System Assessment and Validation for Emergency Responders (SAVER)

Passive Infrared Systems for Remote Chemical Detection Assessment Report

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FOREWORD

The U.S. Department of Homeland Security (DHS) established the System Assessment and Validation for Emergency Responders (SAVER) Program to assist emergency responders making procurement decisions. Located within the Science and Technology Directorate (S&T) of DHS, the SAVER Program conducts objective assessments and validations on commercially available equipment and systems and develops knowledge products that provide relevant equipment information to the emergency responder community. The SAVER Program mission includes:

- Conducting impartial, practitioner-relevant, operationally oriented assessments and validations of emergency response equipment
- Providing information, in the form of knowledge products, that enables decision-makers and responders to better select, procure, use, and maintain emergency response equipment.

SAVER Program knowledge products provide information on equipment that falls under the categories listed in the DHS Authorized Equipment List (AEL), focusing primarily on two main questions for the responder community: "What equipment is available?" and "How does it perform?" These knowledge products are shared nationally with the responder community, providing a life- and cost-saving asset to DHS, as well as to Federal, state, and local responders.

The SAVER Program is supported by a network of Technical Agents who perform assessment and validation activities. As a SAVER Program Technical Agent, National Security Technologies, LLC (NSTec), has been tasked to provide expertise and analysis on key subject areas, including chemical, biological, radiological, nuclear, and explosives (CBRNE) detection, countermeasures, and test and evaluation, among others. In support of this tasking NSTec developed this report to provide emergency responders with information gathered during a market survey of commercially available Passive Infrared Systems for Standoff Chemical Detection, which fall under AEL reference number 07CD-04-DCSO Title: Detector, Stand-Off, Chemical.

For more information on the SAVER Program or to view additional reports on infrared analysis devices for remote chemical detection or other technologies, visit www.dhs.gov/science-and-technology/saver.

POINTS OF CONTACT

SAVER Program
National Urban Security Technology Laboratory
U.S. Department of Homeland Security
Science and Technology Directorate
201 Varick Street
New York, NY 10014-7447
E-mail : nustl@hq.dhs.gov
Web site: www.dhs.gov/science-and-technology/saver

U.S. Department of Energy
National Nuclear Security Administration
Nevada Field Office
P.O. Box 98521
Las Vegas, NV 89193-8521

National Security Technologies, LLC
P.O. Box 98521
Mailstop NLV042
Las Vegas, NV 89193-8521

E-mail: SAVER_NV@nv.doe.gov

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EXECUTIVE SUMMARY

In May 2016, the System Assessment and Validation for Emergency Responders (SAVER) Program conducted an operationally oriented overview assessment of passive infrared (IR) systems for remote chemical detection (IR-RCD). IR-RCD systems are a relatively new technology, only recently becoming mature enough to consider for emergency responder use. IR-RCD technology covers a broad range of capabilities and systems and the emergency responder community is generally not familiar with these technologies. The purpose of this assessment is to give emergency responders a broad overview of IR-RCD technology types and provide information that will be useful in determining whether to further investigate IR-RCD technology. This assessment report, unlike other SAVER assessment reports, does not provide scores or assess operational details on specific systems or devices. It instead evaluates broad categories of devices and provides recommendations of when or where these IR-RCD technology types would be appropriate or useful to emergency responders. The activities associated with this assessment were based on recommendations from a focus group of emergency responders. Neither the focus group members or assessment evaluators had experience using IR-RCD, but all had significant experience with chemical detection issues and the current technologies and approaches used by emergency responders to address remote chemical detection.

Evaluators assessed how useful each *type or category* of IR-RCD would be in a first response scenario and recommend the types of scenarios and organizations that might benefit from a given IR-RCD category. Evaluators used their expertise and experience with chemical detection issues and scenarios to assess when or if different categories (types) of IR-RCD instruments would be useful, if they could be deployed effectively, how they could be deployed, what types of scenarios/responses would benefit from an IR-RCD instrument, and recommendations on what type of instrument would be appropriate for different uses.

IR-RCD instruments have a wide range of capabilities and costs ranging from single-band imagers in the \$75K – \$150K range up to full-imaging hyperspectral systems that can cost nearly \$1M.

The IR-RCD assessment consisted of a four-day workshop where vendors demonstrated their IR-RCD systems under realistic detection conditions. For each IR-RCD system, the emergency responders worked with the vendor to setup and deploy the sensor, perform startup procedures and tasks; take data with the instrument against several different remote chemical releases, analyze the results, and otherwise use the instrument as it would be used in a first response scenario. Where possible the emergency responders operated the IR-RCD instruments and analysis software, though under the direct guidance of vendor representatives. In other cases the evaluators observed and questioned the vendors as they operated the IR-RCD systems.

This approach does not support the standard SAVER assessment and scoring procedures. Individual instruments were not scored and assessed per standard SAVER procedures.

The general findings and recommendations from this IR-RCD assessment are summarized in Table ES-1. A list of advantages and disadvantages of each IR-RCD technology category are provided in Table ES-2.

Table ES-1. Assessment Summary

IR-RCD Category	Comments and Recommendations
Single-band Imagers	• Single-band imagers developed enough to be useful for emergency responders • Costs, while still significant, are in line with specialized instruments for other tasks • Specialized chemical response teams might consider purchase of single-band IR-RCDs • Each sensor is only sensitive to a chemical family • Consider purchase in conjunction with specific facilities
Multi-Spectral Imagers	• Multi-band imagers are minimally useful to emergency responders required to be first on scene at an unexpected event because of difficulties exhibited identifying small moving plumes, instrument size, and setup time • Multi-band imagers may be useful for specific locations, such as at chemical plants, where larger gas plumes might be expected • Units are expensive, relatively complex, somewhat fragile, and require significant training. • Multi-band IR-RCDs had difficulty detecting smaller moving plumes
Hyperspectral Single Pixel Scanners	• Hyperspectral single pixel scanner designs are not generally useful for emergency responders required to be first on scene at an unexpected event mostly because of cost, size of the instrument (except the Rapid Plus), and the time required to scan a scene • Hyperspectral single pixel IR-RCDs, because of their significant stand-off distance, wide area monitoring, and wide range of detected gases, could be useful at specific facilities. • Units are expensive, relatively complex, and can be difficult to move and setup, though the Bruker Detection Systems RAPID Plus could be moved and setup by one person • These instruments require significant training to operate effectively • These instruments could be mounted on a dedicated vehicle • Vehicle mounting could be useful for area monitoring • The three systems evaluated had significant differences in capabilities, ease of deployment, and handling
Hyperspectral Imagers	• Hyperspectral imagers, while useful, are not yet designed or optimized for emergency responders and were not recommended because of cost and complexity • These instruments, because of their significant stand-off distance and wide area monitoring, could be useful at specific facilities or venues • In specialized situations or configurations (i.e., dedicated vehicle) these instruments could be useful • Hyperspectral imaging IR-RCDs are accurate, sensitive, have long stand-off distances, intuitive results displays, and the ability to save data for reach back and remote monitoring • Evaluators did not recommend Hyperspectral imaging IR-RCDs for broader use based on cost, the size, the training required to operate the instrument and interpret results, and the general complexity of the technology

Table ES-2. IR-RCD Technology Category Advantages and Disadvantages

IR-RCD Category	Advantages	Disadvantages
Single-band Imagers	• Full plume image • Easy to use • Handheld and easy to deploy • Very sensitive • Detect small sources at a distance • Can include calibrated images that show temperature	• Requires different cameras for different gases or families of gases • Not rugged • Not intrinsically safe
Multi-Band Imagers	• Can detect a wider range of gases than a single-band imager • Provides color heat-maps of chemical concentration • Full plume image – if plume is present in all bands during the scan	• If gas plume moves and is small, cannot collect all bands with the gas present, this prevents gas identification • Slow scans • Can misidentify gases • Cost
Hyperspectral Single-Pixel Scanners	• Detect and ID a large range of different gases • Provide high resolution spectra that can be saved and used for reach-back (for most instruments assessed) • Have configurable scan area – up to a full circle • Vehicle mounts for mobile operation – can measure while moving	• Takes a long time to scan a scene • Each pixel on the scan represents a detection in time – no immediate plume map (unless plume is relatively stationary) • Systems are generally larger and difficult to deploy with the exception of the Bruker Detection Systems RAPID Plus • Chemical IDs may not be accurate • Cost
Hyperspectral Imagers	• Detect and ID large range of different gases • Provides high resolution spectra that can be saved and used for reach back • Shows real-time moving gas plumes • Very good sensitivity • Very intuitive results presentation	• Cost • Not rugged • Complex and require significant training to operate • Chemical IDs may have uncertainty

In two of the four IR-RCD categories only a single instrument was used to represent the entire IR-RCD category, this may not be representative of the full category. If other instruments in a given category are considered for purchase, the comments and recommendations from Table ES-1, 1-2, and this report can be used to help frame questions or enquiries about other instruments. Instruments should be reviewed individually for their intended use as capabilities and use requirements for IR-RCDs vary significantly.

1. INTRODUCTION

In May 2016, the System Assessment and Validation for Emergency Responders (SAVER) Program conducted an operationally oriented overview assessment of passive infrared (IR) systems for remote chemical detection (IR-RCD). IR-RCD systems are a relatively new technology, only recently becoming mature enough to consider for emergency responder use. IR-RCD technology covers a broad range of capabilities and systems and the emergency responder community is generally not familiar with these technologies. The purpose of this assessment is to give emergency responders a broad overview of IR-RCD technology types and provide information that will be useful in determining whether to further investigate IR-RCD technology. This assessment report, unlike other SAVER assessment reports, does not provide scores or assess operational details on specific systems or devices. It instead evaluates broad categories of devices and provides recommendations of when or where these IR-RCD technology types would be appropriate or useful to emergency responders. The activities associated with this assessment were based on recommendations from a focus group of emergency responders. Neither the focus group members or assessment evaluators had experience using IR-RCD, but all had significant experience with chemical detection issues and the current technologies and approaches used by emergency responders to address remote chemical detection.

IR-RCDs use spectral signatures to remotely detect, identify, and characterize chemicals in the gas or vapor phase. Chemicals absorb light in different narrow spectral bands in a unique manner creating a spectrum that can be used to indicate the presence of a chemical(s), identify the chemical(s), and quantify concentration(s). Depending on the technology and algorithms employed, an IR sensor may be able to uniquely identify a chemical and provide an accurate concentration measurement, or may only be able to identify a chemical family and provide a relative concentration. Some chemicals do not have large signatures in a given IR region, but most toxic industrial chemicals (TICs), chemical warfare agents (CWAs), and other hazardous chemicals commonly encountered in the field are detectable in infrared spectral regions. The degree to that a chemical can be identified and quantified depends on a number of factors that will be presented to varying extents in this report.

IR-RCDs operate by “looking” at a scene remotely and can be either “active” or “passive.” Active sensors provide their own IR light source while passive sensors rely on temperature differences between the gas and background in the target area. This report will only discuss standoff passive systems that do not require a light source for operation. The term IR-RCD will be used to indicate passive IR-RCDs in the remainder of the report. This reports considers standoff systems to be able to operate at a minimum of tens of meters from the gas being measured and some of the technologies evaluated can detect chemicals in the 1 to 5 (and up to 10) kilometer (km) range.

1.1 Evaluator Information

Seven emergency responders from various jurisdictions, including the military, with at least 16 years of experience using chemical detection equipment were selected as evaluators. Only two evaluators were familiar with IR-RCD and they were only familiar with some of the technologies that were evaluated. All of the evaluators were familiar with and had experience with chemical detection needs, obstacles, and challenges that arise during emergency response operations along with the current methods used by emergency responders to address these issues. Evaluators were not asked to assess specific instruments, but were rather tasked with assessing whether or not a general type of IR-RCD would be appropriate for specific emergency response scenarios, and determining types of emergency response agencies or units that might benefit from an IR-RCD technology. Evaluator information is listed in Table 1-1. Prior to the assessment evaluators signed a nondisclosure agreement, conflict of interest statement, and photo release form.

