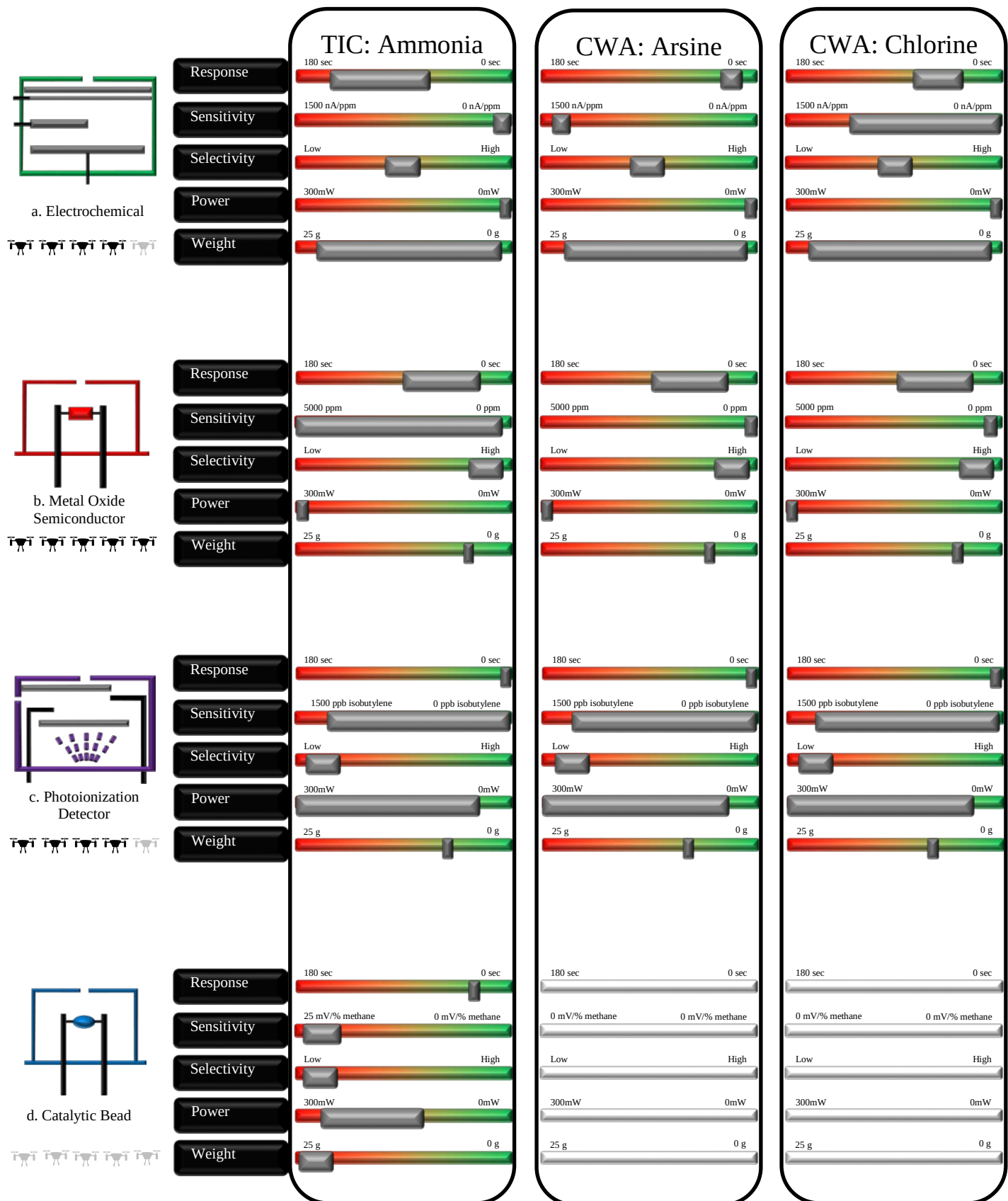


Figure 6: Comparison of Detection Technologies

## 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 to the author's preferences. Although, every decision maker is unique and would assign weights to each node according to their own priorities.

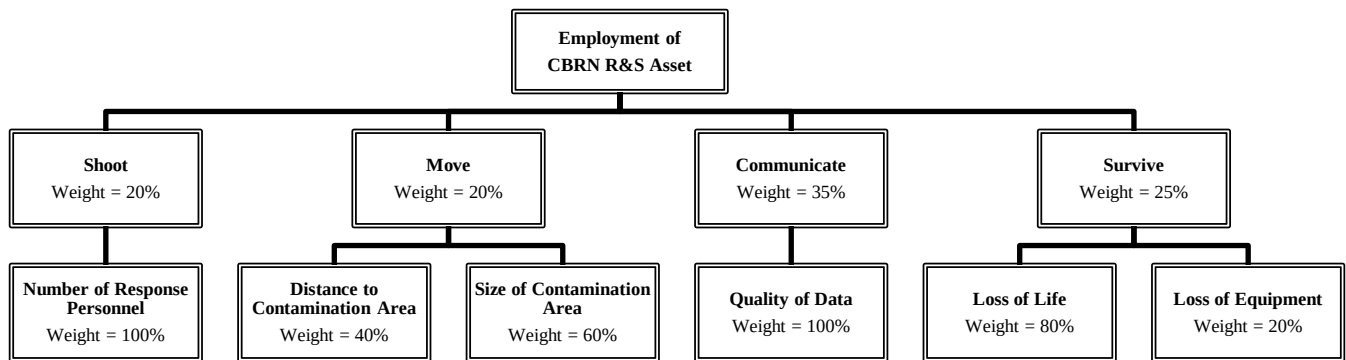


**Figure 7: Objective Hierarchy Model**

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.

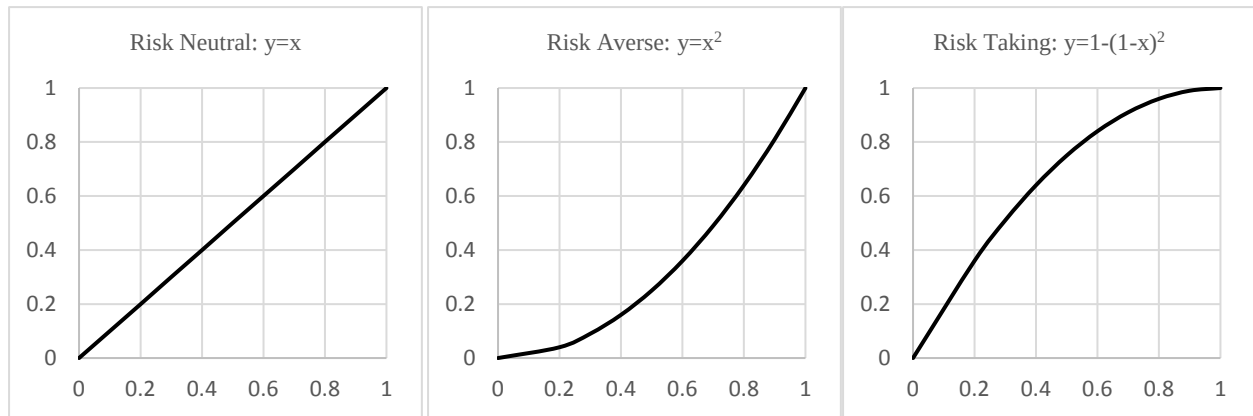


Figure 9: Utility Functions

## 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**

| <b>MOE</b>                               | <b>SUAS</b> | <b>Conventional</b> | <b>Combination</b> |
|------------------------------------------|-------------|---------------------|--------------------|
| 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**

| <b>MOE</b>                               | <b>SUAS</b> | <b>Conventional</b> | <b>Combination</b> |
|------------------------------------------|-------------|---------------------|--------------------|
| 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 assess what 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 allowed 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? |
|-----------------------------------------------------------------------------|-----------------------------------|------------------------------------|-----------------------------------------------------|----------------------------------|--------------------------------------------------------------------------|-------------------------------------|------------------------------------------|---------------------------------|--------------------------------------|--------------------------------------|---------------------------------|-----------------------------|----------------------------------|----------------------------------------|---------|------------|-------------|-------------|-------------|---------|--------------|-------------|-------------|--------------|
| Allyltrimethylchlorosilane                                                  | 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                                |                                        |         |            |             |             |             |         |              |             |             |              |
| Amyltrimethylchlorosilane                                                   | 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           |              |
| Bromotrifluoroethylene                             | 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                                      |         |            |             |             |             |         |              |             |             |              |

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| 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           |             |         |              |             |             |              |

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| 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           |             |         |              |             |             |              |

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| 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           |             |             |         |              |             |             |              |

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| 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                                |                                        |         |            |             |             |             |         |              |             |             |              |

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| 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            |             |             |              |

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| 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 nitrosaminoguanlylidene 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                           |                                  |                                        |         |            |             |             |             |         |              |             |             |              |

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| 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            |             |             |              |

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| 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           |             |         |              |             |             |              |

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| 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                                |                                        |         |            |             |             |             |         |              |             |             |              |

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| 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           |             |         |              |             |             |              |

