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A Sensor Management Architecture Concept for Monitoring Emissions from Open-Air Demil Operations

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Abstract

Sandia National Laboratories, CA proposed a sensor concept to detect emissions from open-burning/open-detonation (OB/OD) events. The system would serve two purposes:

1. Provide data to demilitarization operations about process efficiency, allowing process optimization for cleaner emissions and higher efficiency.
2. Provide data to regulators and neighboring communities about materials dispersing into the environment by OB/OD operations.

The proposed sensor system uses instrument control hardware and data visualization software developed at Sandia National Laboratories to link together an array of sensors to monitor emissions from OB/OD events. The suite of sensors would consist of various physical and chemical detectors mounted on stationary or mobile platforms. The individual sensors would be wirelessly linked to one another and controlled through a central command center. Real-time data collection from the sensors, combined with integrated visualization of the data at the command center, would allow for feedback to the sensors to alter operational conditions to adjust for changing needs (i.e., moving plume position, increased spatial resolution, increased sensitivity). This report presents a systems study of the problem of implementing a sensor system for monitoring OB/OD emissions. The goal of this study was to gain a fuller understanding of the political, economic, and technical issues for developing and fielding this technology.

Acknowledgements

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Contents

Executive Summary

There are numerous multifaceted issues that have broad impacts on open burn/open detonation (OB/OD) of military munitions in the United States, as well as issues that are very specific to particular operational sites. Both sets of factors need to be considered to develop a good representation of the political, economic, sociological, and organizational environment affecting OB/OD. The discussions and review suggest that this environment can have a profound effect on the capability and/or desire of an OB/OD treatment facility to introduce technology to monitor emissions. It is evident that the costs associated with maintaining the capability to perform OB/OD are continuing to increase. However, not all of these costs are financial in nature. Past experience also suggests that facilities need to be able to respond promptly and properly to concerns raised by individuals and outside organizations.

We defined a group of individuals that would potentially interact with the sensor system in various capacities. These individuals were interviewed, and their input and suggestions were collected and summarized in an effort to develop a set of requirements for the sensor system. These requirements include essential features that the system must have such as robustness; reliability; and low cost to install, operate, and maintain. In addition, to provide useful data, the system needs to at least be capable of detecting carbon monoxide, carbon dioxide, particulate size distribution, metals, and nitrogen oxides (NO_x) formation, as well as performing meteorology and plume positioning measurements. Consensus opinion in this area was difficult to obtain, however, and it is clear that a better definition of the minimum set of detectable compounds is needed.

Sandia-developed technology for integrating and controlling a heterogeneous array of detectors is highly applicable to the OB/OD emissions sensing problem. The sensor management architecture (SMA) provides a data interface for visualizing the aggregated sets of data, as well as automated control of and feedback to the individual sensor nodes. This is accomplished in real time via noise-immune, wireless communication.

A group of 15 sensor technology categories is described and evaluated against a set of 12 critical sensor properties. All of the current sensors and sensor technologies available have a major shortcoming with respect to one or more of the properties. The five sensor properties where these technologies generally fall short of meeting the projected requirements are cost, deployability, sensitivity, sampling, and state of development. A number of technologies show promise but require focused research and engineering efforts to demonstrate their applicability to the problem.

The data collected indicate that a number of issues, which are both directly and indirectly related to the sensor system technology, influence the effectiveness of the OB/OD emissions sensing program as a whole. These issues, which will be discussed further below, include the following:

- Deciding what is the final disposition and implementation of an emission sensor system. This includes who the real users of the technology are, who is expected to see the data, and what is the desired mode of operation of the system.
- Assuming that an effective sensor system will be built, demilitarization organizations and operations need to prepare for implementation of the equipment. This includes training, maintenance and operation, and data handling, storage, reporting and auditing.
- Driving future research and development to focus on overcoming the specific technological challenges that prevent many current sensors from inclusion in the proposed system. This includes leveraging sensor development from similar technology arenas and divesting from technologies that do not add value.
- Recognizing the value of physical and chemical modeling and past experimental work to fill in gaps in the data (e.g., resulting from inherent sensor limitations). These added capabilities include both atmospheric plume dispersion models, chemical reactivity models, and confined detonation studies.

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Chapter 1: Introduction

The disposal of outdated, unserviceable, and captured munitions continues to present a growing problem to the military. Open burning (OB) and open detonation (OD) are simple and cost-effective methods for destroying munitions and energetic materials. In recent years, there has been increased scrutiny of the overall impact of OB/OD operations by government officials and the general public. The responses by individual organizations have varied from close cooperation with environmental regulators to closure of facilities to OD operations.

As part of the Technology Coordination Group IX, Sandia National Laboratories, CA (Sandia) proposed a sensor concept to detect emissions from OB/OD events. The system would serve two purposes. First, it would provide data to demilitarization operations about the efficiency of their processes. This data could be used to optimize the OB/OD process to produce cleaner emissions and to increase efficiency. Second, it would provide data to regulators and neighboring communities about the quantities of potentially toxic materials that the operations were dispersing into the environment.

The proposed sensor system uses instrument control hardware and data visualization software developed at Sandia to link together an array of sensors to monitor emissions from OB/OD events. The suite of sensors would be composed of a variety of physical and chemical detectors mounted on stationary or mobile platforms. The individual sensors would be wirelessly linked to each other and controlled through a central command center. Real-time data collection from the sensors, combined with integrated visualization of the data at the command center, would allow for feedback to the sensors to alter operational conditions to adjust for changing needs (i.e., moving plume position, increased spatial resolution, increased sensitivity).

This report presents a systems study of the problem of implementing a sensor system for monitoring OB/OD emissions. The goal of this study was to gain a fuller understanding of the political, economic. and technical issues for developing and fielding this technology. The study was composed of four major components; the resulting reports from each of the four areas are compiled together in this document. The following chapters are the individual reports outlining the discoveries in each of these areas. Chapter 2 describes the current circumstances concerning OB/OD use. Chapter 3 investigates the relationship between the proposed sensor system and the persons and organizations that would interact with it. Chapter 4 gives a thorough description of the sensor management architecture (SMA) concept for the emissions sensor system. Chapter 5 evaluates the suitability of the emissions detection technologies described in the technology discovery document (Appendix E).

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Chapter 2: The OB/OD Environment

I. Introduction

In the most general sense, the operating environment for OB/OD at a demilitarization site reflects the joint influence of numerous local, regional, and national factors. These factors include the following:

- Political trends and priorities
- Economic trends and realities
- Environmental concerns and regulations
- Issues unique to the particular demil workplace

Waste treatment and disposal operations at these sites can also be influenced by larger trends that affect demilitarization priorities in general. These trends include, but are not limited to the following:

- Changes in the organization and structure of the U.S. Army management elements responsible for demil
- Changes in the demil stockpile resulting from recent conflicts, such as those in Afghanistan and Iraq
- Continuing funding pressure on demil technology development and operations
- Political pressure to increase the role of private industry in demil execution
- The growing willingness of concerned citizens and other groups to take legal action to address their complaints about demil operations

Finally, factors that impact demilitarization of particular munitions by OB/OD may also affect implementation of the process. Examples of these include continuing emphasis on resource recovery and recycle (often referred to as R^3) of high-value components and a growing scrutiny of OB/OD operations by environmental regulators.

II. Political Issues

Establishment of the Program Executive Officer for Ammunition (PEO Ammo) and, within that organization, the Program Manager for Demilitarization (PM Demil) positions in the U.S. Army management structure created a new force in the overall demil environment. PEO Ammo's mission includes responsibility for the entire life cycle of conventional munitions. Within that domain, PM Demil's mission is "to perform life cycle management of demilitarization, disposal, and R^3 for conventional munitions for all services, and Department of Defense (DoD) and U.S. government agencies"[1]. Stated goals for the PM Demil include the following, among others:

- Implementing steps leading to a significant reduction in the demil stockpile
- Driving demil operations to increased use of closed disposal options
- Guaranteeing environmentally sound and safe demil operations

Indeed, one of the stated demil program constraints is that demil is "moving away from OB/OD"[2].

An additional political driver is the growing demil stockpile of conventional munitions resulting from conflicts, such as those in Afghanistan and Iraq. While these inventories are not a domestic demil challenge, they can influence the choice of OB/OD for demil operations[3]. The questionable history and state of captured munitions present not only safety challenges but also an environmental challenge because of the requirement that U.S. military operations in foreign countries must be executed in a way that complies with applicable host country environmental regulations. Thus, environmental compliance concerns that impact domestic OB/OD operations are also a serious factor on the international front.

The most powerful and consistent economic elements affecting OB/OD are demil funding levels and the cost structure of demil operations. Low operational cost and high throughput are clear advantages for OB/OD when compared with most other demil options. In a period when demil execution funding has not kept pace with the goal of reducing the size of the demil stockpile, these advantages tend to enhance the appeal of OB/OD.

Based on information presented at the most recent Global Demil Symposia and Demil Users Group Meetings, demil funding is growing overall, but it continues to be below the levels necessary to achieve targeted stockpile reduction. Beginning with 411,000 short tons (contiguous United States only) in the conventional demil stockpile in FY02, and assuming conservative stockpile growth projections, funding on the order of $150M per year is required to reduce the stockpile to 92,000 short tons by FY09. It is clear that the more likely annual funding levels of $100M, or less, are inadequate to achieve the 2010 goal.

Indeed, with a demil backlog of 360,184 tons as of 4/30/03, and an additional 350,000 tons expected to be generated by FY09, it is estimated that it will cost a total of $685M to demil the current and projected stockpile[4]. At the same time, the FY04 funding for conventional munitions demil is $75M, which includes both execution and research and development (R&D). This funding shortfall impacts OB/OD in two ways. Since demil execution is expected to follow funding, lower levels of funding will most likely result in less demil activity overall (including OB/OD).

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[1] Jennings K., "Demilitarization Overview," 11th Global Demil Symposium & Exhibition, Sparks, NV, 19–22 May 2003.
[2] Jennings, K., "PM Demilitarization Overview & Update for DUGM," 12th Demil Users Group Meeting, Atlanta, GA, 28–30 October 2003.
[3] Wheeler, J., "Introduction," ibid.
[4] Ligeno, L. "Conventional Ammunition Demil Program," 11th Global Demil Symposium & Exhibition, Sparks, NV, 19–22 May 2003.

Resource Recovery and Recycle (R^3)

Increased emphasis on viewing the demil stockpile as a resource (e.g., a source of raw materials and components that can be incorporated into new munition items) rather than a liability has a strongly countering effect on expanding the use of OB/OD. R^3-type demil activities can have economic advantages in addition to political and potential environmental advantages even if R^3 leads to operational costs that are higher than those for conventional demil. This is because the revenue derived from sale or reuse of the recovered assets can offset the R^3 costs. In contrast, the products of contained disposal rarely have economic value, while those of OB/OD never do.

An increased emphasis on R^3 is now U.S. Army and DoD policy, and R^3 has clearly gained acceptance by the demil community as the route of choice for execution. In FY02, for example, 78% of demil execution was by some form of R^3, while the remaining 22% was by waste treatment (e.g., OB/OD and incineration)[4]. A decade earlier, in FY92, the figures were nearly reversed, with only 12% of demil executed by R^3 and 82% by waste treatment, primarily via OB/OD.

R^3 activities that were not a part of demil execution a decade ago include the following[4]:

- Propellant conversion to fertilizer
- Explosive D conversion to picric acid
- M117 general-purpose bombs offered on solicitation for TNT recovery
- Commercial Tritonal recovery from 750# bombs
- Magnesium recovery from mortar rounds (still in development)

With an ongoing emphasis on the development of new R^3 technologies for demil, it seems clear that additional pressure will be placed on reducing the use of OB/OD for demil execution.

Design-for-Demil

Spearheaded by the PM Demil, an effort is currently underway to enforce a policy to make sure that all conventional munitions items currently under development conform to "design-for-demil" guidelines established by the DoD. Full implementation of this concept will have a long-term economic influence on the OB/OD environment. In general, design-for-demil considers demil, disposal, and R^3 requirements early in the design process, as well as during normal modifications over the life cycle of the item. This approach should reduce the cost, complexity, and environmental impacts associated with demil, enhancing safety without sacrificing performance. Combined with a significant increase in demil by R^3, design-for-demil is expected to reduce reliance on and the requirement for OB/OD as a demil option as these munitions reach the end of their useful life. In contrast, the munitions items in today's demil stockpile were often designed, developed, and manufactured without any thought of end-of-life issues. In many cases, such as the well-known Area Denial Artillery Munition (ADAM) mine epoxy, which uses a depleted uranium salt-hardening accelerant, the lack of a design-for-demil requirement has resulted in a significant demil challenge.

Reduced Logistics "Footprint"

A key element in the transformation of the U.S. Army, especially associated with the Objective Force Warrior and Future Combat Systems concepts, is the need for a reduced logistic "footprint." Simply stated, this means that fewer munitions items will be required in the future to achieve tactical and strategic objectives. For example, the planned Excalibur artillery system is expected to achieve a "kill" with 3 "smart" rounds in situations where today's units would require 150 "dumb" rounds to provide the same effectiveness.[5] This transformation is expected to have two effects on demil overall and the OB/OD component in particular. First, fewer munitions in the war-fighting inventory will ultimately mean that fewer munitions will need to be demilled. At the same time, smart munitions incorporate items that are of much higher value than what is typically used in today's dumb rounds. Thus, as with the missiles of today, future smart munitions will be worth the additional cost of R^3 processes because of the value of the recovered components. However, given the expected lifetime of munitions presently being developed, the impact of this trend, as well as the effect of design-for-demil, discussed above, on actual demil operations will not be felt for perhaps 20 years.

[5] Izzo, P., "PEO Ammunition Overview," Ammo Conference, 2003.

III. Environmental Issues

Numerous environmental factors can impact the applicability and effectiveness of OB/OD[6]. These include diverse requirements such as maintaining quantity/distance relationships for safety, which means that substantial land area is needed for facilities, and locating neighboring facilities so that OB/OD emissions carried by prevailing winds do not impact their operations. In addition, adverse weather conditions (e.g., high potential gradients near thunderstorms or strong temperature inversions) will generally preclude OB/OD operations. Such factors, when added to site-specific environmental emission constraints imposed by an OB/OD facility permit, can significantly constrain day-to-day facility operations.

Regulatory Compliance

A policy established by the DoD requires regulatory compliance in all aspects of demil operations, including OB/OD. An OB/OD facility requires a Resource Conservation and Recovery Act (RCRA) Subpart X permit and an air emissions permit. OB/OD emissions are regulated by the U.S. Environmental Protection Agency (EPA) at demil facilities. However, the EPA may delegate regulatory authority to states that agree to maintain environmental standards at least as stringent as the federal regulations. Thus, regulation of emissions from OB/OD events can vary from facility to facility depending on the local regulatory environment. Nevertheless, it is clearly DoD policy to comply with applicable environmental regulations at a facility.

The costs of permitting, re-permitting, and regulatory compliance are borne by the operating budget of each installation. Installation commanders dealing with limited budgets keep a sharp eye on operating costs and may resist allocating scarce resources to OB/OD if alternatives offering less environmental impact and lower overall operating costs are available.

Concerned Citizens and Legal Action: A Case Study

Sierra Army Depot (SIAD) is located in Herlong, CA, about 55 miles northwest of Reno and 14 miles due west of the Pyramid Lake Paiute Reservation. SIAD began conducting OB/OD operations about 1970, and until 2001, it was the largest and most active Army OB/OD demil operation. Emissions from SIAD's OB/OD operations were carried by prevailing winds over the local mountains and reached Pyramid Lake and Reno's north valley.

Beginning in 1980, SIAD operated under "interim status." It sought a 10-year permit from the California Department of Toxic Substances Control. California EPA's Department of Toxic Substances Control (DTSC) reported that SIAD's draft permit showed acceptable cancer risks for California and Nevada. California officials said the cancer risk from the depot's OB/OD operations was four in one million for Herlong, CA, where SIAD is located, and one in a million for Nevada. Cancer risk from SIAD OB/OD operations was reported to be less than one in a million. Nevada environmental officials told their California counterparts that they had no faith in the studies and assessments because Nevada had been left out of the process.

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[6] Federal Remediation Technology Roundtable, http:/www.frtr.gov/matrix2/section4/4_27.html.

As a part of a re-permitting process, air monitors designed to measure the concentrations of particulate matter in populated areas were installed to determine if SIAD was exceeding federal, state, or local air quality standards. The study was suspended because the equipment couldn't differentiate between particles emitted by OB/OD and "localized source particles," such as desert dust or particles from forest fires. The study was part of SIAD's Draft Hazardous Waste Treatment and Storage Report and its Environmental Impact Statement. The California Environmental Protection Agency (CalEPA) and the state toxic substances division, in conjunction with the California Air Resources Board, oversaw the air-monitoring project.

In 2003, the Agency for Toxic Substances and Disease Registry (ATSDR), a public health agency of the U.S. Department of Health and Human Services released its public health consultation for SIAD. ATSDR found that inhalation exposures to emissions from SIAD posed no apparent public health hazard. This designation is one of five "hazard categories" ATSDR assigns to sites on the basis of its technical analyses. At SIAD, where community members have been exposed to site-related contamination, but not at levels expected to cause adverse health effects, "no apparent public health hazard" is the designation used.

Until August 2001, SIAD used OB/OD to treat or destroy waste ordnance, such as explosives and propellants. In 2000, after repeated inquiries by U.S. Sen. Harry Reid, D-NV, the Centers for Disease Control was petitioned to evaluate the public health implications of potential exposures to SIAD air contaminants. ATSDR gathered and evaluated data to address community health concerns. As a prudent public health measure, the public health consultation recommends that, if OB/OD is resumed at SIAD, the Army conduct routine air sampling for particulates in residential areas downwind from SIAD.

Lawsuits are a common tool used by concerned citizens. In the fall of 2000, Larry Beach of Milford, CA, who lives 13 miles from SIAD, filed suit against the federal government in U.S. District Court in Sacramento. Beach, who showed videotapes of shock waves from OD blasts shaking his house, sued for repair costs and "special and general damages." In 2001, the commander at SAID estimated the best-case scenario for the outcome of the lawsuit would be no impact on OB/OD[7]. The worst impact of the pending lawsuit would be reduction to 50% of the previous level. Within one year, SIAD had agreed to stop all OB/OD operations except for emergency situations in order to resolve the suit.

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[7] Whitehurst, M., "Sierra Army Depot Update," 2001 Global Demilitarization Symposium & Exhibition, Sparks, NV, 15–18 May 2001.

IV. What Is the OB/OD Environment at a Current Demilitarization Site?

Background

In an effort to answer this question, a Sandia team visited China Lake, CA on January 20, 2004, and engaged in a morning of discussions hosted by China Lake. For this discussion, China Lake was able to bring together individuals at China Lake that represented a spectrum of scientific as well as regulatory interests at their site. A series of questions (included as Appendix A) was used to stimulate and focus the discussion, and Sandia also gave a brief overview of the Sandia sensor architecture memorandum of understanding project for the benefit of the attendees.

The first point to be made is that China Lake is not a typical OB/OD demilitarization site. That is, both the type and scale of its operations are somewhat unique. Particular features that make demilitarization at China Lake atypical include the following:

- Waste treatment operations are preferentially treated by OD (their last open burn was conducted in 1998).
- They usually have only one OD event per month with a total explosive weight on the order of 8K pounds (the upper weight limit per treatment event, as dictated by their permit, is 15K pounds).
- The materials and items included in an OD event are mostly derived from R&D activities at their site (i.e., while the constituents of their wastes are known, these wastes do not generally include munitions items or energetic materials characterized in the Munitions Items Disposition Action System [MIDAS] database and/or the demilitarization stockpile).

These features tend to distinguish the OB/OD demilitarization environment at China Lake from that at sites carrying out more routine waste treatment operations. For example, at McAllister Army Ammunition Plant (MCAAP), multiple OB/OD operations are carried out every day, weather conditions permitting. However, noise considerations and the relatively close proximity of the nearest neighbors at MCAAP limit individual OD events at this site to a range of 200–250 pounds net explosive weight (NEW). Given such wide diversity in site operations, the discussion below will focus on elements of China Lake's OB/OD environment that are similar to those that might be encountered at other sites.

Environmental and Regulatory Constraints

The federal EPA has delegated regulatory authority for China Lake air and solid emissions to the state of California. Currently, air emission regulations are directed out of local offices in Bishop, CA and solid emissions (regulated by RCRA) are directed out of Sacramento, CA. China Lake is treated as a regulated source for purposes of permitting. They are operating under a recently issued air permit; however, at the time of our discussion, negotiations were underway for a pending RCRA permit. We were told the discussion in these negotiations includes the possibility that new waste monitoring requirements will be introduced (and required) in the future.

Permit Assumptions

For purposes of their permit application, the China Lake environmental group has defined per event weight limits for 17 categories of waste items and materials that they treat by OD.[8-17] These categories range from energetic-material-contaminated laboratory containers and wipes to bulk propellants and munitions items. By knowing the constituents and weight of the waste materials to be treated, it is possible to use approved emission factor (weight of pollutant/NEW) databases generated by the EPA[18] to estimate the air and solid releases of compounds of concern in an OD treatment event (e.g., CO and Pb). In situations where new energetic material compounds are being disposed of, conservative estimates of likely emission factors are made based on emission factors from known, similar formulations. The actual treatment limits for each of the 17 categories is established by a formal health risk assessment (HRA) of the affected population assuming all of the pollutants generated in the OD event will cross the facility fence line. Both the annual and per event release limits regulated by the permits are established by the original permit applications.

While the actual OD operations at China Lake have unique features as described above, the permitting process and tracking for air and solid emissions that are in place at China Lake are similar to those required at sites engaged in routine OB/OD waste treatment (e.g., MCAAP). One likely difference, however, is that the munition items and energetic materials that are treated by most demilitarization

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[8] Boggs, Zellmer, AtienzaMoore, Hoover, Quintana, Nissan, Erickson, Chafin, Fridley, Osburn, and Mohn, "Treatment of Energetic Wastes by Open Detonation at China Lake," 2002 Global Demilitarization Symposium, Lexington, KY, 20–24 May 2001.

[9] AtienzaMoore, Boggs, Chafin, Erickson, Fridley, Hoover, Lindfors, Mohn, Nissan, Osborn, Quintana, and Zellmer, "Treatment of Energetic Waste by Open Detonation: Status of China Lake Permit", 2002 Demilitarization Users Group Meeting, San Diego, CA, 29–30 Oct 2002.

[10] Erickson, Chafin, Hoover, Boggs, Zellmer, Abernathy, Thompson, Davis, and Mitchell, "Emission Factors Associated With Treatment of Energetic Hazardous Waste by Open Detonation," 2003 JANNAF Safety and Environmental Protection Subcommittee Meeting, Charlottesville, VA, 25–27 March 2003.

[11] Erickson, AtienzaMoore, Boggs, Chafin, Lindfors, Zellmer, Abernathy, Gerber, Carson, Davis, and Hottenstein, "Emissions from the Detonation of Explosive Contaminated Wastes," 2003 Global Demilitarization Symposium, Sparks, NV, 22 May 2003.

[12] Erickson, Chafin, Hoover, Boggs, Zellmer, Abernathy, Thompson, Davis, and Mitchell, "Protocol for Determining Emission Factors from Open Detonation of Munitions and the Application to TNT-based Explosives," 2003 Global Demilitarization Symposium, Sparks, NV, 22 May 2003.

[13] Zellmer, Boggs, Erickson, Abernathy, and Atienza-Moore, "Treatment of Explosive Hazardous Wastes by Open Detonation at the Naval Air Weapons Station, China Lake, California," 30th NDIA Environmental and Energy Symposium & Exposition, 5–8 April 2004, San Diego, CA.

[14] Erickson, Abernathy, Boggs, Chafin, Davis, Mitchell, Thompson, and Zellmer, "Status of China Lake Permit to Treat Explosive Hazardous Waste by Open Detonation," 2004 Global Demilitarization Symposium, 19 May 2004, Dallas, TX.

[15] Erickson, Abernathy, Boggs, Chafin, Davis, Mitchell, Thompson, and Zellmer, "Health Risk Assessment for Open Detonation," 2004 JANNAF Safety and Environmental Protection Subcommittee Meeting, Seattle, WA, 28 July 2004.

[16] Erickson, Chafin, Abernathy, Zellmer, and Boggs, "Permitting of OB/OD Treatment of Energetic Wastes at China Lake: A Success Story," 2005 Global Demilitarization Symposium, 12 May 2005, Sparks, NV.

[17] Erickson, Chafin, Abernathy, Zellmer, and Boggs, *Emission Factors for Energetic Wastes Treated by Open Detonation*, Naval Air Warfare Center Weapons Division, China Lake, CA (NAWCWD TP 8603, Publication UNCLASSIFIED), May 2005.

[18] The EPA emission factor databases are derived from a number of sources, but they principally rely on data obtained from "bang box" tests. Dr. William Mitchell, retired from EPA Research Triangle Park, NC, has made significant contributions to both the content and organization of these databases.

facilities are fully characterized in the MIDAS database (i.e., derived from the demilitarization stockpile). All of the constituents in such "standard" items are summarized by type and weight in MIDAS, making it a relatively straightforward process to estimate air and solid releases resulting from OB/OD waste treatment.

Current Monitoring and Operational Restrictions at China Lake

There are currently no emission monitors in place at the China Lake OD demilitarization site, which is known as Burro Canyon. There is a metrological data station located on a nearby hill that records local weather conditions. In addition, there are several air samplers and particulate monitors located throughout the China Lake installation, but these monitors are not used in conjunction with their OD demilitarization activities.

Since OD operations at China Lake are relatively infrequent, they are unlikely to be delayed due to weather restrictions. One restriction that is, however, included in their permit precludes OD operations on local "no burn" days in the region. In addition to wind direction, any unfavorable combination of pre-event air temperature, pressure, and cloud cover (all of which are time-of-day dependent) is likely to postpone an OB/OD event, which, in turn, affects operational costs.

V. Personnel and Costs

A summary of the current estimated operational costs involved in an average-sized OD event (~8K pounds of NEW) at the China Lake demilitarization site is included as Appendix B. China Lake personnel provided this estimate, and it is of interest because it identifies the variety of personnel required to plan and safely execute such treatment operations in addition to the enduring costs for facility maintenance.

VI. Conclusions

The discussion above suggests that the OB/OD operational environment in the United States reflects the influence of (1) numerous, multifaceted issues that have broad impacts and (2) some very specific, site-related issues. It is clear that both factors need to be considered to develop a good representation of the environment at a particular OB/OD treatment facility. Our discussions and review also suggest that this environment can have a profound effect on the capability and/or desire of an OB/OD treatment facility to introduce new technology such as an SMA designed to monitor emissions from the facility's operations.

Chapter 3: User Requirements and Needs from an Emissions Sensing System

I. Introduction

The goal of this part of the analysis of an OB/OD emissions SMA is to evaluate the user needs aspects of such a system in order to better understand the system requirements that will most effectively respond to these needs. The first step in this activity is to define the customer set and then to identify those system features and attributes that are important to them. A final subtask is to find a way to measure the relative importance of different system attributes so that system requirements can most appropriately reflect real customer needs.

System functions and attributes are important because they are the means by which any device serves user needs. This theme continually re-emerges throughout the product development literature. Thus, a key first step in any analysis of system requirements is to identify those who will be using the device or system.

A most inclusive customer population is used here in order to capture the widest range of interested individuals. Users are then grouped according to their interests or mode of interaction with the system. Concerns and interest of the several groupings are then identified and explored. Finally, system features and attributes are evaluated in light of the interests and concerns of customer groups.

II. Methodology

The purpose of this user requirements study is to provide one of the four elements that have been identified as key inputs for the overall systems analysis.

Much of the input for the study is based on the experience of the study team supplemented by information supplied by experienced members of the demil community with direct knowledge of OB/OD. This was augmented by material obtained as the result of extensive Internet and database searches. Proceedings of the Global Demil Symposium and Exhibition and Demil Users Group Meeting for 2001, 2002, and 2003 were excellent sources of detailed information on current trends in OB/OD.

In the best of all worlds, extensive interviews and site visits would be used to develop a comprehensive data set from which to synthesize the information contained in this report. These efforts, along with the results of focus groups, are classic methods for the identification and analysis of user needs in product development. Extensive use of these tools was not possible in this study because of limitations of available resources. Nevertheless, the study team believes that due in large measure to the great level of enthusiasm and support given by the demil community, the results reported here are sufficient to provide a valid reference and input for the overall System Analysis effort.

The analytical approach used in Table 1 to evaluate the correlation between user types and system attributes is similar to quality function deployment (QFD)[19], a technique developed for identifying those product functions with the strongest links to satisfying customer needs. The numerical entries in each cell are the "best guess" subjective consensus of the study team and should by no means be viewed definitively. It is believed that the results serve as a valid general guide to the relative importance of the identified system attributes in meeting the needs of the types of users listed. Finally, it is noted that many of the entries in the "target values" row remain to be determined (TBD) because at this stage of the analysis, not enough detail is known about available technologies and the key species to be measured.

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[19] Hauser, J., "The House of Quality," Harvard Business Review, May-June, 1988.

However, setting target values will be a key step at some early stage in the development of systems requirements for the OB/OD SMA system.

III. Who Are the Users?

A first consideration is to answer the question, "Who is a 'customer' or 'user' of the system?" Of the many possible answers, the one that will be used here defines a user as anyone who interacts with the system, or information generated by the system, after it is installed and operating in the field. As noted above and reviewed below, this is a very broad and inclusive definition, but it is appropriate for the task at hand.

IV. Categories of Users

"User," as defined above, covers a very wide range of individuals. These would include, for example, those who operate the system on a routine basis and those who may be called in to maintain, calibrate, or repair the unit. In addition, it encompasses those who rely on the output from the system, such as program or facility administrators; state, federal, and/or local regulatory officials; or the interested general public. This definition also embraces individuals with budgetary or funding roles: those who must provide funds to pay for the installation and ongoing operation of the equipment.

For the purposes of the present analysis, it is useful to develop groupings of users based on the nature of their interest or relationship to the equipment, rather than trying to assess the wants or needs of every individual customer. Taking this approach, three general categories of users for an OB/OD emissions SMA emerge. They are the following:

1. OB/OD operations personnel
2. Regulatory authorities
3. Other interested parties

OB/OD Operations and Support Staff

One important category of users is those who are engaged in ongoing demil OB/OD operations. These individuals will interact with the system on a routine, often daily basis and will be responsible for the start-up, operation, and shutdown of the systems and subsystems. They may also be expected to perform system calibrations and routinely scheduled maintenance, although this responsibility may fall to other support staff if they are available. From a demil operations point of view, certain line managers may also be considered to fall into this category of users, even though they aren't likely to have direct, routine interaction with the system.

Regulatory Community

A second key category of users for an OB/OD emissions SMA is those individuals who are responsible for ensuring that OB/OD operations comply with environmental regulations and that such operations are being performed in accordance with the requirements of applicable permits. Examples of such individuals include federal agencies (e.g., EPA); state agencies (e.g., state EPA, toxic substance control); regional and district agencies (e.g., air and water quality districts); and, perhaps, even local regulatory authorities. These are individuals who are interested in using the system outputs, the emissions measurements themselves, for assurance of regulatory compliance. Indeed, satisfying the concerns of this regulatory community is one of the primary drivers for the development of an OB/OD emissions sensing system.