Table 1-1. Evaluator Information

Participant	Years of Experience	Jurisdiction
Firefighter—HazMat, CBRNE, CT, ICS, WMD	20+	CA
Environmental Protection—CBRNE, HazMat, WMD	20+	FL
Law Enforcement—HSB/ARMOR, CBRNE	20+	NV
Law Enforcement—HazMat, CBRNE, CT, ICS, WMD	20+	VA
Military—CBRNE, CT, ICS, WMD	16-20	USA
Military—CBRNE, CT, ICS, WMD	16-20	USA
Firefighter—HazMat, CBRNE	16-20	VA
Acronyms: ARMOR—All Hazards, Regional, Multi-Agency, Operations, and Response CBRNE—Chemical, Biological, Radiological, Nuclear, and Explosives CT—Counterterrorism HazMat—Hazardous Materials	HSB—Homeland Security Bureau ICS—Incident Command System WMD—Weapons of Mass Destruction	

1.2 Assessment Products

Four different IR-RCD system types were selected for the assessment based on market research and the focus group's recommendations. These four technology types represent the range of IR-RCD systems available, but this list is not exhaustive as other types of IR-RCD systems exist. The four technology types selected provide a useful overview of IR-RCD technologies and were deemed potentially useful in an emergency response scenario. The four IR-RCD system types, selected using information provided by the focus group and the IR-RCD market survey, are:

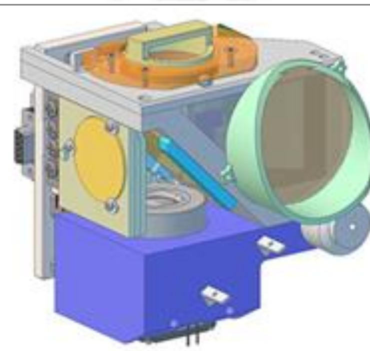
- Single-band imagers
- Multi-spectral imagers
- Hyperspectral scanners
- Hyperspectral imagers.

Within each of these categories from one to three products were demonstrated at the assessment.

Table 1-3 presents the products that were demonstrated along with the category they represent. The FLIR GF320 and the GF304 single-band imagers are represented by a single table entry as they look the same with the exception of the label on the side of the instrument.

Table 1-2. Demonstrated Products

Category	Vendor Product	Product Image
Single-band Imager	**FLIR** GF320 and GF304	*Image of GF306 (GF320 and GF304 are similar)* 
Multi-Spectral Imager	**Bertin** Second Sight® MS	
Hyperspectral Scanner	**Bruker Detection Systems** RAPID Plus	
	Bruker Optics SIGIS-2	

Category	Vendor Product	Product Image
Hyperspectral Scanner	**Mesh Inc.** iMCAD	
Hyperspectral Imager	**Bruker Optics** HI 90	
	Mesh Inc. Firefly	

2. EVALUATION

2.1 Evaluation Process

A focus group of emergency responders met in November 2015 and recommended that the IR-RCD technology assessment not follow a standard assessment procedure. They recommended a non-standard assessment because the technology is so new that most emergency responders (including the focus group participants) are not familiar with IR-RCD advantages and disadvantages, how the IR-RCD systems could be used, how difficult or easy they would be to use, who could use them (training and expertise required), and the types of organizations for which IR-RCDs might be appropriate. Based on this recommendation, rather than scoring individual instruments, the assessment was designed to evaluate categories of instruments and assess their potential usefulness to emergency responders. While the focus is on instrument types, where beneficial, evaluator's comments about specific instruments are included. This is to highlight advantages and disadvantages of these systems, and to help readers identify aspects and specifications that are important for different scenarios and instrument types.

IR-RCDs have a wide range of capabilities and costs ranging from single-band imagers in the $75K – $150K range up to imaging hyperspectral systems that can cost nearly $1M. The focus group participants noted that with very limited experience in the community it is difficult to know which sensor type would be appropriate or even useful. They also noted that they were not familiar with the trade-offs associated with choosing different IR-RCD instrument types.

Based on these recommendations, the IR-RCD assessment consisted of a four-day workshop where vendors demonstrated their IR-RCD systems under realistic detection conditions.

For each IR-RCD system, the emergency responders worked with the vendor to setup and deploy the sensor, perform startup procedures and tasks; take data with the instrument against several different remote chemical releases, analyze the results, and otherwise use the instrument as it would be used in a first response scenario. Where possible the emergency responders operated the IR-RCD instruments and analysis software, though under the direct guidance of vendor representatives.

This approach does not support the standard SAVER assessment and scoring procedures. Individual IR-RCD instruments were not scored or assessed per standard SAVER procedures. As noted, the focus group felt an assessment of the various types or categories of IR-RCDs would be more useful to the community.

2.2 Technology and IR-RCD Operations Overview

2.2.1 Background

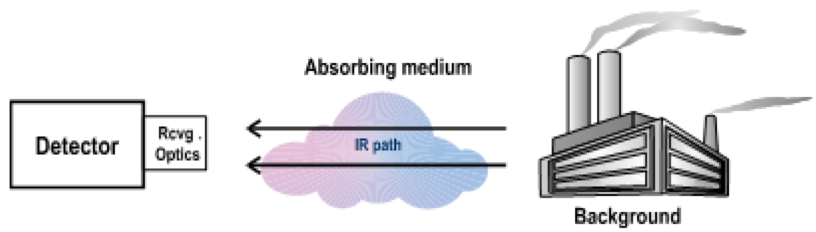


Figure 2-1 Passive IR sensor using a temperature difference between the plume and background

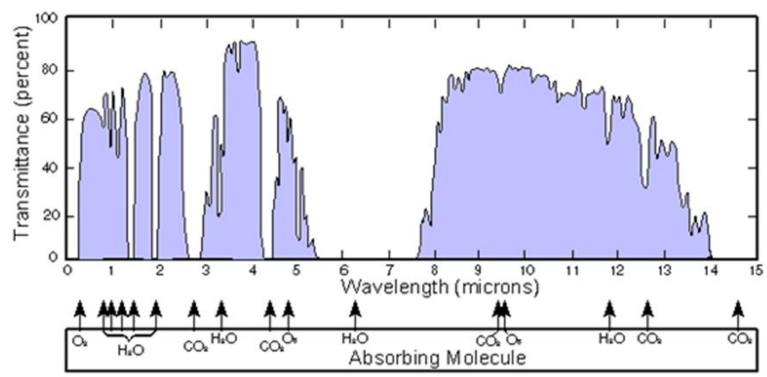


Figure 2-2. Atmospheric transmittance. Strongly absorbing regions appear as white "dips". The molecules that cause the absorbance in those regions are indicated below the spectrum.

IR-RCD analysis devices use spectral signatures to remotely detect, identify, and characterize chemicals in the gas or vapor phase. Chemicals absorb light in different narrow spectral bands in a unique manner creating a spectrum that can be used to indicate the presence of one or many chemicals, uniquely identify the chemical(s), and quantify concentrations. Depending on the design, an IR-RCD may uniquely identify a chemical and provide an accurate measurement of concentration, or may only identify a chemical family and provide a relative concentration. Factors that influence the degree to that a chemical can be identified and quantified include the resolution of the instrument, the region of the spectrum measured, and spectral features of the target chemical.

For inclusion in this report, the IR-RCDs instrument categories met the following criteria:

- Use a passive design
- Work in the IR region
- Capable of uniquely detecting chemicals or families of chemicals
- Detect compounds remotely (>25m).

Appendix A contains a glossary and brief descriptions of terms and concepts related to remote detection of chemicals using passive IR-RCD systems.

2.2.2 Technology Description

Passive IR-RCDs measure IR light absorbed or emitted from a gas as shown in Figure 2-1. The measured spectral data are typically reported in wavelengths in units of micro-meters (µm) which is one-millionth of a meter or wave numbers, which is the inverse of wavelength.

Light absorption measured by the IR-RCD instruments is the same phenomena that can cause some gases to be colored in the visible region, if they emit or absorb in regions visible to humans. IR light is outside our visible range and cannot be seen by humans, but you can think of an infrared detector as essentially detecting the "color" of the gas. The gas can either be glowing (in emission) or as a colored cloud (in absorption).

The IR region is traditionally divided in the mid-wave IR (MWIR) from 2.5 to 8 µm and the long-wave IR (LWIR) from 8 to 15 µm. The MWIR and LWIR are atmospheric regions that are transparent to IR light as shown in Figure 2-2. Most IR light is blocked by water vapor and other atmospheric constituents. The MWIR and LWIR windows are regions where atmospheric interference is low.

For stand-off measurements, atmospheric transmission is crucial. Water and other gases in the atmosphere absorb IR light in different regions and can make these regions essentially opaque; that is, no light is transmitted to the sensor. Figure 2-2 shows a graph of atmospheric transmittance. In this figure, blue represents regions where light is transmitted, white represents regions that are opaque and do not transmit light. The figure also shows which molecules are most responsible for absorbing light in the opaque regions. There are three small transmission windows in the MWIR from about 2 to 5 µm with some breaks, and a large window in the LWIR from about 8 to 14 µm. IR-RCD systems that use the first set of regions are called MWIR sensors, and those that use the second region are called LWIR sensors.

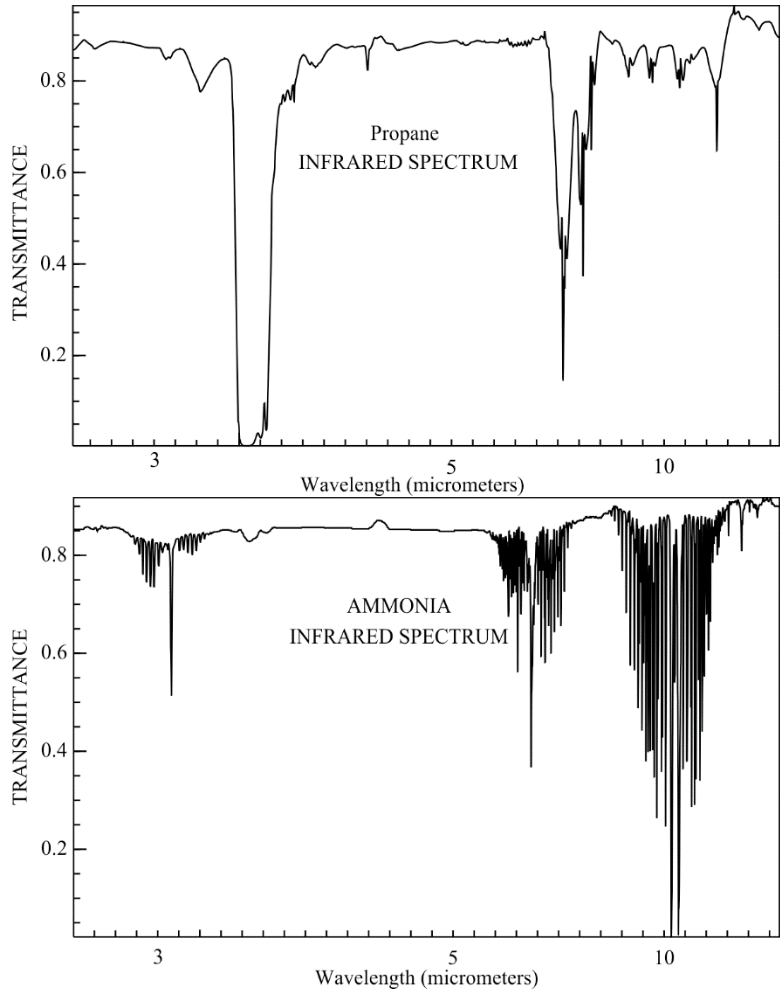


Figure 2-3. Propane (top panel) and Ammonia (bottom panel) transmittance spectra from the National Institute of Standards (NIST) database. Zero indicates no light transmission (opacity) while 1 indicates full light transmission (transparency). Transmittance values are a function of gas concentration.

All objects with temperatures above absolute zero emit energy (e.g., light) in the IR region. Different chemicals emit or absorb light at specific wavelengths creating a unique spectrum or fingerprint that can be used to identify the chemical. Figure 2-3 shows examples of these signatures for propane and ammonia from the MWIR through the LWIR regions.