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| 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.          | Carbon 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-trifluoroethane  |

| 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 naphthalene                   |
| 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 naphthalene     |
| 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. | Ethylenimine          |
| 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 t <sub>90</sub> (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 ( $\Omega$ ) |
|-------------|-------------|-------------------|------------|----------------------|-------------|-----------------------|----------------------------|
| 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_CI23E50 MINI                    | Chlorine          | 1.2- 17    | 450                  | 50          | < 30                  |                   |
| City Technology Ltd. | Chlorine_Shawcity_CI23E50 SENSORIC CLASSIC        | Chlorine          | 1.2- 17    | 450                  | 50          | < 30                  |                   |
| City Technology Ltd. | Chlorine_Shawcity_CI23E50 CTL 4 series adaptation | Chlorine          | 1.2- 17    | 450                  | 50          | < 30                  |                   |
| City Technology Ltd. | Chlorine_Shawcity_CI23E50 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

XXXXXXXXXX

### 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](mailto:Brandon.Barnes@afit.edu) or Robert Eninger, Lt Col USAF (thesis advisor) at [Robert.Eninger@afit.edu](mailto: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

- ☐ O7 or above

Observer Service:

- ☐ Marine Corps
- ☐ Air Force
- ☐ Army
- ☐ Navy
- ☐ Other

## B. Execution

Number of Response Personnel:

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

Mission identification level

- |                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                                                                                                            |                                                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|
| <input type="radio"/> 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. | <input type="radio"/> 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. | <input type="radio"/> Other <input type="text"/> |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|

Mission mode:

- |                               |                                  |                                                  |
|-------------------------------|----------------------------------|--------------------------------------------------|
| <input type="radio"/> Mounted | <input type="radio"/> Dismounted | <input type="radio"/> Other <input type="text"/> |
|-------------------------------|----------------------------------|--------------------------------------------------|

Mission Method:

- |                                |                              |                              |                                |                                                  |
|--------------------------------|------------------------------|------------------------------|--------------------------------|--------------------------------------------------|
| <input type="radio"/> Standoff | <input type="radio"/> Remote | <input type="radio"/> Direct | <input type="radio"/> Indirect | <input type="radio"/> Other <input type="text"/> |
|--------------------------------|------------------------------|------------------------------|--------------------------------|--------------------------------------------------|

Mission duration:

- ☐ 10 minutes
- ☐ 30 minutes
- ☐ 1 hour
- ☐ 8 hours
- ☐ 1 day
- ☐ Multiple days

Hazard type:

- ☐ Chemical
- ☐ Biological
- ☐ Radiological
- ☐ Nuclear
- ☐ Other

Approximate size of contamination zone:

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

Approximate distance to contamination zone/area:

- ☐ 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.

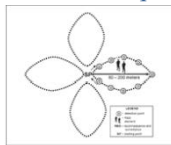


Figure E-9. Dismounted, cloverleaf technique

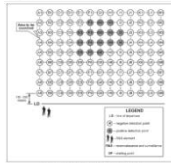


Figure E-10. Dismounted, grid technique

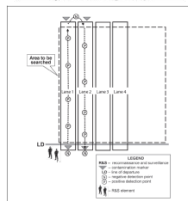


Figure E-8. Dismounted, lane technique

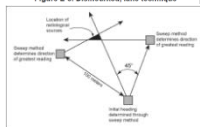


Figure E-11. Triangulation locate technique

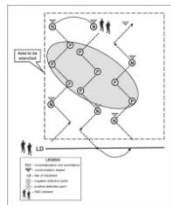


Figure E-7. Dismounted, zigzag technique

☐ Cloverleaf

☐ Grid

☐ Lane

☐ Triangulation

☐ Zigzag

☐ Other

Please describe the technique used to identify:

Which technique was used to observe? Choose one.

- ☐ Area array
- ☐ Critical node
- ☐ Other

Which technique was used to monitor? Choose one.

- ☐ Continuous
- ☐ Periodic
- ☐ Other

What technique was used to survey? Choose one.

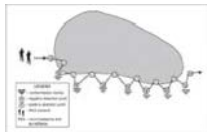


Figure 8-13. Dismounted, bounce-and-bypass technique

☐ Bounce and bypass

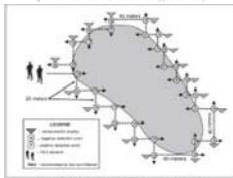


Figure 8-16. Dismounted, box survey technique

☐ Box

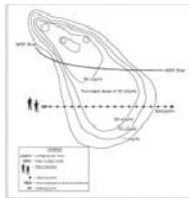


Figure 8-14. Dismounted, course leg technique

☐ Course leg

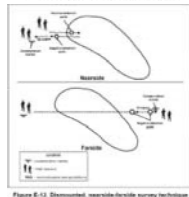


Figure 8-12. Dismounted, nearside-farside survey technique

☐ Nearside-Farside

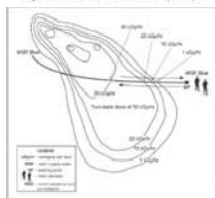


Figure 8-15. Sample preselected dose rate technique

☐ Preselected dose rate

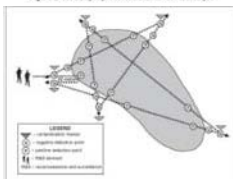


Figure 8-18. Dismounted, star survey technique

☐ 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:      | 2 | 3 | 4 | 5:         |
|  | Failed  |   |   |   | Successful |
|  | Mission |   |   |   | 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.



Confidence in Results:

## Appendix E

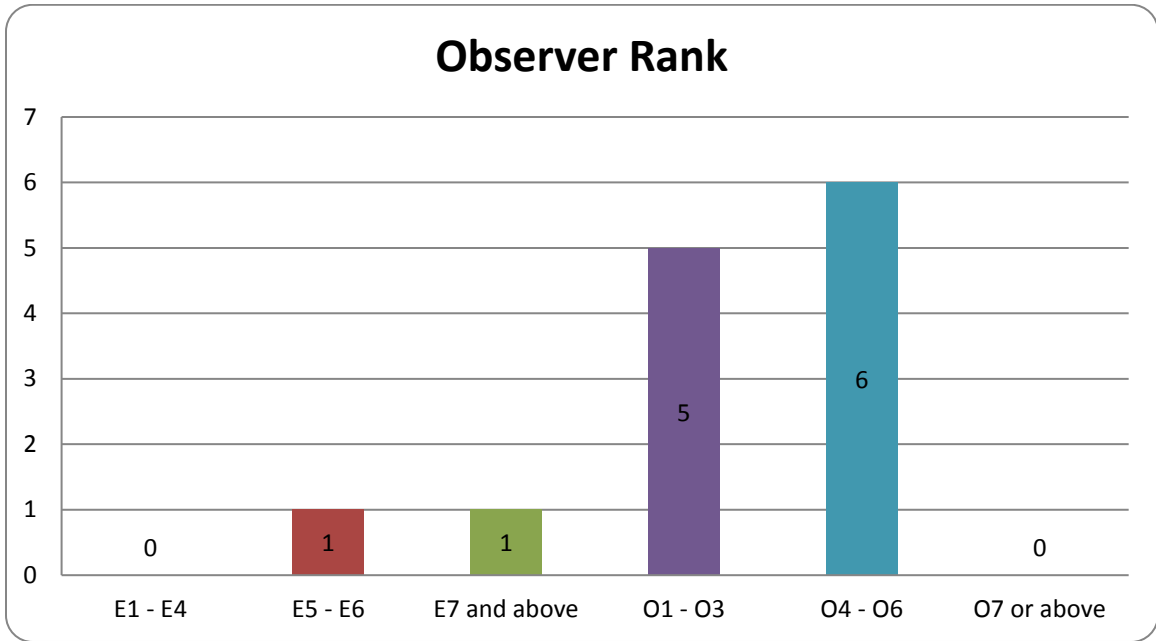


Figure 10: Questionnaire Results: Observer Rank

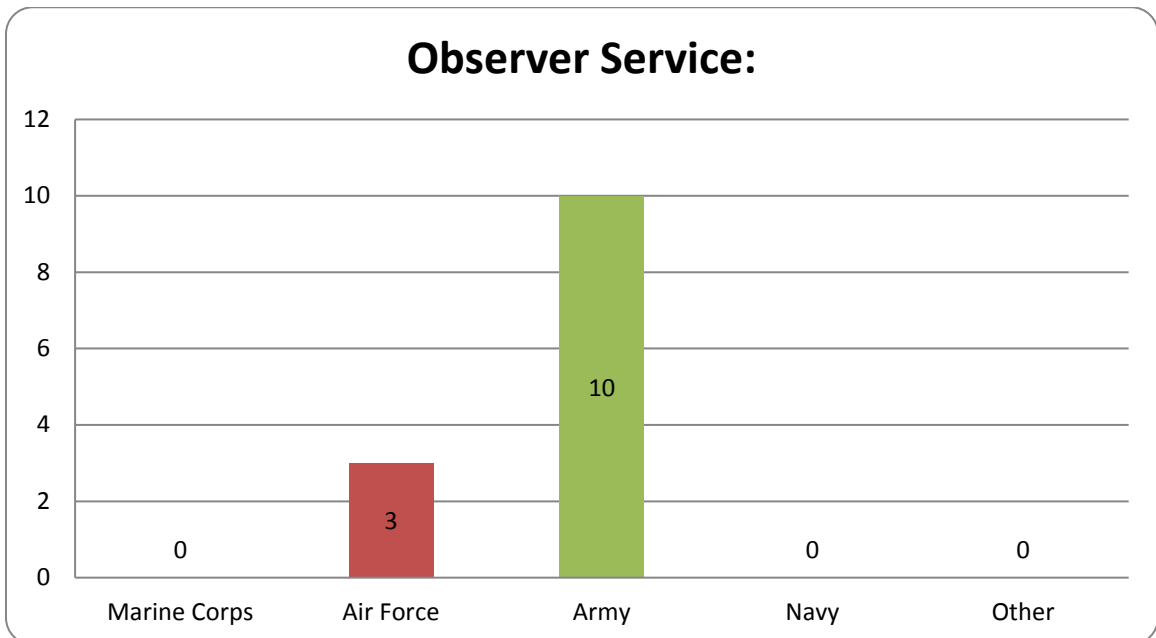


Figure 11: Questionnaire Results: Observer Service

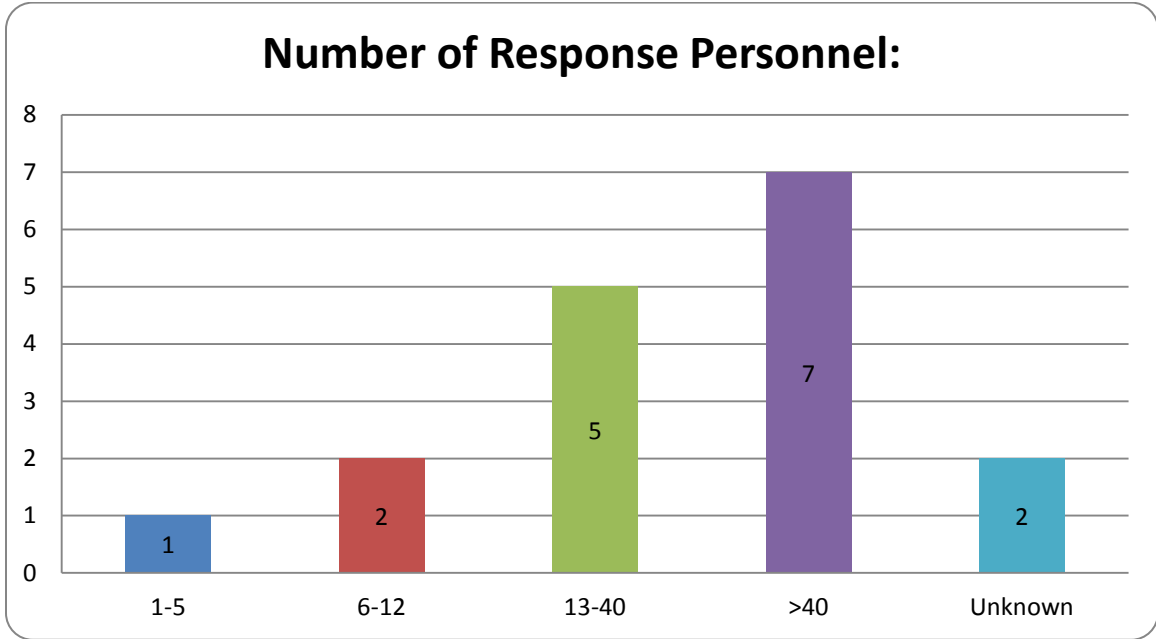


**Figure 12: Questionnaire Results: Number of Response Personnel**

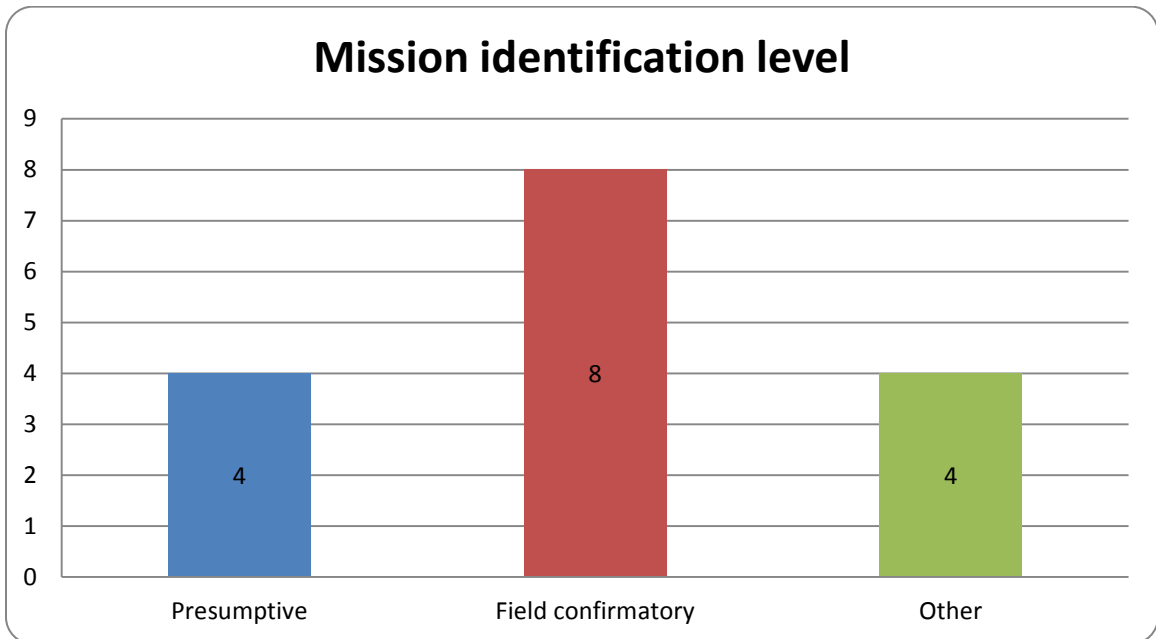


**Figure 13: Questionnaire Results: Mission Identification Level**

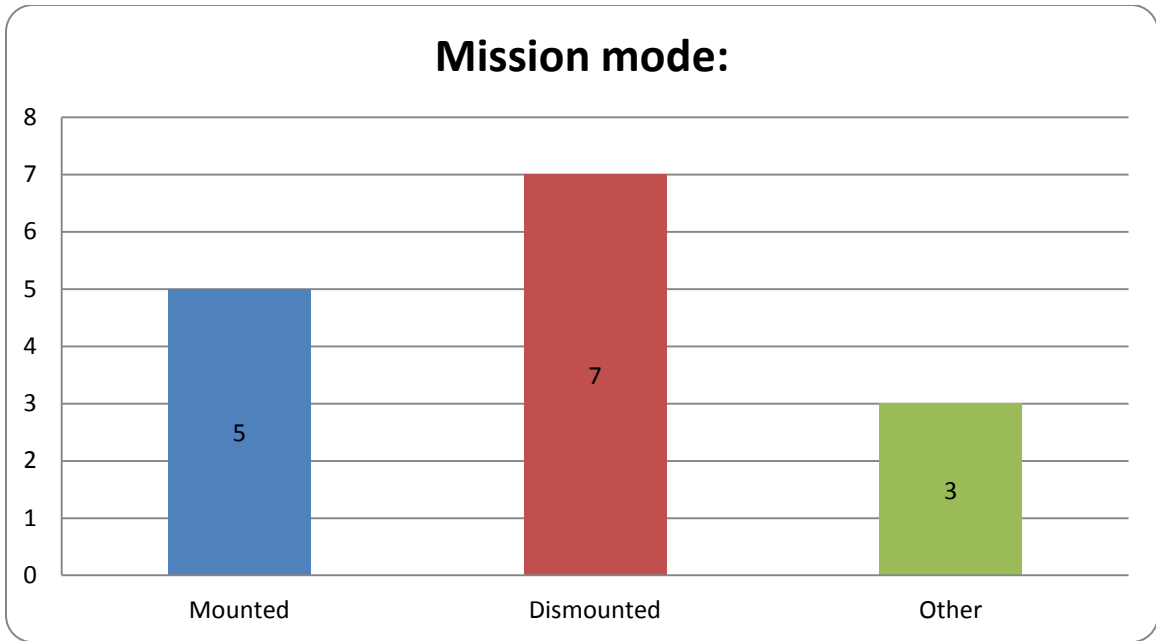


Figure 14: Questionnaire Results: Mission Mode

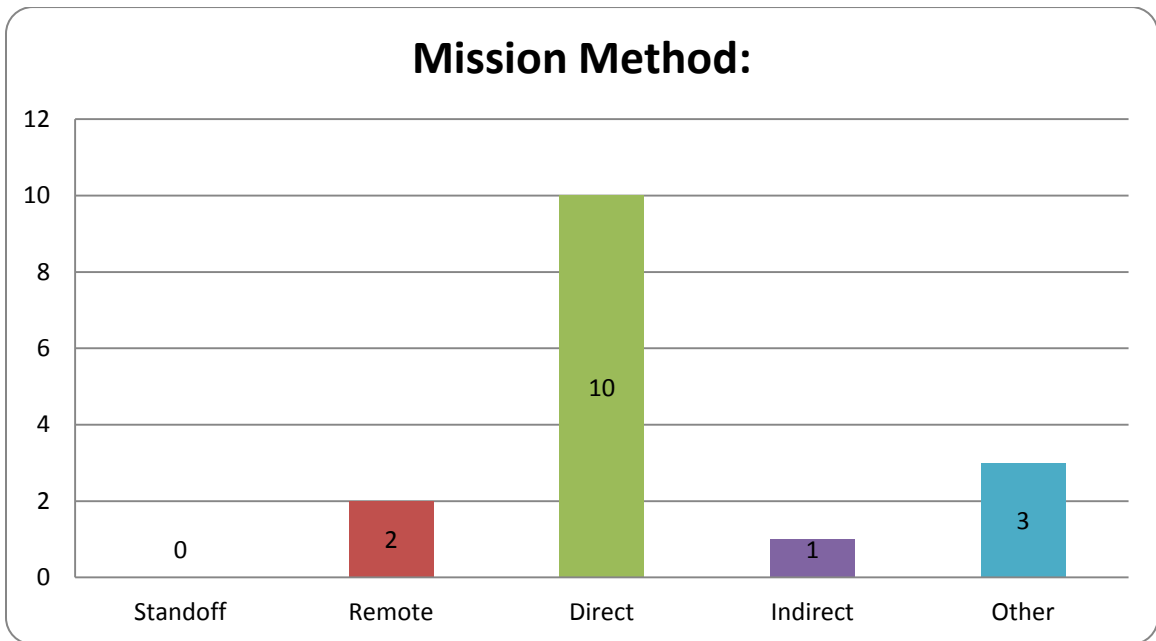


Figure 15: Questionnaire Results: Mission Method