Other Interested Parties

Many individuals who are neither engaged in OB/OD operations nor responsible for assuring regulatory compliance of such operations may still be thought of as users of an OB/OD emissions SMA. This mix of other interested parties includes higher-level program managers at demil installations or facilities, program managers in government agencies (e.g., DoD, Department of Homeland Security [DHS], Department of Energy [DOE]), other nonfederal government agencies, equipment service technicians who may be called in periodically to address a specific equipment problem, the general public (e.g., "concerned citizens"), and scientists interested in interpreting the resulting data. This category of users is somewhat more distant from the routine use of the equipment, and they are not directly responsible for assuring regulatory compliance of the OB/OD operation, but they are nonetheless interested in or affected by the system and its attributes and performance.

V. OB/OD Operations

Who Does the Work and How Is the Work Done[20]?

OB/OD operations work at U.S. Army depots and plants is performed by civilian employees. At contractor facilities (e.g., Hawthorne, NV) the work is done by contractor employees. These individuals excavate the "pits" and place the munitions in them. Generally speaking, the workers have modest education beyond high school, but they do receive the necessary classroom instruction and field training in hazardous waste disposal and explosives safety. Quality assurance specialist ammunition surveillance staff, whose primary function in the OB/OD context is inventory control of the munitions being demilled, may be available to assist with safety.

In this kind of facility, the shift supervisor would most likely be responsible for equipment operation. Typically, the shift supervisor will have long experience in OB/OD operations, having "come up through the ranks." In a typical operation today, the supervisor's responsibilities include recording meteorological data, if that is required, and performing necessary operating checks of equipment. For a future OB/OD emissions monitoring system, the supervisor would be expected to make sure that the system is on and functioning properly.

If any aspect of operation of the OB/OD emissions monitoring system requires training and experience beyond that of the OB/OD shift supervisor, there may be two alternative possibilities. The plant or depot environmental staff, which is responsible for reporting emissions from OB/OD operations to local, state, and/or federal regulators, may offer a more highly trained group of individuals to address such challenges.

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[20] Information provided by personal communication with U.S. Army Defense Ammunition Center (DAC) staff, 2/12/04.

A second alternative is that if the depot or plant has an on-site chemistry facility (not all do), the lab staff might be assigned responsibility for the operation and maintenance of the equipment.

Decisions regarding actual OB/OD operations details are made locally at the plant or depot. Indeed, some decisions regarding the actual stacking configuration of munitions being demilled by OD is determined on-site. In a hypothetical example, if the workload requires OD of hand grenades and anti-tank mines, the anti-tank mines may be used as "donor charge" for the OD event. Generally though, there are standard documented configurations for setting up the detonations. For example, if a certain number of 155-mm high-explosive (HE) projectiles are being demilled by OD, the placement of detonators and detonation cord are well documented and prescribed. If there is no experience with OD of a specific munitions item, then a few test events will be used to verify that a good detonation results. This then will serve as the basis for subsequent OD operations.

Aspects of OD Operations at McAlester Army Ammunition Plant, McAlester, Oklahoma

As one example of "standard" procedures, OD operations at MCAAP may be typical. For any plant or depot, including McAlester, an annual workload (what items and how many) plan is submitted to the Joint Munitions Command (JMC), Rock Island, IL. The JMC funds the workload at a given dollar amount, but decisions are made locally at MCAAP regarding details of OD operations. The amount of explosive per OD event is limited by considerations of the impacts of noise, shock, and other factors on the surrounding community. At MCAAP, there is a permit limit of 500 pound NEW per detonation. In most cases, however, actual OD events at MCAAP are limited to 200–250 pound NEW because experience has shown that larger amounts give rise to complaints from the surrounding community.

At MCAAP, OD events take place in pits that are surrounded on three sides by earthen berms. The munitions themselves are buried prior to detonation as a noise suppression measure. This, of course, produces more dust in the OD plume. Noise and shock suppression are major concerns and determine the limits on the amount of HE that is used per OD event.

Aspects of OD Operations at the Naval Air Weapons Station, China Lake, CA[21]

OD of energetic contaminated waste at the Naval Air Weapons Station (NAWS), China Lake represents an important but atypical OD operation. The work at China Lake is not a part of the JMC program to reduce the demil stockpile. Rather, OD at China Lake (OB was used in the past but has been discontinued at the site) is used for disposal of energetic wastes produced by research, development, test, and evaluation efforts at that facility.

OD events at China Lake are usually done on a monthly basis, but occasionally more frequently depending on need. Typical events will destroy 8,000-10,000 pounds NEW each (China Lake is permitted for 15,000 pounds). The actual OD operations are carried out by US Navy EOD personnel. Simple meteorological data are recorded (e.g., wind speed, direction, humidity) from a location approximately one mile from and well above the detonation site. The explosive waste is not buried but is detonated on the desert surface with "ground zero" being approximately 17 miles from the fence line in the direction of the prevailing wind. OD operations are restricted to "agricultural burn" days (state generated) only. China Lake is in the final phases of the re-permitting process, having developed good working relationships with the CalEPA DTSC for RCRA and the local air quality district on airborne emissions. Though clearly concerned about all aspects of OD emissions, the regulatory community has expressed particular concern about the fate of metals from the China Lake OD events.[22,23]

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[21] Information provided by personal communication with NAWS, China Lake staff,

[22] Boggs, "Metal Emission Factors for Open Detonation of Munitions," 2004 Global Demilitarization Symposium, 19 May 2004, Dallas, TX.

VI. The Regulatory Community

What OB/OD Emissions Are of Regulatory Concern?

The categories of emissions that are of concern in OB/OD fall into five broad categories. These are

- Particulates (especially particulate matter up to 10 µm in size [PM_{10}])
- "Inorganic" products of detonation and combustion (e.g. CO_2, CO, NO_x, SO_x)
- Volatile organic species
- Semi-volatile organic species
- Toxic metals

There are many extensive listings of the chemicals of concern for OB/OD emissions. But it may be helpful to note that the oft-cited reference work of Mitchell and Suggs[24] suggests that emission products from most energetic materials (EM) destroyed by OB and OD processes will be adequately represented by the following analytes: CO_2, CO, NO, NO_2, total saturated hydrocarbons (e.g., ethane, propane, butane), acetylene, propene, benzene, toluene, and particulates. In the present context, it is interesting to note that metal emissions aren't included in the list.

Detailed listings of chemicals of regulatory concern may vary depending on the geographic location of the OB/OD operations and which regulatory agency has authority over the operation. China Lake has, for example, has developed a list of 982 compounds based in total on the following:

- California Assembly Bill 2588, Air Toxic "Hot Spots" Information and Assessment Act
- EPA Region IX Preliminary Remediation Goals
- China Lake 1996 Preliminary HRA
- Compounds from on-site lab tests

From this extensive list, 389 (approximately 40% of the total) have been identified as having health risk concerns and are specifically included in the regulatory guidelines.[25-34]

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[23] Atienzamoore, Boggs, Heimdahl, Pepi, Hibbs, Wells, Martyn, Wooldridge, Gerber, Abernathy, and Zellmer, *Metal Emissions from the Open Detonation Treatment of Energetic Wastes*, Naval Air Warfare Center Weapons Division, China Lake, CA (NAWCWD TP 8528, Publication UNCLASSIFIED), July 2004.
[24] Mitchell, W. & Suggs, J. "Emission Factors for the Disposal of Energetic Material by Open Burn and Open Detonation (OB/OD)," EPA/600/R-98/103.
[25] Boggs, Zellmer, AtienzaMoore, Hoover, Quintana, Nissan, Erickson, Chafin, Fridley, Osburn, and Mohn, "Treatment of Energetic Wastes by Open Detonation at China Lake," 2002 Global Demilitarization Symposium, Lexington, KY, 20–24 May 2001.
[26] AtienzaMoore, Boggs, Chafin, Erickson, Fridley, Hoover, Lindfors, Mohn, Nissan, Osborn, Quintana, and Zellmer, "Treatment of Energetic Waste by Open Detonation: Status of China Lake Permit", 2002 Demilitarization Users Group Meeting, San Diego, CA, 29–30 Oct 2002.
[27] Erickson, Chafin, Hoover, Boggs, Zellmer, Abernathy, Thompson, Davis, and Mitchell, "Emission Factors Associated With Treatment of Energetic Hazardous Waste by Open Detonation," 2003 JANNAF Safety and Environmental Protection Subcommittee Meeting, Charlottesville, VA, 25–27 March 2003.
[28] Erickson, AtienzaMoore, Boggs, Chafin, Lindfors, Zellmer, Abernathy, Gerber, Carson, Davis, and Hottenstein, "Emissions from the Detonation of Explosive Contaminated Wastes," 2003 Global Demilitarization Symposium, Sparks, NV, 22 May 2003.
[29] Erickson, Chafin, Hoover, Boggs, Zellmer, Abernathy, Thompson, Davis, and Mitchell, "Protocol for Determining Emission Factors from Open Detonation of Munitions and the Application to TNT-based Explosives," 2003 Global Demilitarization Symposium, Sparks, NV, 22 May 2003.

Development of an HRA is a key step in the permitting process for the treatment of explosive hazardous waste by OB/OD. Part of the HRA process requires developing an estimate of the cancer, acute non-cancer, and chronic non-cancer risks from the products generated by the OB/OD event. In order to do this, emissions from the detonation and follow-on combustion processes must be determined, along with any collateral material that may be swept up and carried into the plume by the explosive process.

How Are OB/OD Emissions Regulated?

Regulatory Agencies

At some demil facilities, OB/OD emissions are regulated by the EPA. However, the EPA may delegate regulatory authority to states that agree to maintain environmental standards at least as stringent as the federal regulations. Thus, regulation of emissions from OB/OD events varies from facility to facility, depending on the local regulatory environment.

The state equivalent of EPA can take many forms. For example, in California, RCRA provisions regarding toxics are enforced by the CalEPA DTSC, while air quality is subject to the authority of regional air quality districts.

As a specific example in the state of California, NAWS, China Lake treats its energetic wastes with monthly OD events. These operations are subject to permitting by both the CalEPA DTSC, headquartered in Sacramento, CA as well as the Great Basin Unified Air Pollution District, which has its headquarters in Bishop, CA.

OB/OD operations are often limited by meteorological conditions. An example of the "Weather Parameter GO/NOGO Criteria" for OB/OD at Tooele Army Depot (TEAD) can be seen at http://www.tooele.army.mil/obod.htm, and the data for February 24, 2004, is reproduced in "Appendix C. OB/OD Weather Parameter GO/NOGO Criteria at Tooele Army Depot (TEAD)."

At TEAD, critical meteorological parameters include the following:

- Wind speed
- Cloud cover
- Cloud ceiling
- Precipitation
- Thunder/electrical
- Clearing index (a number provided by the National Weather Service involving all weather parameters)
- Visibility

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[30] Zellmer, Boggs, Erickson, Abernathy, and Atienza-Moore, "Treatment of Explosive Hazardous Wastes by Open Detonation at the Naval Air Weapons Station, China Lake, California," 30th NDIA Environmental and Energy Symposium & Exposition, 5–8 April 2004, San Diego, CA.

[31] Erickson, Abernathy, Boggs, Chafin, Davis, Mitchell, Thompson, and Zellmer, "Status of China Lake Permit to Treat Explosive Hazardous Waste by Open Detonation," 2004 Global Demilitarization Symposium, 19 May 2004, Dallas, TX.

[32] Erickson, Abernathy, Boggs, Chafin, Davis, Mitchell, Thompson, and Zellmer, "Health Risk Assessment for Open Detonation," 2004 JANNAF Safety and Environmental Protection Subcommittee Meeting, Seattle, WA, 28 July 2004.

[33] Erickson, Chafin, Abernathy, Zellmer, and Boggs, "Permitting of OB/OD Treatment of Energetic Wastes at China Lake: A Success Story," 2005 Global Demilitarization Symposium, 12 May 2005, Sparks, NV.

[34] Erickson, Chafin, Abernathy, Zellmer, and Boggs, *Emission Factors for Energetic Wastes Treated by Open Detonation*, Naval Air Warfare Center Weapons Division, China Lake, CA (NAWCWD TP 8603, Publication UNCLASSIFIED), May 2005.

For this facility, GO/NOGO status is determined by comparing actual and forecasted weather conditions with parametric values established in conjunction with U.S. Army regulations and the state of Utah.

The Regulatory Perspective

From the perspective of the regulatory community, OB/OD emissions monitoring is a tool to verify compliance with regulatory guidelines and permits. For this purpose, an "ideal" emission monitoring system would be capable of measuring all emissions of concern at whatever level is necessary based on an accepted HRA. This is probably unrealistic, given that many of the most toxic chemicals of concern are produced at the lowest levels.

One attractive approach to the difficult challenge of measuring emissions from OB/OD events is to apply predictive models and simulations of the various phenomena that compose such an event. Thus, many computer models of evolution and dispersion of an OD plume have been developed. For this approach to work, knowledge of the composition of material being burned or detonated (both HE and inert components), a detailed understanding of detonation chemistry, a detailed understanding of combustion chemistry in the "fireball," and the dispersion model for transport of the resulting plume are required. Unfortunately, there is much to suggest that the regulatory community remains skeptical of the validity of such computer modeling of OB/OD.

Practically speaking, it seems reasonable that measurement of some easily detected key emissions might be used to provide validation for assumed releases based on computer modeling of detonation and combustion chemistry and OD plume dispersion.

VII. Program Managers, Administrators, and Other Interested Parties

Program managers and other administrative personnel who are responsible for programs or facilities doing OB/OD are generally concerned about providing the tools and resources necessary to do the job. From this higher level point of view, OB/OD emissions monitoring is useful if it is required or if it allows the job to be done more easily or efficiently.

The primary goal of this user community is improved efficiency of the detonation process while maintaining low treatment costs. These users would be linked to the OB/OD emissions measurement system, but only at an extreme distance. Thus, they are not expected to be concerned by "up close and personal" concerns, such as ease of use, reliability, accuracy, and robustness, except to the degree that these systems attributes affect cost or productivity.

VIII. System Functions

Required functionality strongly influences the ability of a system to respond to the needs of the customer set. It is, after all, the system functions that provide the means to meet user needs. For example a product that incorporates such functional features such as self-diagnostics and self-calibration is likely to be much easier to use than one that is manually calibrated and requires an operator or service technician for troubleshooting.

The outline in Appendix D provides a top-level view of the kinds of functions that will need to be provided by sensors for different kinds of OB/OD emission species. These system functions may be further combined into groups that more directly respond to customer needs. Thus, self-diagnostics and self-calibration may both be elements in the category of "ease of use." Self-diagnostics may also be a factor in short mean time to replace (MTTR), while self-calibration may be related to "accuracy." In this way, system functions can be more directly correlated with responding to the needs of specific users.

IX. User Requirements

System Attributes

Based on the considerations and concepts presented and discussed in the foregoing pages, several general conclusions may be drawn regarding user requirements for a comprehensive OB/OD emission sensing system. Not surprisingly, the primary requirements differ, depending on which category of users is being considered. These are presented in outline form in "Appendix A. Three Types of Users."

The approach used here (there are many alternatives) for evaluating user needs is to numerically score the strength of correlation for a given customer with various features or attributes of a system. This is done in the attached table, where customer categories are featured as rows and various features of the system are listed as columns. If there is no correlation between a customer category and a system attribute a score of zero (0) is recorded. A weak correlation is scored as one (3^0). A modest correlation is given a score of 3 (3^1) and a strong interest or correlation is given a 9 (3^2). The total score for a given feature or attribute may be a useful indicator of the importance of the element to user needs as a whole. Not surprisingly, different categories of users value attributes differently.

For the case shown in Table 1 (see page 34), users were on average, most concerned about robustness, as expressed by a mean time between failure (MTBF), and reliability (scores of 55 and 57, respectively). Sensitivity, specificity, accuracy, and ease of use were also highly valued. Cost factors were recorded as least important overall, although they were highly important to program managers and administrators, whose budgets would have to pay the cost of installation and operation of the OB/OD emissions monitoring equipment. This may be a case where the simple numerical approach needs to be placed in context, because cost is clearly an important consideration when alternative, though less attractive, technologies are available.

Nevertheless, it seems certain that a rugged, reliable system that has a low cost to install, maintain, and operate is essential. The system must also have adequate sensitivity and specificity to assure the accuracy of the results of OB/OD emissions measurements.

Emissions Sensors

Unfortunately the questions of (1) precisely which OB/OD emission species must be measured and (2) what are the best technical approaches to making such measurements remain unanswered. And, based on input from the regulatory and demil communities[35], the appropriate role of computer modeling and simulation in characterizing the composition of the plume generated by an OB/OD event remains unclear. Even so, it can be concluded that the following minimum set of emissions measurement capability is required:

- Meteorology (e.g., wind speed and direction, humidity, etc.)
- Plume tracking
- CO and CO_2
- Particulates
- NO and NO_x
- Metals (if this is determined to be a serious health risk [or regulatory] problem)

[35] Interviews with 12 experts in OB/OD demil were included as a part of the technology survey for the systems analysis.

Meteorological conditions are already considered as a part of the criteria for determining if OB or OD operations can occur. Plume tracking will be required so that other emissions sensing and measuring devices know where measurements need to be taken. The ratio of CO to CO_2 in the plume generated by detonation and combustion chemistries is generally considered as a valid measure of the completeness of combustion during an OB/OD event. There is some controversy as to whether completeness of combustion is sufficient to allow valid estimates of the identities and quantities of organic species in the plume. If this can be done by modeling and simulation, then CO and CO_2 alone may be adequate. If not, additional chemical species sensing elements will be required to fully characterize these emissions. In either case, the measurement of CO and CO_2 is essential.

Particulates in the plume are created during detonation and combustion events, but they are also generated from dust and soil that is swept up in the buoyant OB/OD plume. Determination of particle size distribution, at least between $PM_{2.5}$ and PM_{10} will probably be a key measure of this emission component. Determination of the chemical composition of particulates may be desirable as well.

Considerable attention has been focused on the fate of metals from OD events[36]. Given the intended design of many munitions items to produce shrapnel upon detonation, an assumption that a large portion of the metal content enters the plume as vapor is not valid. And given the ubiquitous nature of iron and other metals in steel in the environment, this is not expected to be an area of concern in OB/OD emissions measurement. However, measures of emissions from vaporization of more toxic metals, such as cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), etc. may ultimately be required.

[36] Mitchell, W., Boggs, T. & Thompson, G. "Toxic Metal Emissions Factors for use in OD Health Risk Assessments," 12th Demil Users Group Meeting, 28–30 October 2003, Atlanta GA.

Table 1. Correlations between Types of Users and System Attributes for OB/OD Emissions Sensor Management Architecture.

	Ease of Use	Ease of Maintenance & Repair	Long Mean Time Between Failure (MTBF)	Short Mean Time to Replace (MTTR)	Sensitivity	Specificity	Accuracy	Low Capital Cost	Low Operating Cost	Reliability
OB/OD Operations										
OB/OD Workers	9	3	3	3	0	0	0	0	0	3
OB/OD Supervisor	3	9	9	9	0	0	0	0	3	3
Explosive Ordnance Disposal Technician	9	3	3	3	0	0	0	0	0	3
Data Analyzer/Interpreter	1	1	1	1	3	3	9	1	1	3
Government Regulators										
U.S. Environmental Protection Agency	1	0	9	3	9	9	9	0	0	9
State Hazardous Materials	1	0	9	3	9	9	9	0	0	9
Air Quality Regulator	1	0	9	3	9	9	9	0	0	9
Occupational Safety and Health Administration	3	3	3	3	0	0	0	0	0	3
Other Interested Parties										
Administrators	3	3	3	3	3	3	3	9	9	3
Program Managers	3	3	3	3	3	3	3	9	9	3
Public	0	0	3	0	9	9	9	1	1	9
Total	34	25	55	34	45	45	51	20	23	57
Target Value	Run by present OB/OD staff	Scheduled maintenance by OB/OD staff	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Higher

Chapter 4: Description of the Sensor Management Architecture (SMA)

Note: This report summarizes capabilities and advantages Sandia's SMA provides the OB/OD sensor system in the absence of user requirements or requests.

Sandia is developing an integrated hardware and software architecture, the SMA, to support rapidly deployable, sensor network integration and control. Supporting applications across wide-area urban settings as well as single facilities, Sandia's architecture was developed by the U.S. DOE/National Nuclear Security Administration (NNSA) to support homeland security applications in integrating heterogeneous weapons of mass destruction detection technologies into unified sensor networks. Sandia's SMA has been deployed in support of three U.S. DOE/NNSA, DHS Science and Technology Directorate, and DoD/Defense Threat Reduction Agency projects.

Two of the key technical challenges addressed with Sandia's architecture are the ability to monitor and control a broad variety of sensor systems that are, for example, scattered throughout a large facility, and to interface with command and control systems both internal and external to the facility. To meet these challenges, the SMA was developed to manage the various sensor systems deployed throughout a facility and to communicate information to local or remotely located control centers. The SMA also integrates command and control capabilities with information received from other aspects of facilities operations.

The SMA facilitates real-time monitoring and control of the sensors by providing status and operational information directly to a control center or remotely located monitoring stations. Sensor systems can provide sophisticated status and detection information, as well as distributed control; alarm threshold levels, data processing algorithms, and other features of the sensors can be changed remotely via the SMA in real time. Status information, including tamper detection, is also provided. This ability to remotely monitor and control many distributed sensors and to include information about their physical security from multiple locations is a critical and essential feature of a robust and secure sensor system. Without this, each sensor would have to be monitored and controlled through direct physical access, which is often not practical, or even possible in hazardous environments.

The SMA is based on two Sandia-developed technologies: intelligent sensing modules (ISMs) and the enterprise modeling framework (EMF). In SMA deployments, the ISM hardware provides the wireless communication and data processing capabilities required for sensor communication, and the EMF software provides the data integration architecture and client/server communication capabilities.

ISMs (as shown in Figure 1) use an innovative combination of embedded computation, noise-immune spread spectrum wireless intercommunication, real-time telemetry for integrated and interfaced sensor systems, and a distributed software framework—a subset of the EMF—for data aggregation and visualization. Up to four external hardware devices, or sensors, can be simultaneously connected to an ISM. Typical interfaced devices include chemical, biological, and radiological detection systems. Standard communication protocols (serial, IP, etc.) between a detector and the ISM are accommodated. The ISM's embedded software framework includes a store and forward mechanism guaranteeing message delivery, message authentication, privacy, and data integrity. In addition, an integrated ISM application loader supports the simultaneous execution of multiple applications, including a device manager that monitors and controls connected detection systems.

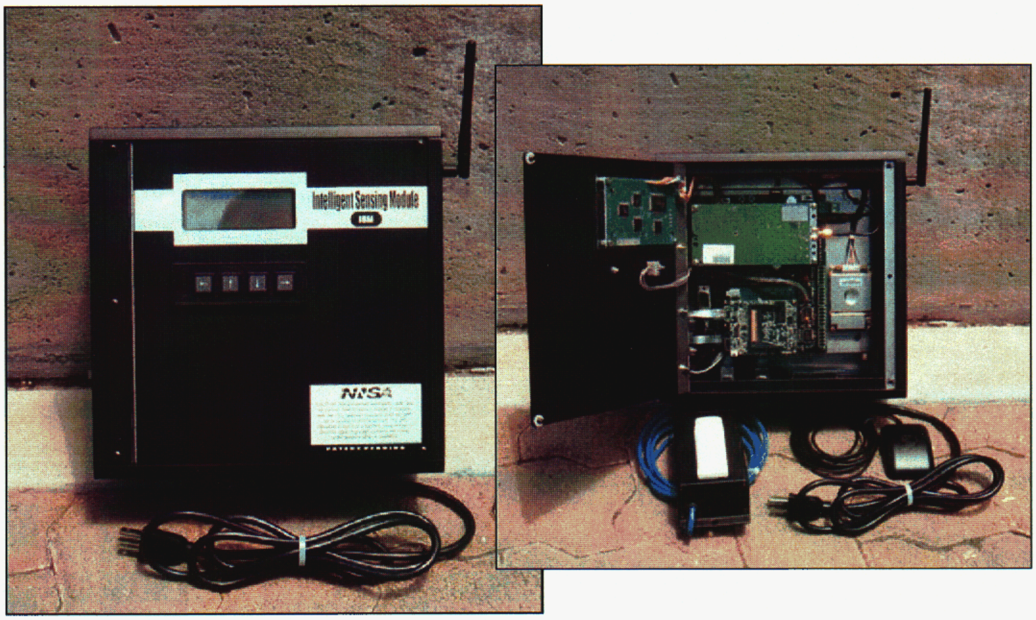

Figure 1. Intelligent sensing module (ISM) v4.1, shown both packaged and with hinged cover open, to include connectivity to an external global positioning system antenna and a single instance of a sensor module.

The EMF is an information unification software framework that supports the creation and execution of computationally and geographically distributed enterprise models. The EMF allows remotely located clients to participate in EMF-based applications based on the user's job function or "role." By providing communication, security, and data integration capabilities, the EMF facilitates enterprise modeling in the areas of operations, decision analysis, decision support, and integrated planning, in particular, the evaluation of complex responses to real-time devices and human-in-the-loop systems containing multiple autonomous, interacting entities. The SMA uses the EMF to integrate remote data feeds (from inside and outside the facility), real-time sensor system integration (via ISMs), and multiple, need-to-know-controlled, distributed human-in-the-loop interaction and control points.

The "role-based" access control enabled by the EMF architecture provides another critical capability of a sensor management system. In a defensive system, role-based access control is desirable to limit the information provided to specific users and to allow only a certain degree of control over sensor systems. This capability allows the exploration of various facilities control configurations without rewriting the monitoring system software. Leveraging the distributed nature of the EMF, the SMA supports multiple software clients at remote locations over network connections. Each of the SMA clients can have complete access to all data and full control of the deployed sensor systems, which greatly simplifies development, testing, and operations. Or, if required by the facilities operation manager, each client can be configured to allow different levels of access to data and control of the deployed sensor systems.

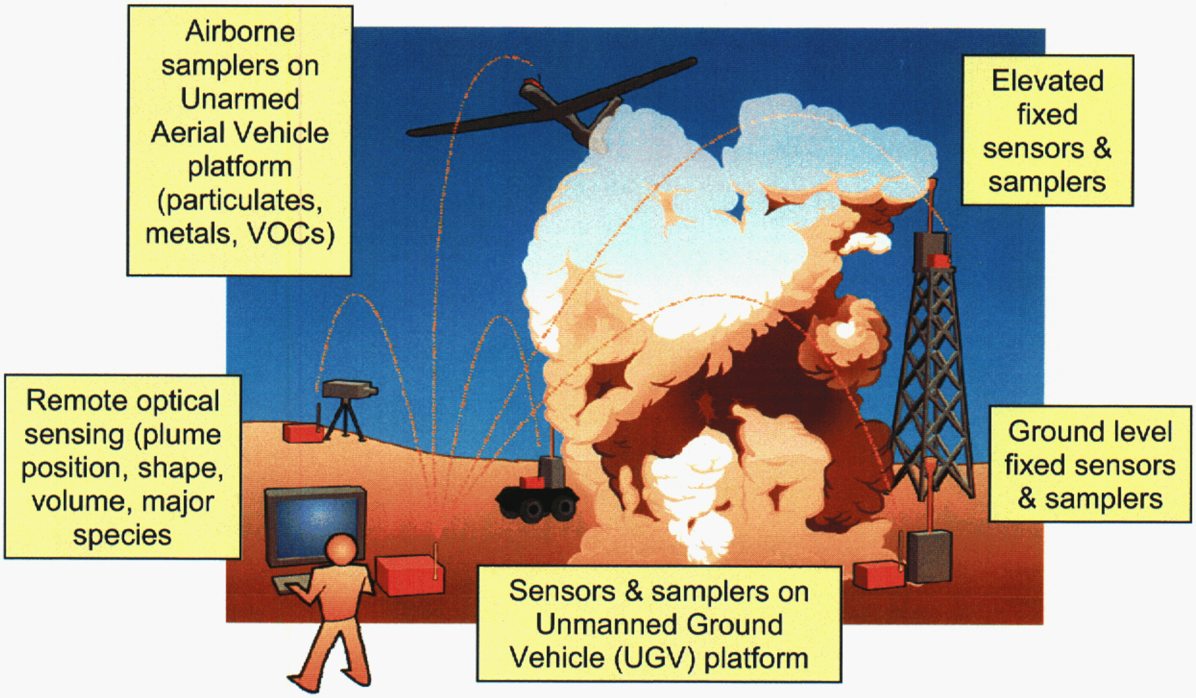

Figure 2. Example OB/OD emissions sensing application through SMA integration.

In the OB/OD emissions sensing application (Figure 2), the ISM's innovative combined use of embedded computation, wireless intercommunication, real-time telemetry for integrated and interfaced sensor and detection systems, and a distributed software framework for data aggregation and visualization provides a seamless means of turning a disjoint collection of sensors into a homogenous sensor network. This capability can vastly improve the user's situational awareness of the OB/OD process in real time and can enable process procedures to be adjusted either automatically, based on preset event thresholds, or through "human-in-the-loop" decision making. The status of the sensor system and specific data are presented to the user at the control center or monitoring station via a graphical user interface (GUI). The SMA GUI is divided into two main sections, as shown in the examples in Figure 3. One half of the display shows a floor plan of the facility. The colored squares indicate the location of sensor systems.

The other half of the display contains tabular panes for each of the deployed sensor systems in the facility, organized by sensor phenomenology category. The sensor system locations on the facility floor plan are actively linked to the tabulated panes of information, so that a mouse click on the correct colored square will bring up a listing of the detectors deployed at that location. In many cases, the SMA has several levels of information that can be displayed for each sensor, including time history plots of collected data, control information, and system performance data. Additional screens allow detailed control of the sensors—for example, setting of threshold levels, data interpretation algorithms, etc.

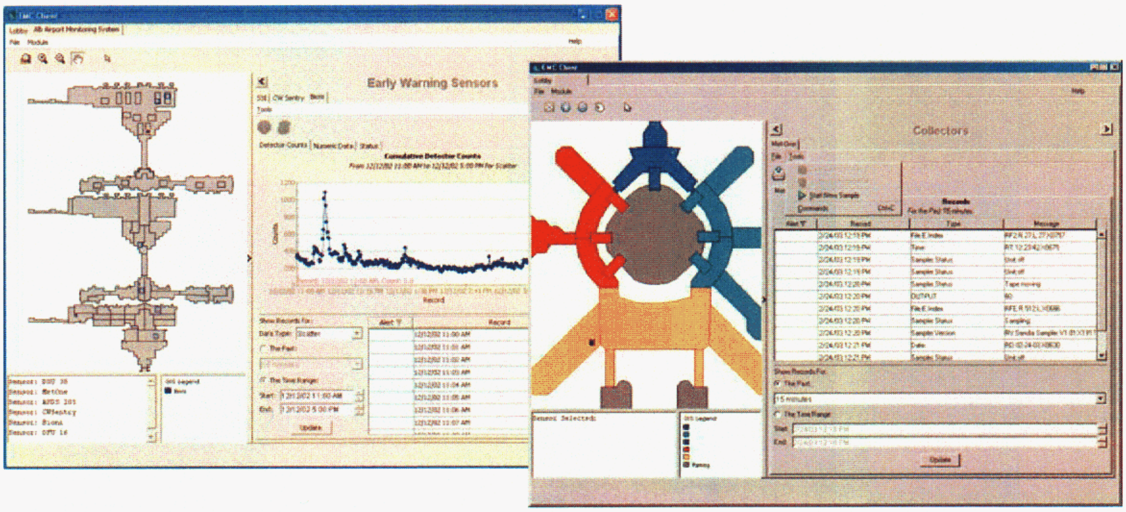

Figure 3: Example EMF screens, showing distributed sensor monitoring and control.