To detect and identify chemicals in the field, IR-RCD instruments take advantage of the thermal and spectral contrast between a chemical plume and the temperature of the scene background (sky, buildings etc.). Chemicals that are hotter than the scene background emit IR energy while those colder than the scene background absorb energy at the same wavelengths, creating chemical-specific spectra that can be measured. Emittance and absorbance spectra are inverses of each other. To detect a gas, the spectrum is measured and compared to library spectra, such as those shown in Figure 2-3, to determine the best match. The matching library spectra is reported as a chemical detection. This process has uncertainty associated with both measurements and matches, that can result in misidentifying a chemical.

Chemical detection and identification relies on the uniqueness of the chemical signature or spectrum measured and whether that signature can be separated from the background materials in the scene and matched against a library spectrum. If a sensor does not have high enough resolution, it might be able to identify a chemical family such as “hydrocarbon” but not the specific chemical such as “benzene.” The same uncertainty could occur if the signal is not strong enough. Weak signals can occur for a number of reasons, such as low concentrations, long stand-off distances, air pollution, or temperature effects. Large temperature differences between the target chemical and the scene background permit a much stronger signal than smaller temperature differences. If the target chemical and scene background are the same temperature, it is not possible to detect the chemical. This is rare, as earth, buildings, sky (e.g., deep space), or other scene backgrounds are generally at temperatures that differ from the local atmosphere and the target chemical gas. Solid chemicals are much more difficult to detect and identify because of lower or non-existent temperature differences. In general IR-RCD stand-off instruments are not used for solid material detection.

“Active” detectors may be used to overcome weak signals from low temperature differences as they provide their own IR source rather than relying on the scene background. Active sensors were not considered in this assessment.

Figure 2-1 shows a schematic demonstrating passive IR detection. If the plume (labeled “absorbing medium” in Figure 2-1) is either warmer or colder than the background, then the plume will either absorb or emit light characteristic of the chemical(s) in the plume, resulting in unique spectra like those shown in Figure 2-3 mixed with spectra from other chemicals in the atmosphere and materials in the scene (background clutter).

Chemicals are detected and identified by comparing the spectra measured by the sensor to library spectra of potential chemicals. Since a typical scene contains many gases, along with background clutter, this library comparison is based on statistical algorithms. Most commercial sensors have automated this process. This approach is statistical and as a result errors can occur and chemicals can be misidentified. Some systems save the measured and matched spectra to allow for further analysis.

IR-RCDs measure and report chemical concentrations as the integrated concentration of gas along the path length through the plume (i.e., the line-of-sight of the detector) with units that are a multiple of the chemical concentration and the path length. For example, a chemical plume with a concentration of 10 parts per million (ppm) and 1 meter in size where the measurement was made would be characterized with a concentration of 10 ppm-meter (10 ppm x 1 m). A second plume with a concentration of 1 ppm, but 10 meters in size where the measurement was made, would also be characterized at 10 ppm-meters (1 ppm x 10 m). Higher concentrations, as measured in ppm-meters, are more easily detected and identified than lower concentrations of the same chemical.

Chemicals that have spectra with stronger absorption or emission variations or “peaks”[i] can be detected at lower concentrations. For example, Figure 2-3 shows the IR spectra of propane (top panel) and ammonia (bottom panel). Both have features in the MWIR region between 2 and 4 µm. Propane has a large feature both deep and broad while ammonia has a much narrower and shallower feature. As a result, in the MWIR region propane can be detected more easily and at much lower concentrations than ammonia. The large absorbance, or “dip” in the propane spectrum at 3.5 µm is a nearly opaque feature that can be used for its detection. Ammonia has stronger features in the LWIR than the MWIR region that can be used for detection with a LWIR detector. Most IR-RCDs operate in either the MWIR or the LWIR, but not both.

A number of variables affect and define IR-RCD system and performance. Appendix A has a glossary of terms.

Detection limits and accuracy are affected by:

- Temperature difference between background and target gas
- Standoff distance
- Spectral bandwidth and resolution
    - Bandwidth is the range of wavelengths (or frequencies) collected
    - Resolution is the spectral width of a single data point. It is also used to refer to the number of data points collected in a region (e.g., hyperspectral resolution is used to refer to detectors that collect hundreds of data points)
- Obscurants in the atmosphere such as smoke, dust, or other chemicals.
- Plume size and concentration
    - Path length – this is the length through the chemical plume as determined by the detector position relative to the plume. That is the line-of-sight of the detector through the plume.
    - Chemical concentration
        - Measured as concentration-length (e.g., ppm-meter) which is a combination of the plume concentration and the length of the path measured by the sensor
        - Typical sensitivities are in the ppm-meter to ppb-meter range
        - Depends on the chemical.

Collection time, an important consideration, varies considerably depending on the type of system and system design. It can be largely affected by spectral and spatial resolution, and scanning area of the IR-RCD.

2.2.3 IR-RCD System Types

IR-RCD detectors use a number of different ways to image gas plumes or acquire the spectra required to detect, identify, and characterize chemicals, or families of chemicals. IR-RCDs can

[i] When speaking of spectra, most people use the term “peaks” to describe spectral features, even though when plotted as transmittance, as in Figure 2.3, they look like “dips”.

either have high specificity (i.e., can identify specific chemicals) or low specificity (i.e., can only identify general chemical families) based on the number of spectral bands that are measured, and the width of, or range of wavelengths covered in a single measured spectral band. The number of bands measured by an IR-RCD can range from a single band, called a single-band detector in this report, to multiple bands called a multi-band detector, to hundreds or even thousands of bands, called hyperspectral detectors in this report. Each band is defined by it its spectral resolution or width reported in either wavelengths or wave numbers.[ii]

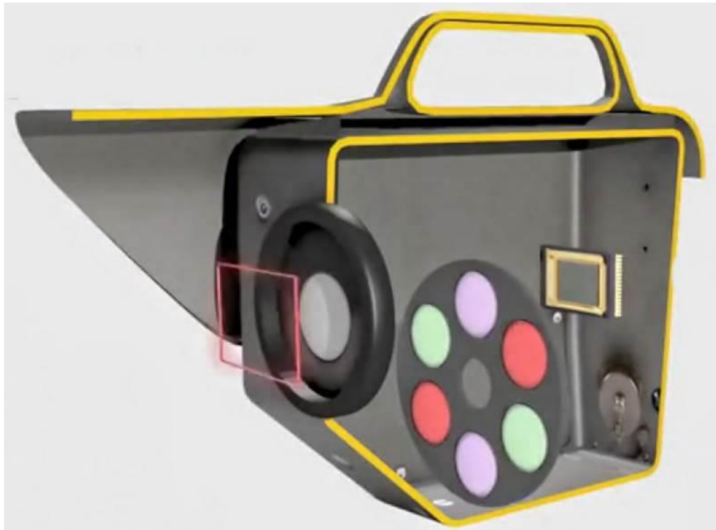


Figure 2-4. Example of a multi-spectral imager that uses several filters in turn to create an image.
Image courtesy of Bertin Technologies.

For this report the different IR-RCD types are catagorized based on the number of bands collected and scanning mechanism used:

- Single-band imagers
- Multi-spectral imagers
- Hyperspectral single pixel scanners
- Hyperspectral imagers.

Bands can be defined in a number of ways. Single-band imagers and multi-spectral imagers typically use filters to define bands. Single-band imagers use a single filter to create the image, while multi-spectral imagers use a series of filters to generate the bands. Most multi-spectral imagers have 6 to 12 separate bands, but they may have up to tens of bands. The spectral region, and the range of wavelengths covered (or spectral width) by a filter (or filters) are frequently selected by the manufacturer based on the spectral features of the target chemical(s).

Single-band imagers collect images similar to a digital grey-scale camera. A filter only allows light in a narrow band to fall on the sensor. For example, Figure 2-3 shows that propane has a large spectral feature at about 3.3 µm. A filter that only allows light in this region to pass creates a sensor sensitive to propane. Other common hydrocarbon gases, such as butane, methane,

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[ii] Wavelength is the period or length over which the wave repeats, usually reported in microns (µm), the wave number is the number of repetitions of a wave in a specified distance, usually reported in cm^{-1} or “per centimeter”. Wavelength is the reciprocal of wave number. By convention multi- and hyperspectral detector resolutions are usually reported in wave numbers (e.g., a resolution of 1 wave number), with a small number indicating a narrower band, while filter detectors are usually report as a range of wavelengths (e.g., with a band from 10.5 to 10.7 µm).

propane, and others have a very similar feature, a single-band imager in this range can thus be used to detect "explosive" gases.

In single-band systems, a narrow band filter provides more specificity (and can be chosen to detect specific chemicals or chemical families) whereas a broader band filter provides less specific chemical discrimination, but may be used to indicate the presence of a broader range of chemicals. Improved chemical discrimination increases with additional and narrower bands combined with algorithms that detect the differences and match specific chemical signatures in a library. Single-band imagers do not use library matching as the detection region (band measured) is chosen to be sensitive to a specific chemical family.

Figure 2-5. Hyperspectral data cube showing spatial dimension in the plane of the image and spectral information into the page. ***Public domain image courtesy of the National Aeronautics and Space Administration (NASA)***

Multi-spectral imagers work in a similar manner. However, instead of having a single filter, they have multiple filters that work in series as shown in Figure 2-4. This results in an image where each pixel contains measurements in several spectral bands. Even with narrow filters, these multi-spectral detectors are usually only able to identify families of chemicals.

Single and multi-band systems generally provide rapid results, with single-band systems providing the most immediate result, at the cost of chemical specificity. They are also less expensive, generally more rugged, and simpler to setup and operate. These simpler designs are less expensive than hyperspectral systems, but are useful if the emergency responder only needs to know a chemical is present or has prior knowledge of the chemicals that may be present, such as methane and propane.

Hyperspectral refers to the fact that each measured spectrum contains a very large number of spectral bands. Hyperspectral sensors typically generate measurements where each image pixel contains hundreds of bands. In the measured image, each image pixel represents a spectrum and the image represents a spatial area as shown in Figure 2-5. Figure 2-5 shows this spectral information as the depth of the image cube going into the page and spatial information across the page.

Hyperspectral imagers can use either Fourier transform or dispersive grating detectors to measure the spectrum. While these approaches use different analysis techniques, the most important issue to first responders is that Fourier-transform IR (FTIR) instruments have moving parts while dispersive grating detectors generally do not. This means that FTIR-based instruments can be more sensitive to movement and vibrations.

While hyperspectral systems are generally significantly more expensive and operation is frequently more complex, the measured data contains a vast amount of spectral information. This spectral information provides increased capabilities such as the ability to differentiate compounds with similar spectra, even at lower concentrations, and the ability to identify and quantify multiple chemicals simultaneously. In some hyperspectral systems, the spectral resolution can be adjusted – with higher resolutions resulting in longer scan times, but even greater specificity.

Hyperspectral sensors can be designed as either imaging or scanning systems. Scanning sensors build up an image of the scene by repeatedly measuring a spectrum at a single point in space then pivoting to a new point in the scene and collecting additional spectra at this new point. These points are relatively large and the "image" is built up of a series of square detection points. For scanning sensors the size of the measured scene can be changed by changing the size of the region scanned. Larger scanned regions (i.e., images) require a longer time to build up as the IR-RCD must measure a larger number of points to create the scene.

Hyperspectral imagers also build up an image but it is done relatively quickly. Usually a full row of pixels are measured at a time, then the next row is measured, until the full scene is imaged. This is done in almost real time. Generally imaging sensors have a fixed scene extent that depends on the optics of the imager – similar to traditional cameras. The measured scene can be changed by using a different lens. Systems can have variable lenses (e.g., "zoom" lenses).

Generally costs of these systems follow complexity, with single-band imagers the least expensive, followed by multi-spectral imagers, then hyperspectral single pixel scanners, and hyperspectral imagers. However, a hyperspectral single pixel scanning system may be comparable in cost to a multi-spectral imaging system. Single-band imagers and hyperspectral imagers generally have the shortest scan times. Multi-band imager scan times depend on the number of bands measured and hyperspectral single pixel scanners scan times depend on the size of the scene being scanned.

2.2.4 Potential Applications

IR-RCDs are designed for outdoor use and are used to detect, identify, and characterize chemical gases and vapors from a distance. They can be used in situations where it is not safe to enter the release area or situations where monitoring of a large area is required.