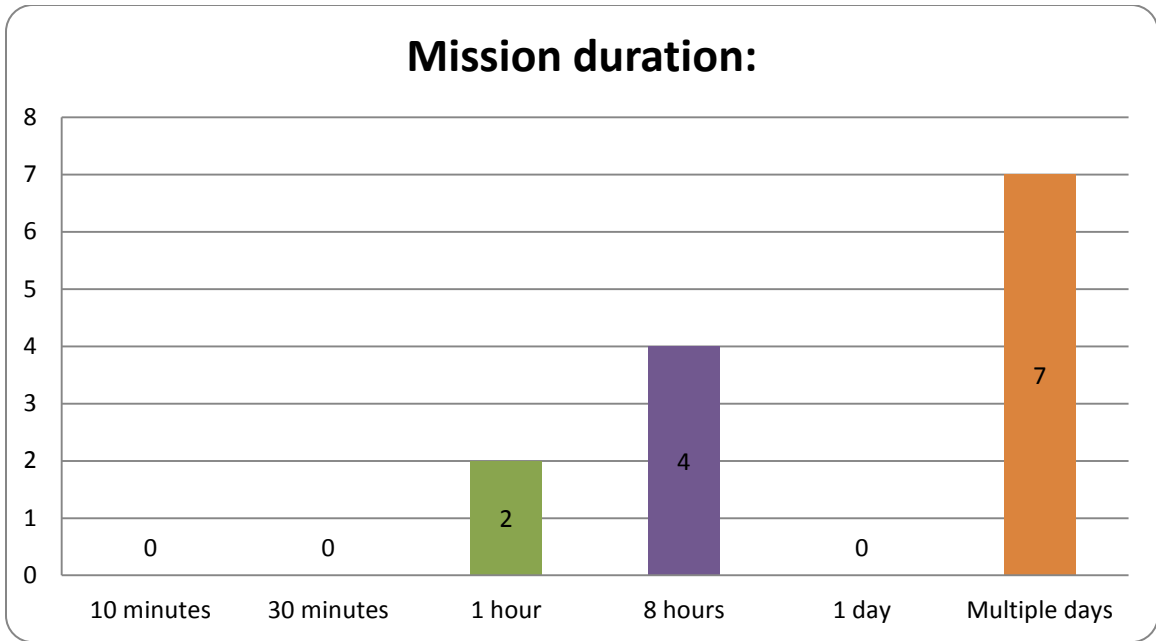


**Figure 16: Questionnaire Results: Mission Duration**

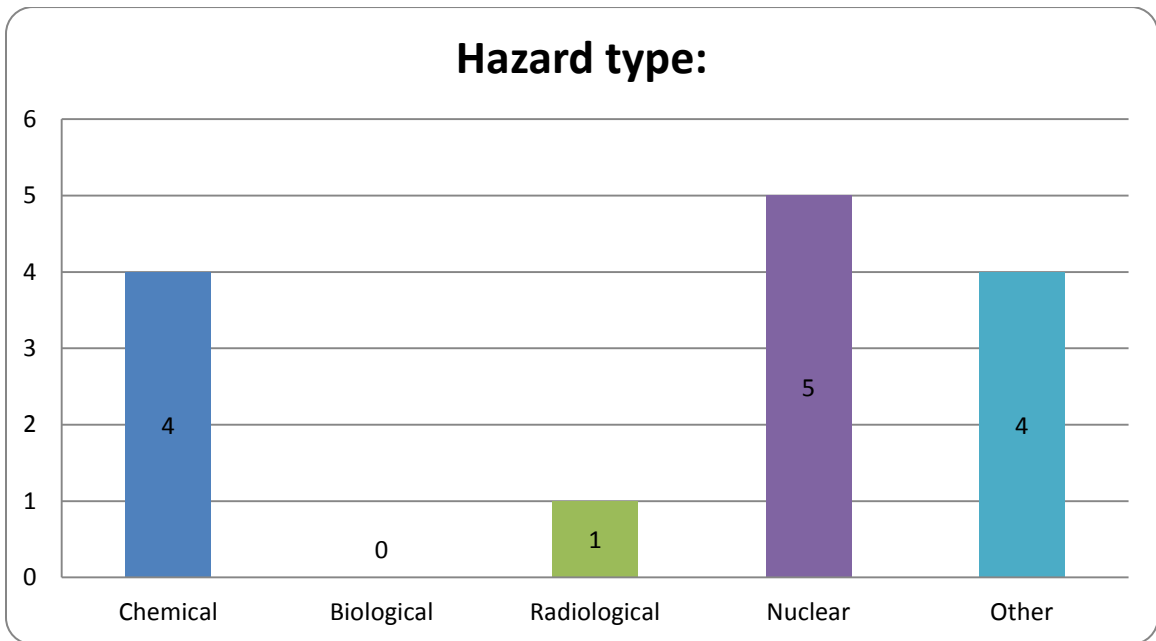


**Figure 17: Questionnaire Results: Hazard Type**

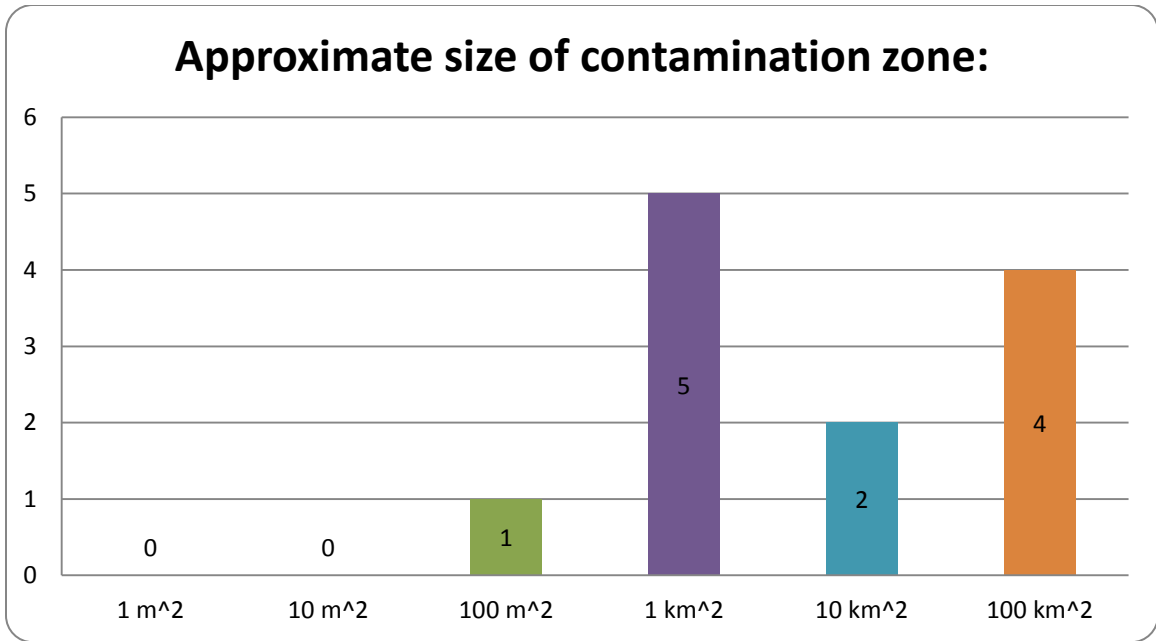


**Figure 18: Questionnaire Results: Size of Contamination Zone**

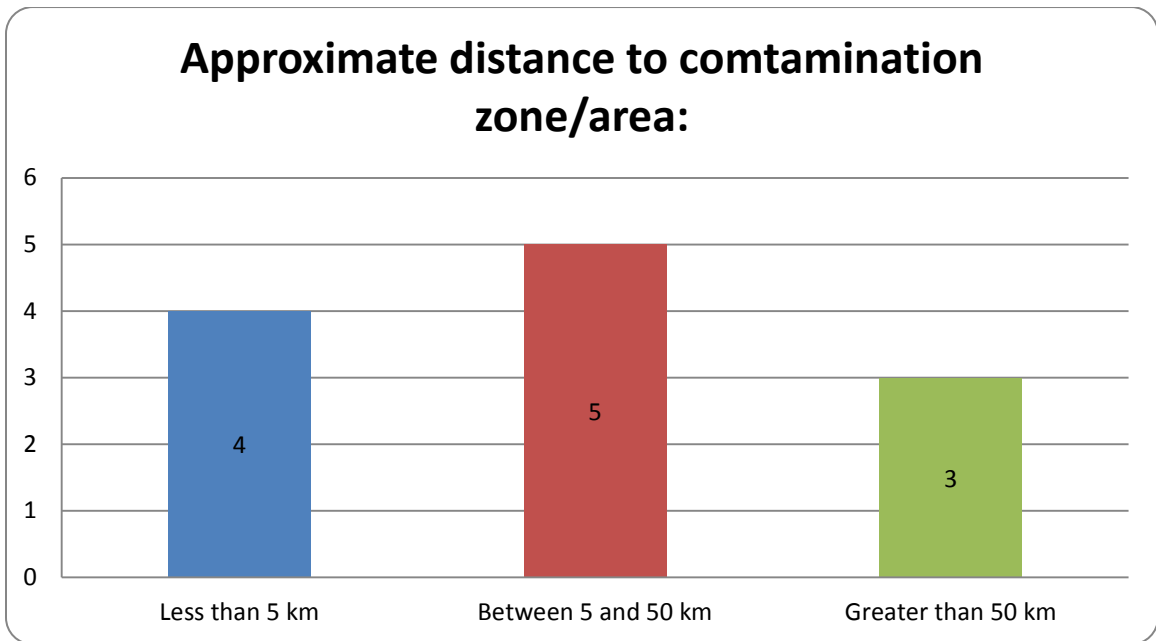


**Figure 19: Questionnaire Results: Distance to Contamination Area**

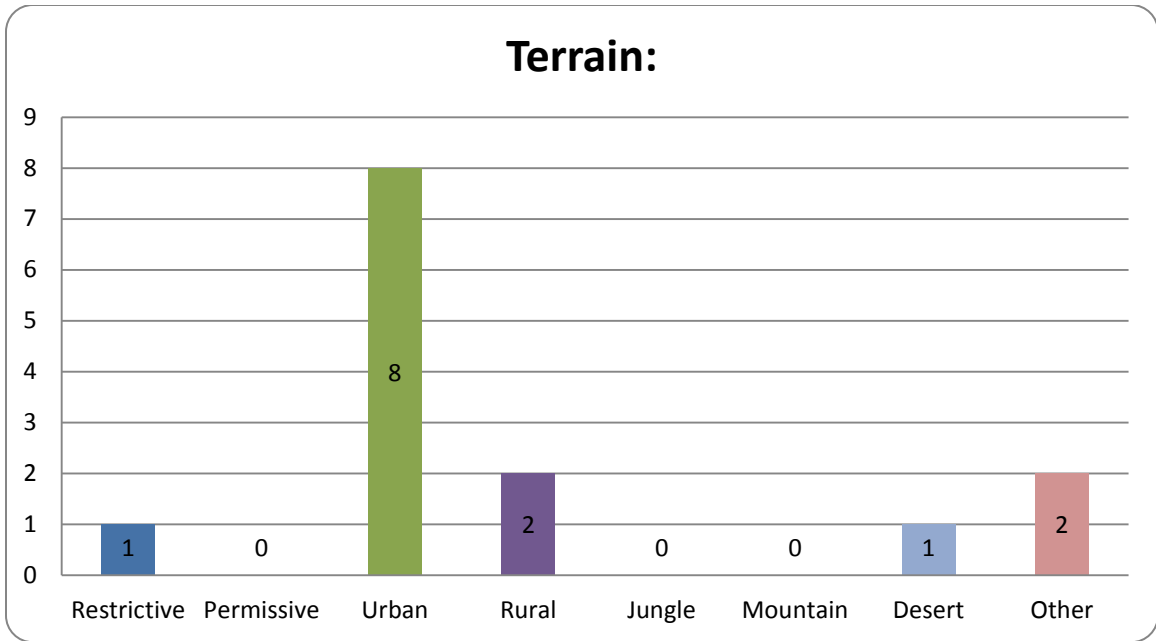


Figure 20: Questionnaire Results: Terrain

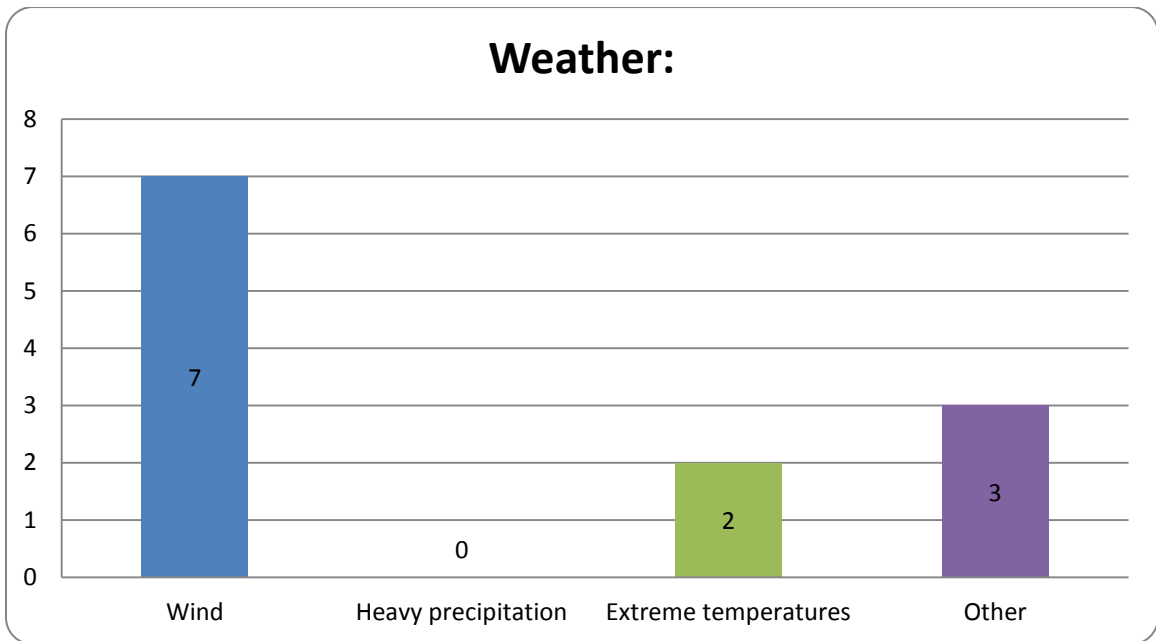