The following summarizes the advantages of the SMA approach to sensor integration and management.

SMA

- An intelligent, rapidly deployable sensor integration and management architecture supporting operations and simulation.
- Integrates heterogeneous, fixed and mobile detection technologies into unified sensor networks.
- Modular hardware and software component design, standards-based (Institute of Electrical and Electronics Engineers).
- Support evaluation, selection, and performance validation of detection systems.
- Scalable detection system architecture.
- Support real-time detection, communication, command, and control.
- Support long-term production deployment.

SMA Hardware (ISMs)

- Simultaneously coupleable to multiple external detection systems.
- Coupleable to environmental sensor modules.
- Support multiple processors, parallel computation, and cooperative execution.
- Plurality of wireless modems, including star topology, peer-to-peer topology, and cellular telephone network control channel.
- Support wireless transmission over long distances and through dense building materials.
- Portability for rapid system reconfiguration and use on mobile platforms.
- Advanced power management.
- Data aggregation through communication with a plurality of sensing modules.
- Communication channel bridging.

SMA Software (EMF/EMA)

- Distributed, need-to-know controlled client access to sensor systems.
- Intelligent embedded model, processor configured to execute a model to predict a measurement from the detector.
- Exporting user interface information, including access to a subset of said information, based on an assigned role.
- Data visualization for real-time and post-event data analysis.
- Interpretation of detection data and preprocessing to a common data format.
- Data management supporting data unification, storage, and retrieval.
- Distributed architecture, bridge local and distant detection systems and participants, with local and distant command and control.

Summary Definitions

Intelligent sensing modules (ISMs) are hardware integration platforms using an innovative combination of embedded computation, noise-immune spread-spectrum wireless intercommunication, real-time telemetry for integrated and interfaced sensor and detection systems, and a distributed software framework for data aggregation and visualization. ISMs intelligently link together sensor systems to provide early OB/OD detection. ISMs are responsible for ad hoc configuration of the sensor network, translation of sensor-collected data, remote wireless control of detection systems, and wireless transmission of results for centralized dissemination.

Enterprise modeling framework (EMF) is an information unification software framework providing need-to-know-based access control to distributed, hierarchical, multi-owner, information systems and simulations. The EMF supports the creation and execution of computationally and geographically distributed enterprise simulation and data models. Remotely located clients participate in EMF-based applications through a user's job function or "role." By providing communication, security, and data integration capabilities, the EMF facilitates enterprise modeling in the areas of operations, decision analysis, decision support, and integrated planning, in particular, the evaluation of complex responses to real-time devices and human-in-the-loop systems containing multiple autonomous, interacting entities.

Sensor management architecture (SMA) is a unified hardware and software architecture that uses the EMF and ISMs to integrate remote confederate data feeds, real-time sensor system integration, and multiple, need-to-know-controlled, distributed human-in-the-loop interaction and control points.

Chapter 5: Review of Sensor Technology Applicability

I. Emissions Sensor Technology Analysis

Disposal of conventional munitions via OB/OD is an enormously complex problem. The issues are only exacerbated by the continual shifts in the political, economic, and environmental factors affecting disposal of munitions as well as changes in the actual U.S. disposal stockpile and the "virtual stockpile" that includes our foreign demilitarization commitments. One of the proposed solutions to address the environmental concerns raised by the potential release of hazardous air emissions, is full-scale monitoring of the chemical species released during an OB/OD operation. This is a difficult task at best, owing to the fact that there are many different possible species that could exist after an OB/OD event and in a variety of states (gas phase, solid-phase particulate, aerosols, particulate adsorbed species, etc.) Additionally, there currently exists no fixed standard for what species at what levels are acceptable or what species should or should not be monitored; each facility was permitted on a case-by-case basis, potentially involving different regulators emphasizing different issues. However, there are technologies available or in development that can detect the possible species of concern, and our goal here is to review those technologies.

The purpose of this document is to provide an accompanying perspective to the technology discovery document in Appendix E. The assessment presented here is the result of comparing stated and perceived criteria for an OB/OD emissions monitoring sensor network against the suite of candidate technologies to determine the suitability of each technology area or device for inclusion. Where applicable, the merits or shortcomings of the technologies are discussed from a scientific, technical, economic, environmental, and/or sociopolitical perspective to give the reader additional information. Since the SMA concept of remotely operating the instrument suite and gathering and displaying the data is an integral part of sensor system, the applicability of the sensor technologies within this architecture will also be discussed.

The analysis is based on the current state of technology and the bounding factors existing in the current OB/OD environment. The reader is referred to the document in Appendix E for full details about the methodology used to unveil the technology list and for more specific information about each device. The reader is also referred to the Sections 2 and 3 for information about the state of limited resources in OB/OD operations that provide the boundaries for this problem. The information provided herein is intended to be accurate and is based only on the currently available information.

II. Critical Properties for Sensor Technologies

There are a number of elements that bound the problem and limit the candidate technologies for use within the sensor system. These elements span a wide range of key issues and include not only technical issues but also the application of resources with respect to the function of the system. It is useful to refine the definition of various properties of the instruments outlined in the Perspectives document. This makes it easier to understand some of the technical issues with respect to implementation in a sensor network.

These properties are defined below and include a description of which state of the property is beneficial for the OB/OD emissions sensor system. These properties form the base criteria for evaluating the sensor technologies listed later in this document. Specific details regarding the preferred state of the property are given where possible. However, the SMA, like all analytical systems, is limited by boundary conditions and it is at the discretion of the customer to choose the appropriate trade-offs.

- Current state of development
- Acquisition cost
- Operational cost
- Operational complexity
- Data complexity
- Data analysis and output
- Fieldability/deployability
- Range
- Sampling interface
- Sensitivity
- Selectivity
- Multiplex advantage

Current State of Development.

This issue addresses the actual state of the technology and its readiness for implementation in the field. There are three general stages in instrument development. Most start with a proof-of-principle, demonstrating whether the theory of the instrument's operational mode actually performs in practice. Usually this involves bench scale designs operated under controlled conditions with specifically tailored samples. Next, the "shoestrings and duct tape" need to be replaced with a more sound engineering design. This stage includes mechanical, electrical, and computer engineering, as well as finalization of any methodology for inclusion in the final instrument. These instruments perform well under a wider variety of conditions with a full variety of samples but under controlled experimental conditions. Last is the robustness or hardness of the instrument for the rigors of field use, especially in the OB/OD field, which has its own set of technical challenges. This model is not necessarily true for one-of-a-kind instruments, where the prototype is usually the final product. The further developed the instrument, the more applicable the system is toward the emissions sensor system.

Acquisition Cost

Each instrument has a capital cost for acquisition of the instrument. This includes, but is not limited to, the base cost of the instrument, additional features, data acquisition equipment, instrument control equipment, and sampling devices. The ISMs along with their associated hardware and software would be included in this cost as required. Less expensive is better on an individual institution basis. However, higher-expense equipment could be shared across organizations, reducing the individual cost commitment.

Operational Cost

Some of the operational costs are specifically related to the instrument such as, but not limited to, instrument consumables, maintenance and repair, and overhead costs (electricity, fuel). There are other nonobvious operational costs, such as salaries for the operator and data analyzer, sociopolitical ramifications of taking the measurements, conformation to local codes of operation (e.g., flight plans, transmission frequencies, etc.), and allowable level of operational interference. Again, the fewer resources required, the better. Additionally, if the system is shared between organizations or sites, there is an advantage in normalizing procedures between operations to decrease the resource requirements for sharing the system.

Operational Complexity

This is related to how much attention the instrument needs to operate at the requisite level of performance. It is also related to the difficulty in operating the instrument and the complexity of the system. Ideally, the instrument would only need regular preventative maintenance and/or replacement of consumables, could be operated remotely, and would not require highly skilled personnel to function. A more operationally complex instrument frequently requires a trained user that is sensitive to potentially disruptive issues with the system. High reliability is a must. As the frequency of user intervention and the required skill of the user increases, the utility of the instrument decreases rapidly.

Data Analysis and Output

Data analysis deals with whether the sample analysis is performed on board the instrument or is simply collected for later analysis. The majority of the instruments will be on-board data analysis. Issues such as required sample volume, sampling time, and analysis time should be taken into consideration. The data stream from these instruments will likely be in electronic format. The data stream could be the results from individual analysis or could be raw data streams that require storage and postprocessing. For sample-collection-only instruments, preservation of the sample prior to analysis (and potentially locating the sampling device) becomes an issue. There is no preference for a particular data stream. The sampling and/or analysis rate could be an issue. It is more difficult to perform in situ sampling for extended periods of time on a dispersing target.

Data Complexity

Though data streams from instruments are electronic, interpretation of the results may still require user intervention. Complex spectra or results that require further calculations make the data stream more complex because they require a higher skill level to analyze, more time to analyze, and an increased resource allocation (time, money, computing power). The simplest system has a single stream of data output that can be read easily and compared to a given standard or required level. Advanced data analysis or storage of the data for later review can decrease the flexibility of the instrument. A required review of data after every analysis to ensure correctness greatly decreases the value of the instrument.

Fieldability/Deployability

This refers to the ability of the instrument to be easily brought to and operated at the OB/OD site and is really an extension of operational complexity. It encompasses how the instrument will be set up in the field for operation. It includes the required complexity of the instrument delivery package (i.e., point detectors need to have a method for transport to the emissions cloud or some other means for insertion), the robustness of the instrument design, and the deployability of the instrument package. This also includes all the logistics of operating the instruments at the field such as, but not limited to, power, consumables and protection from the outdoor environment (e.g., shade, heaters or coolers, armoring). Deployability becomes a major concern due to the environment of the OB/OD operations. For example, there is a period after detonations where flying shrapnel is an issue. Instruments that are not hardened against this danger must be deployed after a certain period of time or deployed beyond a certain distance. An instrument that requires extended periods of setup time in close proximity to the ignition site may not be feasible. In addition, setup immediately after the detonation reaction may be impossible.

Range

This descriptor refers to the distance between the instrument and the sample, or in this case, the mobile OB/OD emissions cloud. There are three different range classes included here: point detector, standoff detector, and internal sample detector. A point detector is an instrument where a sample is brought in from outside the instrument and delivered to the critical analytical components for analysis. In this case, the instrument, or at a minimum the sampling interface, needs to be in close proximity to the emission source. The opposite is a standoff detector, which can perform an analysis while significantly distanced from the emission source. An internal sample detector is unique from the other two in that the sample becomes a part of the critical analytical components. It is different from a point detector in that the emissions cloud is not sampled and delivered to the instrument but is actually internal to the instrument. An example of an internal sample detector, which will be described in more detail later, would be an open-path Fourier transform infrared spectrometer (FTIR) with a retroreflector. The most useful instrument would be a standoff detector. Point detectors can also be used and are limited by their other properties as to whether the instrument can be delivered to the source of emissions and are addressed on a case-by-case basis. Internal sample detectors will also be discussed on a case-by-case basis.

Sampling Interface

This has been discussed in the previous two sections, but it is worth emphasizing again as a separate issue. Some instrument sampling interfaces are more amenable to operation than others, given the constraints of OB/OD operations. This specific issue, especially as related to techniques such as open-path optical detection, will be described in more detail later. The specific sampling method itself can affect the outcome of the analysis. The emphasis here is that the core technology is only one small part of the complex nature of accurately measuring the identity and quantity of a trace species. There has been much discussion about sampling in OB/OD operations and whether point sampling (taking a single sample from a single location or small volume) is representative of the entire emissions cloud. Full-volume sampling instruments, or instruments that can easily and rapidly accomplish a large number of point samples, address inhomogeneities of the plume better than point sampling.

Sensitivity

Likely one of the most important factors for any instrument is whether the instrument has the capability to sense the small concentrations of materials present in the emissions cloud. The detection limit for the target compound, in the particular sample matrix, should be well below the required sensitivity to ensure a good signal-to-noise ratio. The contribution of the background to the detected signal can be significant. Increased background signal can swamp the signal of concern, lower the dynamic range of the instrument and/or raise the detection limit. Selectivity can help to some extent solve these problems (see below).

Selectivity

This relates to how well the detector can specifically detect a target compound of interest in the presence of a complex background containing similar compounds. For example, a sensor that can detect TNT is more selective for TNT than a sensor that can detect aromatic compounds. Since TNT is an aromatic compound, the latter can detect TNT, but will also detect benzene, toluene, and other partially combusted TNT byproducts under which the true TNT signal is hidden. The required selectivity of the sensor is highly dependent on what constitutes the final list of target compounds.

Multiplex Advantage

Whereas selectivity is the detection of target X in the presence of similar compounds Y and Z, the multiplex advantage extends to the capability of measuring X, Y, and Z simultaneously. An instrument that can detect more target compounds at one time is more useful. It reduces the workload of the system but increases the complexity of the data. Instruments that increase in operational complexity or data complexity should significantly increase the value added to the data.

III. General Discussion of the Different Analyzer Technologies

There are a number of relevant technologies that were uncovered during the course of the study. Many of these have been shown to effectively monitor atmospheric emissions of compounds of interest. Some of these have been used for monitoring OB/OD emissions. The reader is referred to the document prepared by Strategic Perspectives, Inc. (Appendix E) for more details regarding the specific implementation of these instruments.

The following discussion will break down the suite of detectors and technologies into general classes. Descriptions of the technology areas are detailed in the Perspectives's report; however, some scientific and engineering principles will be included here to provide the reader a fuller understanding of the technologies. A few additional technologies not listed in the Perspectives document are also described. The advantages and disadvantages of different elements of these technologies will be highlighted in relation to the properties discussed in the previous section. Specific discussion of particular instruments listed in the study is presented later in the document.

- Aerosol mass spectrometry (AMS)
- Light detection and ranging (LIDAR)
- Differential absorption LIDAR (DIAL)
- Tunable diode laser absorption spectrometry (TDLAS)
- FTIR
- Differential optical absorption spectrometry (DOAS)
- Laser-induced emissions
- Plasma-induced emissions
- Passive emissions detection
- Photoacoustic
- Photoelectric
- UV-vis
- X-ray fluorescence
- Gas chromatography
- Air filtration sampling

Aerosol Mass Spectrometry (AMS)

Aerosol particles are introduced into the instrument, and the chemicals are desorbed from the surface. These instruments are capable of measuring negative ion and/or positive ion mass spectra from single aerosol particles. Many different species, including organics, semi-volatile organic chemicals (SVOCs), and metals, can be detected simultaneously. Additionally, the chemical distribution of aerosol particles can be correlated with their size. The instrument may also measure particle size distribution. Data from the system is electronic in format, and the resultant mass spectra are complex. Target masses could be detected, but care needs to be taken to avoid interferrents at identical nominal masses. AMS systems are point detectors. The system typically requires at least one high-peak pulse power laser (for ablation of the aerosol particle), high-vacuum accessories and pumps (for the mass spectrometer) and high voltage (for the mass spectrometer). The instruments are large in size and heavy. In addition, a series of low-power lasers are used to obtain particle size information. Electrical power requirements are steep. One commercial venture is selling aerosol time-of-flight mass spectrometry (ATOFMS) instrumentation. The current price is not known but is likely in the $250,000 to $450,000 range.

Light Detection and Ranging (LIDAR)

LIDAR is an acronym for light detection and ranging. It is similar to radar, except it uses higher-frequency radiation (IR, near-IR, visible, or UV) instead of radio waves. It is an active optical technique, as opposed to a passive optical technique, meaning that the instrument has a radiation source as well as a transceiver. The LIDAR discussed here can detect the presence of aerosol particles in the atmosphere but not their composition (see DIAL). LIDAR has the advantage of having a large standoff distance. As such, it should be readily deployable. LIDAR equipment is very expensive, running near $200,000 per device. LIDAR systems require a high-power laser as their active source. Depending on the wavelength used, safety precautions need to be taken to prevent eye damage. Additionally, for this price, there is very little information gleaned about the composition of the emissions cloud. However, such a device is helpful for directing mobile point-detection systems toward their emissions cloud.

Differential Absorption LIDAR (DIAL)

The DIAL technique could also be referred to as chemical-specific LIDAR. Specific laser wavelengths are chosen for this technique. One wavelength corresponds to the absorption band of the target compound of interest; the other is slightly off resonance. The difference in the returning scattered signal is related to the concentration of species in the air between the laser scattering point and the transceiver. The method has been demonstrated for a number of gas phase species and volatile organic chemicals (VOCs) and at ranges of greater than 1 km. Unlike many of the other detectors described in this section, the LIDAR-based instruments are volume-sampling techniques. They can map the concentrations in the emissions cloud to determine the presence of "hot" and "cool" spots, regions of higher or lower than average concentration levels. This gives a more complete picture of the chemical distribution as opposed to a few randomly selected point samples but greatly complicates interpretation of the results. Neither of the two commercial manufacturers demonstrated the applicability of DIAL for the detection of CO and CO_2, which are two critically important gas components to be measured. The DIAL system requires its own operating crew, and the data output is not easily interfaced with the SMA architecture. DIAL instrumentation requires an enormous initial investment, with systems running in the millions of dollars.

Tunable Diode Laser Absorption Spectrometry (TDLAS)

This technique uses a tunable diode laser source to collect an absorption spectrum of the gas between the transmitter (laser and telescopic optics) and the receiver (photon detector). Typically, this is accomplished in the infrared spectrum so a number of gases can be analyzed including, but not limited to, CO, CO_2, NH_4, aromatics, and hydrocarbons. The instrument can only detect one species at a time but potentially has multiplex advantage, depending on the wavelength range of the laser. These instruments can be small and inexpensive and can be operated remotely. The instrument must be calibrated initially to give good quantitative results with reasonable sensitivity. TDLAS instruments are generally internal sample detectors with the transmitter and receiver placed within 10s of meters of each other. If a long-path gas sampling cell is used, then the instrument becomes a point detector. Other instruments have longer transmission paths but still require a retroreflector in the distance. The short working distances of the device require that it be delivered to the emissions cloud by some mobile source. Fortunately, the systems can be moderately small in size, which facilitates the transportation issue. Cooling is typically required for both the laser and the detector. Where thermoelectric cooling is not sufficient, liquid nitrogen is used making the system less gravity invariant. Light scattering by particulates in the plume will increase the detection limit and reduce the applicability for some species.

Fourier Transform Infrared Spectrometer (FTIR)

Another form of infrared absorption spectroscopy, FTIR has the advantage of being able to detect many gas-phase species simultaneously. Broadband infrared radiation is passed through the sample, and the instrument detects all wavelengths simultaneously. Using an interferometer and the mathematical Fourier transform, an entire spectrum of compounds can be obtained quickly. The species of interest absorbs light of a certain frequency as a function of the stretching or bending frequencies of the molecule. What is detected is only the light that makes it through the sample (i.e., that fraction that is neither absorbed nor scattered by the sample). Scattering by particulate matter in the plume can be significant. FTIR can only detect molecular species, including polyatomic gases and organic compounds. Each target compound exhibits a spectral fingerprint in the FTIR. The intensity of this fingerprint is related to the concentration of a particular target. The individual components of the fingerprint represent specific chemical features of the target molecule (e.g., aromatic ring, C-Cl bond, CH_3 groups). Thus, it becomes necessary to look at more than just a single line in the spectrum for molecules more complicated than simple gases like CO_2 or CO. The spectrum becomes more complex with increasing numbers of species present at the same time. This can lead to measurement errors, reduce the analysis to functional group identification only, and/or require skilled intervention to interpret the data. However, chemometric analysis programs have been shown to successfully deconvolute complex spectra into useful quantitative information. FTIR in these applications is similar to TDLAS; it is an internal sample detector (or can be converted to a point detector). Although FTIR instrumentation costs are generally in the $100,000 range, less expensive instruments are becoming available at about $25,000. FTIR is highly automated and can easily be operated remotely. FTIR instruments can be relatively small in size and lightweight. Like most optical instruments, FTIR is sensitive to vibrations, especially since the interferometer has moving parts. Vibrations from the detonation wave will likely further limit how close the instrument can be to the detonation source. Alignment of the retroreflector is critical for optimal performance. Little maintenance is required for FTIR; however, dryness is critical, as moisture can damage some optical components.

Differential Optical Absorption Spectrometer (DOAS)

This instrument is not significantly different from TDLAS or DIAL. The absorption of light by a gas is monitored both on and off resonance, and the difference between the two signals relates to the concentration of the target species present. The main difference is the type of light source, typically an incoherent, broadband source, and can covers a wider range of wavelengths (IR, vis, UV). Also, the absorption measurement is made as a light source illuminates a sample in direct line of sight of the photon detector, as opposed to a scattered light absorption measurement (see DIAL). These systems work over relatively short distances with a few exceptions. They are internal sample instruments or can be modified to be point detectors. DOAS systems are small, lightweight, and inexpensive. There are a few commercial outlets for these instruments, which were primarily designed for stack or fence line monitoring. They are divided between monostatic (single transmitter and receiver with a retroreflector) and bistatic (separate transmitter and receiver) configuration. These instruments are easily automated and require little or no maintenance except periodic calibration and alignment checks.

Laser-Induced Emissions

This category includes techniques such as laser-induced plasma spectrometry (LIPS) and laser-induced breakdown spectrometry (LIBS). Both use a high-peak pulse power laser system to atomize and excite metal and metalloid components of aerosols. Traditional LIBS systems require close proximity to the sample to be effective; however, efforts are under way to extend the range of LIBS instrumentation. The LIPS system described is a point detector and uses aerosol focusing techniques to increase detectability. The laser system and the detection optics (monochromator, grating, spectrometer) are expensive and delicate pieces of equipment. These techniques are still in a developmental stage and not available commercially.

Plasma-Induced Emissions

The optical emissions generated from metals in LIBS arise from laser-induced plasmas that atomize the molecules and excite the individual atoms. Other plasma sources, including argon and helium inductively coupled plasmas, are also capable of accomplishing the same task. These plasmas are created by inducing ionization in a gas and maintaining the plasma with a high-energy radio frequency coil. Better known as inductively coupled plasma atomic emission spectroscopy (ICP-AES), this instrument is a point detector designed specifically for metals and some nonmetal species. ICP has excellent sensitivity, reproducibility, and accuracy. These instruments are large, heavy, and expensive. They also have a large power requirement. These instruments are not normally designed for field use but have been employed in static stack monitoring processes with great success. Automation is difficult and normally requires a skilled operator. Frequent attention is required for replenishing plasma gases and replacing components.

Passive Emissions Detection

Unlike many of the other instruments previously discussed, passive emissions sensing does not use an instrumental energy source to drive the detection of either absorbed or emitted radiation. Instead, it relies on the infrared emissions from target compounds that have a temperature greater than absolute zero. In the ideal case, the target sample is hotter than the surrounding environment; thus, the emission intensity is greater. However, as has been observed in the operation of these instruments, sampling occurs after the targets have cooled to ambient temperature for OD events (due to the emissions background caused by the hot aerosols in the emissions cloud). Because they rely on passive emissions, they are excellent standoff detectors. These instruments are still under development. The scattering of light by particulates can limit the utility of this technique.

Photoacoustic

These detectors are typically used for measuring soot or carbon black. Photoacoustic FTIR spectroscopy can be used to gain information about composition of the gases. They operate very similar to other absorption instruments except the photon detector is replaced with an acoustic detector. Soot particles absorb light and then emit that light as heat. The heat changes the pressure inside an acoustic cell and changes the response at a sensitive microphone. These systems are point detectors that sweep air into the acoustic cell for analysis. They are small and relatively inexpensive. However, the need for measuring soot concentration is unknown with respect to OB/OD operations. However, if the signal could be interpreted to give a particle size distribution, this could be a very useful technique.

Photoelectric

The photoelectric detector is a very selective instrument. It is designed for the detection of polycyclic aromatic hydrocarbons (PAHs) only. It is not sensitive to the small 2- to 4-ring members of the PAH family (e.g., naphthalenes, anthrenes, 4-ring pyrenes). Like many of the other compounds mentioned in this document, the potential levels of PAHs in the emissions cloud are not known. PAHs are generally created from the burning of complex fuel sources such as coal, oil, wood, etc. It is not likely that high explosives (HE) themselves will generate any PAHs, since HE emissions are usually small molecular compounds. However, they will be generated by other materials found in the operation, such as binding compounds, insulation, dunnage, etc. Thus, the PAH potential is highly dependent on the operational load and is not likely a primary target compound for detection. This device is a point detector. The instrument is relatively small and inexpensive but highly sample specific. There is also some question about the accuracy relative to other, more formal environmental sampling methods.

UV-Vis

This technology is similar to other open-path, line-of-sight absorption detection technologies (FTIR, DOAS, TDLAS). The difference is in the radiation frequency; instead of operating in the infrared, the instrument operates in the ultraviolet. UV operation narrows the range of compounds that can be observed to those that absorb UV radiation (ammonia, hydrogen sulfide, aromatics). UV penetration depth in air is limited, especially with the presence of some of the species generated during the detonation. Penetration depth will also be affected by particulate density. The instrument described in the technology discovery document may actually be considered a DOAS instrument. This instrument is an internal sample device. Additionally, the range of the instrument is relatively short compared to other similar instruments. This may be due to the increased scattering, and thus lower signal strength, inherent to operating at short wavelengths. The transmitter and receiver, individually, have small footprints, and the instrument is quite inexpensive. This technology can be automated easily and has no consumables except flash lamps.

X-ray Fluorescence (XRF)

X-ray fluorescence (XRF) is used for the detection of metals and some selected nonmetals. When the sample is bombarded with x-rays, electrons from inside the metal atoms are lost. When electrons return to fill in the vacated spaces, light is given off specific to the metals present. The sensitivity of the instrument is related to the complexity of the instrument (more sensitive instruments are larger, heavier, consume more power, and cost more). XRF is a point detector similar to ICP. The size and expense of the instrument is related to the required sensitivity. To achieve the sensitivity likely needed for detecting trace metals in OB/OD emissions clouds would require a higher-end instrument (as opposed to handheld XRF alloy sorters). Higher-end instruments run in the $100,000+ range. Additionally, there are extra precautions to take around x-ray sources for health and safety reasons. XRF has not been used to measure metals in the air directly but has been employed to analyze filters on which atmospheric particulates have been captured. These instruments are easily automated and require little regular maintenance.

Gas Chromatography (GC)

In gas chromatography (GC), a sample plug is passed through a chemically coated tube. The target compounds in the sample mixture separate from one another and are detected as they exit the tube. The time from injection to elution identifies the compounds of interest. GC instrumentation is sensitive and can detect a wide range of different compounds. Although the spectrum of targets is large, the number that can be seen in a given analysis is limited by the method used. For example, CO, CO_2, and other light gases cannot be detected at the same time as SVOCs. GC instrumentation is typically moderately sized and heavy (50–100 lbs), although current development is aimed at significant size reduction. Consumables are typically required to be replaced at regular intervals. However, there have been recent efforts to miniaturize GC onto microfluidic platforms. These instruments are currently used for chemical agents and other toxic industrial chemicals but could be adapted to the range of targets compounds for OB/OD operations. These research-level microfluidic systems have not been tested for light inorganic gases. There are a number of instrument manufacturers for the larger instruments, which are moderately priced. The microfluidic instrument is still under development but has been field-tested multiple times. The sensitivity of these instruments is good, and the selectivity and multiplex advantage are very high. GC instrument costs vary widely, from $6,000 to $100,000, depending on features.

Air Filtration Sampling

Filtered air sampling is the EPA standard method for collecting environmental samples. Air and the entrained aerosols and particulates are sorted and retained on filters from various materials (glass, Teflon, etc.) The filters are analyzed using various instrumental methods including weight, thermal desorption, and chromatography. The collection system is large and requires an analytical lab and personnel to actually perform the analyses. Thus, it is not well-suited for real-time data analysis. The range of species detectable depends on the arrangement of the instrument, the types of filters used, and the analytical methods. In the past, these systems have measured particulate concentration and size, VOCs, SVOCs, and inorganic species with relatively low selectivity and sensitivity. When combined with the appropriate laboratory analysis, air filtration sampling can provide significant improvements in selectivity and sensitivity.

IV. Focus on Specific Devices, Part 1: Higher Potential Technologies

Some of the technologies described above have potential for inclusion into an OB/OD sensor system. However, many of these technologies still have some roadblocks related to the key issues discussed in Section 2. This section will discuss specific devices, why they are potentially useful, and the hurdles to overcome to make the instrument fieldable for the sensor system.

General Note

It is useful to emphasize at this point that the target compounds for detection by the sensor system are not well defined. The Mitchell and Suggs EPA report suggests that the measurements of CO, CO_2, NO, NO_2, total saturated hydrocarbon, acetylene, ethylene, propylene, benzene, toluene, and particulate will provide sufficient information to "adequately represent" the emissions from OB/OD events. Additionally, there has been particular concern about metal emissions of OD operations, with key interest on toxic metals such as lead, mercury, and chromium. For the discussion below, the analysis will focus on detection of these specific compounds though future work may prove that there are additional materials that require observation.

The majority of the instruments listed here are not ready for inclusion in an emissions sensor system. Generally, the instruments have one or more of the following drawbacks, relating back to the critical properties outlined in Section 2:

- Costs are too high.
- The instrument is not at an advanced stage of development and/or not commercially available (has a reduced level of reliability and robustness).
- The instrument was originally designed for another application and requires some research to demonstrate its applicability to the OB/OD emissions sensing problem.
- The instrument is difficult to field/deploy. Engineering research needs to be performed to develop a deployment platform.

Additionally, there is some skepticism regarding whether any optical-based technique is capable of making sensitive enough measurements to garner any reliable information from the emissions cloud. Work performed by China Lake and presented at the 2004 Global Demilitarization Symposium suggests that by the time the dust particles settle out of an OD plume, air has diluted all but the major species in the plume to below theoretical absorption detection limits.[37] This places an extra burden of proof on the optical techniques and certainly favors alternate methodologies.

[37] Parr, Erickson, Boggs, "Open Detonation Plume Environment as Relates to Optical Remote Sensing of Pollutants," 2004 Global Demilitarization Symposium, 19 May 2004, Dallas, TX.