Depending on the technology, IR-RCDs can detect chemicals up to 6 kilometers away and provide wide area surveillance that would not be practical with multiple point detectors. IR-RCDs can document plume evolution and transport providing visual references to predict movement and areas that may be impacted. Possible scenarios that could benefit from IR-RCD monitoring and use include:

- Verification that an event was an improvised chemical device (ICD)
- Survey an area to find bodies using decomposing gases
- Provide event security - perimeter monitoring
- Arson investigation - find accelerants
- Identify chemical threats before entering area
    - Fire fighting
    - Industrial release
    - Transportation accident

    - Tank car derailment
- Compliance monitoring (environmental compliance)
    - Industrial monitoring
    - Agricultural chemical monitoring and characterization
    - Leak detection or location
- Vapor intrusion into buildings
- Odor investigation
- Post-disaster surveys
- Plume tracking
- Oil spill or other large release characterization and monitoring
- Detect and/or characterize chemical suicide sites
- Detect covert drug production labs
- Natural gas leaks
- Detect and identify CWA releases
- Provide chemical warfare and TIC decontamination surveillance.

3. ASSESSMENT METHODOLOGY

The IR-RCD assessment occurred over four days. On the first day of the assessment a subject matter expert (SME) and facilitators presented a safety briefing and an overview of the IR-RCD types to be assessed, the assessment process, procedures, and schedule to the evaluators. Each IR-RCD was then assessed in two phases: (1) a vendor provided technology overview and (2) an operational demonstration where the evaluators, to the extent possible, participated in setting up and operating the systems under the supervision of the vendors.

3.1 IR-RCD Assessment Scope

The evaluators assessed four categories of passive IR-RCD systems: 1) single-band imagers, 2) multi-spectral imagers, 3) hyperspectral scanners and 4) hyperspectral imagers.

Standard SAVER assessment procedures of each system being objectively scored against a set of common criteria were not followed. Rather each category of IR-RCD was assessed using from one to three IR-RCD systems to represent the category. The evaluators were tasked with identifying criteria or features that would affect emergency responder use and evaluating which scenarios might benefit from such technology.

Figure 3-1. Evaluators (left side) working with a vendor (right side) to operate an IR-RCD and gather data on operations.

Evaluations were not quantitative. No overall assessment scores, category scores, or criteria scores were calculated. This assessment reports the evaluators' recommendations on the four IR-RCD categories. Specific comments are included on individual IR-RCD systems to provide readers with a better understanding of the features or capabilities that the evaluators considered important for emergency responder applications. Individual IR-RCD systems were not assessed but provided a guide to identify the types of questions and issues that might be considered during an evaluation and to provide information that allows readers to become familiar with the advantages and disadvantages of the different types of IR-RCDs.

Figure 3-1 shows evaluators setting up an IR-RCD with vendor oversight. Where possible evaluators operated the instruments and evaluated results. However, since these were complicated instruments and the evaluators only received minimal training, vendor representatives were present to assist in instrument operations and to help explain and analyze results.

3.2 Technology Overview and Operational Briefing

Prior to operating each system, vendors briefed the evaluators on system capabilities, specifications, and operations. These briefings included classroom presentations and basic training on how to set-up and operate the systems. This was followed by hands-on familiarization with the instruments as part of the operational training. A "hands-on" briefing is shown in Figure 3-2.

Figure 3-2. Hands-on evaluator training before IR-RCD operation.

This stage was interactive with the evaluators questioning and discussing system topics and operational questions with the vendor representatives. While the evaluators were given information and experience on individual IR-RCDs, they were tasked with evaluating the IR-RCD categories, assuming the IR-RCDs provided in this assessment are representative of the IR-RCD systems in that category.

3.3 Operational Assessment

During the operational assessment, evaluators assessed each IR-RCD category based both on their hands-on experience using the IR-RCD and watching and interacting with the vendor for some tasks. The SMEs and facilitators assisted the evaluators in understanding sensor capabilities and output, and the vendors assisted with system operations. The products were assessed in two scenarios: (1) Setup and Preparation and (2) Remote Gas Detection. Evaluators used the individual IR-RCDs one at a time and completed the assessment notes for each IR-RCD before assessing the next. Only one vendor was present at a time.

3.3.1 Setup and Preparation

The evaluators, working with the vendor representatives, setup the IR-RCD systems for use. This included connecting various modules, such as power supply, sensor module, and control module or computer together; performing setup procedures, system checks, field calibrations, and system verifications where required.

Figure 3-3. The test range used for the assessment. Sensors were setup under a sunshade with gas releases occurring approximately 80 meters away.

3.3.2 Remote Gas Detection

Two or more gases were selected for each IR-RCD. Different gases were used for different instruments as each IR-RCD had different capabilities. For example, MWIR instruments would not be able to detect gases with only LWIR signatures.

After setup, the evaluators and vendor representatives verified that the instrument was ready for measurement. Then a gas was

Figure 3-4. Gas releases used for the single-band imagers, the left panel shows the propane cylinder with a hose running up under the building eves, the center panel shows a common cigarette lighter releasing butane, and the right panel shows an evaluator imaging a SF_6 release.

released at a distances from a few meters to approximately 80 meters as shown in Figure 3-3. Once the instrument detected the gas, the evaluators assessed the time to detection and the results display. Different gases were released in series or simultaneously, depending on the instrument capabilities. This continued until all the gases used in the evaluation of a given IR-RCD instrument were complete.

The following gases were used in the assessment: Butane from a lighter, propane from a large cylinder, ammonia (NH_3) as a concentrated aqueous solution poured in a pan, acetone and ethanol as liquids poured separately on sponge blocks in a pan, sulfur hexafluoride (SF_6) from a small cylinder, and refrigerant gas from a small can of commercially available "dust off."

Gases were released through a variety of methods. These included gases released from cylinders, some with tubes allowing the gas to be released under building eaves or behind obstacles as shown in the left and right panels of Figure 3-4; liquid releases that included pouring the chemical (i.e., "spilling") into pans or other containers as shown in Figure 3-5 (top), and gas releases performed by spraying refrigerants from commercial dust remover canisters, (bottom panel of Figure 3-5), or from butane cigarette lighters (middle panel of Figure 3-4).

Figure 3-5. Pouring chemicals into a pan (top panel) and using commercial dust remover to release refrigerants (bottom panel).

Depending on the IR-RCD type, various tasks were performed during the release, such as evaluating the IR-RCD's ability to provide information on plume movements (i.e., plume tracking), evaluating various amounts of gas release (i.e., concentration), and performing detections from various distances. For example, the single-band imagers are handheld instruments, and evaluators walked the instruments around the release points evaluating detection at various distances to better understand and evaluate system performance and any issues associated with operations. IR-RCD instruments in the other categories had fixed locations, generally tri-pod mounted, and gas release points were moved if applicable.

3.4 Data Gathering and Analysis

Each evaluator was issued an assessment workbook that contained note-sheets for recording their impressions of the IR-RCD system, the IR-RCD category, and recommendations on the applicability of the IR-RCD category to various scenarios.

Evaluators captured their impressions of the advantages and disadvantages for the assessed IR-RCD categories as well as general comments on the IR-RCD assessment and the assessment process. At the conclusion of the assessment, the evaluators reviewed their notes for all IR-RCD categories and made adjustments as necessary.

4. ASSESSMENT RESULTS

The following results and recommendations are for first response scenarios. That is where the responders are responding to a call, are not able to setup equipment ahead of time, and there are unknown or potentially unknown chemicals present. Evaluators did not consider scenarios such as venue or facility monitoring and protection where systems could be setup or prepared ahead of time.

The overall assessment results for the four IR-RCD categories ranged from recommendations to “consider this technology” for single-band imagers, to “limited use for emergency responders” for the hyperspectral single pixel scanners and multi-band imagers. Evaluators were impressed with the hyperspectral imager’s sensitivity, speed, and ability to display results in real time, but because of current cost, fragility, and complexity, do not recommend this category for rapid incident response at this time.

However, even with the limited use recommendations, the evaluators did identify different scenarios where all these technologies could be beneficial. Table 4-1 presents a summary of the assessment results for each instrument category. Detailed assessment comments follow in subsequent sections on each technology category with limited comments on individual products.

Table 4-1. Assessment Summary

IR-RCD Category	Comments and Recommendations
Single-band Imagers	• Single-band imagers developed enough to be useful for emergency responders • Costs, while still significant, are in line with specialized instruments for other tasks • Specialized chemical response teams might consider purchase of single-band IR-RCDs • Each sensor is only sensitive to a chemical family • Consider purchase in conjunction with specific facilities
Multi-Spectral Imagers	• Multi-band imagers are minimally useful to emergency responders required to be first on scene at an unexpected event because of difficulties exhibited identifying small moving plumes, instrument size, and setup time • Multi-band imagers may be useful for specific locations, such as at chemical plants, where larger gas plumes might be expected • Units are expensive, relatively complex, somewhat fragile, and require significant training. • Multi-band IR-RCDs had difficulty detecting smaller moving plumes
Hyperspectral Single Pixel Scanners	• Hyperspectral single pixel scanner designs are not generally useful for emergency responders required to be first on scene at an unexpected event mostly because of cost, size of the instrument (except the Rapid Plus), and the time required to scan a scene • Hyperspectral single pixel IR-RCDs, because of their significant stand-off distance, wide area monitoring, and wide range of detected gases, could be useful at specific facilities. • Units are expensive, relatively complex, and can be difficult to move and setup, though the Bruker Detection Systems RAPID Plus could be moved and setup by one person • These instruments require significant training to operate effectively • These instruments could be mounted on a dedicated vehicle • Vehicle mounting could be useful for area monitoring • The three systems evaluated had significant differences in capabilities, ease of deployment, and handling
Hyperspectral Imagers	• Hyperspectral imagers, while useful, are not yet designed or optimized for emergency responders and were not recommended because of cost and complexity • These instruments, because of their significant stand-off distance and wide area monitoring, could be useful at specific facilities or venues • In specialized situations or configurations (i.e., dedicated vehicle) these instruments could be useful • Hyperspectral imaging IR-RCDs are accurate, sensitive, have long stand-off distances, intuitive results displays, and the ability to save data for reach back and remote monitoring • Evaluators did not recommend Hyperspectral imaging IR-RCDs for broader use based on cost, the size, the training required to operate the instrument and interpret results, and the general complexity of the technology

Table 4-2. Key IR-RCD Instrument Specifications

Vendor	Product	MSRP	Spectral Region (µm)	Measurement Type	Spectral Resolution (cm^{-1})	Data Results	Weight (kg)	Range
Single-band Imagers								
FLIR	GF304	~$90K	8.0 – 8.6	Filter	NA	SB Image	~2	1m – 2 km
FLIR	GF320	~$90K	3.2 – 3.4	Filter	NA	SB Image	~2	1m – 2 km
Multi-Band Imagers								
Bertin Technologies	Second Sight® MS	~$220K	7 – 12	Filter	NP	MS Image	10.2	2 m to 5 km
Hyperspectral Single Pixel Scanners								
Bruker Detection Systems	Rapid Plus	~$225K	7.5 – 14	Michelson /FTIR	4	HS Pixels	30	Up to 5 km
Bruker Optics	Sigis-2	~$300K	6.6 – 14.5	Michelson /FTIR	0.5 – 1.8	HS Pixels	65	Up to 10 km
MESH Inc.	iMCAD	~$225K	7 – 13	Michelson /FTIR	0.5 – 8	HS Pixels	~40	Up to 6 km
Hyperspectral Imagers								
Bruker	HI 90	~$600K	7.5 – 14	Michelson /FTIR	0.7 – 4	HS Image	NA	>5 km
MESH Inc.	Firefly	<$100K	7 – 14	Michelson /FTIR	4 – 16	HS Image	~10	NP

Notes:
cm^{-1}—inverse centimeters
FTIR—Fourier Transform Infrared
HS—hyperspectral
km—kilometer
Michelson/FTIR— a type of Fourier Transform Infrared detector using a Michelson interferometer
MS—multispectral
NA—not applicable
NP—information not provided
SB—single band
µm—micrometer

Figure 4-1. Evaluators using the single-band imagers

4.1 Single-band Imagers

4.1.1 Assessed Equipment

The IR-RCD Market Survey Report identified six single-band imagers, all made by FLIR. The FLIR GF-series of imagers all have the same form factor but each is fitted with a different filter or detectors (LWIR or MWIR) for detection of selected chemical families.