Figure 21: Questionnaire Results: Weather

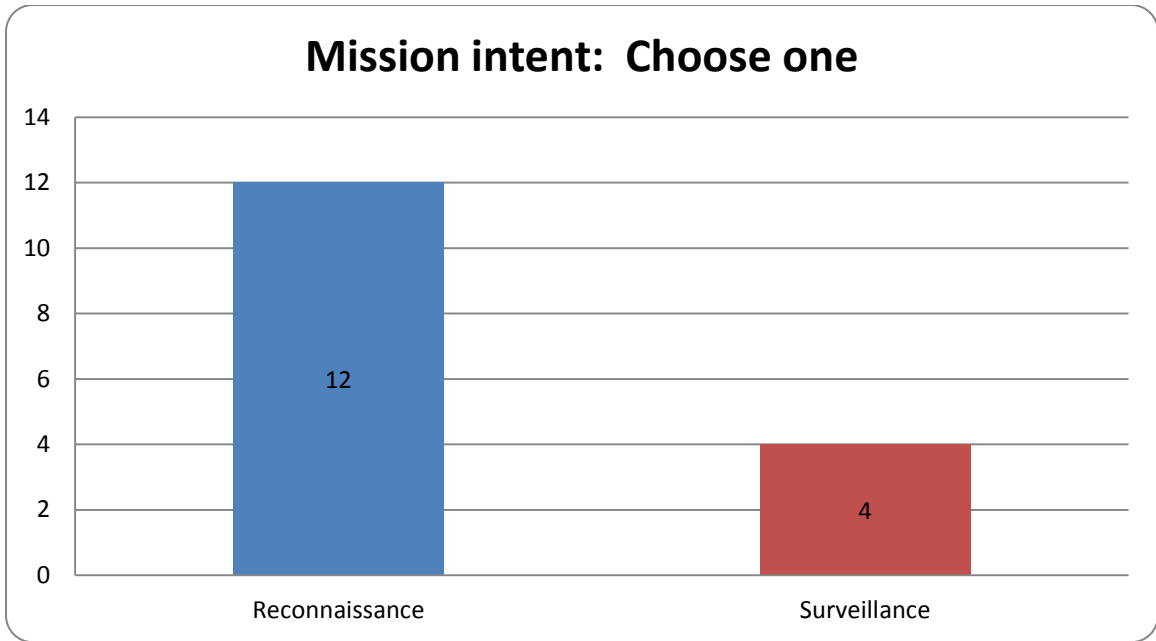


Figure 22: Questionnaire Results: Mission Intent

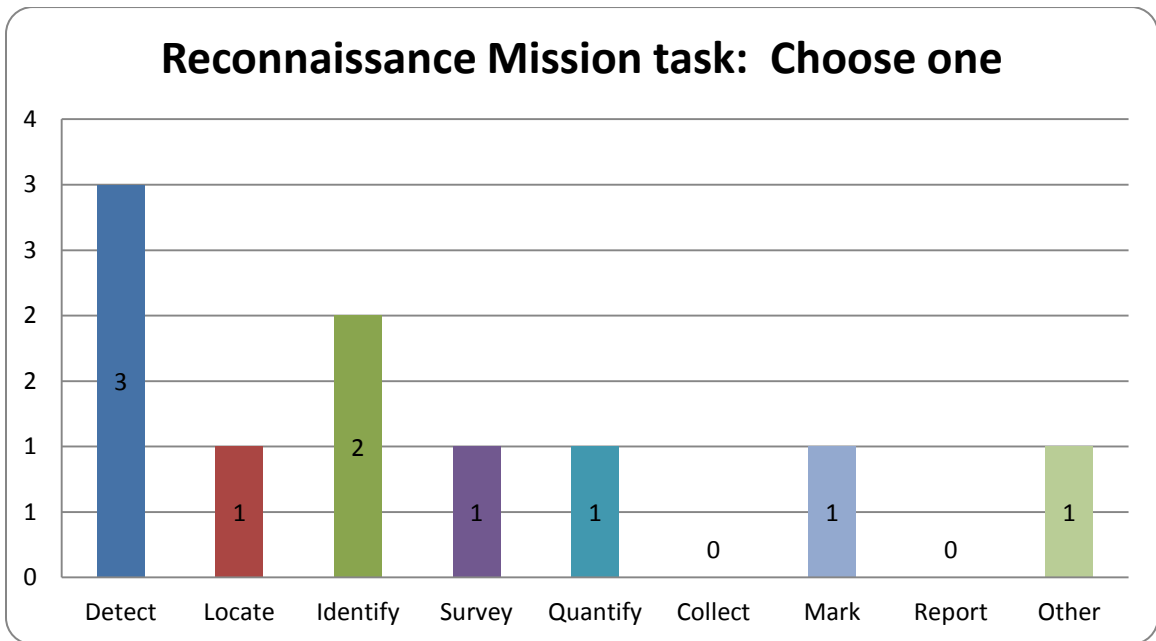


Figure 23: Questionnaire Results: Reconnaissance Task

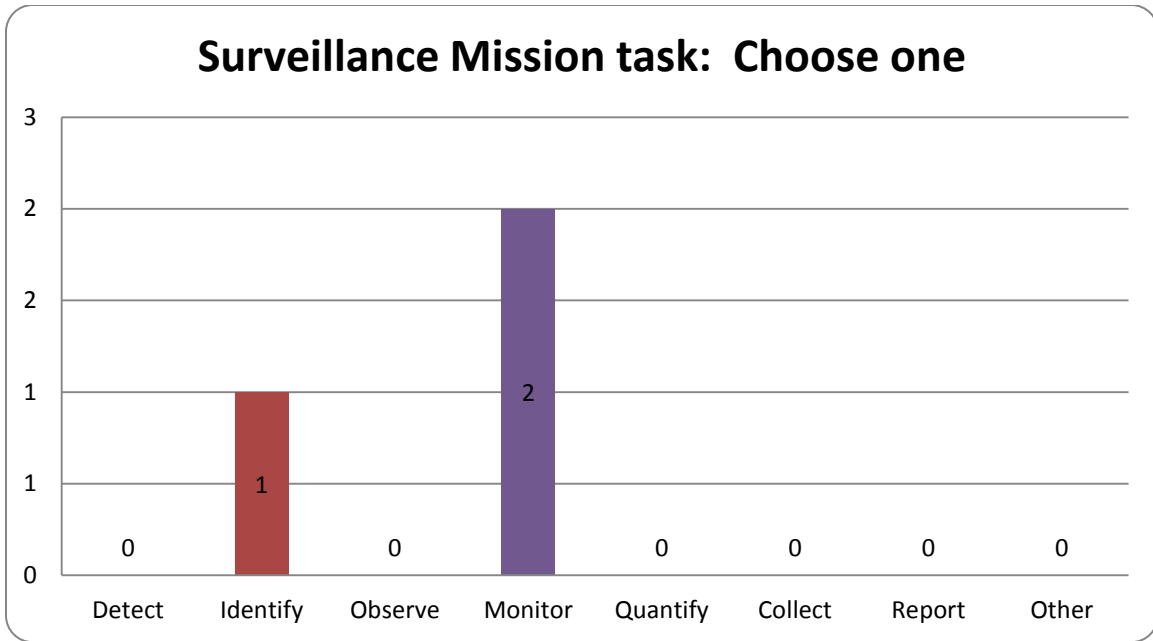


Figure 24: Questionnaire Results: Surveillance Task

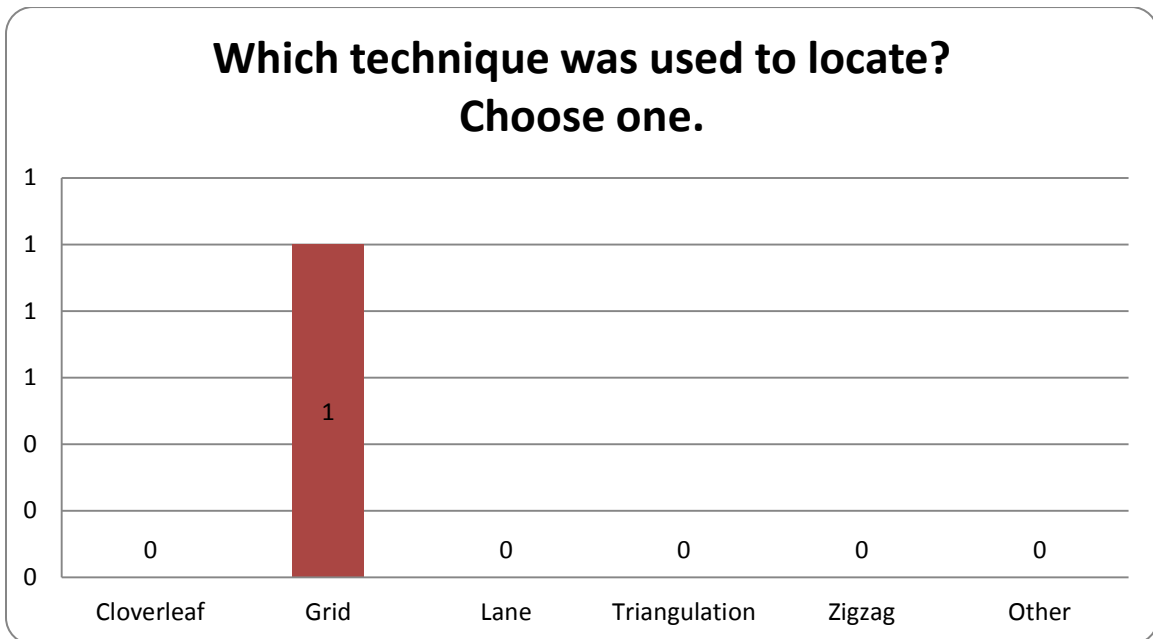


Figure 25: Questionnaire Results: Locate Techniques Used

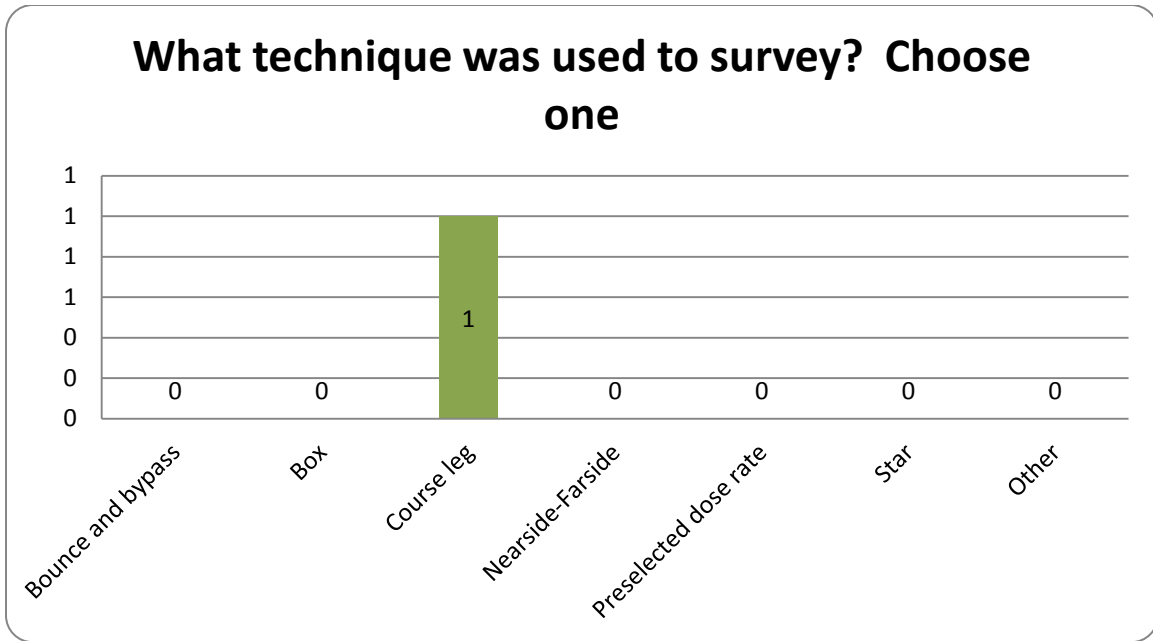


**Figure 26: Questionnaire Results: Survey Techniques Used**

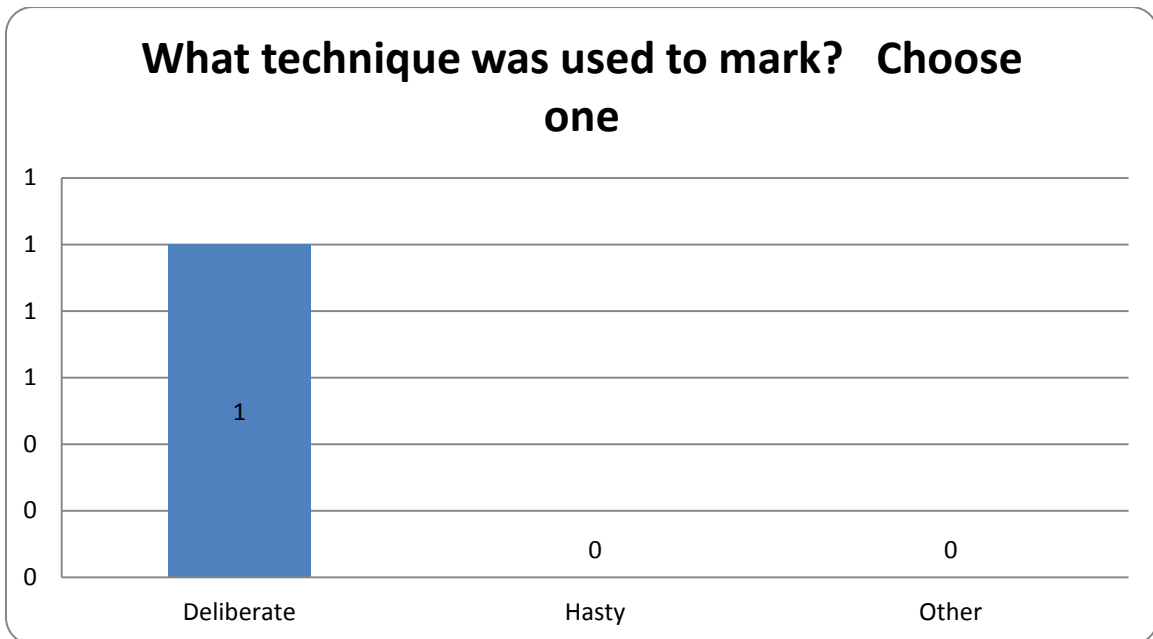