Aerosol Detecting LIDAR

LIDAR will be inherently important, at least in the initial stages of the sensor system development. Knowledge of the location of the emissions cloud is required if any point detection system will be applicable. Since point detection systems represent the widest variety of detectors at the most reasonable cost for the widest spectrum of target compounds, this is a crucial bit of information. At a minimum, LIDAR could be used to track emissions clouds and then the data used later to confirm which atmospheric dispersion models are the most accurate. There are a number of fundamental problems with LIDAR. It is not easily incorporated into a data feedback system to direct mobile sensors to the heart of the emissions cloud. It still requires an operator to interpret the data. Additionally, the only commercially available model has a 5-minute scan time, which may or may not be fast enough depending on atmospheric conditions during monitoring. Looking at the current configuration of the instrument, it is difficult to understand where the scanning capabilities come from. Cost is an issue, especially in light of the depth of information gained from the technique; that is, the system must have a LIDAR and another detector to gain any kind of emissions characterization information.

DIAL

Assuming that DIAL can detect the target compounds at the desired concentrations, this would be an extremely powerful tool alone. Operating in the infrared region, DIAL could detect the organics of concern and, in the ultraviolet, could detect the inorganic gases. The standoff nature of the instrument ensures that there is no interference of the operation, and measurements can be performed from very long distances. Additionally, since the technique samples the entire emissions cloud, there are no sampling issues to interfere with the results other than reduction due to light scattering by particles in the plume. However, this method is cost-prohibitive. In addition to the acquisition cost, which is in the millions, there are no domestic manufacturers. This means additional importation costs. Specialized personnel would need to be trained to operate the instrumentation. Since the instrument is mounted in a van (or mobile home), there are costs associated with vehicle upkeep. One company has recognized these impediments and thus leases their services to take measurements with their equipment (cost does not include transportation and lodging). The technology is powerful enough that research into lowering the cost, possibly by selectively reducing the functionality, could result in a more applicable instrument format.

Short-distance FTIR, TDLAS, and DOAS

These three instruments can be mounted on a mobile platform and taken into the emissions cloud. In these cases, the instrument/retroreflector or transmitter/receiver pair (the instrument nodes) could be placed in close proximity to one another and aligned on the mobile platform. FTIR is by far the largest of the three instruments and could require greater resources to make mobile. The sampling issue also applies here, as well as with every other point detection instrument or sampler. The scan time for these types of instruments is fast enough that many samples could be taken in a short period of time, thus better mapping the emissions cloud volume. Again, FTIR has the larger constraint, having the slowest acquisition time of the three instruments. Cost is an issue for many of the FTIR instruments but becomes less of a concern for the DOAS and some of the TDLAS instruments.

Heath Consultants: Remote Methane Leak Detector (RMLD)

With some adaptation, this instrument could be included into the sensor system with little problem. The system is currently designed for the detection of methane and is targeted for the natural gas industry. In the current arrangement, it could be able to detect total saturated hydrocarbons. With a shift in the wavelength, it could be used for total unsaturated hydrocarbons, benzene, toluene, acetylene, and possibly even CO or CO_2. The tunable laser diode switches between on and off resonance to analyze for a particular gas. The instrument relies on the laser scattering from background objects no greater than 30 m in distance. The current instrument is human portable and includes a handheld detection head and a shoulder-carried power supply/electronics package. Mounted aboard an aerial platform, this instrument could be flown through the emissions cloud and collect data for a particular gas of interest. The main problem with this instrument is that it is designed for a single gas species only. However, since it is very low cost, a number of systems, tuned for different gases, could be used. The actual standoff operating distance is also a concern. There needs to be a backscattering source in close proximity to the sample. It is unlikely that aerosols and particulates in the emission cloud will provide sufficient scattered intensity to detect the trace levels of target compounds (the inherent sensitivity of the instrument as a whole could be an issue since it was designed to detect methane leaks). There is still the potential resource problem involved with flying small, unmanned aerial vehicles (UAVs); aircraft have to be flown automatically, which could be expensive, or manually, in which case personnel would have to be trained.

Northrop Grumman: Mobile Chemical Agent Detector (MCAD)

This is a passive FTIR system for the detection of chemical and biological weapon clouds. It is being developed in conjunction with Block Engineering (spectrometer manufacturer) and a separate system developer. This system has been deployed in a number of field experiments and has had excellent results. The instrument designer is currently investigating the detection of toxic industrial chemicals with this device. The instrument can be mounted onto a vehicle and delivered to a detection point. From there, the instrument is scanned over an area looking for potential agents. Using FTIR, all the organic target compounds could be detected simultaneously (assuming the spectrum is not overly congested). The practical issues will be developing the instrument methods for the target compounds of interest, delivering the instrument to the point of detection, as well as scattering from particulates in the plume. There are other spectrometers developed by Block Engineering that do not have nearly the standoff distances as those quoted for the mobile chemical agent detector (MCAD) system. Additional information would be required to understand these discrepancies. Again, cost will be a serious issue including the acquisition cost of the instrument itself (likely in the $200,000 range) and a delivery vehicle. There are a number of other passive infrared devices being developed by both commercial entities and the DOE National Laboratories. Based on the successes of the MCAD instrument, passive IR sensing has potential for detecting a specific range of target compounds. Its utility for accurately measuring concentrations of light gases has still yet to be proven.

Hong Kong Baptist University: Fourier Transform (FT) Instrument

These researchers presented a talk about an improved method for performing Fourier transform (FT) measurements for a wide range of wavelengths. FTIR interferometers use a laser source to track the position of the moving mirror. This is a critical component in the system, and the spectral accuracy of the measurement is dependent on this information. To gain the required positional accuracy, the reference laser must have a wavelength significantly shorter than the analysis wavelengths. This is not a problem for FTIR, as inexpensive and stable HeNe lasers are available. For FT-vis or FT-UV absorption spectrometry, economical reference sources are not available. However, the researchers claim to have developed a new method for tracking the mirror position, eliminating the need for a laser reference and opening the path for FT methods at shorter wavelengths. This technique could lead to an improved multiplex advantage for observing target atomic species in the UV or visible range, such as those described in Section 3. There is limited utility for molecular spectroscopy.

Laser-Induced Breakdown Spectroscopy (LIBS)

This is another technique that has particular merit, primarily because it can be a standoff instrument operated from a significant distance. Additionally, LIBS looks for metal emissions, which appear to be of acute concern to government regulators at this time. The two issues of concern for the future applicability of LIBS will be the cost of instrument acquisition and the sampling strategy. The sampling strategy refers to the requirement to point the instrument at the emissions cloud. In the absence of LIDAR, modeling, or other visual indication of the cloud location, LIBS will have to be a field scanning technique. This is offset by the fact that the metal emissions are likely to be bound up to the aerosol particles, and those are easily visible for a short duration after the event. Though the data complexity and interpretation is simple, the system is operationally complex.

μChemLab Gas Phase Instrument

Like any other gas chromatographic instrument that is designed for measuring VOCs and SVOCs, the μChemLab instrument has the potential for measuring trace organics, such as explosives, remaining behind in the emissions cloud. The advantage comes from the small size, the entire device being about the size of a Kleenex box. This includes the power supply (batteries) and the sampling interface. μChemLab has been demonstrated for the detection of chemical weapon agents and a number of toxic industrial chemicals. With additional research, the instrument may be adaptable to light gases, such as CO_2 and CO, which are critical target compounds for measurement. Particle size and density could present issues with plugging.

SnifferSTAR

Though similar in concept to μChemLab, the SnifferSTAR device is less sensitive and less selective. The SnifferSTAR device was designed to be built into the wings of small UAVs. Sampling is accomplished via ram air ducts in the device. The preconcentration detection coatings are designed specifically for particular target compounds. In addition to SVOC and possible VOC detection, some metal detection may be possible. The potential level of sensitivity is unknown, and the instrument may require significant sampling time to collect a detectable amount of material.

V. Focus on Specific Devices, Part 2: Unsuitable Technologies

This section deals with instruments that have been judged to have little potential for use in monitoring OB/OD emissions. These instruments are not applicable to the sensor system because they have one or more of following characteristics:

- The instrument adds little value to the analysis for the resource expense required for its implementation. Though the instrument may be fieldable, the cost to do so outweighs the value or the data obtained by doing so.
- The instrument has a highly limited scope of deployability. This refers to instruments that require enormous resources to deploy properly or, in the absence of those resources, can only be deployed in a manner that limits the instrument's ability to add value to the analysis.
- The instrument does not address an issue of concern, or the technique is not applicable to the problem.

The following discussion will address specific devices and technologies and why they fall into the failure modes described above.

Long-Range, Open-Path Instruments Requiring Retroreflectors or Transmitter/Receiver Pairs

These instruments are primarily optical absorption spectrometers operating anywhere from the infrared to the ultraviolet wavelength region. The range of these instruments comes from the spatial distance between the two instrument nodes. In the case of retroreflectors, the distance can at least be doubled, or the sensitivity doubled, because the primary radiation beam is passing though the sample twice (out to the reflector and back) before detection. For example, if the retroreflector is placed 500 m from the instrument, the effective pathlength is 1 km. These are line-of-sight instruments, meaning that the instrument nodes must be pointing at each other and aligned properly. There is a potential that the alignment can change as a result of the detonation shock wave. Manufacturers go to great lengths to maximize the out-of-alignment angle between the two nodes that does not affect accuracy/sensitivity. For transmitter/receiver pairs, this angle is about 1°. With retroreflectors, a special optical component is used to ensure the reflected beam is returned exactly parallel to the incident light. The problem with these systems is the fixed nature of the instrument nodes. If the emissions cloud does not pass between the two points, the measurements cannot take place. Additionally, there is the sampling issue of where to sample the emissions cloud. Proper placement of the instrument nodes could require significant construction projects in close vicinity to the detonation or burning site. Much like the passive emissions systems, timing of sampling is a problem. The opacity of the emissions cloud must be optically clear, as well as cool in temperature, for the instrumentation to work properly. The location of the instrumentation must coincide with the sample preparation required. In terms of monitoring the emissions cloud shortly after the OB/OD event, this type of instrumentation is not practical. The information available from such devices is potentially applicable, but the instrumental layout is inappropriate. These monitors would be more useful as fence line monitors in situations where it is known that the cloud will regularly pass through a certain point (due to atmospheric properties) and the target compounds can be detected (before atmospheric dispersion and dilution drop the concentrations below detectability).

Matrix Isolation FTIR

This technique involves depositing materials onto a substrate at low temperatures and subsequently performing an FTIR analysis on the remaining thin film. Typically, matrix isolation is performed at liquid helium temperatures (8 kelvin). The technology discovery document suggests that some work is being performed at higher temperatures (near liquid nitrogen temperatures of 77 kelvin) to eliminate the trapping of some gas species. Matrix isolation equipment is complex and requires a skilled operator. The deposition process is done at a very slow rate to ensure that the unwanted species are not trapped in the matrix film due to flash freezing. There are two main reasons for using matrix isolation techniques. First, intermediate reaction species can be trapped at the cold temperatures, eliminating the need for ultrafast spectroscopic methods for performing structural studies. Second, the sample introduced is highly diluted so as to isolate individual molecules from one another in the frozen matrix. This results in sharper spectral lines and provides a spectrum that is more structurally rich. Neither of these advantages is required for the analysis of OB/OD emissions. The instrumentation is expensive, labor intensive, and complicated. It has no real-time applicability to the problem.

Inductively Coupled Plasma (ICP) and X-ray Fluorescence (XRF)

The goal of these two instruments is to measure metal emissions from the OB/OD operation. Either of these methods will likely prove to be more sensitive than a long-range LIBS instrument, depending on the amount of metals emitted. However, the same issues that affect matrix isolation FTIR apply to ICP and XRF. Both techniques would be better served as off-site (that is, away from the OB/OD location) methods for analyzing filtered air samples. The currently available XRF instrumentation described in the technology discovery document already operates in this fashion. Filtered air is collected for several minutes. The filter is subsequently analyzed by XRF for the metals of concern. The commercial instrument is no more than an automation of the entire sample collection/filter replacement/filter analysis procedure. The ICP instrument has a faster data delivery rate because the filter is not required. Instead, the gas stream is entrained directly into the plasma gas feed. Both instruments have deployability issues due to their size and complexity. ICP instruments are normally quite large in size and weigh hundreds of pounds. Additionally, both instruments are expensive. The added value from deploying the instruments to the field as opposed to bringing samples back to the laboratory is not justified.

Photoacoustic Detector and Photoelectric Aerosol Detector

Both of these instruments have the positive features of reasonable cost and simplicity. However, neither instrument addresses relevant target compounds. The photoacoustic detector does not give enough information about particle composition and does not report particle size distribution. The particular classes of PAHs that the photoelectric aerosol detector senses are not applicable at this time. If further work reveals that large ring number PAHs are of concern, then the photoelectric detector could have some application.

Aerosol Mass Spectrometry (AMS or ATOFMS)

These instruments can provide a wide range of applicable data to understand the OB/OD emissions issues. First, composition-specific information as a function of particle size can be obtained. Not only does the instrument give the particle size distribution, but it can also give information about particular target compounds present in the particles of greatest concern. Second, the instruments can detect a large number of the target compounds, including SVOCs and metals that are bound up to aerosol particles. Third, some potential target compounds of interest are only going to be found on the aerosol particulates, such as HCl or other acids. Because of the volatility of HCl and the high-vacuum ionization region, it may be difficult to get a spectrum of this species on the particle. It would be more likely to find a chloride salt. The instrument cannot detect the unbound inorganic gases or the VOCs. The major issues relate to the resource requirements to operate the instrument, the deployability, and the quantitation of the results. To be effective, the instrument needs to sample the native source of the aerosol particles. Much, if not all, of the crucial information would be lost if the emissions cloud were gas-sampled and brought back to an ATOFMS in the lab. However, ATOFMS instruments are very large and heavy. They also have a steep power requirement. The two ATOFMS instruments referenced in the technology discovery document weigh 800 lbs. A large aircraft would be required to sample in the higher-altitude regions of the emissions cloud and would present a significant expense. The instrument could be operated from a large van on the ground, but then the data is subject to sampling accuracy issues. However, the aerosols might not have the same dispersal range and could rain out of the emissions cloud at short enough distances (in high enough concentrations) to gather some useful information. The cost of the instrument, as well as the operational cost, is very high. ATOFMS is a complex instrument that requires skilled personnel to operate and maintain the instrument and analyze the data. Although it may be possible to monitor individual mass spectral peaks to correlate to certain species, the entire mass spectrum is really required for some target compounds. The spectral intensity can be measured and compared to standards. This calibration is not straightforward, but it is possible. The bigger issue is in determining what concentrations measured at the surface have to do with concentrations and distributions within the plume. The goal is to have the emissions sensor system determine the amount, likely in pounds, of material emitted from the event. The AMS instrument has no possible method for returning a quantity measurement since it has no method for measuring and relating the detected levels to an internal standard or such. This is in addition to the fact that the instrument is a point sensor and can give no information about the total distribution of materials in the cloud. This technique does have potential application for monitoring at the fence line and at other downwind sites of potential contamination. Optimized monitoring protocols still must be addressed by the investigators.

Air Filtration Sampling

Machinery such as the EPA air sampling denuders will not find significant applicability for OB/OD emissions monitoring at the detonation/burn site. Very similar to some of the technologies previously discussed in this section, it is better suited for fence line monitoring. This is particularly true since the sample spacing is usually 24 hours and then filters are sent to a laboratory for a suite of chemical analysis. The air samplers are big, usually 12–15 feet tall to provide enough stages to separate out the different air components ($PM_{2.5}$, PM_{10}, inorganics, SVOCs, etc.) Some miniaturized, very high-volume flow rate air sampling system might find applicability.

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VI. Conclusions

A wide variety of chemical sensors have been discussed here. By far, the majority of these instruments are optical-based devices. This is an advantage because optical spectrometers have the potential for a large standoff distance between the instrument and the sample and typically are not hampered by high consumable costs. Conversely, optical spectrometers can be mechanically sensitive and complex instruments. The suite of sensors also covers the broad range of target compounds to be detected. Given unlimited resources, an array of sensors could be selected and implemented into a sensor system. However, this is a resource-bounded problem. That is, the limited availability of resources that can be applied to solve the problem decreases the range of potential solutions.

Given these constraints, there are no commercially available chemical sensors at this time that could be included in the OB/OD emissions sensor system that satisfy the full range of user requirements. Overall, the two biggest factors that currently impede the implementation are acquisition/operational costs and fieldability/deployability. For the most part, the key instruments that would provide the required useful information are too expensive to acquire for a single site operation. The same applies for the operational costs, including the deployment costs.

Another factor that affects the outcome is the state of development of some instruments, particularly commercial instruments that require "retrofitting" for this particular application. A number of these instruments likely have the capability for detection of emissions from OB/OD operations after an initial study to show that they can detect the compounds of interest at the appropriate concentration levels. There are two specific areas to consider for adapting these high-potential instruments for the sensor system. First is adjusting the instrument chemistry and/or physics for detecting the specific molecules of concern. This involves adjusting absorption wavelengths or column and detector coatings. It may even involve more extensive instrument development. The second area is adapting the instruments for use in the field. This includes environmental hardening and performing engineering modifications to the instrument for transport as necessary. This work would require significant research and engineering dollars after a reproof-of-concept stage to show sensitivity of the instrument down to the required concentration levels.

There are a number of components of the sensor system that need to be addressed even before the inclusion of the first chemical sensitive detectors. As described in Section 3, most OB/OD sites have a GO/NOGO status based on weather. Meteorological data collection and recording would be easily implemented into the emission sensor system. This data could be used as inputs for atmospheric dispersion models included in the software framework to help track the location of the emissions cloud and determine the degree of dilution over time. Inclusion of weather monitoring equipment would be part of the first step to develop the main hardware components and software interface of the sensor system. In spite of the fact that none of the previously discussed technologies are ready for inclusion in the sensor system, there is a fair amount of preliminary work that still needs to be performed. Additionally, with some strategic collaboration, potentially valuable instruments could be obtained on a temporary, cooperative basis for testing and preliminary design.

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Chapter 6: Path Forward

This section reviews the principal conclusions drawn from the four major areas of the systems study (Chapters 2–5). These conclusions highlight a number of important issues related to emission sensing for OB/OD events. By focusing on these issues, the authors seek to generate critical discussion among members of the demilitarization community. It is anticipated that this discussion and any future additions to the work presented here will lead to the creation of a sensor system for OB/OD events that effectively addresses the needs of the community.

I. Summary

There are numerous multifaceted issues that have broad impacts on OB/OD in the United States, as well as issues that are specific to particular operational sites. Both sets of factors need to be considered in developing a representation of the political, economic, sociological, and organizational environment affecting OB/OD. The discussions and review suggest that this environment can have a profound effect on the capability and/or desire of an OB/OD treatment facility to introduce technology to monitor emissions. It is evident that the costs associated with maintaining the capability to perform OB/OB continue to increase. However, not all of these costs are financial in nature. Past experience suggests that facilities need to be able to respond promptly and properly to concerns raised by individuals and outside organizations.

We defined a group of individuals that would potentially interact with the sensor system in various capacities. These individuals were interviewed, and their input and suggestions were collected and summarized in an effort to develop a set of requirements for the sensor system. These requirements include essential features that the system must have such as robustness; reliability; and low cost to install, operate, and maintain. In addition, in order to provide useful data the system must, at a minimum, be capable of detecting carbon monoxide, carbon dioxide, particulate size distribution, and metals, as well as performing meteorology and plume positioning measurements. Consensus opinion in this area was difficult to obtain, however, and it is clear that a better definition of the minimum set of detectable compounds is needed.

Sandia-developed technology for integrating and controlling a heterogeneous array of detectors is highly applicable to the OB/OD emissions sensing problem. The SMA provides a data interface for visualizing the aggregated sets of data, as well as automated control of and feedback to the individual sensor nodes. This is accomplished in real time via noise-immune, wireless communication.

A group of 15 sensor technology categories is described and evaluated against a set of 12 critical sensor properties. All of the current sensors and sensor technologies available have a major shortcoming with respect to one or more of the properties. The five sensor properties where these technologies generally fall short of meeting the projected requirements are cost, deployability, sensitivity, sampling, and state of development. A number of technologies show promise but require focused research and engineering efforts to demonstrate their applicability to the problem.

The data collected indicate that a number of issues, which are both directly and indirectly related to the sensor system technology, influence the effectiveness of the OB/OD emissions sensing program as a whole. These issues, which will be discussed further below, include the following:

- Deciding the final implementation of an emission sensor system. This includes identifying the actual users of the technology, who will review the data, and what is the desired operating mode of the system.
- Assuming that a sensor system is implemented, preparing demilitarization operations organizations to use the equipment. This includes training, maintenance and operation, and data handling, storage, reporting and auditing.
- Driving future research and development to focus on overcoming the specific technological challenges that prevent many current sensors from inclusion in the proposed system. This includes leveraging sensor development from similar technology arenas and divesting from technologies that are of lesser utility.
- Recognizing the value of physical and chemical modeling and related experimental work to fill data gaps from the sensor system resulting from inherent sensor limitations. These added capabilities include atmospheric plume dispersion models, chemical reactivity models, and confined detonation studies.

II. Ultimate Need of the Demilitarization Community

The primary goal of an emissions sensor system for monitoring OB/OD is to provide information about the amount of material released into the environment. For the EPA's Toxic Release Inventory (TRI), these quantities are expressed as pounds of material released annually. Emission factors (which are based on a more general definition for emissions quantities) defined for explosives oxidized under a particular set of conditions are expressed in mass of a certain compound released per mass of explosive. These emission quantities can be used to satisfy regulatory and reporting requirements, as well as provide a basis for operation optimization, testing, and tracking. The current high-level design of the emissions sensor system will provide the data necessary to measure the quantities of materials released. Care needs to be taken that the sensor data stream can be analyzed to obtain sufficiently accurate emission factors.

There are several secondary goals that could be achieved by the sensor system. These should be identified and included in the sensor system design. The gaps between the sensor system design features and the requirements for the system should be addressed early in the design process to ensure that the desired performance requirements are met.

A part of this challenge is defining all of the chemical species that need to be detected by the sensor system. It is not feasible to detect all compounds present in the emissions cloud. Many of the toxic chemicals of concern are generated in such small quantities that it is unrealistic to expect any instrument to detect their presence once they are diluted in the atmosphere. This measurement limitation leads to a reliance on computer modeling as an essential postevent data analysis component for determining the amount of materials released. The sensor system would measure the quantities of a few key chemical species and then input this data into a model as boundary constraints to calculate the unmeasurable compounds. Significant resources have been invested for research in this area, resulting in viable definitions for key species to be monitored. Unfortunately, this research has not gained wide acceptance to date.

III. Repercussions of Success

If the need is great enough, an effective and reliable emissions sensor system for OB/OD events will eventually be developed. The time frame for this depends on several factors, particularly the focusing of resources to address existing technological problems. However, the potential consequences of implementing a sensor system on OB/OD operations should be addressed early in the development of the system to avoid any undesirable outcomes.

A major concern expressed during interviews for this study was the potential for mandated monitoring if a sensor system existed. The air emissions regulators that permit the OD operations at China Lake have suggested that direct emissions monitoring at the facility may be required. However, the staff at China Lake has successfully explained to the regulatory community that direct air monitoring is currently technologically unfeasible. As a condition of their permit, China Lake will continue to investigate air-monitoring techniques. Some of the individuals interviewed expressed the concern that if a sensor system did exist, then their facility would be required to monitor all events, independent of the cost and reliability of the monitoring system. If the system failed to operate properly during an OD operation, the facility could receive a violation of its air emissions permit.

It is essential to separate actual capabilities of an instrument system from perceived or desired capabilities that are not currently available or technically feasible. This will prevent unwarranted and unachievable restrictions on operations. The variability of OB/OD organizations and operations directly impacts the use of a fixed system at each site. Such a system would have to be operated by existing employees at demilitarization sites. These individuals would therefore be required to take on additional work and training to use the sensor system. The design of the sensor system must be tailored to its eventual users, including their background and experience, and how often the system will be operated. For example, a system that is used occasionally, perhaps only to monitor when a significant operational change is implemented, needs to be more robust toward long periods of inactivity. Operation of a sensor system might be, to a certain extent, intrusive on current demilitarization operations. Operational flexibility needs to exist to absorb the required level of intrusion and the attention the system needs for optimal operation. Additionally, OB/OD operators need to perceive that the additional tasks associated with operating the sensor system are important and that they add value to the operations being performed.

There will be a significant amount of data generated by an emissions sensor system. Several questions naturally arise in considering the appropriate handling of such data. These questions include the following:

- What information is needed from the data?
- What can be accomplished with the data?
- What processes/procedures should be used to store, archive, and audit the data?
- Should some forms of data manipulation be restricted?
- Should some of the data be granted a special classification?
- Given that the data exists, what additional dissemination actions might be required beyond those currently anticipated?

IV. Focused Sensor Research and Development

The systems study concluded that there are no technologies currently ready for implementation in an OB/OD sensor system. This assessment is based on the philosophy of building a complete system from new components to achieve the minimum monitoring requirements described in Chapter 3; it is supported by two observations. First, sensors that would likely make a significant contribution toward effectively measuring the quantities of materials released are too expensive to acquire, deploy, and operate. Second, sensors that might make a contribution toward measuring quantities of materials released require significant scientific and engineering development to ensure their effectiveness.

However, with focused effort, a number of these technologies could be tested and potentially adapted for use in OB/OD emissions sensing. Focused effort means direct application of resources (such as money, time, etc.) In the commercial marketplace, OB/OD emissions sensing is considered a small market, and the potential return on investment for a company dedicating its own resources toward this development could be small or possibly even negative. Thus, resources for adapting and improving sensor technologies for OB/OD will have to come from inside the demilitarization community.

One potential route for resource optimization is to leverage the considerable development of technologies for standoff and point detection of chemical- and biological-weapon releases. Some of this work will be applicable to monitoring OB/OD events. Instead of investing major resources to design a sensor from first principles, less commitment of resources could be required to adapt chemical and biological equipment to issues specific to OB/OD. The DOE labs developing sensor technologies for OB/OD emissions monitoring are also involved in technology development for chemical and biological releases. Additionally, there is much to be learned from the wide variety of environmental monitoring instrumentation currently on the market. Fence line and stack emission monitors measure general classification of compounds that the OB/OD emission sensor system would also measure. This does not preclude the pursuit of new technologies if excellent solutions arise. However, new technologies should first be carefully scrutinized. During the evaluation, particular attention should be focused on two key areas. First, can the sensor produce the required result (pounds of pollutant released)? Second, is the complete cost of operation within the construct of the sensor system reasonable? Evaluating sensors against the 12 critical sensor properties described in Chapter 5 will help address these two questions.

There is an important issue concerning the level of maturity of the sensor design. Certainly, the most preferred sensor would be off the shelf since the packaging and operation methodology would be expected to be robust and well proven. However, even an off-the-shelf device can be fickle and require user intervention and adjustment. For every adjustment required, such as turning a knob or changing a voltage, if the adjustment could be automated, then the SMA can control the adjustment automatically. This would require that a screw adjustment has an attached motor, motor control, and a sensor to tell the system when the adjustment has been properly made. A person can do these adjustments easily using feel, sight, judgment, and skill; a machine needs the movement and sensing built into it at an additional cost. Knowing the skill level of the personnel that will operate the sensor system, a cost/benefit analysis can be made for upgrading a particular sensor for the level of automation required to determine if the sensor remains a viable option.

V. Role of Modeling

Physical and chemical modeling needs to be a key element of a viable OB/OD emissions sensor system. As mentioned previously, there is no chemical sensing technique, now or in the foreseeable future, which will allow for the measurement of all of the different compounds released from an OB/OD event. In particular, there are no techniques to trap or confine all the material released in an open-air event so that concentrations of the final products can be measured unambiguously. The extremely low concentrations of some products combined with high dilution factors associated with outdoor operations means that the concentration of some compounds will always be below achievable detection limits. Since many of these compounds, which account for a very small percentage of the final products, are the toxic materials of concern, modeling will be the only efficient method for obtaining emission quantities with reasonable accuracy. However, modeling of both actual OB/OD events and confined detonation experiments that provide empirical data has not received wide acceptance within the scientific and regulatory community. The skepticism with which modeling is viewed must change since modeling data will ultimately be a vital component of a successful OB/OD emissions sensor system. For example, data from modeling experiments, such as calculated cloud volume and spatial distribution of chemical species in the cloud, would be needed to calculate the total quantity of materials emitted from a series of point measurements. Changing this skepticism will require efforts within the demil and regulatory community that demonstrate the effectiveness of physical and chemical modeling.

VI. Conclusions

Despite the lack of development and available sensors capable of providing direct OB/OD emissions detection, significant work can be done now to prepare for the likely emergence of usable sensors in the future. First and foremost would be addressing some of the issues presented in this systems study. As a next step, the elements of this study could be discussed among potential users and program sponsors. Important definitions of requirements and tradeoffs can be developed. Such an approach also serves to inform the demilitarization community of the potential benefits of the sensor system and thereby garner their support for developing a prototype.

There are also other avenues for incorporating technologies into the sensor system to demonstrate its capability. For example, programs within the DOE and DHS are developing a wide range of sensing instrumentation in related areas such as chemical and biological detection and environmental sensing. Near-term work in developing sensors for OB/OD emissions can take advantage of technologies emerging from such programs to accelerate the development of their system capabilities. A particular example is the extensive capabilities in cloud tracking LIDAR that are under development at Sandia National Laboratories. It is likely that collaborative work could be done to implement and demonstrate this technology for OB/OD cloud observation.

Additionally, there is significant ongoing development work that relates directly to the communication, visualization, and analysis elements of the system. This work can be leveraged to aid in the development of intelligent sensing modules for demil applications. Some numerical modeling of the relevant chemical processes would also need to be included, as would calculations based on the sensor data to determine the quantities of materials released from the OB/OD event.

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Appendix A: Questions Used During the Systems Study

Questions Addressing the OB/OD Environment at Your Demil Site

Regulatory

What is the mix of OB versus OD at your site (average total weight of each per year permitted; typical per month executed)?

Can your OB/OD site treat wastes generated by other DoD sites?

What MIDAS items (type, item, quantity/operation) are included in the current OB/OD permit for your site?

How are non-MIDAS items (e.g., R&D units or EM) characterized under permit?

Operations and Monitoring

What are the meteorological restrictions at your site for OB? For OD? Do these operations tend to be seasonal?

Do you engage in any routine monitoring of emissions (solid and gaseous) from OB/OD events? If so, what do you monitor and how? How are the data used?

Are on-site, ground clean-up operations required under your permit? If so, what level of clean-up is required?

Do you operate permitted disposal facilities that are alternatives to OB/OD? If so, what fraction of your total waste disposal requirements for EM is met by these alternative facilities? What emissions are permitted from these facilities?

Location

Considering prevailing winds, how close is your OB/OD site to the facility fence line? To your nearest neighbors (people, animals, water, farmland)?

Are there on- and/or off-site ground water/aquifer concerns?

Are there noise issues with your nearest neighbors?

Are there emissions issues with your nearest neighbors?