The evaluators assessed two single-band imagers, the FLIR GF320 and the FLIR GF304. The GF320 provides a context image that is calibrated for temperature, operates in the MWIR from 3.2 to 3.4 µm and is optimized for the detection of combustible hydrocarbon gases such as butane, methane, propane, etc. The GF304 operates in the LWIR from 8.0 to 8.6 µm and is optimized for refrigerant gas detection. It also provides a context image calibrated for temperature. The FLIR GF series detectors cost about $90K.

In operation, single-band imagers resemble older black and white video cameras. Detection results are provided in the form of a video that can be watched in real time through the eye-piece or the flip out monitor or saved for later review and analysis. While results are immediate, they are not quantitative. They show relative concentrations in terms of how dark or bright the plume is but do not provide concentration measurements. Evaluators found single-band imagers were generally simple to setup and operate and were more portable and intuitive than sensors in the other evaluated IR-RCD categories.

4.1.2 Assessment Details

The evaluators were briefly trained on the operation of the single-band imager IR-RCD systems, then allowed to use them under the direction of the vendor as shown in Figure 4-1. Evaluators noted that operation and interpretation of results was intuitive. The FLIR imagers provided real-time information in the form of video images that could be viewed through a view finder or on a flip out display as shown in Figure 4-2. The systems came with hard deployment cases as shown in Figure 4-3.

For the assessment of the GF320, propane gas was released from a cylinder with a 20 foot tube attached and butane was released from a common cigarette lighter. Gas was released into a number of different areas, some with a simple background such as a wall, and some into a more complex background, such as under the eaves of a building. The various release methods are shown in Figure 3-4.

Gas detections appeared as dark or light regions in the image as shown in Figure 4-4. Unfortunately no images were made of actual assessment results.

Figure 4-3. Deployment cases for the FLIR sensors.

As noted, these imagers work by detecting a gas either as an absorbance or emission. In absorbance mode, the gas absorbs light and appears dark, as shown in the top panel of Figure 4-4. In emission mode, the gas is hotter than the background and "glows" appearing light, as shown in the bottom panel of Figure 4-4. The FLIR instruments results are shown on a context image that is calibrated for temperature, thus the hot exhaust stack, shown in the bottom panel of Figure 4-4, appears light because it is hot.

While it is more difficult to see the gas plume in the still images in Figure 4-4, the evaluators found that gas leaks, due to movement, were readily apparent in video displays. The grey-scale context image (the portion other than the plume), shows the location of the plume in the scene. The evaluators noted that the capability to see chemical leaks or plumes in the context of thermal information would be beneficial for fire fighters or other emergency response scenarios in which temperature anomalies are important information.

4.1.3 Single-band Imagers: Conclusions and Recommendations

The evaluators assessed two different sensors, the FLIR GF304 and the FLIR GF320. These two FLIR sensors were used to represent the single-band IR-RCD category.

The evaluators recommended that single-band imagers would be useful to emergency responders. However, they noted that these instruments are somewhat complex and fragile and would be more useful on specialized teams that are trained and tasked with chemical detection. The IR-RCD single-band image assessed cost approximately $90K each.

Figure 4-2. Results from the FLIR single-band imagers evaluated could be viewed through a viewfinder or on the flip out display.

Evaluators made the following comments:

- While complex, specialized users could be quickly trained to operate and use this category of IR-RCD.
- The controls were simple and intuitive. Operation followed familiar methods and was very similar to a video camera.
- The results, presented as moving video, were intuitive and easily understood.
- Because of size, operational requirements, and training to understand results, evaluators commented that a dedicated operator would be needed.
- The evaluators noted that a non-specialist emergency responder would not carry this type of instrument.
- Evaluators noted the sensors could be tripod mounted for scene monitoring and surveillance.
- Evaluators commented that a main use for this type of instrument would be leak detection and situational awareness.
    - Evaluators did not see the lack of gas concentrations as a drawback for these uses.
- While a number of different models exist with the same form factor differing in the chemical family detected, evaluators commented that a typical emergency responder unit would only purchase one or two varieties. Since the instruments are limited to chemical families, such as flammable gases or refrigerants, evaluators recommended that emergency responders carefully consider needs and potential scenarios before purchasing.
- Evaluators noted that these types of sensors would be appropriate to purchase in coordination with a specific facility, such as an oil refinery or chemical plant where the types of chemicals that could be potential be released be known *a priori*.

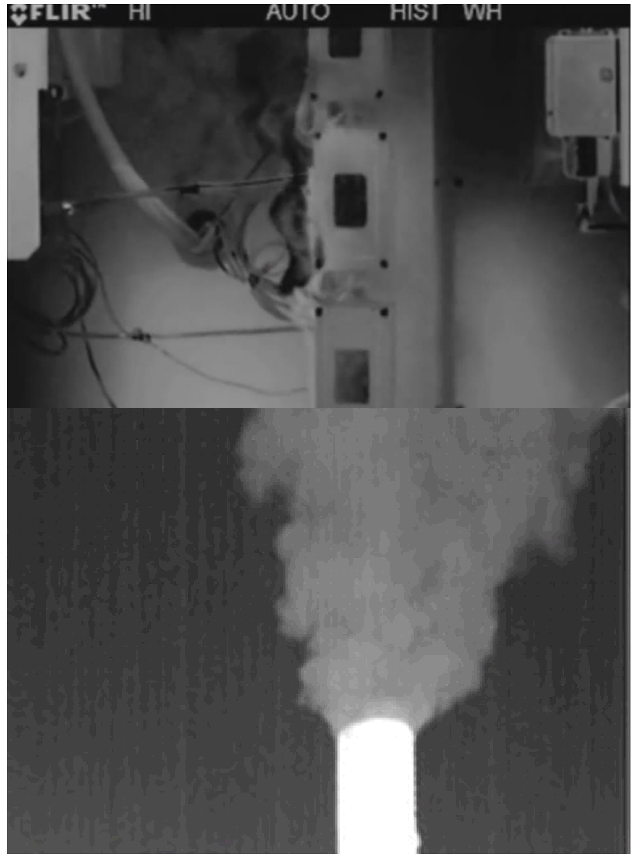

Figure 4-4. Example FLIR video frames showing gas detection in absorption (darker color) in the top panel and emission (lighter color) in the bottom panel.

The evaluators stated that single-band imagers would be useful for emergency responders. Costs, while still significant, are in line with specialized instruments for other tasks. They considered the main weakness with this type of IR-RCD is that each sensor is only sensitive to a family of chemicals, potentially requiring several separate systems. They noted that specialized chemical response teams would be likely candidates to consider purchasing these types of instruments, or that purchases for other teams be made with specific chemical facilities or venues in mind.

The evaluators made some instrument specific comments that, while specific to the evaluated instruments, may also be informative to emergency responders considering other single-band image IR-RCDs.

FLIR GF304 and GF320

Advantages

- Easy to use
- Handheld
- Data saved on standard SD cards
- Four hours on battery – rechargeable
- Very sensitive
- Saw very small sources from 100's of feet
- Detects methane and other combustible gases such as propane and butane (GF320)
- Six minute start-up, relatively quick
- Intuitive operation
- Records data and scene as video
- Grey-scale context image is calibrated for temperature

Disadvantages

- Requires separate camera for each chemical family
- Does not identify specific chemicals
- Does not provide chemical concentrations – though relative concentrations can be seen
- Not intrinsically safe
- Lenses are expensive
- Not rugged

4.2 Multi-Spectral Imagers

4.2.1 Assessed Equipment

The IR-RCD Market Survey Report identified three multi-spectral imagers; two made by Bertin Technologies and one made by Chemring. These multi-spectral imagers differ in the IR region used, MWIR or LWIR, and the filters selected to cover the region.

Multi-band imagers use a series of filters to generate images in 6 to 8 bands as shown in Figure 4-5. These systems are larger and require more time to set up than single-band imagers. They are typically operated from a fixed mount or tripod, with a separate computer or display. The display shows gas detections, colored by concentration, superimposed on a greyscale context image, as shown in the bottom panel of Figure 4-5.

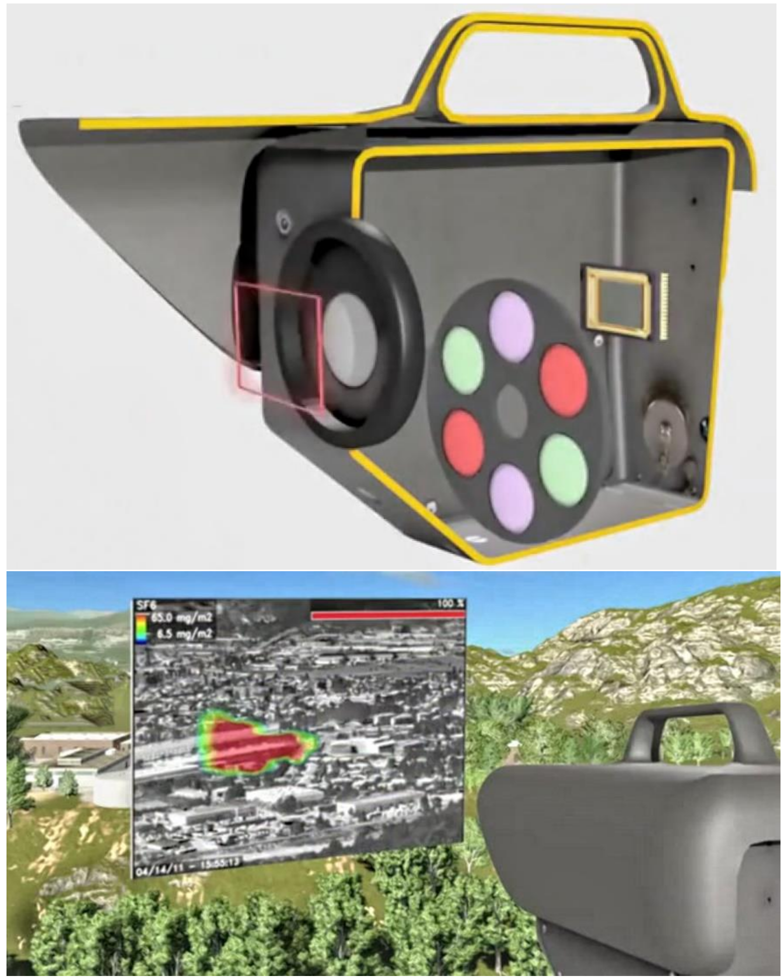

Figure 4-5. The top panel is a cartoon showing how the multi-spectral imager works. A series of filters are placed in the image path to generate the different bands. The bottom panel shows the results of comparing these bands to the library, gas detection is displayed over a greyscale image.

The evaluators assessed one multi-spectral imager IR-RCD, the Bertin Technologies Second Sight® TC, to represent this category. The Second Sight® TC operates in the LWIR from 7 to 12 µm and uses filters to acquire 6 spectral bands across this range. During the assessment an image (i.e., 6 bands) took approximately 30 seconds to capture because the instrument was set to a higher sensitivity to detect the smaller plumes. The specifications indicate capture times on the order of 2 seconds if the instrument is operated in a less sensitive scanning mode. The Second Sight® TC costs approximately $220K.

4.2.2 Assessment Details

The evaluators were given a brief overview of the Second Sight® TC, then moved to the assessment range where they assisted the vendor in setting up the instrument as shown in Figure 4-6.

The instrument was modular, with separate power supply (top panel of Figure 4-6), detector head (bottom panel of Figure 4-6), and results analysis and display, which was performed on a connected laptop (Figure 4-7). The evaluators noted that the instrument was relatively easy to setup as each piece was easily movable and cables were well marked and easy to connect.

The instrument provides a "heat" map (cooler colors indicative of lower concentrations) of chemical locations/concentrations along with the chemical identification overlaid on grey-scale context imagery, all as video in a real-time display. This information can also be saved or archived. A mockup of the results display is shown in Figure 4-5. The evaluators found the results display to be intuitive and easy to read.