**Figure 27: Questionnaire Results: Mark Techniques Used**

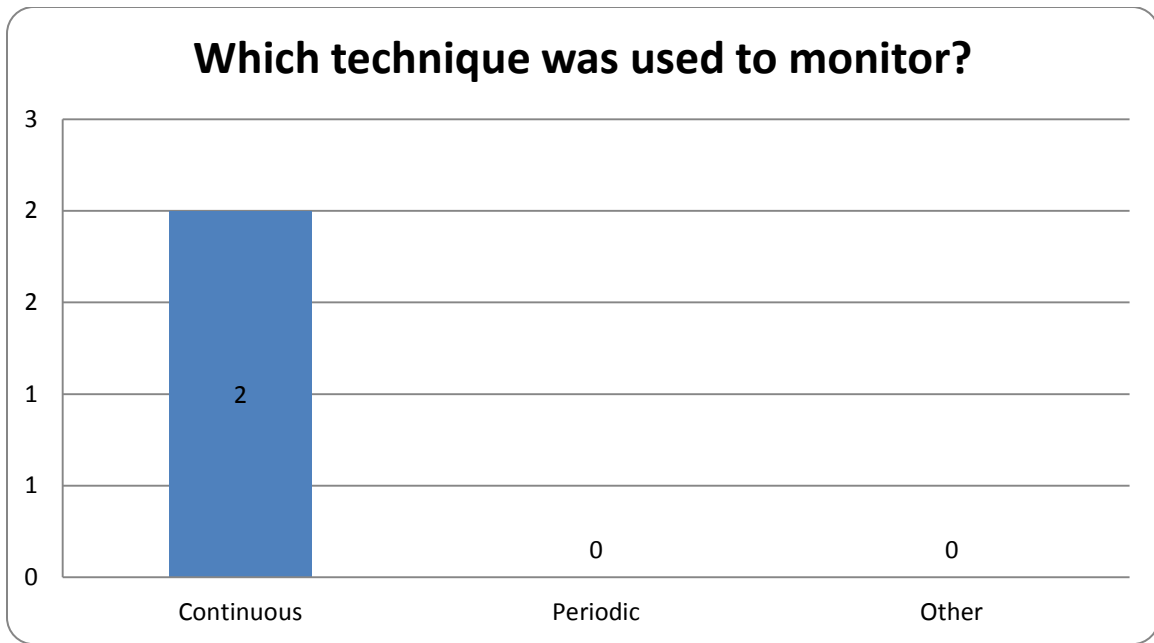


**Figure 28: Questionnaire Results: Monitor Techniques Used**

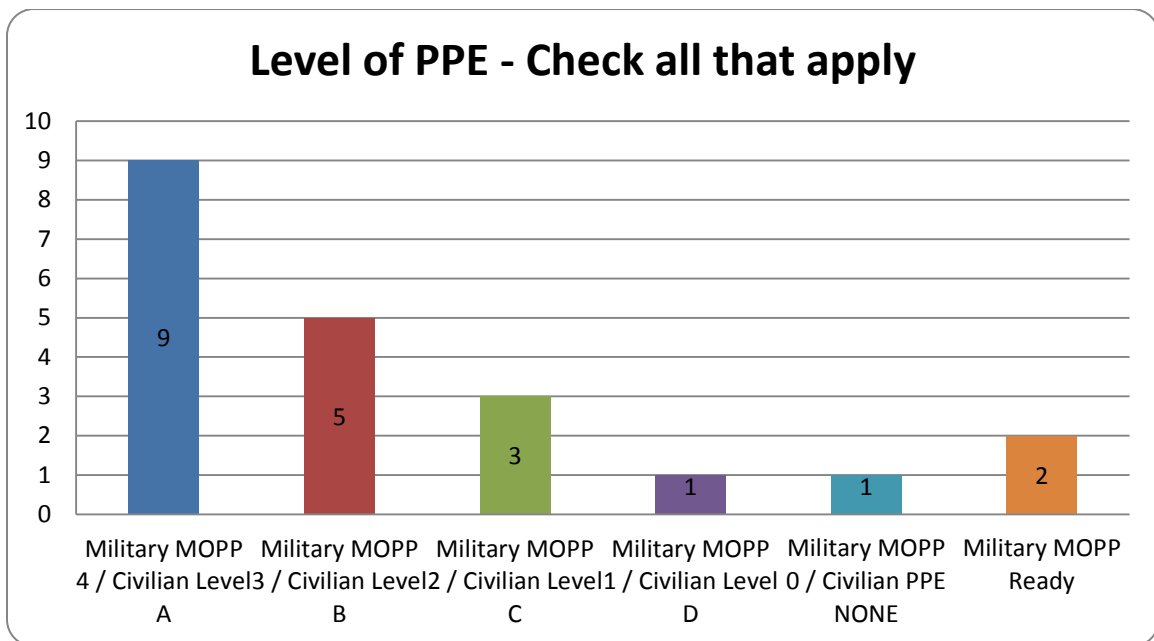


**Figure 29: Questionnaire Results: Personal Protective Equipment**

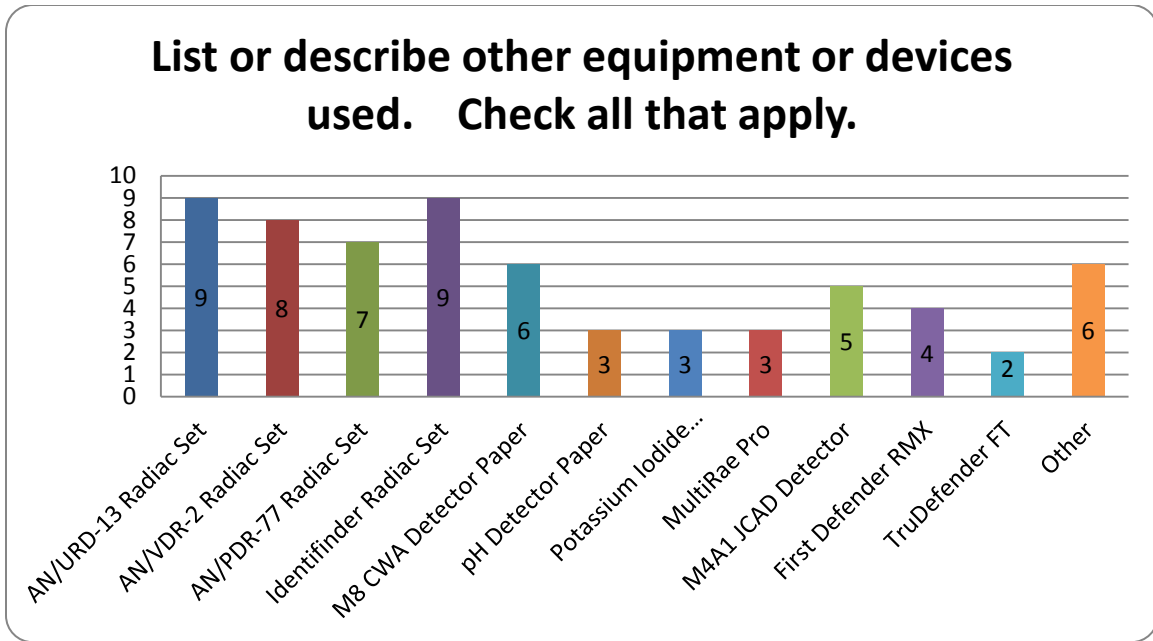


Figure 30: Questionnaire Results: Equipment Used

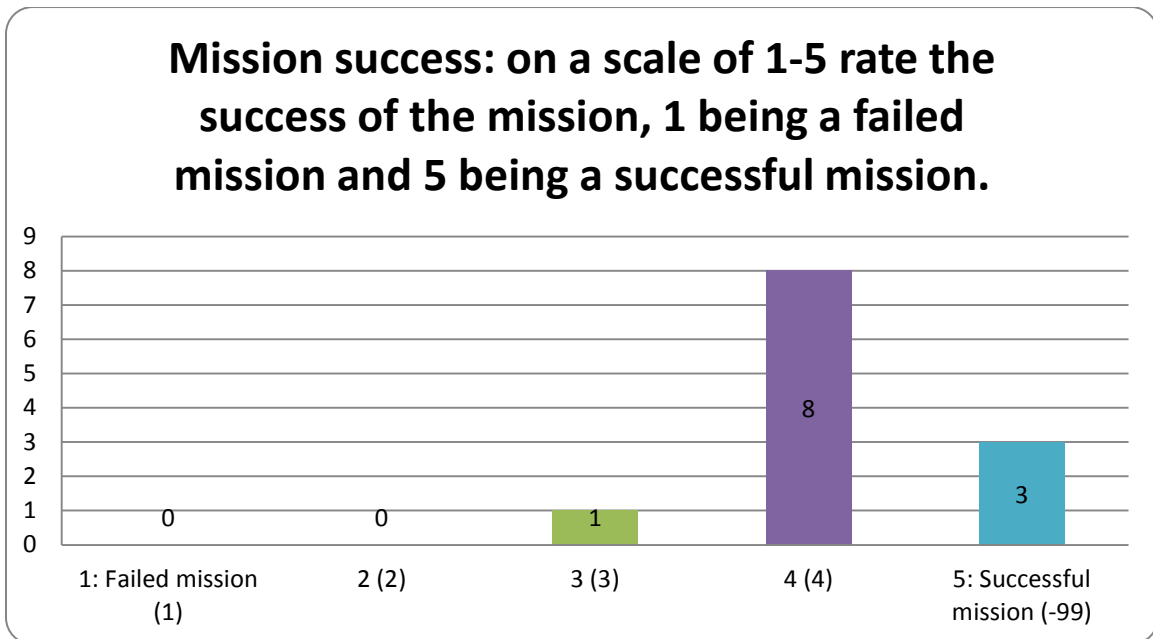


Figure 31: Questionnaire Results: Mission Success

**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.**

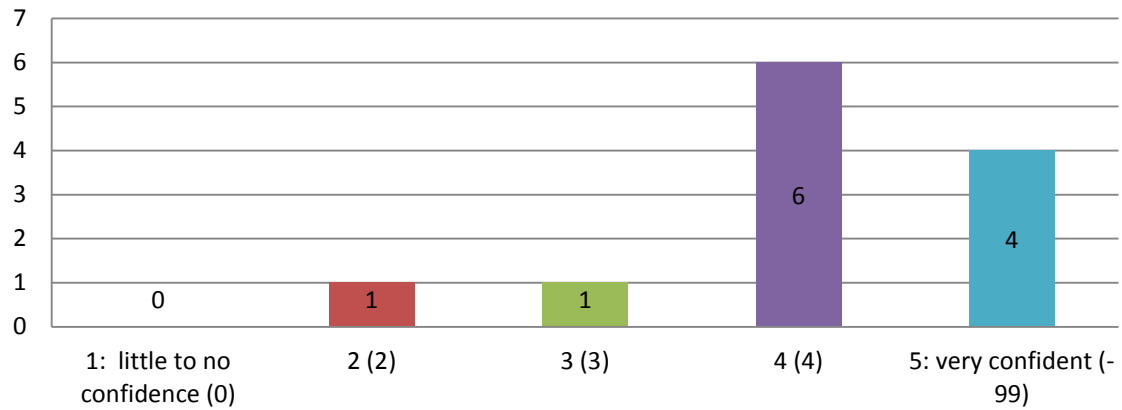