Three Types of Users

1) User type 1 includes: Demil operations
    - i) EOD technicians,
    - ii) Facility managers,
    - iii) Data analyzers/interpreters,
  - b) Questions asked
    - i) Ease of Use
      - (1) Who will be responsible for operation of this equipment?
        - (a) What is their level of training and experience?
        - (b) How much time will they devote to this task?
      - (2) Who will be responsible for maintenance of this equipment?
        - (a) What is their level of training and experience?
        - (b) How much time will they devote to this task?
      - (3) Who will be responsible for data records and archives?
      - (4) Who will be responsible for reviewing data and results?
    - ii) Reliability
      - (1) MTBF? (mean time between failures)
      - (2) MTTR?
    - iii) Impact on operations?
2) User type 2: Regulators
    - i) EPA
    - ii) State
    - iii) OSHA
  - b) Questions asked
    - i) Sensitivity?
    - ii) Specificity?
      - (1) Which chemical species must be measured?
    - iii) Accuracy?
      - (1) How accurate must the measurements be (e.g. +/- 10%, +/- 100%, etc.)?
    - iv) Instantaneous vs. integrated releases?
      - (1) TRI and HAP reporting is based on annual releases
        - (a) Are event-by-event measurements required?
        - (b) Can "representative sample" events be used?

3) Other interested parties include
    a) Examples
        i) Administrators
            (1) Installation/facility
            (2) Executive level (e.g., DOE, DoD, DHS, etc.)
        ii) Other government
        iii) Public
        iv) Equipment service techs.
        v) Other
    b) Questions asked
        i) Costs
            (1) Capital?
                (a) What is an acceptable total cost for acquisition, installation & start-up of this equipment?
                    (i) If use of the equipment reduces operational concerns?
                    (ii) If use of the equipment is required to allow OB/OD?
            (2) Operating?
            (3) Service?

System Functions—What the System Must Do

1) What stand-off sensors must do
    a) Calibrate
    b) Find plume
    c) Take/record data
    d) Analyze data
        i) Interpret into common format
        ii) Make sense of the data as appropriate
    e) "Housekeeping"
        i) Calibrate
        ii) Self-diagnose
        iii) Other
2) What in situ sensors must do
    a) Find plume
    b) Collect sample
        i) Large volume/small volume?
        ii) Pre-concentrate?
        iii) Other?
    c) Analyze sample
        i) Gas or particulate
        ii) Physical vs. chemical characterization
            (1) Elemental
            (2) Size/mass
            (3) Polarity
            (4) Charge/mass
            (5) Etc.
        iii) Other
    d) Record data
    e) Analyze data
        i) Interpret into common format
        ii) Make sense of the data as appropriate
    f) "Housekeeping"
        i) Calibrate
        ii) Self-diagnose
        iii) Other
3) What the integrated system must do
    a) Communicate
    b) Make sense of the information from ISMs
    c) Report results
    d) Archive results
    e) System "Housekeeping"

Questions for Use of Sensor Management Architecture in OB/OD Systems

User-Related

1) To what extent is real-time data presentation to the user desired for process/response control? Is real-time data comparison/correlation between sensors important? Are warning alarm levels required?

2) What ancillary types of measurements (pressure, temperature, humidity, etc.) made locally at each detector would be useful?

3) What other types of site data from sources other than interfaced sensors will need to be dealt with?

4) Should the system be stand-alone? Is wireless communication between sensor nodes and the data control station desired? Are there any safety issues with using wireless transmission and the presence of explosive devices?

5) Are there any existing centralized command and control points the system must interface with? How should external data, like that from the Sensor Management System, be integrated?

Sensor-Related

6) How many different sensor types (chemical and other) will be employed? What is the overall number of sensors to be deployed?

7) What data types are output from each sensor? Can the sensors be remotely controlled via command inputs? What are typical sensor sample and data rates?

8) What types of communication does each sensor type support? What are the data message rates and transmission bandwidth requirements?

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Appendix B: Estimated cost for an OB/OD operation at China Lake

Estimate of China Lake OD costs
(obtained via Lauren Zellmer 2/27/2004)

Donor material:

($50/box; assume 10 boxes)

$500/event

EOD labor prior to event:

(3 Days; One person; $65/Hr)

$1755/event

Environmental labor prior to event (tracking):

(4 hrs; one person; $65/hr)

$260/event

Weapons & SWPL* labor prior to event (paperwork):

(Assume 24 hrs; $65/hr)

$1560/event

Weapons & SWPL labor prior to event (loading):

(Assume 6 personnel; 3 hrs each; $65/hr)

$1170/event

EOD labor for event:

(8 personnel; 5 hours; $65/hr)

$2600/event

Weapons & SWPL personnel labor for event (transport):

(Assume 4 persons; 2 hrs each; $65/hr)

$520/event

Road maintenance:

($2500/year; 10 events/year)

$250/event

Forklift for unloading at OD site is free (today).

Storage of donor is free also.

Estimate does NOT include costs for vehicle maintenance, environmental annual permit fees, environmental permitting, and range operations.

GRAND TOTAL = ~$8600/Event

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*SWPL = Salt Wells Propulsion Laboratory

Appendix C: OB/OD Weather Parameter GO/NOGO Criteria at Tooele Army Depot (TEAD)

Demilitarization Calendar

Demilitarization: February 24, 2004	MORNING	AFTERNOON
OPEN BURN:	NO GO	NO GO
OPEN DETONATION:	NO GO	NO GO

OPEN BURN:	*GO*	*NO GO*
WIND SPEED	3-20 mph/gusts to 30 mph	Greater than 20 mph/gusts greater than 30 mph
OPEN DETONATION:		
WIND SPEED	3-15 mph/gusts to 20 mph	Greater than 15 mph/gusts greater than 30 mph
PARAMETERS THAT APPLY TO BOTH OPEN BURN & OPEN DETONATION		
CLOUD COVER*	Less than 80%	Greater than 80%
CLOUD CEILING*	Greater than 2,000 ft.	Less than 2,000 ft.
PRECIPITATION	Less than 75% chance	Greater than 75% chance
THUNDER/ELECTRICAL	Less than 50% chance	Greater than 50% chance
CLEARING INDEX**	Greater than 500	Less than 500
VISIBILITY	Greater than 1 mile	Less than 1 mile

* Cloud cover and ceiling are used in conjunction with each other. Operations will not be scheduled when the cloud cover is greater than 80% and the cloud ceiling is less than 2,000 ft.

** Clearing index is a number provided by the National Weather Service involving all weather parameters.

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Appendix D: ISM Engineering Requirements Summary

Environment	Industrial, and weatherproof.
Emplacement	Fixed, and mobile.
Embedded Computation	Capable multi-tasking operating system, supporting Java Virtual Machine (JVM), local nonvolatile file storage, and Fast Fourier Transform (FFT) class algorithm execution.
External Device Interfaces	Support up to four external (detection / sensor) devices interfaced. Support 10/100 Ethernet, USB 1.1 (client and host), RS-232/422/485, and SPI and I2C interfaces. [It is assumed the external devices have significant power requirements, and are supplied with their own shore power.]
Position Sensing	World coordinates (with sky-view satellite access). Movement and orientation sensing.
Environmental Sensing	Tethered, remote location environmental sensing of temperature, pressure, humidity, light intensity, and motion.
Power	Automatic power switchover between shore (AC, DC) and battery power, including in-vehicle power sources. Support 2-4 hour battery operation. Power consumption target < 650mA while transmitting, depending on options.
Standardization	Standard data reporting and device control format.
Communication, Topology & Standoff Distance	Unstructured, noise immune, secure wireless communication. [a] Intra-node-network communication, base / repeater, unstructured, high-power (~1W), long distance (~25-60 miles), supporting intercommunication within facilities with significant, dense building materials. [b] Peer-to-peer, unstructured, minimal power (100mW), short distance (~500 ft). [c] Guaranteed delivery, remote network connectivity, cellular telephone network based, low data rate.
Device & Software Configuration	Automatic device configuration, supported by untrained personnel. Wireless remote software configuration, including device interface loading. Wireless device configuration and first responder query through structured wireless link.
Network Configuration	Wired and wireless network configuration. Base / repeater configuration support. Ad hoc network configuration.
Size	Unconstrained, target ~0.15ft3.
Production Cost	Unconstrained, target <$8k per unit, actual $2-7k depending on options.
Weight	Unconstrained, target < 3lbs, depending on options.
Operating Environment	Primary unit, 0 to +65C, 0 to 95% non-condensing humidity. Environmental sensors, -40 to +75C, 0 to 95% non-condensing humidity.
Security	Tamper detection, integrated data authentication and encryption.

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Appendix E: A Survey of Sensor Technologies and Devices for OB/OD Emissions Monitoring

PERSPECTIVES

A Survey of Sensor Technologies and Devices for OB/OD Emissions Monitoring

March 18, 2004

Presented to:

The Conventional Munitions Demilitarization
Program Management Team
Sandia National Laboratories

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Table of Contents

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I. Introduction

Background

Demilitarization is any process by which military items are rendered unsuitable for their intended application. Demil may involve destruction of the unit or processing and recovery of certain valuable or useful components. There is a large and growing stockpile of damaged or obsolete conventional munitions and components in the demil stockpile. Indeed, the DoD demil backlog was 360,184 tons as of April 30, 2003, and 350,000 tons are expected to be generated by FY09. [38]

Up until about a decade ago, open burning and detonation (OB/OD) were the most common methods of disposal of items in the conventional munitions demil inventory. OB/OD is both safe and cost effective. Recently, however, these demil processes are being subjected to ever increasing scrutiny by environmental interests, including governmental regulatory agencies and concerned citizens, because emissions from OB/OD operations represent an uncontrolled release of potentially hazardous air and ground pollution.

Sandia National Laboratories plays an active role in several areas of the Joint DoD/DOE Munitions Technology Development Program, which was established in 1985 through a memorandum of understanding (MOU) between the DoD and the DOE. The purpose of this program is to facilitate adaptation and application of technologies developed by DOE for use in the nuclear weapons stockpile to problems of high interest by DoD.

Development of new and/or improved demil technologies is included under "Technology for Life Cycle Engineering: Demanufacturing and Demilitarization."

One of Sandia's MOU demil projects for FY04 is entitled, "OB/OD Emissions Sensing and Sensor Management Architecture." The project proposed to use an intercommunicating network of optical and chemical sensors to characterize the emissions from OB/OD events so that 1) environmental concerns could be addressed and 2) the OB/OD processes could be optimized. Although this project was originally envisioned as primarily a technology development and deployment activity, the investigators realized early on that a rigorous systems analysis of the feasibility, challenges and cost effectiveness of the proposed system is a key first step. Four areas of input form the basis for such an analysis. These are descriptions of:

1. The OB/OD environment
2. Definition of users and user needs
3. Review of potentially applicable sensor technologies
4. Characteristics and requirements of Sandia's ISM technology

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[38] *Ligeno, L. "Conventional Ammunition Demil Program," 11th Global Demil Symposium & Exhibition, Sparks, NV, 19-22 May, 2003.*

Objectives

Perspectives was asked to assist the Sandia project team with input 3 above, review of potentially applicable sensor technologies, by performing a technology benchmark study and writing a report identifying and describing the status of OPB/OD emissions sensor technologies. The study includes both stand-off sensors and *in-situ* measurement devices.
The goals of the study and report are to:

1. Identify sensors/systems that have been deployed to monitor OB/OD emissions

2. Identify and describe sensors/systems that have been proposed for monitoring OB/OD emissions

3. Identify and describe sensor technologies that are likely future candidates for monitoring OB/OD emissions. This aspect is addressed by

    a. Describing systems identified by the demil R&D community as having potential for application in this area,

    b. Surveying commercially available multi-analyte systems intended for monitoring emissions from combustion sources (e.g. incinerators, power plants, etc.) and

    c. Reviewing plume tracking/analysis systems proposed for characterizing Chem/Bio threats.

Approach and Methodology

Perspectives began this study by reviewing the 2001 through 2003 proceedings of the major regular symposia for the OB/OD community: The Global Demil Symposium, & Exhibition; and the Demil Users Group Meeting. In addition, copies of a number of preliminary draft reports and summaries of earlier OB/OD emissions monitoring tests were obtained and reviewed. (The proceedings of three year's worth of meetings (past three years) amounted to some 8500 pages; a thousand or more pages of other hardcopy-only material were also reviewed.)

As a part of this study it was important to assure the most complete and accurate understanding of sensors and systems that had been deployed in past attempts to measure emissions from OB/OD events. To do this, Perspectives' research team drew upon the knowledge and expertise of a dozen experienced experts in the general demil community as well as those having direct experience in OB/OD emissions testing and emissions monitoring technology. These individuals were asked to participate either by phone or in-person in a structured interview session.

The session covered such issues as:

- The individual's experience in OB/OD emissions monitoring,
- Knowledge of past OB/OD emissions monitoring test programs,
- Identification of technologies used in the past and awareness of currently used technologies,
- Suggestions for and status of candidate OB/OD emissions monitoring technologies,
- Identification of others working on potentially applicable technologies, etc.

Interview notes were transcribed immediately after the interview sessions for later review and analysis. Institutions represented by those interviewed in-depth are shown in the table below.

Affiliation of Individuals Interviewed
AFRL/MLQ (TRW) (Air Force Research Laboratory, Air Expeditionary Forces Technologies Div.)
Applied Ordnance Technology (AOT)
ARDEC (Army Armament Research Development & Engineering Center)
Army Environmental Center (AEC)
China Lake NAWS (Naval Air Warfare Center Weapons Division)
Defense Ammunition Center (DAC)
Los Alamos National Lab (LANL)
Lawrence Livermore National Lab (LLNL)
NSWC Crane (Naval Surface Warfare Center, Crane Division)
Sandia National Lab (SNL)

All individuals contacted contributed enthusiastically and cooperated fully with this interview effort. The views expressed and information provided by the interview subjects was a key resource and an invaluable component of this study.

The published literature on OB/OD and leads uncovered from the interviews were used as entry points for extensive on-line research into appropriate candidate sensor devices and techniques. Though not completely limited to the defined bounds of the study (e.g. sensors that have been deployed, sensors that have been proposed, candidate future sensor technologies that are 1) identified by the demil R&D community, 2) commercial multi-analyte systems for combustion monitoring, and 3) plume analysis systems for characterizing Chem/Bio threats), Perspectives' on-line research efforts were strongly guided by this scope. (As with the OB/OD symposia, on-line resources were voluminous. Five thousand or more pages of on-line reports, journal articles, manufacturer's brochures, and presentations were reviewed for relevant materials.)

Sources such as the Strategic Environmental Research and Development Program (SERDP) and Environmental /Security Test Certification Program (ESTCP) websites and related links were searched and proved to be very useful and productive sources of information and initial contacts for follow-up. A number of manufacturers of commercial sensing devices were contacted by e-mail and telephone; and the material from their replies often proved helpful.

Perspectives' research team participated with the Sandia OB/OD MOU project team in a benchmark project review meeting on February 25, 2004. Perspectives presented an overview of the effort, reviewed approaches and methods used, and presented a summary of progress to that date. Several challenges with the early vision for organization of the information in the final report were identified and discussed at this meeting. In particular, much of the information was seen as not classifiable as originally anticipated and there is considerable ambiguity as to what is a "commercially available" sensor. The need of the Sandia team to evaluate, classify and sort the emission sensor information once the information is presented in final report form was identified as a key need and concern. To address this issue, Perspectives agreed to provide as a separate deliverable: a summary table of sensors in Excel spreadsheet format in addition to the final written document.

Caveat: The DoD sponsorship and applied nature of much of demil technology development, including OB/OD sensors, sometimes makes access to detailed research reports and other potentially useful documents difficult. Perspectives made exhaustive efforts to cover the available, relevant material thoroughly and completely.

About This Report

The report is organized as follows:

- Chapter II contains highlights from this study.
- Chapter III provides an overview of some of the advantages and disadvantages of various types of sensor technology that could potentially be used for OB/OD emissions monitoring, based on comparisons found in the literature. The views of interviewees on OB/OD sensing are also discussed here.
- Chapter IV gives a brief review of past sensing activity that was performed during various OB/OD monitoring experiments and tests.
- Chapter V contains detailed descriptions of a variety of available sensors which have potential for use in monitoring OB/OD -- that is, those that are either in commercial production or that have been developed and field-tested. The devices are grouped by type of sensor (FTIR, DIAL, etc.) and are then arranged alphabetically under that heading.
- Chapter VI contains detailed descriptions of various sensors with potential for use in monitoring OB/OD. These are technologies that are not yet mature, and are in various stages of development. The devices are grouped by type of sensor (FTIR, DIAL, etc.) and are then arranged alphabetically under that heading.
- Chapter VII reviews a conference of interest.
- The Appendix supplies general descriptions of the technologies covered in this report, for the readers' convenience.

Under separate cover, Perspectives will supply an Excel file containing key information on the devices described in this report.

Perspectives has provided contact information – addresses, telephone and fax numbers, e-mail addresses and web sites – for nearly all the important developers and companies whose work is described in this document. Wherever possible, hyperlinks to online source material have been included.

Note: Throughout the report, references are made to SERDP programs (e.g., "CP-1197"). The SERDP (Strategic Environmental Research and Development Program) funds many different emissions-related activities and these programs are identified by number. Most of the programs dealt with in our report are in the compliance program (CP) thrust area.

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II. Highlights

This chapter of the report supplies highlights of the results of this research.

Past Sensing Work

Previous experimental work on characterizing emissions from OB/OD tests has been fraught with problems. Emissions can either be studied by *in situ* collection (for later analysis in the lab) or by the use of stand-off sensor devices, far enough removed from the detonation to survive.

Sampling is difficult to perform – helicopters, blimps, and balloons have been used to capture aerial samples, but these methods have all been troublesome. Perhaps the best results have come from buried evacuated cylinders, triggered by the blast shock wave to open. Besides the mechanical difficulties inherent in sample grabbing from a detonation plume, there is the fundamental question of the nature of the plume cloud itself – many suspect it to be non-homogeneous in composition.

The use of stand-off sensing at OB/OD tests has also proven difficult. High dust levels make laser transmittance challenging, background atmospheric clouds confuse the results, and the equipment used has often been expensive and prone to problems.

Another problem with OB/OD emissions monitoring is the very low levels of many of the species of interest to regulators – detonation of 60 tons of propellant yields only one pound of VOCs. Sensing devices must be very sensitive to detect such low levels in the plume.

Present-Day Sensor Modalities That Might Be Used

Fourier Transform Infra-Red spectroscopy (FTIR) is widely available as commercial instruments. The devices are expensive, however – from the upper tens of thousands of dollars to much higher figures. Advantages of FTIR include compactness, portability, and the ruggedness of many units. Earlier FTIRs were challenging to operate; modern commercial units are much more user-friendly. The operational ranges of FTIR devices are reportedly from 150 meters or so to five kilometers. Hundreds of chemical species are included in the databases of some of the commercial devices.

Aerosol Mass Spectrometry (AMS) is a widely used tool. AMS can be used either for single-particle analysis (such as the TSI 8800 Atomic Time-of-flight MS provides) or for providing quantitative data on assemblages of particles (Aerodyne AMS). Van-mounted AMS units have been deployed on city streets in a number of field trials measuring vehicle emissions. AMS is still expensive and difficult to operate and interpret, however.

Commercial **LIDAR** units are capable of producing plume profiles in a few minutes. Excessive dust and background clouds could still be a difficulty with use of LIDAR for OB/OD sensing, though.

DIAL (Differential Absorption LIDAR) is very expensive – on the order of $1.5 to $2 million per unit. (These units can be rented, for about $15k - $20K per day.) It is also reportedly very complicated to operate. DIAL produces very good results, however. Good results in plume tracking have been obtained from van-mounted commercial DIAL units.

TDLAS (Tunable Differential Laser Absorption Spectroscopy) is commercially available from a number of vendors, selling typically for a few tens of thousands of dollars. Commercial applications are for leak detection and gas monitoring at ranges as far as a few hundred meters. Units are compact and portable, with quick response times.

Commercial DOAS (Differential Optical Absorption Spectroscopy) units are portable, rugged, and user friendly. Ranges of up to several km are possible, and levels of many species can be measured accurately.

Other innovative techniques are also being used for pollution and emissions monitoring. Inductively coupled spectrometry and X-ray fluorescence are used for monitoring metals emissions (but only from samples). Particulates are being measured by ATOFMS (Aerosol time-of-flight mass spectrometry), photo-acoustic devices, and photo-electric aerosol detectors are used for PAHs (polycyclic aromatic hydrocarbons).

Sensing in the Future

Several very small devices are likely in the next few years or coming decade: MEMS-based IR spectrometry, cermet (ceramic metallic) microsensors, Echelle grating spectrometers. Many research groups are working with aerosol mass spectrometers for pollution measurement; more of these will be commercialized. MIFTIR (matrix isolation FTIR) offers promise of increased sensitivity. Laser-induced plasma spectroscopy (LIPS) and laser-induced breakdown spectroscopy (LIBS) both offer potential for stand-off monitoring of aerosols. Mie-scattering LIDAR is being developed to produce “data cubes” for plumes. Non-cryogenic DIAL is being developed. Work on comparatively low-cost near-IR TDLAS is underway. Multi-axis DOAS uses scattered sunlight from various directions (as compared with “normal” DOAS, which uses zenith-scattered sunlight), and shows much promise in plume and pollution monitoring.

Miniaturization will be increasingly valuable. FTIR spectrometers are now in experimental production for military use, which are small enough to be flown in UAVs. Very small sensors are likely in the not-too-distant future. DARPA has just announced a new initiative – TACTIC (Threat Agent Cloud Tactical Intercept and Countermeasure), to foster development of detection technologies to rapidly discriminate and identify airborne clouds. The techniques desired are to be rapid, sensitive, selective, and accurate. One example that DARPA gave is use of very small sensors inserted into the cloud, telemetering their readings.

Summary Table of Devices

The chart below briefly summarizes the wide variety of devices covered in this report and their key attributes.[39] *In the chart below, the "Status" column shows whether devices using the technology are commercially available ("com.") or in development ("dev."), either by scientists or by industry; the "No. of Devices" column tells how many devices using that particular technique are discussed in this report; the "Species detected" column gives general information as to broad categories of analytes; and the "Notes" column gives brief annotations on such issues as sensitivity of the device or the maximum range for stand-off sensing ("v." stands for "very").*

Summary Table of Sensor Device Types in This Report

Type of sensor (basic tech in use)	Status	No. of devices	Species detected	Notes
AMS (Aerosol Mass Spectrometry) / ATOFMS (Aerosol Time-of-Flight MS)	Com. & Dev.	3 (plus links to many more)	Aerosols, particles	Ranges in km
Cermet microsensors	Dev.	1	Many species	
CIMS (Chemical Ionization MS)	Dev.	1	Many species	V. sensitive
DIAL (Differential Absorption LIDAR)	Com. / Dev.	3	Aerosols, VOCs, H20, etc.	V. expensive; ranges in km
DOAS (Differential Optical Absorption Spectroscopy)	Com. / Dev.	4	Many species	Compact, accurate, ranges in km, rugged
Misc. spectrometric techniques	Dev.	4	Hundreds of species	Range to 1.5 km; some are compact, some are micro in scale
FTIR (Fourier Transform IR) spectroscopy	Com. / Dev.	11	Hundreds of species	Open-path, ranges to 5 km, can be v. compact, some v. sensitive, less expensive than many other methods
LIBS (Laser-Induced Breakdown Spectrosc.)	Dev.	1	Metals, others	V. sensitive, range to 100 m.
LIDAR	Com. / Dev.	6	Aerosols	
LIPS (Laser-Induced Plasma Spectrosc.)	Dev.	2	Metals	Short range so far
PA (Photo-Acoustic sensor)	Com.	1	Particles (soot, etc.)	
PAS (Photoelectric Aerosol detector)	Com.	1	Aerosols, particle-bound hydrocarbons	
TDLAS (Tunable Diode Laser Absorption Spectr.)	Com. / Dev.	7	Many species	Stand-off, portable, open-path
X-ray fluorescence	Com.	2	Metals	In situ measurements

[39] *For more detailed summary information, the Excel file, supplied under separate cover, provides a chart showing each device/technology receiving fuller treatment in the body of this report.*

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III. Overview: Advantages and Disadvantages of Emissions Testing Techniques

In reviewing the literature for this report, Perspectives found several useful characterizations and comparisons of some of the technologies. Problems with FTIR for OB/OD were discussed; DIAL, FTIR, and DOAS were compared as to their merits for use in emissions studies in cities; and a paper compared the results of DIAL as an ozone monitor in comparison to UV photometers. Those results are summarized here. [40]

In addition, the interviews that Perspectives conducted with specialists in the field of OB/OD and emissions studies gave insight as to the problems with OB/OD testing as these individuals perceive them. Some pertinent and provocative comments from those interviews are given at the end of this chapter.

Potential Disadvantages of Open-Path FTIR

OB/OD tests took place at a test range in Socorro, NM in 2001. Several sensors and techniques were evaluated then. The commercial open-path FTIR (Fourier transform IR spectroscopy) operated by SNL at the Socorro tests was found to have several disadvantages:

- All spectral elements were observed simultaneously, adding noise
- Low spectral resolution
- Non-cryogenic operation
- Requires complicated calibration

Key requirements for measurement were rapid acquisition (to avoid changes in plume radiance), the need to separate effects of aerosol radiance and intervening atmospheric species (H2O, CO, and CO2), and the need for narrow spectral resolution in order to detect narrow-line emitters such as CO and CO2.

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[40] Note: This chapter is not intended to serve as a global comparison of technologies. Such a comparison would be difficult because of the complexity of the variety of OB/OD emission testing situations (e.g., the need to monitor special mixes of species, the need for varying levels of sensitivity, equipment placement requirements, power availability, etc.).

Comparison of DIAL, FTIR, and DOAS for VOC Measurements

A presentation (p. 60) at a conference in Austin, in October 2003, by two scientists from the **University of Houston** discussed "Measurement Methods, Innovative Source and Flux Measurements Building Emissions Inventories with Remote Sensing Open Path Spectroscopy." Their summary of advantages and disadvantages of the three methods is shown (condensed) below:

Comparison of DIAL, FTIR, and DOAS for VOCs		
Method	**Pros**	**Cons**
DIAL (Differential Absorption LIDAR)	Can create 2D and 3D plots; can identify hotspots	Very expensive; complicated to operate
FTIR	Can speciate myriads of VOCs	Technically challenging to operate (better computing has recently made this much better); requires a retroreflector
DOAS (Differential Optical Absorption Spectroscopy)	Simplest, but only by comparison. Still regarded as difficult in practice.	Can be difficult in practice; requires a retroreflector

Comparison of DIAL with UV Photometers for Ozone Measurement

In 2000, a team of scientists from the Pacific Northwest National Laboratory, NOAA, Brookhaven, and Battelle took simultaneous air quality measurements – ozone – in Houston from a variety of locations, primarily using UV photometers and chemoluminescence analyzers. The results were compared with simultaneous airborne DIAL measurements. The agreement of DIAL measurements with *in situ* airborne photometer and chemoluminescence analyzer measurements was "remarkably" good. (See here for more detail on these activities.)

Views from the Experts

Perspectives interviewed a dozen scientists with expertise in the field of OB/OD and emissions testing. They were asked for their thoughts on the major technical challenges in current OB/OD monitoring, and about which technology areas might be most helpful for OB/OD monitoring. Some representative responses are given here.

These experts expressed a fair degree of pessimism about both sensing of OB/OD emissions and sample "grabbing." Samples are very difficult to obtain from OB/OD, and the perceived non-homogeneity of the plume makes extrapolation of results (from those taken from a small part of the cloud to the composition of the entire cloud) "a nightmare." Stand-off sensors are expensive, and often not sensitive enough for many species.

- Sensors are neither appropriate nor needed because empirical data from the lab and limited outdoor work (sampling) continue to prove the validity and reliability of computer models.
- None of the sensors are sensitive enough for VOC analysis.
- Optical remote sensing will not work (well enough). The only sensing system that stands a chance is *in situ* sampling / analysis.
- The big question is what's in the plume. Lab work can find out the answer quicker, better, faster, and cheaper than outdoor monitoring.
- Stand-off sensing with IR can't penetrate the dust cloud. IR spectra are very complex.
- The inability of technologies to make measurements of low-concentration species at a distance and very soon post-detonation is a severe problem.

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Emissions Monitoring for OB/OD Events in the Past

This section gives a brief review of sensing devices used in major past OB/OD events.

1984 Dugway Field Tests

In 1984, OB/OD was conducted at Dugway and helicopters flew through the plume collecting samples. **Onboard gas analyzers** attempted to monitor NOx, SOx, HCl, CO, CO2, etc. Turbulence and dust damage to engines was a major problem. Few analytes were recovered. **Solim Kwak** was the program manager.

SNL Work in the AETC in the 1990s

Army-sponsored emissions studies were conducted in the **Air Emissions Test Chamber** (AETC) at **Sandia National Lab**. Located inside the chamber were various samplers, a low-flow bubbler system (for total aerosol chloride and ammonia), an aerodynamic particle sizer, and an **open-path FTIR** (Fourier transform infra-red) spectrometer. Outside the chamber were continuous gas analyzers and a closed-cell FTIR device.

SNL modified a commercial **TDLAS** (tunable diode laser absorption spectrometer) for dual-species spectroscopic measurements. Successful time-resolved measurements were made for CO2 and H2O. CO was detected just at the limit of the instrument. The greatest challenge was maintaining laser transmittance through the high dust levels. It was felt that the greatest possibility of obtaining information on transient molecular species, such as CO and HCN, was just after the detonation, when dust levels were at their highest. This may also be a limiting factor for future use of lasers for OB/OD monitoring. (See W. Einfeld *et al.*, Instrumentation Advances in Emissions Characterization from Propellant / Explosive Combustion," SAND-96-0772C.)

SNL Airborne Work in the 1990s

The sensing equipment used in the SNL AETC studies was installed in an airplane and used to sample plumes from OB/OD at Dugway Proving Grounds. This was to serve as a comparison between Bang Box and open OB/OD validity as a source of emission factors.

DAC-Sponsored X-Tunnel Work at the Nevada Test Site in 1996–97

The **Defense Ammunition Center** sponsored a series of tests of munitions detonation from December 1996 through March 1997. The tests took place at the X-tunnel facility at the Nevada Test Site. Participating institutions included **Bechtel**, **LLNL**, **LANL**, **Radian**, and **SNL Livermore**. Sampling provided gas for analysis, and filters collected particulates. LANL tested its Los Alamos Aerosol Sampling System (LAASS) to measure aerosol concentrations and collect samples. (See B. W.Bellow *et al.*, Executive Summary of Phase I Demonstrations: Detonation of Conventional Weapons: 155-mm High Explosive M107 Projectiles," UCRL-ID-131252. Copies available from Perspectives.)

Bang Box Experiments at Dugway

The Army installed a **Bang Box** at the Dugway Proving Ground that was similar to the AETC at SNL. Sampling equipment inside the chamber included high-volume samplers (Hi-Vol) for measuring particle mass, metals, and SVOCs (semivolatile organic compounds); Hi-Vol-based PM10 sampler; EPA PS-1 samplers for SVOCs and chlorinated dioxins and furans; and EPA Method 26 samplers for HCl and Cl2. Continuous emission monitors (CEMs) were located in the airlock attached to the chamber, as were collection canisters. (See William Mitchell and Jack Suggs, "Emission Factors for the Disposal of Energetic Materials by Open Burning and Open Detonation (OB/OD)," EPA/600/R-98/103, August 1998.)