Several different releases were performed for the Second Sight® TC, including liquid chemical evaporation (i.e., pan spills) and gas cylinder releases.

Figure 4-6. Evaluators working with the vendor to setup the Bertin Technologies Second Sight® TC instrument.

While the instrument was able to detect and identify larger plumes or gas releases, it struggled with smaller releases that would be common in some emergency response scenarios. These include leaks and smaller spills. The instrument seemed to have difficulties with these smaller plumes because of the scan time. The instrument analyzes spectral data derived from 6 spectral bands, each band taking a few seconds to collect. Thus, the target gas from a small, or rapidly moving plume would only be present in a few bands in any given pixel as the plume had moved before the next band was measured. This made chemical detection and identification problematic. On larger plumes this was not as much of a problem as the plume covered more of the image area and was likely to be located in a pixel during all six scans.

Figure 4-7. Controls and results display on the attached computer.

4.2.3 Multi-band Imagers Conclusions and Recommendations

The evaluators assessed the Bertin Technologies Second Sight® TC in the multi-band imager IR-RCD category. This sensor was the single example in the multi-band IR-RCD category.

The evaluators recommended that multi-band imagers are only minimally useful to emergency responders required to be first on scene at an unexpected event. Instruments tested in the multi or hyperspectral imaging categories are not yet designed or targeted for the emergency responder community. They noted that these units are expensive, relatively complex, and require significant training to operate effectively. Evaluators noted that such instruments may be useful for specific locations, such as at chemical plants, where larger gas plumes might be expected during an emergency response. Evaluators noted that it might be appropriate to purchase this type of IR-RCD in coordination with a specific facility or venue where larger gas plumes might be a concern.

They felt that the difficulties the instrument exhibited with small moving plumes would limit the applicability of multi-band imagers for typical first response scenarios that have smaller, moving plumes, such as smaller leaks, or drug operations. The conclusion that multi-band imagers have not yet been optimized for emergency responders is based on scan time and how it affected the detectability of smaller plumes, the size of the instrument, the inability to hand-hold the instruments, the training required to operate the instrument and interpret results, and their cost. They noted that the units are expensive, relatively complex, somewhat fragile, and require significant training to operate effectively.

The sensor assessed to represent the multi-band imager category of IR-RCD detectors cost approximately $220K that is representative of this category based on the SAVER market survey.

The evaluators made some instrument specific comments, which, while specific to the evaluated IR-RCD instrument, are informative to emergency responders considering these technologies.

Second Sight TC®

Advantages

- Had both screening and higher sensitivity scanning modes with differences in scan times
- Easy to interpret displays
- The colored chemical detection video combined with the context video was intuitive and provided results that were easily understood.
- The resolution of the chemical detection image was very good compared to the image from the single pixel scanners

Disadvantages

- The time required to collect each band was too slow for smaller releases in the high sensitivity mode – the plume location changed between band measurements, causing problems with detections
- Chemical specificity was limited both due to the limited number of bands and gas movement between band measurements
- The controls were software-based on a connected laptop and require training and familiarization for effective operation

4.3 Hyperspectral Single Pixel Scanners

Hyperspectral single-pixel scanning IR-RCD systems build up an image by recording individual single pixel measurements and then moving to a new pixel, scanning incrementally across the scene to build up a complete image. The IR-RCD systems evaluated in this category collected hyperspectral data (100's of bands). The pixels are relatively large – that is they have low spatial resolution and thus each pixel covers a relatively large part of the scene.

Figure 4-8. Bruker Detection Systems RAPID Plus is a single contained unit that connects to a computer for control and results analysis.

Hyperspectral single pixel scanners generate very high resolution spectra and have long stand-off detection distances – on the order of kilometers. They have good detection, identification, and characterization capabilities, limited by scene background and temperature differential. Because a number of single pixel measurements are required to create a scene, it can take significant time to complete a scan, on the order of minutes. However, the scan of an individual pixel is rapid, meaning presence or absence of chemicals in a pixel does not change significantly over the scan period, unlike the multi-spectral scanner.

Single pixel scanners have a user-adjustable scanning area, allowing the operator to specify the horizontal and vertical area to be scanned. Some instruments support a full 360 degree horizontal scan. Scanning over larger areas requires more time.

The hyperspectral data support more accurate and extensive chemical identification and characterization. While processing for these systems can be done on-board, it is more commonly done on a separate attached computer. While much of the identification and characterization is automated, informed results analysis and interpretation can require significant training and experience for complex situations.

Figure 4-9. Evaluators operating the Bruker Optics SIGIS-2

4.3.1 Assessed Equipment

The Market Survey identified five hyperspectral single-pixel scanning imagers and the evaluators assessed three hyperspectral single pixel scanners to represent this IR-RCD category. The systems assessed were: The Bruker Detection Systems RAPID Plus (Figure 4-8), the Bruker

Optics SIGIS-2 (Figure 4-9), and the Mesh Inc. iMCAD (Figure 4-10).

The Bruker Detection Systems RAPID Plus (Figure 4-8) is a hyperspectral FTIR scanning single pixel detector based on a Michelson interferometer with spectral resolution of 4 cm^{-1}. It operates in the LWIR from 7.5 to 14 µm. Detections and analysis are done using the Bruker OPUS RS software. The system weighs about 30 kg (~70 lbs). There are several chemical libraries available and alarm times can be as low as 2 seconds. The detection range depends on gas concentrations and field conditions but can be greater than 5 km. It costs about $225K.

Figure 4-10. Vendor setting up the Mesh Inc. iMCAD with evaluators observing and assisting.

The Bruker Optics SIGIS-2 (Figure 4-9) is a hyperspectral FTIR scanning single pixel detector based on a Michelson interferometer with spectral resolution from 0.5 to 1.8 cm^{-1}. It operates in the LWIR from 6.6 to 14.5 µm with a cooled detector. It can scan up to 360 degrees. Detections and analysis are done using the Bruker OPUS RS software. It weighs about 65 kg (~150 lbs). There are several chemical libraries available with alarm times as low as 2 second. The detection range depends on gas concentrations and field conditions but can be greater than 10 km. It costs about $300K.

The Mesh Inc. iMCAD (Figure 4-10) is a hyperspectral FTIR scanning single pixel detector based on a Michelson interferometer with spectral resolution from 0.5 to 8 cm^{-1}. It operates in the LWIR from 7 to 13 µm. It can scan up to 360 degrees. Detections and analysis are integrated with the detector. The results display for the instrument includes an inset showing the detector field of view. The sensor, scanner, and power supply are separate units and weigh about 17, 16, and 5.9 kg, respectively (~40 lbs, ~40 lbs, and ~14 lbs, respectively). There are several chemical libraries available with alarm times as low as 2 seconds. The detection range depends on gas concentrations and field conditions but be up to 6 km. It costs about $225K.

Hyperspectral data allow in-depth analysis that provides detection of a large number of chemicals with the ability to detect multiple chemicals simultaneously. On some systems the spectral resolution can be adjusted – higher resolutions result in longer scan times.

All the instruments provided results in the form of “heat” maps of chemical locations/concentrations along with context imagery as video in a real-time display that can also be saved or archived. The context video was grey scale. An example of the display and control software for Mesh Inc. iMCAD is shown in the top panel of Figure 4-11. Since these are scanning instruments, the plume map is built up from single pixel scans, each slightly staggered in time. The results displays were similar, though some instruments showed boxes around each sampled pixel area and some showed more “smooth” heat maps. The evaluators found the results displays to be intuitive and easy to read.

4.3.2 Assessment Details

Evaluators were given brief overviews of each of the three systems assessed. Then they assisted the vendors in setting up and operating the instruments.

A number of different releases were performed for these instruments, including liquid chemical evaporation (i.e., pan spills) and gas cylinder releases, spills on cardboard (Figure 4-11, lower panel, left) and leaks from plastic bags (Figure 4-11 lower panel, right).

Figure 4-11. iMCAD control panel and results (top panel) while the bottom panel shows releases for the SIGIS-2 including alcohol evaporating from a pizza box and freon dispersed from a plastic bag.

The instrument specifications, for all the single pixel imaging IR-RCDs, stated that they could detect ammonia, so ammonia spills were presented to each instrument. A concentrated aqueous solution of ammonia was poured into a large plastic container as shown in the top panel of Figure 3-5. Ammonia is a toxic chemical frequently encountered in emergency response scenarios; however, it is somewhat difficult to detect using LWIR due to lack of large spectra features in this region. This can be seen in spectrum shown in the bottom panel of Figure 2-3, where the ammonia spectrum has unique features, but they are smaller and more complex than the flammable gas spectrum shown in the top panel.

Setup of the instruments provided a range of experiences. For all three instruments the cables were well marked and easy to connect. The Rapid Plus was the easiest to setup, the instrument was self-contained and was easily moved by one person, it only needed to be connected to a power supply and control computer. The iMCAD was slightly more complex with additional modules as shown in Figure 4-12. Each module was easily moved or carried by a single person, but connection of each module did take some time. The SIGIS-2 was large and heavy requiring at least two people to move and setup. It is a single system that is connected to a control computer, and is often installed and mounted, ready for use, on mobile platforms.

All of the systems used a connected laptop computer for the controls and results display. There were differences in the software and this affected both the ease of controlling the instruments and understanding the results. All the instruments provide “heat” maps of chemical locations/concentrations along with context imagery as video in a real-time display that can also be saved or archived. Some of the instruments also presented both the measured and matching library spectra to the operator for more in-depth analysis. The evaluators noted that software made a significant difference in the operation of the systems and analysis of the results. However, the specific differences in the software were not assessed, so no details are presented.

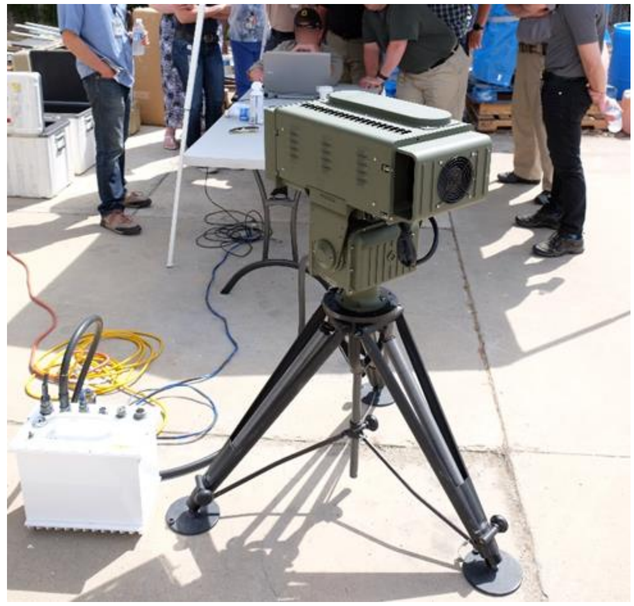

Figure 4-12. iMCAD detector and power supply in the foreground with evaluators operating the system in the background.

Unlike the multi-spectral IR-RCD instrument, these instruments were generally able to detect and identify all the releases with a few exceptions. As noted, the plume did move during the time required to scan a scene, so detection results were not necessarily “plume shaped.” But single pixels would indicate the chemical was present at a pixel location, when that location was measured, even if the real-time movement of the plume was not completely imaged as the plume might move between each pixel measurement.

Figure 4-13. SIGIS 2 detector in the foreground with evaluators operating the system in the background.

One of the differences the evaluators noted were the spectral libraries included with each instrument. Gas detections and identifications are dependent on these libraries. Libraries were provided in different configurations, with some vendors charging more for extended or custom libraries.

4.3.3 Hyperspectral Single Pixel Scanners Conclusions and Recommendations

The evaluators assessed three systems, the Bruker Detection Systems RAPID Plus, the Bruker Optics SIGIS-2, and the Mesh Inc. iMCAD in the IR-RCD hyperspectral single pixel scanner category. These sensors were used to represent all sensors in this IR-RCD category.

The evaluators recommended that hyperspectral single pixel scanners are not generally useful to first responders as they have not yet been designed or optimized for emergency responders required to be first on scene, at an unpredicted event. They noted that these units are expensive, relatively complex and can be difficult to move and setup. The exception was the Bruker Detection Systems RAPID Plus which could be easily moved and setup by one person. These instruments require significant training to operate effectively.