**Figure 32: Questionnaire Results: Confidence in Results**

## Appendix F

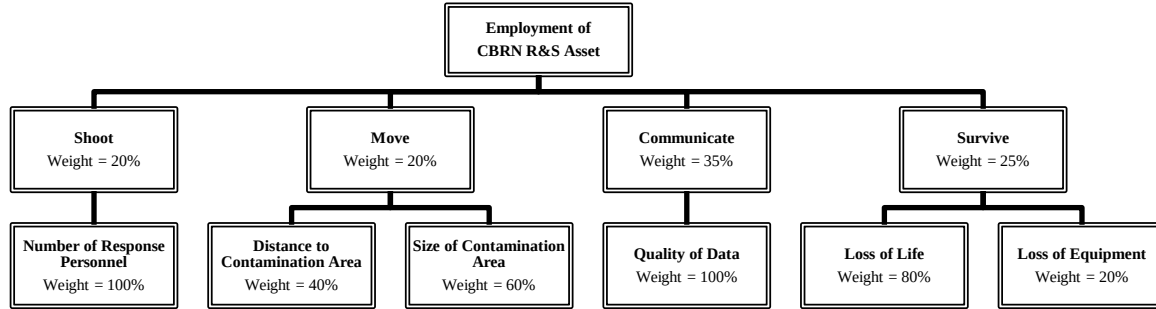


Figure 33: Friendly Scenario Objective Hierarchy Decision Tree

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

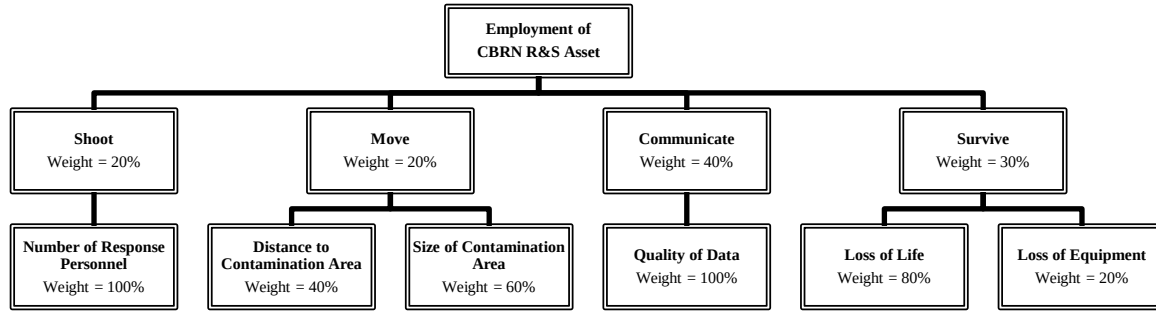


**Figure 34: Hostile Scenario Objective Hierarchy Decision Tree**

**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.

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |             |                                   |                               | Form Approved<br>OMB No. 074-0188                                        |                                                                                               |
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| 14. ABSTRACT<br>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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| U                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | U           | U                                 | UU                            | 161                                                                      | 19b. TELEPHONE NUMBER (Include area code)<br>(937) 255-6565, x 4511 (Robert.Eninger@afit.edu) |