Naval Surface Warfare Center Blimp Tests

In July 1998, and again in August 1999, a team led by **Edward Baroody** used two **blimps** to collect gases and solids from a detonation plume (from missile segments). Plume sampling devices were attached to the blimps (no measurements – only collections – were made in flight). Samples were collected within 25 seconds of detonation. (See Mitchell L. Lindsay *et al.*, "Use of blimps to collect in-situ reaction products from detonation plumes," source unknown, copies available from Perspectives.)

Socorro Tests

Balloon-borne sensing and collection

John Stephens and others from **LANL**, plus team members from **LLNL** and **SNL**, carried out balloon-borne sensing and sample collection of OB/OD at the **Energetic Materials Research and Testing Center** in **Socorro**, NM in 2001. The balloons were tethered between 400 and 750 meters from the firing point.

There were two types of sensor packages: "small" and "large" (a prototype of a future blimp-borne package):

Small Payload	Large Payload
Real-time CO2 sensor	Rapid CO2 monitor (one-second response)
GPS receiver	GPS receiver
Microcomputer controller	Aerosol mass monitor (TSP, PM10, PM2.5)
Telemetry link	Temperature and humidity sensors
Blower (for sample bags)	Whole air sampler
	Absolute and differential pressure sensors
	Magnetic sensor (for heading)
	Real-time video link

Stephens concluded that the sensor which most needed to be added to the "small" package was a real-time CO2 monitor. Development of a small lightweight aerosol sensor would be very useful for the small package. This would enable calibration of concurrent ground-collected LIDAR data to determine aerosol concentrations throughout the cloud. (See chapters in data report: "Enhancing Techniques for Open Burn / Open Detonation (OB/OD) of Conventional Munitions," John R. Stephens, coordinator, including chapters on "Balloon-borne plume monitoring and sampling," by John R. Stephens; and "Standoff Monitoring of Infrared Emissions from OB/OD Events," by S. E. Bisson *et al.* Copies available from Perspectives.)

LIDAR and FTIR at the Socorro tests

A cloud-tracking **LIDAR** from **LANL** was also used in the Socorro OB/OD tests. **LLNL** provided a high-resolution **Echelle spectrometer** and a broadband calibrated **IR camera**. Air samples were analyzed using EPA methodology for VOCs, SVOCs, and metals in particulates.

SNL provided an open-path passive FTIR spectrometer. The distance of the FTIR from the OB/OD site was ½ km or more. The **Bomem MB-100 FTIR** was used in mid-IR and long-IR modes, by switching detectors (MCT or InSb). Long Wave IR (LWIR) was thought to offer the most promise for future OB/OD monitoring. The instrument could not be used for measurements until about two minutes after the shot, since it was kept in a bunker during the detonation. Cloudy skies presented problems because of interference from background radiation. A major uncertainty after the Socorro tests was the effect of aerosols which have a tendency to fill in window regions with radiation, and can add so much opacity to the plume as to prevent passage of the laser signal.

Naval Surface Warfare Center Ground Canister Collection

In August and October 2001, and again in the summer of 2003, **NSWC** teams used **buried evacuated ground canisters** to collect samples from OB/OD at Hill AFB. The canisters were buried 50, 100, and 150 feet from an open detonation – a stage 2 segment of a Trident missile in August 2001 and a complete Sprint missile in October 2001. The shock wave from the detonation caused sample tubes to open. The test in the summer of 2003 used 15 buried canisters. (See Mitchell L. Lindsay, *et al.*, "Use of ground canisters to collect reaction products from detonation plumes," Task Doc NOOO3096PO-Sep 2000-Dec 2001, source unknown, copies available from Perspectives.)

U.S. Army Environmental Center (AEC) Munitions Emissions Study

Tamera Rush of the AEC is in charge of a program to characterize munitions emissions. For each type of munition, a detailed test plan is prepared. The detailed test plan (DTP) is approved by the EPA Emissions Measurement Center. Sampling is done for PM10, PM2.5, toxic metals, VOCs, SVOCs, energetics, CO, NOx, SO2, HCN, and others. Both small and large caliber munitions are tested in a sealed volume chamber; exploding ordnance is tested in the Dugway Bang Box facility or in the large octagon test chamber or the blast sphere at Aberdeen. Point of impact and point of discharge field tests were conducted in 2001 and 2002.

James Bach of the Army's Aberdeen Test Center was to present a paper at the March 2004 UXO Countermine Forum on "Air Emissions of Toxic Release Inventory Chemicals from Munitions Use on Ranges." A team from Battelle, Aberdeen, NSWC, Brookhaven NL, PNNL, and Vexcel is developing, evaluating, and applying approaches to determine Toxic Release Inventory (TRI) emissions discharged on ranges under realistic conditions (CP-1197). Two types of field campaigns are being conducted: measuring emissions from weapon discharge, and measuring emissions from detonation of munitions upon impact.

A December 2001 field trial used scanning aerosol LIDAR and 3D photogrammetry to account for dilution in emissions clouds. A field trial in October 2002 measured emissions from weapons firing. A September 2003 trial quantified emissions at the point of impact.

Requirements are that the chemical measurement tools be able to quantify up to 80 trace TRI chemicals at levels in the ppt to ppb range, with high specificity, in a moving cloud of a few tens of seconds duration. The instruments include real-time air sampling mass spectrometers, whole air collectors, aerosol samplers, and individual monitors for specific chemical species. (This information comes from a no-longer-available cache of a web page of abstracts for the UXO Countermine Forum, which has been removed from the web.)

Vexcel was contracted by **Battelle** to use its 3D photogrammetry program, **FotoG**, to determine the size of emissions clouds at the point of shell impact. Four video cameras photographed the area of impact beforehand to create a 3D model of the impact area. Cameras at the same locations filmed the impact. The combination of these images yielded a model that shows the boundaries of the emissions cloud. (Press release here.) Information on FotoG here.)

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Chester (Chet) Spicer of **Battelle** gave a SERDP presentation in 2003 in which he reviewed past and present efforts in TRI emissions monitoring from munitions. SERDP **CP-1197**, with Spicer as Program Manager, is titled "A Field Program to Identify TRI Chemicals and Determine Emissions Factors from DoD Munitions Activities (CP-1197)." (Project CP-1197 began in FY01.) The CP-1197 team consists of researchers from Battelle, Aberdeen Test Center, the Naval Surface Warfare Center, Brookhaven National Laboratory, the Pacific Northwest National Laboratory, and Vexcel.

CP-1197 had these main steps planned:

1.1 Develop list of target TRI chemicals

1.2 Select munitions / activities

1.3 Prepare mini-LIDAR for munitions applications

1.4 Select measurement methods

1.5 Laboratory testing of measurement systems

2.0 Conduct plume dimensions field trial

3.0 Conduct point of discharge field studies (field campaign completed in October 2002)

4.0 Conduct point of impact field studies (field campaign scheduled to be completed in October 2003)

The CP-1197 team identified **124 Toxic Release Inventory chemicals** that were either reported to be, or were likely to be, emitted from munitions. They selected from this list 25 "high-priority" HAPs plus approximately 50 other TRIs for measurement. This table, from the CP-1197 2003 presentation (page 10), gives the filtered-down list and the planned measurement techniques:

Whole Air Sampling / GC-MS		
acetaldehyde	vinyl chloride	chlorobenzene
acrolein	toluene	chloromethane
acrylonitrile	allyl chloride	chloroprene
benzene	bromomethane	ethyl benzene
1,3-butadiene	carbon disulfide	methyl tert-butyl ether
carbon tetrachloride	acetonitrile	vinylacetate
chloroform	benzyl chloride	bromoform
1,2-dibromoethane	1,2-dichlorobenzene	o-xylene
1,2-dichloroethane	1,4-dichlorobenzene	m-xylene
1,2-dichloropropane	1,3-dichlorobenzene	p-xylene
1,1,2,2-tetrachloroethane	hexachloroethane	styrene
tetrachloroethylene	1,2,4-trichlorobenzene	naphthalene
trichloroethylene	carbonyl sulfide	

Filter sampling / ICP-MS		
arsenic	beryllium	cadmium
chromium	lead	manganese
nickel	mercury	aluminum
antimony	barium	cobalt
copper	selenium	silver
thallium	zinc	
Atm. Pressure Chemical / Ionization Tandem MS		
nitroglycerine	formic acid	hydrogen cyanide
chlorine	o-dinitrobenzene	m-dinitrobenzene
p-dinitrobenzene	2,4-dinitrotoulene	2,6-dinitrotoluene
N-nitrosodiphenylamine	N-nitrosodimethylamine	N-nitrosodiethylamine
aniline	dimethylphthalate	diethylphthalate
dibutylphthalate	nitric acid	hydrogen chloride
Proton Transfer Reaction-MS		
anthracene	naphthalene	quinoline
nitrobenzene	o-dinitrobenzene	m-dinitrobenzene
p-dinitrobenzene	2,4-dinitrotoluene	2,6-dinitrotoluene
phenol	2-nitrophenol	4-nitrophenol
2,4-dinitrophenol	benzidine	biphenyl
dibenzofuran	4-aminobiphenyl	
UV Photoionization Monitoring		
PAHs		
Derivatization / Fluorescence Monitoring		
formaldehyde		
Ancillary Measurement		
carbon monoxide	carbon dioxide	total hydrocarbons

As part of CP-1197, an **Aerodyne AMS** (aerosol mass spectrometer) was used to measure point-of-discharge fine particle emissions at the Aberdeen Test Center in a series of tests of weapons muzzle emissions in the fall of 2003. The AMS was used to quantify inorganic sulfates, nitrates, carbonates, chlorides, and the total organic particle mass. Specific toxic compounds identified and quantified included particle-bound cyanides, polycyclic aromatic hydrocarbons (PAHs), and several transition metals. (A brief summary of the AMS work is here.)

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IV. Available Devices with Potential for OB/OD Emissions Monitoring

This section describes sensor devices that are either being marketed commercially (either to researchers or to government entities) or have been developed and successfully used in field experiments by researchers. These could potentially be used for OB/OD monitoring. The material below is categorized by the type of sensing technology used.

FTIR (Fourier Transform Infra-Red) Spectroscopy

FTIR: Fourier Transform Infrared Spectroscopy -- a method of obtaining infrared spectra by first measuring the interferogram of the sample using an interferometer, then performing a Fourier transform on the interferogram to obtain the spectrum.

Block Engineering Model 100 FTIR

Block Engineering, a division of Spectra Optics, makes a compact FTIR known as the Model 100. The company describes is as being reliable, compact, and lightweight. Cryogenic or thermoelectrically cooled detectors are available. The Model 100 is supplied in four basic configurations as shown in the table below:

Block Engineering Model 100 FTIR Specifications				
Model	**100-BSW**	**100-BLW**	**100-LW**	**100-SW**
Spectral range	2.5-5.5 µ	7-13.5 µ		2.5-5.5 µ
Spectral resolution	4, 8, & 16 cm^{-1}	2 (opt.), 4, 8, 16 cm^{-1}		4, 8, 16 cm^{-1}
Field of view	0.5 x 0.5°		1.5 x 1.5°	
Aperture size	7.8 cm		2.54 cm	
Size (w/o scope)	9 x 6 x 6.25 inches			
Weight	12 lbs		10 lbs	

The Model 100 sells for $125,000 to $165,000. Block has sold more than 40 Model 100s to date. It has been incorporated into Predator UAVs and is the basic component of Northrop Grumman's MCAD device.

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Block Engineering I-LSCAD

Block Engineering is developing the **I-LSCAD** (Improved LSCAD) for **ERDEC** (the US Army's Edgewood Research, Development, and Engineering Center). This is to be an improved version of the only-recently-developed LSCAD (**Lightweight Standoff Chemical Agent Detector**). The I-LSCAD is an FTIR spectrometer which is intended for use in UAVs or military vehicles.

The LSCAD is optimized to operate between 7-13 μ, with a minimal spectral resolution of 4 cm^{-1}. The field of view is 1.5 x 1.5°. The I-LSCAD will share most of the parameters of the LSCAD, but will be somewhat smaller and lighter, at 9 x 6 x 5.5 inches, and about 10 pounds. Improvements made for the I-LSCAD include replacing the HeNe laser with a solid-state laser diode and improving the instrument in general while making it smaller and lighter. (A paper on the I-LSCAD design can be found here.)

Bruker OPAG 22

Bruker Daltonics sells a portable FTIR device they call the **OPAG 22** (Open Path Gas Analyzer). The device is marketed for such applications as stack plume tracking and fence-line monitoring. Analysis time is reportedly less than 10 seconds. The OPAG 22 is hardened for field operations, and uses the patented "RockSolid" interferometer design. The OPAG 22 can be obtained in either passive or active mode. It uses a narrow-band MCT detector, and has a 30-mrad field of view. It measures 400 x 370 x 260 mm and weighs 19 kg. (Bruker's webpage for the OPAG 22 is here.)

Bruker RAPID

Bruker Daltonics also makes a portable FTIR chemical detector, **RAPID**, for the military and homeland security market. (The device is evidently made in two versions: military known as the Hawk, and civilian, known as RAPID.) The Bruker RAPID device weighs 28.7 kg, occupying a footprint of 500 x 331 x 386 mm. The device uses the patented "RockSolid" interferometer design for stability. The RAPID has a reported five-km range, with elevation angles from -10° to +50°. The manufacturer refers to a 3-second time to turn 360°, but users have reported that the Bruker unit takes 110 seconds to perform a full 360° scan. The database includes all known chemical warfare agents and important toxic industrial chemicals (TICs), and new compounds can be added. Up to twelve species can be monitored simultaneously. (The web page for the RAPID is here.)

EDO Systems RAM 2000

EDO Corporation recently purchased **AIL** (**Airborne Instruments Laboratory**) and now markets its FTIR unit as the **RAM 2000 ™**. The company says the RAM 2000 can provide real-time identification and quantification of more than 250 chemicals, with detection levels mostly in the range of 0.1 to 15 ppb (path-averaged). Its range is up to 500 meters (spectrometer to retroreflector). Spectral range is 700 to 4,000 cm^{-1}. Resolution is 0.5 cm^{-1} maximum. Scan time is 1.7 seconds per scan. It operates continuously and unattended. Installed systems have operated for more than four years continuously. The RAM 2000 is a monostatic FTIR, using a continuous-scan Michaelson interferometer. The telescope is a 10-inch Newtonian. The retroreflector has 37 cubes, with accuracy of 5 arcseconds. EDO sells the RAM 2000 for $150,000 (complete with standard retro array, FTIR head, and system computer), or leases it for $14,000 (and up) per month. "Systems are in stock." (Communication from EDO in March 2004; the company's information sheet on the RAM 2000 is here.)

Two reports, which appear to be about the use of the RAM 2000, are shown below:

- **Robert Kagann** (then of Spectral Solutions of Cumming, Georgia; now at **Arcadis**) gave a presentation on "Infrared Active Open-path Spectroscopy to Measure Chemical Agents and Hazardous Air Pollutants" at an EPA symposium in 2002. He cited the advantages of open-path monitoring as large-scale, continuous, in-situ, remote, and tomography (source characterization and plume-concentration mapping). System specifications were not provided, but the slides mention systems in use for fence-line coverage at a chemical facility in New York and at a facility in South Carolina. Presumably this was the AIL RAM 2000 FTIR (now the EDO RAM 2000) which had been installed at chemical plants at Harriman, NY and Elgin, SC.
- At the same EPA symposium, **Ram Hashmonay** of Arcadis gave a talk on "Extinction Spectroscopy for Characterization of Particulate Matter Size and Concentration in Fugitive Plumes." FTIR was used in an experiment at the Louisville landfill to monitor dust for CO, and methane. It had a range of 5 km. Details of the equipment used were not provided.

MIDAC AM Open Path FTIR Air Monitoring Systems

MIDAC, of Costa Mesa, California, markets open-path FTIR devices for field applications. They have been used in a number of volcanic studies, as well as for fence-line monitoring and rocket plume monitoring.

The **AM Open Path FTIR** is a portable unit which can be set up within 15 minutes. It can be placed "hundreds of meters" from the emission source. The AM Open Path FTIR is available in two configurations: the emissions package and the remote source (bistatic) package.

Lori Todd, **Kathleen Mottus**, and **Robert Katz** of the OP-FTIR Tomography project at UNC Chapel Hill are using MIDAC FTIR units in their attempts to develop monitoring techniques for workplace air. (The project web page is here.) A new technique is being developed for exposure assessment, source monitoring, and model validation. The technique provides spatially and temporally resolved estimates of chemical concentrations in work-place air, by combining the chemical measurement capability of OP-FTIR spectroscopy with the mapping capability of computed tomography (CT) to create 2D contaminant concentration maps non-invasively and in near real-time.

They feel their "environmental CAT scanning technique shows real promise as a rapid and accurate method for mapping chemicals over large areas" (size of area undefined, however). (See abstract here.)

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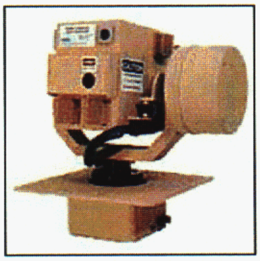
Northrop Grumman MCAD (Mobile Chemical Agent Detector)



Northrop Grumman manufactures the Mobile Chemical Agent Detector (MCAD) for the military and homeland security market. The MCAD uses passive FTIR. A man-portable version is available, weighing 18 pounds, in three modules. The device has a five-km range, for "all known" chemical and biological agents.

Available versions include 1) Man-portable, in three modules for point and shoot operations and unattended operations (weighs under 18 lbs. for all three modules); 2) Vehicle-mounted (the module weighs 25 lbs); 3) Maritime; 4) Aircraft, with a fixed Field of View, strap-on airworthy pods; and 5) UAV, with gimbals and fixed mounts.

Northrop Grumman acts as a systems integrator in producing the MCAD. Northrop uses the Model 100 FTIR built by Block Engineering (see section above). This is integrated with software from MESH and other Northrop Grumman components.

(The above data on the MCAD was obtained by Perspectives in the summer of 2003 . The material is not currently available on the Northrop web site.)

Unisearch IMx FTIR

Unisearch Associates, of Concord, Ontario, Canada, sells an FTIR device for industrial monitoring – the **IMx**. Open-path monitoring is possible by adding telescope-based accessories to the base unit. The IMx base library currently includes more than 200 molecular species, of which many – 30 to 50 or more – can be monitored simultaneously in real time. Unisearch says the device is ruggedized, and "highly immune" to the vibration and temperature swings that plague other FTIR systems. The IMx can be figured either for monostatic or bistatic operation. Unisearch Associates advertises the IMx industrial FTIR monitor as compact, with "unparalleled" stability and immunity to vibration and temperature swings.

Cells with optical path lengths to 150 meters can be used, or the device can be hooked up to telescopes for open-path monitoring. The IMx has three reference libraries: 25°C, with approximately 200 compounds; 100°C (60-80 species); and 185°C (60-80 species). The unit's software, developed with the **Nicolet Corporation**, "eliminates essentially all the problems with field FTIR units, particularly linearity problems."

The IMx sells for $90,000 to $130,000, depending upon which configuration is purchased.

Communication with a scientist at Unisearch revealed that the practical limit for their FTIR system is about 500 meters with standard retroreflectors. This could be pushed to about one km, but the reflectors are expensive. Data time scale is typically about one minute.

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AFRL / ARCADIS - proposed RS protocol

At a meeting in June 2000, **Patrick Sullivan** of the **AFRL** and **Ram Hashmonay** and **Mark Modrak** of **ARCADIS** described their new protocol for the measurement of nonpoint emission sources. Their method:

- Uses OP-FTIR (or other OP method) multiple beams to determine vertical and horizontal gradients.
- Uses optimization algorithms to directly reconstruct the mass equivalent plume downwind from the source.
- Has no need for tracer release or an inverse dispersion modeling approach for plume characterization.
- Emission flux is determined by plane-integrated concentration *x* wind speed.

Sullivan describes the technique as Path-integrated Optical Remote Sensing (PI-ORS) in a current summary page for an ESTCP project, "Optical Remote Sensing Method to Determine Strength of Nonpoint Sources," which can be found here.

> PI-ORS uses multiple beam paths and optimizing algorithms to give a time-averaged, mass-equivalent concentration field across a plume of contaminant, from which the emission rate can be determined without dispersion modeling. Reflectors are deployed in a radial asymmetric pattern that includes the emission area source, from which the approximate boundaries of the plume's origin can be determined. When the plume is located, the array of reflectors is redeployed in a vertical plane immediately downwind and centered across the plume's origin. The PI-ORS system scans from reflector to reflector in a constant pattern, separately accumulating values for each reflector to generate a long-term average in each spatial element. The novelty is in placing a two-dimensional array of reflectors so the absorption information can be directly translated, by a tomographic algorithm, into time-averaged area concentrations without using dispersion model estimates. Source strength is effectively the product of the sum of the area concentration elements multiplied by the average wind speed during the determinations.

The presentation reviewed an AFRL-sponsored field experiment conducted in Oxford, NC by ARCADIS under EPA guidance. Sullivan *et al.* gave the following table for cost comparisons between conventional methods (undefined) and their optical remote sensing protocol:

#	*Task*	*Conventional ($)*	*ORS + Conventional ($)*
1	Preparation	22,000	7,000
2	Set-up	6,000	3,000
3	Test	50,000	30,000
4	Report	25,000	10,000
5	Travel	7,000	5,000
6	Subcontractor Expenses	60,000	15,000
7	Other Expenses	20,000	30,000
	Total	190,000	100,000

They concluded that the OP multiple beam method can provide accurate quantification of area sources, with lower cost and less complexity than conventional methods. (The presentation can be found here.)

A more recent presentation referred to a new adaptation of this technique as **RPM (Radial Plume Mapping)**:

> This method uses an optical sensor mounted on a scanner, which sequentially directs an optical beam from a single location to multiple reflectors. An optimization algorithm is used for mapping the field of concentration across the plume of contaminant. When scanning is performed on a horizontal plane, hot spots of fugitive emissions can be located. The RPM method, along with the wind measurements, can also be used to measure emission fluxes from an area source, when the scanning is performed on a vertical plane downwind of the area source. This presentation describes the results from a controlled demonstration study that applied this approach.

[Taken from a poster (page 31) presented at the December 2003 SERDP meeting. The work is done under CP-0214.]

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IMACC - open-path passive FTIR (Unknown FTIR device)

A presentation by **Robert Spellicy** of **IMACC** at a NARSTO conference in Austin in October 2003 discussed the "Evaluation of Passive FTIR to Determine Efficiency of Operating Industrial Flares." The paper was to report on data from tests that had been conducted using a passive FTIR system. No manufacturer was given, nor were identifying details provided. The project involved testing passive FTIR to determine its capability to provide the desired data quality for measurements of flare combustion and destruction efficiency, and provide estimated mass emission rates. Speciated emissions were to be measured, if possible. [No results were mentioned in the abstract (see page 63). Testing was done at a test flare facility in Oklahoma. See here.]

Information Resource on FTIR (University of Wisconsin)

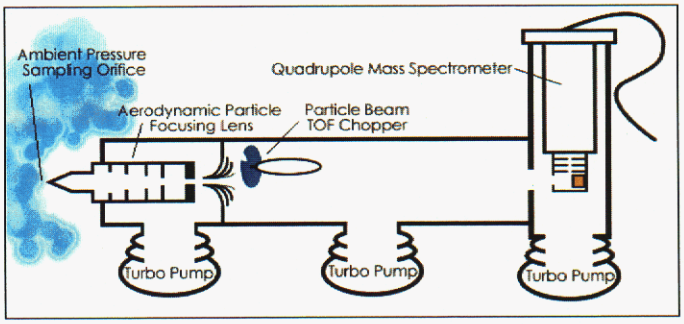
The library at the Space Science and Engineering Center of the University of Wisconsin, Madison maintains an on-line "**High Spectral Resolution FTIR Bibliography**." The web page is updated frequently, and in January 2004 was 42 pages long.

Aerosol Mass Spectrometry (AMS)

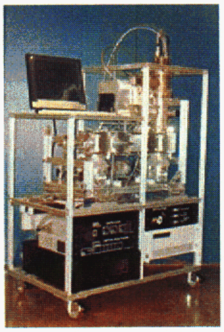
AMS: Basic AMS design consists of three main parts: an aerosol inlet, a particle sizing chamber, and a particle composition detection section. Each section is separated by small apertures and is differentially pumped. Particles are sampled from ambient pressure and focused by an aerodynamic inlet into a narrow beam (~1 mm diameter) as they enter into high vacuum. Particle aerodynamic diameter is determined by measuring particle velocity via particle time-of flight over a known flight path. Particle chemical composition is determined via flash vaporization (or other methods) followed by electron impact ionization mass spectrometry.

Aerodyne AMS

Aerodyne Research Incorporated (ARI), of Billerica, MA, developed a widely-used **aerosol mass spectrometer**. The AMS has become a widely used tool for research. Aerodyne was founded by **Charles Kolb**. (See the AMS web site here for links to many pages of information on the AMS and its users.)



The AMS was designed to provide real-time quantitative information on size-resolved mass loadings for volatile and semi-volatile molecular components found on or in ambient aerosol particles. It works on assemblies of particles, and can provide only limited single particle information.

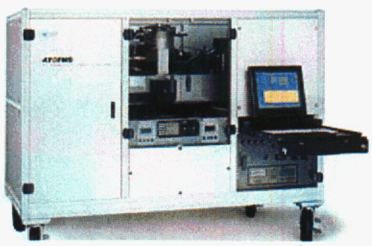


The AMS has been installed in a mobile lab operated by Aerodyne. This mobile lab has been used in vehicle emission studies in a number of cities. An Aerodyne AMS was used to measure point-of-discharge fine particle emissions at the Aberdeen Test Center in a series of tests of weapons muzzle emissions in the fall of 2003. The AMS was used to quantify inorganic sulfates, nitrates, carbonates, chlorides, and the total organic particle mass. Specific toxic compounds identified and quantified included particle-bound cyanides, polycyclic aromatic hydrocarbons (PAHs), and several transition metals. (This was part of SERDP CP-1197. A brief summary of the work is here, page 32.)

The Aerodyne AMS is currently the only commercially available system of its kind. It uses a dual-MS system to provide information on both particle aerodynamic diameter and aerosol composition in a single shot. It provides real-time quantitative measurement of size-resolved aerosol mass for non-refractory fine particulates (30 nm to about 2.5 mm), and offers fast (1-10 seconds) measurement of particle size distributions and non-refractory chemical composition. Maximum data rate is 100 Hz, sensitivity is 0.1 mg / m³, and the volume flow rate is 100 cm³ per minute. The AMS weighs 90 kg and the electronics rack is another 97 kg. The AMS is about 36 x 36 x 24 inches; the electronics rack is 36 inches high. It has been deployed from ground sites, trucks, and aircraft.

Contact information for Aerodyne Research
Aerodyne Research Incorporated 45 Manning Road Billerica MA 01821
Telephone: 1-978-663-9500 Fax: 1-978-663-4918
E-mail: info@aerodyne.com Web site: www.aerodyne.com

TSI ATOFMS Model 3800



TSI Model 3800

TSI Incorporated, of Shoreview, MN, makes a commercial aerosol time-of-flight mass spectrometer, its **Model 3800**. This ATOFMS was developed in cooperation with **UC Riverside**. The Model 3800 measures single particle size and chemical composition in the range of 0.3 to 3 µm (up to ten µm with the optional disperser). It can save mass spectra at up to ten particles per second. The Model 3800 uses two distinct ToF technologies: one for particle size determination, the other for particle chemical composition determination. The Model 3800 analyzes airborne solids and semivolatile liquids. The particle-sizing lasers are 50 mW at 532 nm; the desorption / ionization laser is 3 mJ / pulse at 266 nm, with a maximum pulse rate of 20 Hz. Operating temperature is 10-35°C. The maximum operating altitude is 2000 meters. The unit weighs 360 kg, measures 170 x 74 x 130 cm, and uses 4kW maximum power (220-240 VAC). (A description of the unit is here.)

An aerodynamic focusing lens (AFL) developed by the University of Minnesota can be purchased as an accessory for the Model 3800. The AFL replaces the standard inlet nozzle, and allows more efficient sampling and a higher analysis rate. Transmission is close to 100%.

Contact information for TSI
TSI Incorporated 500 Cardigan Road Shoreview, MN 55126-3996
Telephone: 1-651-483-0900 Fax: 1-651-490-2748
E-mail: tsiinfo@tsi.com Web site: www.tsi.com

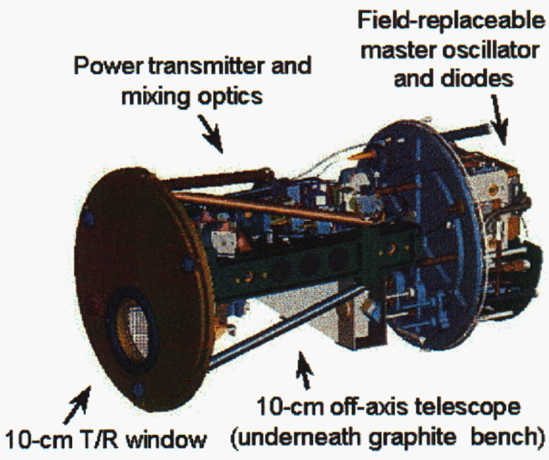
LIDAR (Light Detection and Ranging)

LIDAR: An acronym for **l**ight **d**etection **a**nd **r**anging, describing systems that use a light beam in place of conventional microwave beams for atmospheric monitoring, tracking and detection functions.

Coherent Technologies WindTracer coherent optical laser radar

Coherent Technologies (CTI) of Boulder, Colorado makes the **WindTracer**, an eye-safe IR Doppler radar. The WindTracer is capable of detecting aerosol particles as small as 0.2 microns. It can produce local vertical wind profiles to 10 km in less than five minutes. Hemispherical scans to 16 km are produced in ten minutes. The WindTracer has a stated detection range of 15 km for high concentrations (undefined) of aerosols, with detection sensitivity of "a few hundred to a few thousand" particles per liter. Wind data is measured simultaneously. Minimum range is 400 meters; range resolution is 50-100 m. Detection sensitivity is stated as 100-1000 particles per liter. The WindTracer weighs 285 pounds, and occupies 3.3.cubic feet.

Coherent Technologies says that Dugway uses the WindTracer as the referee for bio-aerosol sensor tests.