The evaluators did note that these instruments, because of their significant stand-off distance and wide area monitoring, could be useful at specific facilities or venues. But noted that if a venue or facility purchased this type of instrument, the operator(s) would need significant training and experience.

They noted that a hyperspectral single pixel scanner could be mounted on a dedicated vehicle. In this configuration the evaluators noted the technology could be useful for area monitoring and other first response tasks.

The IR-RCD systems assessed to represent the hyperspectral single pixel scanner category of IR-RCD detectors all cost over $200K that is representative of this category based on the SAVER market survey.

Evaluators made the following general comments:

- The controls were software-based on connected laptops and would require training and familiarization for effective operation.
- The colored chemical detection points combined with the context video was intuitive and provided results that were easily understood.
- Results interpretation requires training in the technical theory of operation of the instruments.
- The evaluators noted that these types of sensors would be appropriate to purchase in coordination with a specific facility where larger gas plumes might be a concern.

The evaluators concluded that hyperspectral single pixel scanners are not generally useful for first responder. They noted that in specific situations (i.e., facility monitoring) or configurations (i.e., dedicated vehicle) these instruments would be useful. The reasons they gave for not recommending the instruments for broader use is based on scan time, the size of the instruments, the inability to hand-hold the instruments, the training required to operate the instrument and interpret results, the general complexity of the technology, and the cost.

The evaluators made some instrument specific comments, which while specific to the various instruments, are informative to emergency responders considering these technologies.

Bruker Rapid Plus

Advantages

- Weather-proof and rugged
- Can operate while moving
- Easy to deploy, move, and setup
- Small or large library available (smaller library supports more rapid detection, larger library searches greater number of chemicals.
- Domestic manufacture

- Low maintenance costs
- Available on-line software

Disadvantages

- Did not detect many of the releases, though the chemicals were in the target library
- Locked up on several occasions during the demonstration
- Misidentified several of the released chemicals
- To compare measured and matched spectra requires optional expensive (~$30K) software
- Was the slowest of the three systems to alarm
- The display image distorted over time and the display was cluttered making it difficult to interpret results

Bruker SIGIS-2

Advantages

- Extended library – displays the best spectrum match along with other candidates
- Can be mounted on a vehicle
- The software interface was intuitive and easy to use – especially the methods to set the scanning area
- Could capture screen shots
- Would show both measured and library spectra
- Could see the spectra at each pixel that alarmed
- Could operate while moving
- Control/analysis computer included

Disadvantages

- Requires two people to deploy
- In general the weight and size are large
- Erases entire scan on completion of scan including all alarms and colors
- Each software installation (i.e., each computer) requires $1K license

Mesh iMCAD

Advantages

- It was weather proof
- Could search a reduced (targeted) or full spectral library
- Could operate while moving
- Saved spectral data
- Downloads both the measured and library spectra selected for matching for use in reach-back assistance
- System global positions system (location) unit integrated with the software

- Individual pixels being measured in near real time, but significant time (up to minutes) to scan a full scene.
- Could perform tomography to develop three-dimensional maps if multiple units or measurements are available.

Disadvantages

- Detection history did not fade – display became cluttered over time
- No battery access to change in the field
- Slow overall scene collection because the scene is scanned pixel by pixel
- Had problems with moving plumes because of scan time

4.4 Hyperspectral Imagers

IR-RCD hyperspectral imaging (HSI) sensors create an image where each image pixel represents a spectrum and the image represents a spatial area that is measured at the same time, similar to a digital camera. HSI systems capture the entire image in near real time, rather than building up an image using repeated measurements/pixels as the hyperspectral scanning systems do. This means that moving gas plumes or leaks can be more easily detected and visualized.

Figure 4-14. HI-90 hyperspectral imaging IR-RCD with evaluators in the background.

4.4.1 Assessed Equipment

The evaluators assessed the Bruker Optics HI-90 (Figure 4-14). Additionally, they were briefed on an upcoming FireFly design by Mesh Inc. that will incorporate new approaches to reduce the cost and complexity of these HSI systems.

The Bruker Optics HI-90 is a hyperspectral FTIR imager based on a Michelson interferometer with spectral resolution from 0.7 to 4 cm^{-1}. It operates in the LWIR from 7.5 to 14 µm. Detections are overlaid on a visual context image for analysis as shown in Figure 4-15, using the Bruker OPUS RS software.

There are several chemical libraries available. Stated alarm times are as low as 2 seconds. The detection range depends on gas concentrations and field conditions but can be greater than 5 km. The HI-90 costs about $600K.

The Mesh Inc. Firefly is a conceptual design of a low-cost, hyperspectral FTIR infrared imager based on a Michelson interferometer that will operate in the LWIR. The goal is to significantly reduce the size and cost of hyperspectral imagers, with goals in the 10 kg and $100K range, respectively. Prototype optical designs have been built and demonstrated. The detection range will depend on gas concentrations and field conditions but it is expected to be greater than 5 km.

Figure 4-15. HI-90 real-time results showing detection of a plume overlaid on grey-scale context imaging.

4.4.2 Assessment Details

For the HI-90, the evaluators were given a brief overview of the system then assisted the vendors in setting up and operating the instrument.

Setup of the HI-90 was straight forward. The cables were well marked and easy to connect. The unit consisted of the sensor head, two power supply boxes, and a control computer as shown in Figure 4-16.

A number of different releases, very similar to those performed for the hyperspectral single pixel scanners, were performed including liquid chemical evaporation (pan spills) and gas cylinder releases. An ammonia evaporation was presented similar to that described before and shown in the top panel of Figure 3-5. Ammonia is somewhat difficult to detect using LWIR because spectra does not exhibit large features (bottom panel of Figure 2-3).

The HI-90 had both the system controls and the results display on a connected laptop computer. The results display included a “heat” map of chemical locations and concentrations along with context imagery - all as presented as a video in a real-time display that could be saved or archived.

Figure 4-16. HI-90 in the foreground with the powersupplies shown under the table and the control computer on top of the table.

The HI-90 was able to detect and identify all the releases while providing real-time video of the moving plumes. The evaluators noted that the instrument performed well and provided very good information and representations of the gas presence and motion.

4.4.3 Hyperspectral Imagers: Conclusions and Recommendations

The evaluators assessed the HI-90 and were briefed on the conceptual design of a new system, the Firefly. The HI-90 represents the current commercial-off-the-shelf IR-RCD hyperspectral imagers. The Firefly design is more suited for the emergency responder community based on proposed design and projected cost, and could be available in the next few years.

The evaluators concluded that hyperspectral imagers, while useful, have not developed to the point to be considered for emergency responders because of cost and complexity. They noted that in some specialized situations or configurations (i.e., dedicated vehicle) these instruments would be useful. The reasons they gave for not recommending the instruments for broader use is based on cost, the size of the instruments, the inability to hand-hold the instruments, the training required to operate the instrument and interpret results, and the general complexity of the technology.

They noted that while these units provide very impressive results, they are very expensive and operators would need to have significant training and background to maintain and oversee the instruments. Instrument operation and results interpretation, while still requiring training, is more intuitive.

They recommended that while the hyperspectral imagers provide valuable real-time information on gas locations and movements, the costs and required training make these systems impractical for emergency responders at this time. They did note that if the Firefly system were able to meet the target specifications, then they would reconsider recommending this category for more uses. The Firefly would still require extensive training for operations and interpretation, but the cost, size, and weight would make the system more suitable for emergency responders.

The evaluators did note that these instruments, because of their significant stand-off distance and wide area monitoring, could be useful at specific facilities or venues. But also noted that if a venue or facility purchased this type of instrument, the operator(s) would need significant training and experience.

They also noted that a hyperspectral imager could be mounted on a dedicated vehicle that could be dispatched to a scene. In this configuration the technology could be useful for area monitoring.

The HI-90, that represented the hyperspectral single pixel scanner category of IR-RCD detectors, cost over $600K. This cost is representative of this category based on the SAVER IR-RCD Market Survey.

Evaluators made the following comments:

- Results interpretation requires training in technical theory
- The evaluators noted that these types of sensors would be appropriate to purchase in coordination with a specific facility where costs and training could be justified.
- The evaluators noted that the hyperspectral imagers were significantly more useful than the hyperspectral single pixel scanners because of the ability to provide video of plume size and movement.

The evaluators made some instrument specific comments, which while specific to the evaluated instrument, are informative to emergency responders considering these technologies.

Bruker HI-90

Advantages

- Fast detection and good live video showing moving gas plume
- The colored chemical detection video provided real-time information on gas plume size, concentration, and movement – they noted this was valuable information.
- Detection video combined with the context video was intuitive and provided results that were easily understood.
- Small pixels – high spatial resolution

- Large spectral library
- Intuitive software interface
- Most sensitive and accurate of any of the instruments evaluated in this report
- Very good results overlays, with multiple photos
- Easy image retrieval and review
- Large library of chemicals for detection and analysis

Disadvantages

- Not weatherized
- Required ~15 minutes of time to set- and warm up
- Setup was cumbersome and complex
- Expensive

5. SUMMARY

IR-RCD technology category results summary are presented in this section. Advantages and disadvantages of the assessed IR-RCD technology categories are highlighted in Table 5-1.

Table 5-1. IR-RCD Technology Category Advantages and Disadvantages

IR-RCD Category	Advantages	Disadvantages
Single-band Imagers	• Full plume image • Easy to use • Handheld and easy to deploy • Very sensitive • Detect small sources at a distance • Can include calibrated images that show temperature	• Requires different cameras for different gases or families of gases • Not rugged • Not intrinsically safe
Multi-Band Imagers	• Can detect a wider range of gases than a single-band imager • Provides color heat-maps of chemical concentration • Full plume image – if plume is present in all bands during the scan	• If gas plume moves and is small, cannot collect all bands with the gas present, this prevents gas identification • Slow scans • Chemical IDs may not be accurate • Cost
Hyperspectral Single-Pixel Scanners	• Detect and ID a large range of different gases • Provide high resolution spectra that can be saved and used for reach-back (for most instruments assessed) • Have configurable scan area – up to a full circle • Vehicle mounts for mobile operation – can measure while moving	• Takes a long time to scan a scene • Each pixel on the scan represents a detection in time – no immediate plume map (unless plume is relatively stationary) • Systems are generally larger and difficult to deploy with the exception of the Bruker Detection Systems RAPID Plus • Chemical IDs may not be accurate • Cost
Hyperspectral Imagers	• Detect and ID large range of different gases • Provides high resolution spectra that can be saved and used for reach back • Shows real-time moving gas plumes • Very good sensitivity • Very intuitive results presentation	• Cost • Not rugged • Complex and require significant training to operate • Chemical IDs may not be accurate

The general findings and recommendations from this IR-RCD assessment are summarized in Table 5-2. Assessment Summary. Note that in two of the four IR-RCD categories only a single instrument was used to represent the entire IR-RCD category. If other instruments in a given category are considered for purchase, the comments and recommendations from Table 5-2 can be taken into consideration when enquiries about that instrument are made.