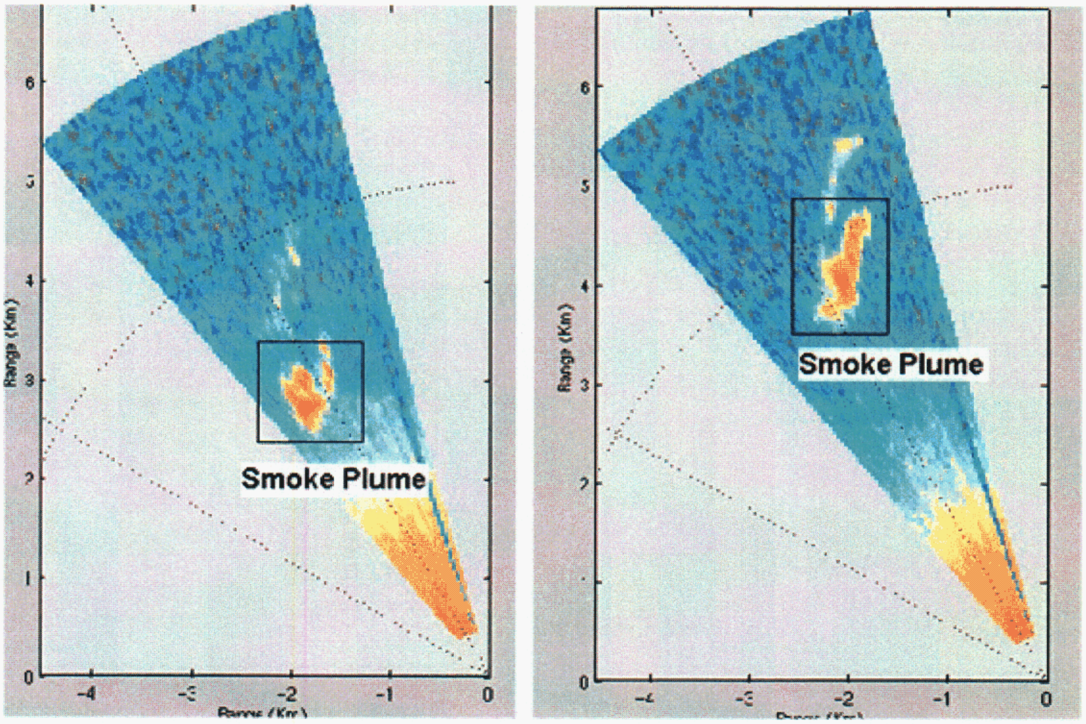


Coherent Technologies *WindTracer*

Specifications provided by Coherent Technologies for the trailer-mounted model:

Trailer Mounted Remote Sensor	
Specification	**Horizontal Profile**
Typical Range	8km to > 15 km
Minimum Range	400 m
Range Resolution	50 – 100 m
WS Velocity Resolution	0.5 m/s
Detection sensitivity	100 - 1000 particles/liter
Weight	285 lbs
Volume	3.3 cubic feet

Arizona State University LIDAR environmental sensing: **Ron Calhoun** and **Joe Fernando** of ASU have been using a Coherent Technologies WindTracer LIDAR (with funding from the Army Research Office) in smoke plume tracking. ASU participated in a July 2003 experiment in Oklahoma City that was sponsored by the ARO, DTRA, and the EPA. The image below is from a presentation (page 20) made at the FAME (Frontiers in Assessment Methods for the Environment) symposium in Minneapolis in August 2003.



Calhoun, Fernando, and J. Peccia, all of ASU, are scheduled to present a paper titled "Tracking aerosol plumes: LIDAR, modeling, and in-situ measurement" at an SPIE meeting in April 2004. Further details were not available at the time of this writing; the paper possibly concerns the Oklahoma City work.

Orca LRS-100 LIDAR

In the mid-1990s, a program at the **University of Utah,** sponsored by the **Army Research Office,** was to have designed and built an alexandrite laser receiver. **Tom Wilkerson** of Utah was the PI; **Orca Photonics** of Redmond, WA was the vendor. Orca built an instrument, the **AROL**, which was not only a near-IR alexandrite laser receiver, but also contained an independent Nd:YAG laser for stand-alone LIDAR operations at 532 nm. Orca now markets the LIDAR as the LRS-100 aerosol LIDAR system. The baseline version is at 532 nm, but other configurations are possible, such as a dual-polarization system, or an eye-safe 1.57 μ version. A representative from Orca quoted LRS-100 costs as ranging from $150,000 to $250,000, depending upon configuration and options, with $175,000 being an average price.

Orca later made an improved version of the LIDAR, called the **AROL-2**, which was essentially the first-generation AROL plus two digital (photon counting) channels for greater sensitivity and range. The AROL-2 scanned in zenith only; this is also evidently true for the LRS-100. (See web page here, abstracts here and here, and article by Wilkerson on AROL-2 performance here.)

Orca *LRS-100*

Contact information for Orca Photonic Systems
Orca Photonic Systems, Inc. 14636 NE 95th Street Redmond, WA 98052
Telephone: 1-425-702-8706 Fax: 1-425-702-8806
E-mail: info2@orcaphotonics.com Web site: www.orcaphotonics.com

DIAL (Differential Absorption LIDAR)

DIAL: The Differential Absorption LIDAR technique uses two LIDAR signals at slightly different wavelengths, one of which is chosen at the center of an absorption line of the gas under study, and the second one in a weakly absorbing spectral region. When the wavelength difference is sufficiently small the backscatter and extinction are the same except for the gaseous absorption. Differential absorbtion allows for detection of trace gases at several kilometers from the system.

Custom-made DIAL cost estimates

A February 2002 paper by **Stanley Shewchuk** of the **Saskatchewan Research Council** and **Robert Spellicy** of **IMACC** entitled "Well test Flare Plume Monitoring" (SRC 11303-2C01), reviewed various dispersive and non-dispersive remote sensing options. The article also reviewed work using DIAL to monitor atmospheric Hg and SO2.

The authors give an estimate for design and fabrication of a DIAL system as follows, based on estimates in 2002 for **Orca Photonics** to provide a turn-key system, fully tested and validated:

Estimated Cost in 2002 for a Custom-built DIAL System	
Basic LIDAR hardware	$550,000
Telescope / scanner system	$250,000
Vehicle and system build-out	$400,000
System integration	$300,000
Software development, integration, and testing	$200,000
System characterization, calibration, and testing	$500,000
Total	**$2,200,000**

They say that a commercial system could be purchased (early 2002) from Optech or Elight for about $1,500,000 to $2,000,000. All vendors quoted development time of eight to twelve months.

Elight UV11 DIAL

A German company, **Elight Laser Systems**, markets a **mobile DIAL van**, the **LIDAR UV11.** Detection limits and ranges are given below for some pollutants (taken from the company's brochure for the UV11, available here). The operational point is 250 meters, the best spatial resolution is 7.5 m, and a 90° scan typically takes about 15 minutes.

Characteristics of Elight Mobile UV11 DIAL		
Species	**Detection limits (µg / m³)**	**Range (meters)**
SO2	8	2200
NO2	20	2500
Ozone	2	2100
Toluene	10	1700
Benzene	10	1600
Aerosols	0.05 /km extinction)	3000

Contact information for Elight
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E-mail: info@elight.de Web site: www.elight.de

LLNL DIAL for CALIOPE

CALIOPE (Chemical Analysis by Laser Interrogation of Proliferation Effluents) was an LLNL project, managed by Hal Goldwire, to develop and test remote sensors to detect and measure chemical concentrations in air. A series of tests were carried out at the Nevada Test Site in the mid-1990s. Known concentrations of chemicals were injected into well-characterized plumes and measured at remote stations.

> Under the auspices of the DOE's CALIOPE program, LLNL's **LS&T** built a high-repetition-rate, frequency-agile, solid-state laser transmitter for a differential absorption LIDAR system to conduct remote sensing from an airborne platform. As part of DOE's Airborne Proliferation Detection Experiment (APEX), LS&T participated in a series of remote chemical sensing tests conducted at the Nevada Test Site aboard Phillip's Laboratory's KC-135 ARGUS aircraft. The infrared (IR) LIDAR laser beam was generated by an optical parametric oscillator pumped by diode-pumped Nd:YAG lasers. Frequency tuning was achieved by rapid-angle tuning of the pump beam using an acoustic-optics beam deflector. The system had an average power of 2 W and could be repetitively pulsed at 10 kHz and tuned in the 3.2- to 3.6-μm region. After several flights, the LS&T team was able to operate this sophisticated solid-state laser transmitter reliably in the harsh airborne environment.

(See write-up on laser here.)

Spectrasyne Ltd. mobile DIAL system

Spectrasyne Ltd.. of the UK is the self-proclaimed world leader in DIAL-based environmental surveying for the oil and gas industries. Their DIAL unit is a duplex setup, allowing simultaneous measurement of the concentration of two species or species groups. Spectrasyne units are used to measure mass emission rates (and quantification) of VOCs and aromatics from oil refineries, etc.

Spectrasyne systems are used regularly to monitor for VOCs (individually or as mixtures), benzene, toluene, NO and NO2, methane, and “many others.”

Spectrasyne's DIAL is mounted in a 12-meter long vehicle, the **Environmental Surveying System (ESS)**. The ESS contains two complete Nd:YAG pumped, dual wavelength dye lasers to provide the multi-wavelength source for DIAL measurements. The laser systems incorporate frequency doubling and mixing accessories to give a range of UV and IR wavelengths to augment the visible and near-IR spectrum produced by the dye lasers alone. The ESS also has a meteorological mast and a number of mobile meteorological stations, connected telemetrically. Typical "cocktails" of fugitive species abundant at oil industry sites are measured in a spectral region around 3 μ wavelength where absorption of most of the light hydrocarbons overlap. This region thus provides the opportunity for the DIAL system to identify the majority of atmospheric species in a single measurement. Spectrasyne says that in a number of controlled experiments using measured quantities of emissions, the maximum divergence from the DIAL measurements was 15%

Spectrasyne does not sell this system to others. Rather, it sells its services -- preparation, data analysis, and reporting. Cost estimates for Sepctrasyne's services were an average of about $16,000 per day, plus travel and subsistence costs. (Source: communication from Spectrasyne, March 2004.)

In late 2003, **Allan Chambers** of the **Alberta Research Council** gave a presentation on "Well Test Flare Plume Monitoring – Results of DIAL Measurements in Alberta." The test was able to track SO2 plumes to at least two km, and were able to detect levels < 450 μg / m³. The results were accurate, as indicated by incinerator plume mass flows. The instrumentation gave a good picture of plume breakup and dispersion. The DIAL unit worked in the rain (but not in fog). It had to be at least 50 m from the plume. The unit could be set up on site within an hour. Since the tests were performed, the instrument has been improved, and flare plume scans are now possible in approximately 1-2 minutes.

TDLAS (Tunable Diode Laser Absorption Spectrometer)

TDLAS: These laser spectrometers use for their light source laser diodes which are tunable to frequencies for particular gases of interest.

Aerodyne TDLAS

Aerodyne Research, of Billerica, MA, offers custom-built TDLAS systems. Customers have included almost a dozen world-wide research institutions (environmental, agriculture, energy, geography, etc.) and corporations (Shell, Philip Morris). Among the applications of the device are remote sensing of emissions and remote monitoring of pollutants and fence-line monitoring. (It is unclear from the text if these are actual applications, or merely potential ones.)

The Aerodyne TDLAS offers wide spectral coverage and "extreme" sensitivity, from 0.1 to 1.0 ppb detectivity). Its design offers a multipass absorption cell with astigmatic mirrors which can provide a path length of 36-300 m in a small volume (0.3 to 5 liters) and give fast response time (0.05 to 1 sec). Aerodyne offers a modular optical layout which allows either long-path *in situ* sensing or point extractive sampling using the absorption cell. Spectral processing is done via rapid scan averaging with spectral fitting. Data collection and calibration cycles are automated, providing continuous output.

Aerodyne gives the following specifications for several models of TDLAS (the two "D" models have dual diodes):

Aerodyne TDLAS systems			
Model	**TDL-36**	**TDL-300-D**	**TDL-O-D**
Example of Species	CH4, NO2	NO2, HNO3, HOCl, C2H5	NO, NO2, CO2, CO
Base path	20 cm	88 cm	Open path retro-reflector
No. of passes	182	334	
Path length	36 m	295 m	Unstated
Volume	0.3 l	5 l	
Time constant (w/ 300 l / min pump)	0.05 sec	1 sec	
Size	2 x 2 feet	2 x 4 feet	2 x 4 feet
Weight	70 kg	140 kg	140 kg
Electronics rack	30 x 22 x 15 inches		

Contact information for Aerodyne Research
Aerodyne Research Incorporated 45 Manning Road Billerica MA 01821
Telephone: 1-978-663-9500 Fax: 1-978-663-4918
E-mail: info@aerodyne.com Web site: www.aerodyne.com

Heath Consultants RMLD: TDLAS methane detector:

Heath Consultants of Houston markets commercial leak detectors for monitoring for methane leaks from pipelines. A presentation by company personnel at a December 2002 kick-off meeting at the National Energy Technology Laboratory described present performance and future performance of what they called the **RMLD** (remote methane leak detector). This is a TDLAS device. The working range was up to 30 meters, and projected sales price was about $10,000. The alpha prototype was delivered in December 2002 and introduction of the product was planned for fall 2003.

This unit is evidently based on the prototype developed by scientists at Physical Sciences Inc (PSI) and described in a paper presented by Michael Frish and others in November 2000 at an SPIE conference. That prototype unit had a 20-m range.

Contact information for Heath Consultants
Heath Consultants 9030 Monroe Road Houston, TX 77061
Telephone: 1-713-844-1300 Fax: 1-713-844-1309
E-mail: marketing@heathus.com Web site: www.heathus.com

Norsk Electro Optikk TDLAS LaserGas and Dust monitors

Norsk Electro Optikk (NEO), a Norwegian company, manufactures several models of TDLAS gas and dust monitors. They are made in both open-path and dual-path models. Response time is less than two seconds. There are **LaserGas** models for O2, HCl, HF, NH3, CO, Co2, H2O, H2S, HCN, NO, NO2, CH4 and other hydrocarbons, as well as models for two gases simultaneously, or a gas and temperature. The path length has a 6-meter maximum, however. Both CO and CO2 can be measured at a detection limit of 30 mg / m^3. (See here for more information on the LaserGas monitors.) The **DM4 Dust Monitor** has a path length range of 100 – 400 meters, depending on concentration. (See here for more information on the DM4 open-path dust monitor.)

Unisearch LasIR

Unisearch Associates, of Concord, Ontario, Canada, sells a TDLAS unit they call the **LasIR.** It comes in models designed for stack monitoring, point monitoring, and remote monitoring – the LasIR-R model. Paths of "up to one km" are claimed. Measurable species include: HF, HCl, HBr, HI, HCN, CO, CO_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_8, CH_2CHC_l, NO, NO_2, NH_3, H_2S, H_2O, O_2, D_2O, and HOD. Measurements can be made in less than one second, sensitivities to below 1 ppbv can be attained (dependent upon path length), and measurements are unaffected by particles or rain. The LasIR sells for about $20,000. (Communication from Unisearch, March 2004.)

The LasIR electronics weigh 15 kg and the telescope and retroreflector weigh 5 kg and 1 kg, respectively. The electronics unit measures 46 x 22 x 45 cm. More than 100 LasIR systems are in commercial operation, at smelters, landfills, refineries, incinerators, and other types of industrial operations. Stated detection limits are in the sub-ppbv range when used in ambient situations at >100 m. Typical response time is one second.

The table below is from a Unisearch brochure and gives the detection limits for the LasIR, with a one-second-response time.

Detection Limits for the Unisearch LasIR			
Gas	**Stack**	**Remote**	**Point**
	(4m) ppmv	***250m (ppbv)***	***12m (ppmv)***
HF	0.02	0.25	0.005
HCl	0.25	4.0	0.025
HBr	6.0	100	1.0
HI	0.3	5.0	0.05
NH_3	0.6	10	0.1
H_2O	0.2	4.0	0.05
H_2S	2.5	40	0.25
CO	75	1000	5.0
CO_2	75	1000	5.0
O_2	250	4000	40
NO	25	1000	3.0
NO_2	3.0	50	0.5
HCN	0.02	0.3	0.03
CH_4	0.25	4.0	0.05
C_2H_2	0.6	10	0.1
C_2H_4	0.5	10	0.05
C_2H_6	10	200	1.0
C_2H_8	10	200	1.0

Contact information for Unisearch
Unisearch Associates Inc 96 Bradwick Drive Concord, Ontario, Canada L4K 1K8
Telephone: 1-905-669-3547 Fax: 1-905-669-8652
E-mail: info@unisearch-associates.com Web site: www.unisearch-associates.com

DOAS (Differential Optical Absorption Spectroscopy)

DOAS: The process whereby column abundances of trace-species are derived from measurements of electromagnetic radiation in a specified spectral interval. The main advantage of this technique over others is that it allows real-time measurements of several different trace-gas species with a single instrument. To perform DOAS, two spectra are necessary: one, referred to as the reference, in which the light has passed through little (ideally none) of the absorber in question; and one in which the light has passed though a large amount of the absorber. The retrieved DOAS quantity is the apparent column density (ACD). When the instrument is pointed towards the sun the measured signal comes from direct sunlight. In this case the physical interpretation of the ACD is relatively straightforward: it represents the difference in the column density of the absorber between that along the line-of-sight and that in the reference. Often, however, the viewing direction is away from the sun and so the source of the measured signal is scattered light. The ACD no longer has a clear physical interpretation as the path of the light through the atmosphere is complex and the measured sunlight may have been scattered in the atmosphere or reflected by the surface several times. (Source here.)

Cambridge Volcanology Group: DOAS

Andrew McGonigle and others at the **Cambridge Volcanology Group** in England have developed, in collaboration with **Bo Galle** of **Chalmers University of Technology** in Gothenburg, a miniature UV spectrometer for measuring SO2 flux from volcanoes. (See here. McGonigle's home page is here. The Chalmers Optical Remote Sensing Group page is here.)

The abstract of Galle's 1999 thesis gives the following description of his DOAS work:

> This dissertation deals with the development and application of instrumentation and measurement strategies based on long path UV and IR absorption spectroscopy for atmospheric research. The instrument development comprises a novel design of a transmitting / receiving telescope facilitating the use of single ended DOAS measurements and a unique 1 km open multireflection cell which, combined with an FTIR spectrometer, is capable of ppb level measurements of a large number of different gases. A shorter version of the system, with 200 m optical path, has proven very valuable for industrial hygiene studies. The measurement strategy development involves the use of dual beam DOAS spectroscopy to improve background concentration monitoring, an approach to studying emissions from aircraft using zenith sky DOAS, the development of the Time Correlation Tracer technique for measurements of fugitive emissions, various gradient methods and the megachamber concept for area integrated measurements of biogenic emissions.
>
> The various instruments and techniques have been applied in a large number of field campaigns including measurements of: SO_2, NO_2, NO, O_3, HNO_2, and CH_2O in urban and background air; biogenic emissions of N_2O, CH_4, and CO_2 from various ecosystems; NH_3, N_2O and NO from liquid manure spreading; ethylene, propylene, ammonia and various hydrocarbons from industrial activities; terpenes, peracetic acid, ammonia and various hydrocarbons from indoor industry; total methane emission from landfills; and total columns of O_3, NO_2, HC1, HNO_3, HF, ClO, COF_2, N_2O and $ClONO_2$ of importance for stratospheric ozone depletion. All this work has been carried out in strong international collaboration.

The Cambridge Volcanology Group's portable DOAS was used in Montserrat in 2003 to detect bromine emissions from a distance of six km. (See article here.)

Results with the portable DOAS used to measure H2S from volcanoes in Italy were reported in an article in *Geophysical Research Letters* (Vol. 30, No. 2, 1652, June 2003). When DOAS had been used previously for volcanic SO2 monitoring, skylight was used as the source radiation. To go from the SO2 spectrum at 300 nm to the H2S one at 200 nm, an artificial light source had to be added. They used a deuterium lamp. Open-path configurations of up to 40 m were used. At an open path of 10 m, detection limits were 2 ppmm. Tests with calibrated mixtures showed the instrument had an accuracy of better than 5%. "The approach has applications for monitoring airborne concentrations of H2S and SO2 and for measuring the ratio of these two species at a time-step as short as one second, day or night, given a power source of 50 W."

A paper by Galle *et al.* in the *Journal of Volcanology and Geothermal Research* vol. 119, pp. 241-254 (2002) described the mini-DOAS unit:

> The system is based on an **Ocean Optics USB2000** spectrograph, fiber-coupled to a telescope. The spectrometer uses an asymmetric crossed Czerny Turner configuration with a focal length of 42 mm (input) and 68 mm (output). It has a 2400 lines / mm plane grating with enhanced efficiency between 200 and 400 nm, which, combined with a 50-μm slit, delivered a spectral resolution of ~0.6 nm over the wavelength range of 245-380 nm. A cylindrical lens was used to reduce the image of the slit to the size of the detector. The detector, operated at ambient temperature, was a 2048-element linear CCD-array (Sony ILX511) treated for enhanced sensitivity below 360 nm. The size of each element is 13 μm (width) by 200 μm (height). The full well capacity of this diode is 160 000 photoelectrons. The dark current and the electronic offset at room temperature were 9 counts / sec and 178 counts per scan, respectively, and the read-out noise was ~3 counts per scan. The inter- element variability in sensitivity was generally less than 0.5%, though it was as much as 2% for some diodes. Residual noise was measured by ratioing two scans of a halogen lamp spectrum (after dark current and offset correction). Although the read-out and shot noise should further decrease with increasing number of photo electrons, the residual noise did not decrease below 0.1-0.2% peak-to-peak. The spectrometer's optics, detector and electronics (for read-out of the CCD-array, A/D conversion and spectral averaging) are built into a very compact (89 mm x 64 mm x 34 mm, 0.2 kg) unit. The unit was powered (1 W power requirement) via the USB-port of a laptop computer, which also supported data transfer.
>
> Ultraviolet light scattered from aerosols and molecules in the atmosphere is collected by means of a custom-built telescope (length 25 cm, diameter 3 cm) consisting of two quartz lenses. The first lens defines the field-of-view of the telescope (20 mrad), while the second acts as a field lens and decouples the image of the sky from the spectrometer input. This eliminates the risk that a non-uniform illumination of the telescope field of view (caused by varying cloud cover) is transferred to the detector elements. As each detector element's sensitivity varies across its surface, such non-uniform illumination could distort the spectra. A filter (Hoya U330), blocking visible light >360 nm, was used to reduce stray light in the spectrometer. Light was transferred from the telescope to the spectrometer by means of a 3-m-long optical fiber bundle, consisting of four individual 200-μm-diameter fibers, arranged in circular (telescope side) and linear (spectrometer side) configurations. The fibers were made of solarisation-resistant quartz. The software used for controlling the spectrometer, as well as for evaluating the spectra, was a custom-built program, DOASIS.

Spectrex SafEye Xenon 700 DOAS

Spectrex sells a flash-type IR open-path gas detector, called the **Xenon 700**. The SafEye Xenon 700 consists of a xenon flash IR transmitter and an IR receiver, which can be separated from 4 to 140 meters apart. The spectral response is from 2-4 µm. Operating range is from -40 to 55°C. The Xenon 700 sells (price quote in March 2004) for $8,273, with one gas detector, one light source, and two mounts. The units are small, as seen in the following table:

Size of the Spectrex SafEye Xenon 700				
Component	**Length**	**Width**	**Height**	**Weight**
Detector	210 mm	145 mm	154 mm	4.2 kg
Source	255 mm	135 mm	175 mm	4.6 kg
Tilt mount	120 mm	120 mm	140 mm	1.9 kg

(More information on the SafEye Xenon 700 can be found here and here.)

Spectrex also sells the **SafEye 400**, a flash-type UV open-path gas detector. The SafEye 400 is available in ten different models, with varying ranges and other attributes. Range for H2S is from 1-100 meters; other gases have detectable ranges from 1-50 meters. The SafEye sells (price quote in March 2004) for $9,719 complete. (Data on the SafEye 400 is here and here.)

Contact information for Spectrex
Spectrex Inc. 218 Little Falls Road Cedar Grove NJ 07009
Telephone: 1-800-452-2107 Fax: 1-973-239-7614
E-mail: spectrex@spectrex-inc.com Web site: www.spectrex-inc.com

Unisearch DOAS

Unisearch says its fence-line UV DOAS monitoring system is designed to operate unattended for long periods of time. Excellent performance is attained on SO2 and a number of other species. Unisearch developed the **DOAS 2000** in collaboration with Thermo Environmental Instrument Inc. (The instrument is no longer shown on the Thermo web site, however.)

The DOAS 2000 was tested in five field campaigns and in two DOAS inter-comparison tests. The system produced "reliable and accurate" measurements of O3, SO2, and NO2. The system was evidently developed at the **Swiss Federal Institute of Technology**, by a team led by **Rodrigo Jiminez**. *(Further information: A poster from 2000 on the DOAS 2000 is here. A web page describing the development of the instrument is here. A March 1999 presentation on the DOAS is here. A paper on "DOAS as an Analytical Tool for Effective Air Pollution Management" is here.)*

A cache of the **Thermo** page giving specs for the DOAS 2000 said the separation distance was 25 to 1000 meters (species dependent), the optical path length was 50 to 2000 meters, averaging time was 10 seconds to 24 hours, the nominal wavelength range was 200 to 650 nm, the scan range was 32 nm, and a typical detection limit was 1 ppb.

The National Institute of Water and Atmospheric Research (NIWA) in New Zealand has used a DOAS 2000, and lists its advantages as:

- It provides the ability to continuously measure many pollutants that could not be measured previously in New Zealand.
- Multiple pollutants can be measured simultaneously.
- Monitoring over a wide area (open path to one km) provides a more representative picture.

NIWA uses the DOAS 2000 to measure NO2, NO, HNO2, NO3, SO2, O3, NH3, and VOCs. (See their page on the DOAS 2000 here.)

IR: AIM 8800 Series Open-Path Ambient Air Analyzer

Air Instruments and Measurements (AIM) makes an **8800** series analyzer that the company says can consist of one or more of the following: **NDIR analyzer**, advanced **DIR dispersive IR analyzer**, and / or a **DUV dispersive UV analyzer**. Each is capable of continuously monitoring multiple gases, plus opacity and dust. The path is in the 10s to 100s of meters. The system is described as rugged. Species include NH3, NO, NO2, HONO, N2O, H2S, Cl2, ClO2, HCl, O3, BTX, HCHO, butadiene, and others. (See here.)

The NDIR analyzer is described by the company as follows:

> A patented NDIR analyzer capable of measuring up to 6 gases simultaneously, and up to 10 gases as a special order, with interchangeable measurement modules, further expanding its capabilities. The measurements are made by either GFC (gas filter correlation, for CO, NO, HCl, CH_4, N_20, etc), or DOAS (differential optical absorption spectroscopy).
>
> The system includes either a TE cooled PbSe detector, or PbS detector, with spectral response from the near IR to 5.3u. Measurement sensitivity is limited by path length. For extractive systems, we normally supply a compact low volume multipass [White-type] sample cell, and can offer path lengths from 0.5 cm for liquids, to 100m for measuring gases like HCl, HF, etc. at or below 10mg/m3. A standard 10m cell can be used to easily measure most gases of interest at 100ppm full-scale up to 5000 ppm full-scale.

The DUV is described as a newly developed and patented:

> novel multicomponent dispersive UV [DUV] analyzer measuring from below 200 nm to the visible, with an ultra-stable pulsed xenon arc source and a single or dual monochromator, each with a 1024-element CCD array detector, for low ppm and ppb levels of permanent gases such as NO, NO_2, NH_3, $S0_2$, H_2S, Cl_2, 0_3 as well as VOCS such as benzene, toluene, xylene, phenols, furans, chlorobenzenes, amines, etc.

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Inductively Coupled Spectrometry for MMCEMS

Inductively coupled spectroscopy: uses a plasma as both an excitation and an atomization source.

The **Naval Air Warfare Center Weapons Division** at China Lake developed a **MMCEMS (multi-metal continuous emissions monitor system)** for HAP metal emissions. An ESTCP project for validation of the MMCEMS took place at Tooele (stack emissions from a deactivation incinerator) and at a Plasma Arc Hazardous Waste Treatment System at a plant in California. Eight of ten metal analytes were measured satisfactorily (Ba, Cd, Cr, Mn, Ni, Pb, Sb, Sr, and Y). The MMCEMS was developed by **Brian Selzer** and employs an argon inductively-coupled plasma (ICP) spectrometer for analyzing gases that are sampled from the stack. The Navy licensed the technology to TJA Solutions (now a part of Thermo Electron), who was selling it as the **TraceAir** device. (In early 2001 the device was selling for about $360,000.) (The ESTCP validation report is here.)

X-ray Fluorescence: Cooper's X-Ray-Based CEM for Metals (XCEM)

Cooper Environmental Services has developed an X-ray-based continuous emission monitor (**XCEM**) for use in measuring stack effluent. X-ray fluorescence is used for analysis. Samples are collected on a resin-impregnated filter tape. As many as 19 metals can be measured simultaneously every 20 minutes.

In 2002, the XCEM was certified for use by the ETV Advanced Monitoring Systems (AMS) Center. The XCEM was tested for accuracy on Sb, Ba, Cd, Cr, Pb, As, Hg, Ni, and Zn. (See manufacturer's page here and brief article here.)

Cooper Environmental also makes a continuous emission mercury monitor (**XCMM**), also based on X-ray fluorescence. (See here.)

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Optical: AFRL's Digital Camera Opacity Determination

Michael Calidonna of the **Air Force Research Laboratory** is principal investigator for an ESTCP compliance project: "An Alternative to EPA Method 9 – Field Validation of a Digital Recording and Analysis System for Opacity Compliance Measurements." Method 9 uses trained human observers who make visual estimates of air opacity every 15 seconds. Calidonna's method uses a COTS digital camera to capture images and a laptop for analysis for opacity. He sees the system as a cost-effective, objective, forensically reproducible, and legally defensible alternative to Method 9. (See summary sheet here.)

Particulate Detection

University of Utah: Work on particulate emissions

A team led by **Adel Sarofim** and **JoAnn Lighty** at the University of Utah has been working on SERDP CP-1106, "Characterization of particulate emission: Size Fractionation and Chemical Speciation." Three techniques for rapid measurement of fine particles are used.

Aerosol time-of-flight mass spectrometer (ATOFMS): Through 2002, CP-1106 had enhanced the ability of the ATOFMS to analyze ultra-fine particles, calibrated it with advanced chemical analysis of filter samples, and applied the ATOFMS to various sources, including coal combusters, vehicles, and rocket firings.

Photo-acoustic detector (PA) and Photo-electric aerosol PAH detector (PAS): The CP-1106 team developed a compact system for measuring PA, PAS, CO2, and particle concentrations that permitted the development of fuel-based emission factors; compared the PA to impactor measurements of elemental carbon; and applied the PAS to DoD sources, including aircraft, vehicles, and fuel comparisons.

Accounts of CP-1106 work can be found here, here, and here (draft final report, October 2003). In September 2003, the Utah group also published a "User Guide for Characterizing Particulate Matter," available here. This useful document discusses various types of particle sensors – photo-acoustic analyzers, photoelectric aerosol sensors, and ATOFMS, giving pros and cons. They also give some cost information. At the time of the report (fall 2003) a PA system assembled from "premium" components is about $36,000, including a computer. This is expected to decrease in the future. A Micro Orifice Uniform Deposit Impactor (MOUDI) is about $12,000. The PAS 2000 costs about $15,000. This compares to very expensive and time-consuming methods of chemical analysis of PAHs from filter samples. An ATOFMS costs about $360,000. If many samples are collected for analysis, the costs can soon add up, and will be in the range of the cost of the ATOFMS.