Table 5-2. Assessment Summary

IR-RCD Category	Comments and Recommendations
Single-band Imagers	• Single-band imagers developed enough to be useful for emergency responders • Costs, while still significant, are in line with specialized instruments for other tasks • Specialized chemical response teams might consider purchase of single-band IR-RCDs • Each sensor is only sensitive to a chemical family • Consider purchase in conjunction with specific facilities
Multi-Spectral Imagers	• Multi-band imagers are minimally useful to emergency responders required to be first on scene at an unexpected event because of difficulties exhibited identifying small moving plumes, instrument size, and setup time • Multi-band imagers may be useful for specific locations, such as at chemical plants, where larger gas plumes might be expected • Units are expensive, relatively complex, somewhat fragile, and require significant training. • Multi-band IR-RCDs had difficulty detecting smaller moving plumes
Hyperspectral Single Pixel Scanners	• Hyperspectral single pixel scanner designs are not generally useful for emergency responders required to be first on scene at an unexpected event mostly because of cost, size of the instrument (except the Rapid Plus), and the time required to scan a scene • Hyperspectral single pixel IR-RCDs, because of their significant stand-off distance, wide area monitoring, and wide range of detected gases, could be useful at specific facilities. • Units are expensive, relatively complex, and can be difficult to move and setup, though the Bruker Detection Systems RAPID Plus could be moved and setup by one person • These instruments require significant training to operate effectively • These instruments could be mounted on a dedicated vehicle • Vehicle mounting could be useful for area monitoring • The three systems evaluated had significant differences in capabilities, ease of deployment, and handling
Hyperspectral Imagers	• Hyperspectral imagers, while useful, are not yet designed or optimized for emergency responders and were not recommended because of cost and complexity • These instruments, because of their significant stand-off distance and wide area monitoring, could be useful at specific facilities or venues • In specialized situations or configurations (i.e., dedicated vehicle) these instruments could be useful • Hyperspectral imaging IR-RCDs are accurate, sensitive, have long stand-off distances, intuitive results displays, and the ability to save data for reach back and remote monitoring • Evaluators did not recommend Hyperspectral imaging IR-RCDs for broader use based on cost, the size, the training required to operate the instrument and interpret results, and the general complexity of the technology

Emergency responder agencies that consider purchasing IR-RCD should carefully research the various categories of IR-RCDs available for their overall capabilities and limitations as applicable to their potential use scenarios. Other factors to consider include associated requirements in terms of training, operation complexity, and cost in relation to their agency's operational needs. The evaluators suggested the potential purchasers carefully consider the various potential use scenarios and purchase the type of IR-RCD instrument best suited for that use.

APPENDIX A. GLOSSARY AND DESCRIPTIONS

These definitions and descriptions are not precise technical definitions, but are meant as a guide to help readers understand the technical language used in this report.

Active – A sensor that provides a light source as part of the measurement. Often these sources are lasers at specific wavelengths, but other sources such as heated black bodies, or lamps with filters to provide light in the selected spectral regions may be used instead. See **Passive**

Band – The region of the spectrum that is sampled in a measurement in that spectral range. A single filter instrument has just one band, multispectral has multiple bands, (to 10’s of bands) and a hyperspectral detector might measure spectra in hundreds to thousands of bands. Bands can have different spectral widths. See **Bandwidth**/**Resolution**.

Bandwidth – The width of a single spectral measurement. This can be reported in wavelengths or wave numbers. The bandwidth and spectral resolution are often used interchangeably. See **Spectral Resolution, Wave Length** and **Wave Number.**

Cooled Detector – A sensor where the focal plane that measures the spectra is cooled (usually mechanically). Since these measurements are in the IR region and are essentially measuring the temperature of the scene, cooled focal planes provide much better signal-to-noise measurements. Cooling the focal plane adds cost and complexity to the system.

Concentration – see **ppm-meter**

Delta (T) Temperature – The difference in temperature between the gas or chemical being measured and the scene background (sky, buildings, trees etc.). The larger the delta T, the easier it is to detect chemicals. See **Detection Limit.**

Dispersive System - A method or type of system for measurement of IR spectra that use a grating to directly separate incoming light into spectral bands similar to a prism. See **FTIR.**

Detection Limit – The lowest concentration that can be detected by the sensor. For passive systems, it is a function of the difference between background and chemical temperatures (delta T), standoff distance, spectral bandwidth and resolution of the instrument, chemical spectral signature, and obscurants in the atmosphere such as smoke, dust, or other chemicals.

Detector Types – Detectors types differ in the spectral range, resolution and number of spectral measurements that are made. The number of measurements can range from a single band called a filter detector in this report, to multiple bands called a multi-spectral detector, to hundreds or even thousands of bands, called a Hyperspectral (HS) detector. Each band is also defined by it its spectral resolution. See **Spectral Resolution, Wave Length** and **Wave Number.**

Spectral resolution is measured as either wavelength or wave number. The wave length is the period or length over which the wave repeats, usually reported in µm, the wave number is the number of repetitions of a wave in a specified distance, usually reported in cm-1 or “per centimeters.” Detector types can be either imaging or scanning systems. Scanning sensors measure at a single point but can create images by measuring a single point then moving to a new point in the scene, and repeating, thereby building up the image.

HSI sensors create an image where each image pixel represents a spectrum and a spatial area is measured at the same time, similar to a digital camera. Most HSI instruments measure a horizontal line across the imaging chip with spectral bands measured on the other dimension. The image is created by measuring successive horizontal bands across the scene. HSI refers to the fact that each spectrum has a very large number of spectral values with a fine wavelength resolution. HSIs typically generate images where each image pixel contains hundreds to thousands of spectral bands.

Field of View – The area that can be measured or scanned by a detector usually reported in degrees. For imaging detectors this is determined by the lens used, while for scanning systems this can often be configured.

Filter Detector – See **Detector Types**

FTIR – A method or type of system for measurement of IR spectra that uses a moving mirror, such as a Michelson interferometer, or other methods to measure a signal and create an interferogram. The interferogram is then transformed to a usable spectrum with a mathematical Fourier transform. Fourier transform spectrometers offer advantages over dispersive spectrometers. (1) The interferometer's detector in effect monitors all wavelengths simultaneously throughout the entire measurement; this offers an increase in signal to noise ratio while using only a single detector element; (2) the interferometer does not require a limited aperture as do grating or prism spectrometers, that require the incoming light to pass through a narrow slit in order to achieve high spectral resolution. This is an advantage when the incoming light is not of a single spatial mode. The other common method or system for measuring IR spectra are dispersive systems use a grating to directly separate incoming light into spectral bands similar to a prism. See **Dispersive System**

Fourier-transform IR – See **FTIR**

Hyperspectral Imaging/HSI – HSI sensors create an image where each image pixel represents a spectrum while the image covers a spatial area that is measured at the same time, similar to a digital camera. Most HSI instruments measure a horizontal line across the imaging chip with spectral bands measured on the other dimension. The image is built up by mosaicking successive horizontal bands across the scene. Hyperspectral refers to the fact that each spectrum has a very large number of spectral values with a fine wavelength resolution. HSIs typically generate images where each image pixel contains hundreds to thousands of spectral measurements. See **Detector Types**

Hyperspectral – A detector that measures a large number, hundreds to thousands of spectral bands. See **Detector Types**

Imaging System – See **Detector Types**

Infrared/IR – IR light is outside the visible region and cannot be seen by humans. The IR region spans the electromagnetic spectrum from 0.7-1000 microns. For convenience this is typically separated into different regions such as near-IR, MWIR, and LWIR. This report is mainly concerned with MWIR and LWIR regions. Objects with temperatures above absolute zero emit energy (e.g., light) in the IR region in patterns based on their chemical composition. Different chemicals emit or absorb light at specific wavelengths creating a unique spectrum or fingerprint that can be used to identify the chemical. These patterns are based on the vibrational energy of various chemical bonds. Chemicals that are hotter than the scene background emit IR energy while those colder than the scene background absorb energy at the same wavelengths, creating these chemical-specific spectra. The emittance and absorbance spectra are inverses of each other.

Longwave IR – See LWIR.

LWIR – The region of the spectra from about 8 to 14 µm. See **IR Regions.**

Midwave IR/MWIR – The region of the spectra from about 2 to 5 µm. See **IR Regions**.

Multi-Spectral – A detector that measures several to tens of spectral bands. See **Detector Types**

Passive – A sensor or detector system that measures light (electromagnetic radiation) emitted or reflected by an object or gas. It does not provide a light or energy source to assist the measurement. Active systems provide their own IR light source while passive systems rely on temperature differences between the gas and background in the target area. See **Active**

Peaks – Areas of a chemical spectra that look like peaks or valleys when the spectra is plotted as a line and correspond to a chemical's (or family of chemicals') absorbance or emission signatures at particular wavelengths. A chemical with strong (or high) narrow peaks can usually be detected at lower concentrations than a chemical with weak (or lower) broader peaks. Figure 2-3 shows an example of a chemical with a broad, strong peak (propane) and one with a narrow, weak peak (ammonia). In the figure the spectra are plotted as transmittance so the peaks look like valleys. See **Spectra** and **Spectral Signature**

Passive IR for Systems Remote Chemical Detection/IR-RCD – A passive IR analysis device. These are detectors that measure spectra in the IR range and are used for stand-off chemical detection. For purposes of this report, stand-off means several meters or more.

ppm-meter – Units for concentration measurements for standoff IR sensors. This measurement is a multiple of the chemical concentration, and the path length through the plume being measured. For example, a chemical plume 1-meter in size with a concentration of 10 parts per million (ppm) would be characterized as 10 ppm-meter in concentration. A second plume 10-meters in size with a concentration of 1 ppm would also be characterized at 10 ppm-meters.

Resolution – For this report, this generally refers to the spectral resolution of the system, though can also refer to the spatial resolution. Spectral resolution is generally reported in wave number, though it can also be reported as the width of a measured band in wavelength. Higher resolution provides more information allowing more accurate matching of a chemical's spectra. Higher resolutions usually also mean higher costs and longer scanning times. Resolution can also refer to spatial resolution. The spatial resolution is the physical size of a single pixel being measured.

Scanning System – See **Detector Types**

Spectra – a measurement of light intensity at different wave lengths. This is often used to refer to a measurement made by an IR detector that consists of light intensity measurements in different infrared bands. Different chemicals absorb or emit light over specific wavelengths and this pattern or spectra can be used to identify the chemical.

Spectral Library – A database of different measured chemical spectral signatures or spectra. Software compares measured spectra to these libraries to determine if a chemical is present. Most spectral libraries are supplied by the detector vendor. There are third party libraries. Some libraries can be extended by the user.

Spectral Signature – Chemicals absorb light in different narrow spectral bands in a unique manner creating a spectrum that can be used to indicate the presence of a chemical(s), uniquely identify the chemical(s), and quantify their concentration(s). Chemical spectra can have large, easily identified features or peaks, or may have smaller, less easily identified features or peaks. Spectral features that are unique to an individual chemical, or to a class of chemicals are called spectral signatures. The spectrum of a chemical affects the concentration and distance over which it can be successfully detected.

Spectral Region – the portion of the electromagnetic spectra where the instrument collects light. It is often defined based on detector capabilities, chemical spectral features and in windows where there are no strong atmospheric interferents. Water and other gases in the atmosphere absorb IR light in different regions and make these regions opaque; that is, no light is transmitted. Figure 2-2 shows a graph of atmospheric transmittance along with the molecules most responsible for absorbing light in the opaque regions that are white in the figure. There are three windows from about 2 to 5 µm with some breaks called the midwave IR (MWIR). There is a large window from about 8 to 14 µm called the longwave IR (LWIR). In FTIR spectroscopy, the longwave is often referred to as the “fingerprint” region due to the unique complexity of spectra in this region which can be used to detect and identify chemicals. See **MWIR** and **LWIR.**

Spectral Resolution – The width of a single spectral measurement. This can be reported in wavelengths or wave numbers. The bandwidth and spectral resolution are often used interchangeably. However, spectral resolution is also sometimes used to state how many spectral measurements are made in a region. Higher spectral resolution (smaller number) often comes at the cost of slower scan speed, but gives greater accuracy and thus a higher likelihood of chemical identification. See **Bandwidth, Wavelength** and **Wave Number.**

Spectrum (plural: Spectra) – See **Spectral Signature**

Stand-Off Distance – The distance between the sensor and the chemical plume. It is often used to state the maximum range that a chemical can be detected. Passive systems can have ranges up to 5 or 6 kilometers or more, though detection is dependent on the background, concentration, and the specific chemical as some chemicals have larger spectral variations or signatures making them easier to detect.

Wavelength - The period or length over which the wave repeats, usually reported in microns (µm) or nanometers (nm). Wavelength is usually used when talking about a region of the spectra, but can be used in talking about spectral resolution. A range of wavelengths is used to decribe a system or region such as from 10.5 to 10.7 µm. By convention, multi- and HS detector resolutions are usually reported in wavenumbers, (See **Wavenumber**) with a small number indicating a narrower band, while filter detectors are usually report as a range of wavelengths.

Wavenumber – The **number** of repetitions of a wave in a specified distance, usually reported in cm^{-1} or "per centimeters." Wavenumber is usually used when talking about spectral resolution or a specfic point in the spectra, but is also used when defining spectral regions. See **Wavelength**