The "User Guide" had these comments on PAS:

- Used primarily for soot
- Works from a variety of sources and from ambient air
- Portable, suitable for field use
- Operates best between 40-100°F
- Particle concentrations should be in the range of 50 ng / m^3 to 100 mg / m^3

The PAS qualitatively measures the concentration of particle-bound polycyclic aromatic hydrocarbons (PAHs). PAS may give a qualitative measurement of total PAH concentrations more rapidly and more cost effectively than traditional methods, such as filter extraction and subsequent GC-MS.

"User Guide" comments on PAS:

- Cannot provide concentrations of individual PAHs
- Developing a calibration curve for each instrument and source can be expensive and time-consuming
- PAS readings should be maintained below 50 picoamps. Measurement of anything but ambient air requires dilution with dry, particle-free air.
- The PAS inlet temperature must be kept constant.
- PAS is relatively easy to operate, and provides results rapidly.
- PAS is not as accurate as chemical analysis methods
- PAS is a good choice when transient measurements are desired.

Their comments on ATOFMS as a technique:

- Commercially available ATOFMS detects PM in the range of 300 nm to 3 μm, but ATOFMS can be modified with an aerodynamic lens to detect particles as small as 50 nm
- ATOFMS is mobile and can be used in the field, but it weighs 800 pounds and the lasers may need alignment after transportation.
- The ATOFMS requires 20 amps of 220-240 VAC and 20 amps of 110-120 VAC.
- The ATOFMS should operate between 50-95°F.
- A trained scientist must operate the ATOFMS.
- Aerosol MS (AMS) may be more quantitative than ATOFMS, but ATOFMS can provide information on chemical associations within individual particles (which AMS cannot).

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Optra Fresnel: sapphire split-prism spectrometer

In 2001, **Optra, Inc.** won an EPA SBIR award to develop a low-resolution (15 nm) Fresnel sapphire split-prism spectrometer specifically tailored to identification of engine emission molecular species. The device was to examine the 3-5.5 μm range, allowing for the extraction of concentration information for CO2, CO, NO, HCs, and particulates. The spectrometer would be compact and rugged, containing no moving parts. (See SBIR description here and press release here) There was no further word on this device.

V. Technologies under Development with Potential for OB/OD Monitoring

This section covers sensors and technologies that are under development, that is, reported as work in progress. Some of these are perhaps years from field trials; others may be in initial field trial stage already.

SNL MEMS-Based IR Spectrometer

This unit is designed to be used in OB/OD situations and is to be:

- MEMS-based
- Mid-IR (3-5 μm) and long-wave IR (8-12 μm)
- Passive
- For stand-off monitoring for TRIs, plume tracking, and key species – CO2, CO, CH4
- Adaptable in real-time for particular species
- More economical, since it eliminates the need for costly array detectors and lasers
- More sensitive, due to use of a single-element detector

Passive IR monitoring offers several advantages: it is entirely passive, can allow near-real-time measurement, and is relatively low in cost. The use of a MEMS device will eliminate the need for an array detector. The device under development is cryogenic in operation, and this allows on-detector real-time integration of several spectral lines. MEMS will also allow processing of the spectrum at the optical level, enabling real-time differential measurements. Spectral resolution of about 0.2 cm^{-1} is anticipated. The device will have large sky coverage.

LLNL Echelle Grating Spectrometer (EGS)

Chuck Stevens at **LLNL** has been working on an **Echelle grating spectrometer (EGS)** that "provides high resolution snapshots with a sensitivity approaching theoretical limits." The second-generation prototype described in 2001 had spectral coverage from 2.8-4.2μ and a spectral resolution of 0.5 cm^{-1}. EGS could provide OB/OD monitoring with multiple lines of sight. Real-time aerosol analysis would be possible, including single-particle size and composition. The EGS occupies about 2.2 cubic feet and weighs 120 pounds, and uses 300 watts of power.

The EGS has been tested on controlled stack releases of CO, CO2, and methane at 0.5 km, and plans are to move to one km and then 1.5 km. Detection limits are expected to be less than one ppm for most species. Plume transparency is a major issue for the EGS, however.

Groups Working with Aerosol Mass Spectrometers

AMS: Basic AMS design consists of three main parts: an aerosol inlet, a particle sizing chamber, and a particle composition detection section. Each section is separated by small apertures and is differentially pumped. Particles are sampled from ambient pressure and focused by an aerodynamic inlet into a narrow beam (~1 mm diameter) as they enter into high vacuum. Particle aerodynamic diameter is determined by measuring particle velocity via particle time-of flight over a known flight path. Particle chemical composition is determined via flash vaporization (or other methods) followed by electron impact ionization mass spectrometry.

The Aerosol Mass Spectrometry Web Page, maintained at the **University of Colorado** by **Jose-Luiz Jiminez**, has links to many groups working with experimental aerosol mass spectrometry. He divides the field into two broad categories – laser vaporization and thermal vaporization – and subdivides these further.

Currently doing experimental work with AMS (aerosol MS, laser desorption-ionization)			
Instrument	**Researcher**	**Institution**	**Brief Description**
PALMS	Dan Murphy	NOAA Aeronomy Lab	Laser ionization, ATOFMS, has been flown
ATOFMS	Kim Prather	UCSD	Developed the TSI 3800, working on 2nd generation transportable devices
RSMS	Murray Johnston & Tony Wexler	U Delaware; UC Davis	Instantaneous single particle TOF MS; now in 3R^d generation; tested at supersites
Single particle MS	Jan Marijnissen	TU of Delft	
Single particle laser ablation ToFMS (SPLAT-MS)	Dan Imre; Alla Zelenyuk	Brookhaven NL	
Single particle laser ablation TOFMS (SPLAT)	Stephan Borrmann	University of Mainz	Next-gen device designed for small aircraft
Particle blaster	Bill Reents	Bell Labs	
Single particle MS	Michael Zachariah	U Minnesota	
Laser ablation MS (LAMS)	Greg Evans	U Toronto	
Single particle MS	Klaus-Peter Hinz; Bernhard Spengler	U of Giessen	
Real-time MS	Peter Reilly	ORNL	Ion trap MS
Single particle MS	Rainer Vogt	Ford (Aachen)	
Single particle MS	Denis Phares	Texas A&M	
Aerosol MS	Joe Petrucci	U Vermont	
Single particle analysis and sizing system	Niels Jensen	Joint Research Center of the EU	
Single particle MS	Tomas Baer; Roger Miller	UNC	Two-laser system

Currently working on AMS using laser vaporization and chemical ionization are groups headed by **Kim Prather** at **UCSD** and **Peter Reilly** at **ORNL**.

Paul Ziemann of **UC Riverside** is working on a **particle beam thermal desorption MS (PB-TDMS)**. **Jochen Schreiner** and **Konrad Mauersberger** of the **Max Planck Institute for Nuclear Physics** are working on an **aerosol composition MS (ACMS)**.

Among those working on AMS with thermal vaporization and chemical ionization are groups headed by **Thorsten Hoffmann** at the **Institute of Spectrochemistry and Applied Spectroscopy** in Dortmund (**atmospheric pressure-chemical ionization MS, or AP-CIMS**); **Paul Wennberg** at **Caltech** (gas and particle-phase selected-ion CIMS (SI-CIMS); and Jim Smith and Fred Eisele at NCAR (thermal desorption CIMS (TDCIMS).

Working on AMS with thermal vaporization and laser photoionization is Geoffrey Smith at the **University of Georgia** (aerosol MS).

FTIR Spectroscopy

FTIR: Fourier Transform Infrared Spectroscopy -- a method of obtaining infrared spectra by first measuring the interferogram of the sample using an interferometer, then performing a Fourier transform on the interferogram to obtain the spectrum.

Matrix Isolation FTIR (MIFTIR) research at York University

The **Harris Group** at **York University** in Toronto is working on development of **MIFTIR** for use in atmospheric studies. MIFTIR is said to incorporate the scanning capabilities of FTIR with the signal enhancement capabilities due to multi-reflections within an integrating sphere. A CO2 matrix is obtained with many trace gas components embedded within. (See here for more information.)

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FTIR-VIS-UV

At a meeting in England in October 2003 **P. K. Lim** and other scientists from the Department of Physics, **Hong Kong Baptist University**, were to present a paper on "Fourier Transform IR-Visible-UV Spectroscopy." Only an abstract was available at the time of this writing, but they claimed:

> The Fourier transform spectrometer (FTS) has emerged to play a dominant role in infrared spectroscopy used extensively in many diverse fields covering areas such as medicine, chemistry, biology, physics and the process industry. Very little attention has been made to commercialize the FTS for the visible and UV wavelengths. The main reason for this is the difficulty in tracking the precise position of a scanning mirror of the FTS over very long distances. The way to track the position of the movable mirror is usually done by a Michelson interferometer. When a helium neon laser is used as the light source, the positional accuracy is about L/2 without employing sophisticated phase detection techniques. Thus the free-spectral-range of most commercial FTS systems is restricted to longer wavelengths in the infrared commercial FTS systems covering the visible to UV wavelengths, they are very bulky and expensive due to the incorporation of sophisticated technologies needed to track the scanning mirror making them not affordable for mundane uses. We have invented anew form of optical interferometer that can track the scanning mirror to very high resolutions, easily up to$\lambda / 20$, over very long distances with out the need of sophisticated phase detection techniques. We have constructed very compact FTSsystems covering from the UV to the visible and the infrared wavelengths. The spectralbandwidth of our FTS systems is only limited by the optical components and the optical detectors.

Optra low-cost OP-FTIR spectrometer

An April 2000 press release announced award of a contract from the Air Force to **Optra, Inc**. to develop a compact low-resolution open-path FTIR spectrometer incorporating a Nanoscale ® position sensor as the reference channel. The system is designed for optimal signal-to-noise ratio and selectivity for identifying medium-sized industrial organic molecules in the 7-14 µm spectral range. The device was expected to be compact, portable, and low in cost, due to the short stroke length, the nanoscale reference, and the uncooled detector.

In November 2002, Optra won an SBIR Phase II award from the USAF to deliver a low-cost compact ruggedized OP-FTIR spectrometer for use as an air quality monitor for toxic chemicals used in enclosed spaces such as hangars. The spectrometer is to work in the 8-13 µm range with 16 cm^{-1} spectral resolution. The system will incorporate a novel encoder-based metrology system to replace the He-Ne laser interferometer used in most FTIR systems, and it will use an uncooled DLATGS pyroelectric detector, as well as a low-cost press-molded plastic retroreflector array. (See press release here.)

The Phase II prototype instrument was 10½ x 8½ x 7¼ inches, and weighed under 14 pounds, including a 6-inch telescope. Power and control was via a "suitcase" PC which contained two PCI boards for the OP-FTIR. A 24-inch plastic retroreflector that weighs less than 16 pounds has also been produced. (See poster abstract here, page 47, from the December 2003 SERDP meeting.)

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LIPS and LIBS (Laser-Induced Plasma Spectrometer and Laser-Induced Breakdown Spectroscopy)

LIPS: An apparatus for detecting elements in an aerosol which includes an "aerosol beam focuser" for concentrating the aerosol into an aerosol beam; a laser for directing a laser beam into the aerosol to form a plasma; a detection device that detects a wavelength of a light emission caused by the formation of the plasma. The detection device can be a spectrometer having at least one grating and a gated intensified charge-coupled device. The apparatus may also include a processor that correlates the wavelength of the light emission caused by the formation of the plasma with an identity of an element that corresponds to the wavelength. Furthermore, the apparatus can also include an aerosol generator for forming an aerosol beam from bulk materials. (Source here.)

LIBS: A pulsed laser beam (532nm) is focused with a lens to the target, which can be gas, liquid, or solid to induce a micro-plasma in the focal area. The induced plasma is of very high temperature (about 10,000K). Any material in the plasma is excited and it produces strong optical emission. Spectroscopy analysis of the emission gives information about the properties of the material present in the laser induced plasma. (Source here.)

NFESC / ORNL ABF-LIPS

Bryan Harre of the **Naval Facilities Engineering Service Center** (chief investigator) and **Meng Dawn Cheng** (the instrument developer) of **ORNL** gave a presentation at an EPA symposium on a "Portable Aerosol Beam-Focused Laser-Induced Plasma Spectrometer (ABF-LIPS) for Metal Emission Characterization." An ABF-LIPS would be physically small and rugged, and offer time-resolved analysis capability for improved resolution and detection. (A description of the ABF-LIPS instrument by Cheng is here.)

They felt that aerosol focusing increased the signal-to-noise ratio substantially at lower laser energy, enabling the use of a small compact laser excitation source. Levels of detection for some species (based on lab tests, with the species in a simple matrix) were 400 ng / m^3 for Cr and 1000 ng / m^3 for Hg.

The ESTCP project summary sheet sees potential for ABF-LIPS for continuous emission measurement, but the only examples they cite are for indoor measurements.

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ORNL Echellette-Based ABF-LIPS

Meng Dawn Cheng and others at **ORNL** tested an **Echellette-based ABF-LIPS** at the Naval Aviation Depot in San Diego in July 2003. The unit was tested in a chromium-plating shop and other areas, but the range of the unit was not mentioned in the poster available here (page 34), from the December 2003 SERDP meeting. Quantitative determination of detected species "remains to be a challenge." The unit was field mobile. (This work was done under CP-0213; the ABF-LIPS work was first supported under CP-1060.)

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Army Research Laboratory LIBS (Laser Induced Breakdown Spectroscopy)

Andrzej Miziolek and others at the **ARL** at Aberdeen Proving Ground have been working on **LIBS**. The technique uses a pulsed laser to create a micro-plasma on the target material. This is coupled with an array spectrometer to capture the transient light. LIBS offers several advantages: rugged and robust; very sensitive (nanograms); briefcase-sized or smaller; real-time response; and can be used either as a point detector or in stand-off mode. Distances of 100 meters and greater have been demonstrated. (This information is from a poster (page 43) presented at the December 2003 SERDP meeting and from a recent paper. A LIBS web site is here.)

The LIBS is currently being tested at Aberdeen Proving Ground to track burning metal powders (Al and Mg), and to characterize the chemical composition of nanoscale energetic materials.

A field-portable version is under development, containing a compact broadband spectrometer, handheld probe, computer, and batteries in a backpack. Spectral coverage is from 200-980 nm. The first prototype is to be ready in April 2004, built by Ocean Optics, and weighing 7 kg. (See article on LIBS here.) Commercial LIBS systems currently are very expensive -- $100,000 and up.

LIDAR

LIDAR: An acronym for **l**ight **d**etection **a**nd **r**anging, describing systems that use a light beam in place of conventional microwave beams for atmospheric monitoring, tracking and detection functions.

Brookhaven Mie-scattering LIDAR (Mini-Mie)

As part of SERDP CP-1197, **Arthur Sedlacek** at **Brookhaven National Laboratory** is developing a **Mie-scattering LIDAR** by reconfiguring Brookhaven's mini-Raman LIDAR system (MRLS). Mie scattering:

> involves the scattering of light off of particulates/aerosols whose size is comparable to the wavelength of light used. Since the particulate content within the plume will be different from the ambient background, a pronounced change in the Mie scattering LIDAR signal will be expected at the boundary between the ambient atmosphere and the plume itself. Therefore, a vertical scanning Mie LIDAR platform will enable the short-range, standoff (100-150 m) interrogation of the munition plume boundary.

The Mie LIDAR is designed to sweep up and down to produce cross sections of the plume. Successive collections results in a "data cube" which contains LIDAR images as a function of time.

Tests conducted in 2003 successfully detected misted water vapor at a distance of about 100 m under single laser shot conditions. (Planned laser distances of 300 meters were referenced elsewhere.) Range resolution was on the order of 1½ meters. The scanning mechanism was to be implemented by August 2003 and additional field tests conducted. (Sedlacek discussed the mini-Mie and the conversion of the MRLS briefly here.)

NASA Goddard HARLIE (Holographic Airborne Rotating LIDAR Instrument Experiment)

Geary Schwemmer and others at **NASA Goddard** developed the **HARLIE** in the late 1990s, and have field tested it in several atmospheric-sensing campaigns. The device is described as follows: (from the HARLIE web site)

> It uses a 40 cm diameter by 1 cm thick Holographic Optical Element (HOE) as the receiver collecting and focusing aperture. It has a 45 degree diffraction angle and a 1 meter focus normal to its surface. It is continuously scanned up to 30 rpm, and can also operate in step and stare or static modes. Its 160μrad focal spot matches the 200 μm fiber optic field stop which delivers the light to the aft optics package. The aft optics contains a collimating lens, a 500 pm interference filter, focusing lens, a Geiger mode Avalanche Photo Diode, and measures 2.5 cm x 2.5 cm x 15 cm. The transmitter is a continuous diode pumped Q-switched Nd:YAG laser delivering 1 mJ pulses at a 5 KHz rep rate. The beam is expanded to 15 mm diameter before being transmitted through the center of the HOE, which also acts as the collimating lens of the beam expander, transmitting a 100μrad beam. The entire transmitter/receiver package can be placed within centimeters of an aircraft instrument window so that a 52 cm clear aperture window allows for an unobstructed view in all directions around the conical scan.

Mounted on its transportation dolly, HARLIE can operate on the ground in any of 8 elevation positions spaced 45° apart. In this figure the system is pointed up, so the HOE appears on top. It is mounted in a large ring ball bearing with a ring gear pressed into the inner race. It is belt driven by a DC servo motor with an overall gear ratio of 123:1. A 12 bit encoder on the motor shaft yields a 12.5 μrad resolution in the azimuth pointing position. The electronics rack contains the data system, the laser power supply and chiller, the scan motor controller and power supply, a GPS receiver, and an aircraft INS interface. The detector output is ping-ponged between a pair of 24 bit scalers to eliminate dead-time during the read-out cycle. A time history of backscatter profiles are displayed on the computer monitor in real-time as a false color image.

The HARLIE transceiver package weighs 118 kg, and measures 56 x 69 x 102 cm. The electronics rack is another 138 kg.

Schwemmer reported that the HARLIE device has demonstrated that using a rotating HOE to collimate, scan, and collect 1064-nm laser light for direct detection LIDAR is a practical and economical alternative to conventional reflective and refractive optical systems. Significant size and weight reductions are achieved, at no sacrifice in performance. "This technology will soon be available commercially, perhaps as an off-the-shelf option for manufactured LIDARs." Systems are under development and testing at Utah State, Houston Advanced Research Center, and NASA Goddard. (Source here.) Current work is focusing on using HARLIE to characterize plume extent and dispersion.

(The web site has a bibliography of papers on HARLIE for further information.)

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NCAR 1540 nm LIDAR prototype

Steven Oncley of **NCAR** (the **(National Center for Atmospheric Research**, in Boulder) gave a presentation on "New Tools to Study Motion of Trace Gases in the Atmosphere" at the FAME (Frontiers in Assessment Methods for the Environment) symposium in Minneapolis in August 2003. He discussed a 1540-nm eye-safe LIDAR developed by NCAR. The prototype was developed in the summer of 2003, and plans were being made for field deployment with a beam-steering unit in FY04. They report that the LIDAR is capable of "seeing" aerosol features to more than a 10 km range. (See here and here. A scientific paper is reportedly nearly ready for submission.)

ITT Industries aerosol LIDAR

Scott Higdon of **ITT Industries** has been working on the development of an eye-safe near-IR LIDAR for aerosol and cloud measurements. One has been delivered to **Hampton University** for atmospheric studies. The receiver uses a 10-inch catadioptric telescope. (Scott Higdon, "Development of eye-safe LIDAR technology for aerosol and cloud measurements," paper presented at the EPA ORS Workshop, July 30, 2002. Copy available from Perspectives.)

Various devices from Coherent Technologies
In addition to the other products described elsewhere in the report, Coherent Technologies states that it has been developing various laser radar technologies including differential absorption LIDAR (DIAL), differential scattering LIDAR (DISC), and polarametric LIDAR sensors. Also, it is building tunable transmitters spanning the spectrum from ultraviolet to far-infrared to satisfy specific LIDAR remote-sensing applications.

DIAL (Differential Absorbing LIDAR)

DIAL: The DIAL technique uses two LIDAR signals at slightly different wavelengths, one of which is chosen at the center of an absorption line of the gas under study, and the second one in a weakly absorbing spectral region. When the wavelength difference is sufficiently small the backscatter and extinction are the same except for the gaseous absorption. Differential absorbtion allows for detection of trace gases at several kilometers from the system.

NCAR high-power water-vapor DIAL

NCAR (**National Center for Atmospheric Research**), in collaboration with the **University of Hohenheim** (Stuttgart, Germany), is developing a high-power LIDAR to measure atmospheric water vapor. The unit will be flown in NCAR aircraft. The University of Hohenheim in 2003 achieved 40 watts of transmit power at the wavelength necessary to pump devices that will change the wavelength to that necessary to measure water vapor. (See brief mention here.)

TDLAS (Tunable Diode Laser Absorption Spectrometer)

TDLAS: These laser spectrometers use for their light source laser diodes which are tunable to frequencies for particular gases of interest.

TDLAS under development by MetroLaser
MetroLaser, Inc, of Irvine, California, is developing (with some **NSF** sponsorship) a TDLAS for emissions monitoring. Details were scarce, but the company says that their TDLASs exploit recent developments in semiconductor diode laser technology to make possible sensitive detection without the need for cryogenic cooling.

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TDLAS research at York University in Canada

The research group at **York University** in Toronto, headed by **Geoff Harris,** is working on developing an airborne version of the TDLAS they have developed and used in a number of field exercises, measuring atmospheric NH3, H2O2, and other species. Path lengths of "100s of meters" are obtained. The Harris Group is working with both mid-IR and near-IR TDLASs. The near-IR unit offers the advantage of comparatively low cost and portability and compactness. The group is working with **Unisearch** in developing a near-IR TDLAS, for measuring CO, CO2, ammonia, H2S, and acetylene. (See here for more information.)

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DOAS – MAX-DOAS Work from University Of Heidelberg

DOAS: The process whereby column abundances of trace-species are derived from measurements of electromagnetic radiation in a specified spectral interval. The main advantage of this technique over others is that it allows real-time measurements of several different trace-gas species with a single instrument. To perform DOAS, two spectra are necessary: one, referred to as the reference, in which the light has passed through little (ideally none) of the absorber in question and one in which the light has passed though a large amount of the absorber. The retrieved DOAS quantity is the apparent column density (ACD). When the instrument is pointed towards the sun the measured signal comes from direct sunlight. In this case the physical interpretation of the ACD is relatively straightforward: it represents the difference in the column density of the absorber between that along the line-of-sight and that in the reference. Often, however, the viewing direction is away from the sun and so the source of the measured signal is scattered light. The ACD no longer has a clear physical interpretation as the path of the light through the atmosphere is complex and the measured sunlight may have been scattered in the atmosphere or reflected by the surface several times (Source here.)

A group at the **University of Heidelberg** (**G. Hönninger** *et al.*) published a paper in November 2003 on a new technique they call "multi-axis differential optical absorption spectroscopy" or **MAX-DOAS**. This uses scattered sunlight received from multiple viewing directions, as opposed to conventional DOAS devices which use zenith-scattered sunlight.

The conclusions of the paper are quite favorable to MAX-DOAS:

> In this study we have shown that Multi Axis DOAS is an emerging, new variant of the scattered light DOAS method. It is based on mature instrumental techniques which have been established over the last decades albeit for other purposes. Although its development is still ongoing, MAX-DOAS has proven to be successful in several applications including monitoring volcanic plumes (SO2, BrO), natural emission of trace gases (e.g. reactive bromine, BrO) from salt lakes, sea ice, and the ocean surface as well as for pollution monitoring. Further applications like study of urban or forest fire plumes, studies of three dimensional trace gas distributions, balloon borne applications, or study of radiative transfer in clouds still remain to be fully explored.
>
> Although MAX-DOAS cannot replace active DOAS or other complementary measurement techniques (e.g. for nighttime observations an active system is needed), in many cases MAX-DOAS is a powerful alternative to traditional methods. As shown in this paper, there are numerous applications where successful measurements have been performed using MAX-DOAS and, in fact, a series of measurements has become only possible because of MAX-DOAS. Particular advantages of MAX-DOAS are the simple and compact instrumentation, the easy deployment and low power consumption (passive technique), the fact that vertical profile information of gases up to several kilometres above the ground can be derived in combination with RTM calculations and the high time resolution also during low visibility conditions. Using advanced radiative transfer models, the slant column densities derived for the various MAX-DOAS viewing directions can be interpreted and combined to yield a more complete data product than other measurement platforms can provide. Additionally, information on aerosol profiles and properties can be obtained from MAX-DOAS O4 (and O2) measurements which are a by-product of most MAX-DOAS applications. With these aerosol data, necessary input for the RTM can be taken from the very measurement without need for further instrumentation. In the future, enhanced data analysis algorithms for MAX-DOAS combining spectral analysis, radiative transfer modeling and inversion techniques for profile retrieval will further extend the capabilities of MAX-DOAS.

CIMS from AFRL

SERDP Compliance Project CP-192, completed in FY98, was led by **John Ballenthin** of the AFRL. Several advantages of CIMS (chemical ionization mass spectrometry) were cited: extreme sensitivity (as low as 1 ppt); integration times of less than one second; highly selective; excellent immunity to false positive responses or interferences; and ruggedness. One potential application was fence-line monitoring for chemical clouds. Further information was not available. (The summary sheet on CP-192 is here.)

Naval Research Laboratory Ultra Broadband Sources

In ESTCP project CP-1061, **Antonio Ting** of the **NRL** was developing a new class of **UB radiation sources** for active remote sensing of HAPs such as NOx and SOx. Multiple HAPs should be detected simultaneously; and real-time ranging and tracking at "extended distances" should be possible. Active remote sensing of test HAPs was under way in Ting's lab in mid-2000; evidently nothing further has been reported. (See the SERDP summary for CP-1061 here. CP-1061 was completed in FY00.)

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Argonne National Laboratory Cermet Sensors

Under SERDP CP-1243, a team led by **Natalia Mashkov** at the **Argonne National Laboratory** is using cermet (ceramic-metallic) electrocatalytic microsensors that are capable of evaluating emissions in near-real-time (within seconds). The ANL cermet sensors function at elevated temperatures and can detect a variety of chemical species, at levels ranging from ppb to ppm. CP-1243 has the aims of developing miniature sensors and portable sensor arrays capable of rapid detection and characterization of trace air toxic compounds in near-real-time. CP-1243 began in FY02. (See here.)

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Direct Flux Measurements of VOCs

A team of scientists from **Washington State University** and the **Pacific Northwest National Laboratory** gave a paper in October 2003 on use of **eddy covariance (EC)** and **disjunct eddy covariance (DEC)** methods, combined with fast chemical sensors to measure direct emissions of a range of VOCs. Source footprints range from a few hundred meters to several km. Direct flux measurements have been made from a tower in Mexico City (using a fast alkene sensor in EC mode and a proton transfer mass spectrometer (PTR-MS) in DEC mode. (Abstracts from the October 2003 NARSTO meeting are here, see p. 61.)

Scientists from **Argonne National Laboratory** and from PNNL were to give a presentation at the same meeting on "Measuring Trace Gas Fluxes from an Aircraft Platform." They used eddy sampling techniques in conjunction with various fast- and slow-response sensors to measure NMOCs (non-methane organic compounds).

Meteorological: NCAR's Intelligent Sensor Array

NCAR (**National Center for Atmospheric Research**) is developing the **Intelligent Sensor Array (ISA)**. This is to use small, unattended ground sensors that are networked, low cost ($100), with 100 meters or less separation. NCAR has done work with Deborah Estrin of UCLA's Center for Embedded Networking Systems (CENS), and has submitted a proposal to the NSF. Sensors tested so far are for standard meteorological measurements. (See here)

General Techniques: DARPA's New TACTIC Program

On February 23, 2004, DARPA issued a solicitation for a new program, **Threat Agent Cloud Tactical Intercept & Countermeasure (TACTIC)**. TACTIC has two parallel programs: TACTIC-DT (*Detection Technologies*) and TACTIC-CM (*Countermeasures*). Awards are to be made in May 2004. (To receive further information on the TACTIC program, one must register at the web site. Perspectives has done so, and will furnish copies of any material on request.)

The goal of TACTIC-DT is to develop detection technologies that can rapidly discriminate and identify chemical and biological airborne clouds with low false-alarm rates. Detection is to be rapid, sensitive, and selective. Types of technique are up to the proposers, but DARPA gave two examples of strategies: 1) injection of taggants into the cloud that change properties upon exposure to a specific agent, or 2) deployment of remote point sensors directly into the cloud that report the identity of the agent using a communications link.

Performance goals are to detect concentrations of 10g / m^3 within one minute of cloud release, at 10 km distance. The probability of detection should be at least 0.9 and the probability of false alarm should be $<10^{-2}$. Technology should be demonstrable within 15 months of contract award.

Sampling Techniques: NCAR's TRAnsect Measurement (TRAM)

NCAR (**National Center for Atmospheric Research**) scientists have developed a prototype sensor package which can be moved along a cable stretched between towers. This approach allows "the spatial variation of a variety of atmospheric quantities at small scales." The system uses the RMT CO2 analyzer, a sonic anemometer, a GPS receiver, and a TAOS attitude / heading sensor. (See brief mention here and write-up here.)

VI. A Note on AWMA's Air Quality Measurement Conference

The "Symposium on Air Quality Measurement Methods and Technology 2004" is worth noting. The program has a number of presentations of interest. (Preliminary program and registration information here.)

Dates: April 20-24, 2004
Location: Research Triangle Park, NC
Sponsor: AWMA (Air and Waste Management Association)

Among the more relevant papers scheduled to be presented at this meeting are the following:

Measurements of NOx and PM Emissions from Light and Heavy-Duty Diesel Vehicles in Motion: Katey Lenox, Al Akerman, Curt Ayers, Meng-Dawn Cheng, Thang Dam, Howard Haynes, Ralph McGill, FEERC, Oak Ridge National Laboratory; John Storey, Marc Simpson, Oak Ridge National Laboratory; Walt Fisher, Galt Technologies, LLC, et al.

Low Cost OP-FTIR Spectrometer for Air Quality Monitoring: Julia Rentz, OPTRA

Use of Open-Path FTIR to Investigate Community Complaints Concerning Chemical Exposure: Robert H. Kagann, Ram A. Hashmonay, ARCADIS; Mary Uhl, Kenneth Lienemann, Air Quality Bureau, New Mexico Environmental Department; Anthony Barnack, Air Quality Monitoring, Oregon Dept. of Environmental Quality

Aerosol Measurements from Open-Path Fourier Transform Infrared Spectroscopy: Jaya Ramaprasad, Robert Crampton, Chang-Fu Wu, Michael G. Yost, Environmental & Occupational Health Sciences, University of Washington

Performance Evaluation of the New MSP Wide-Range Particle Spectrometer (WPS): Jason Rodrigue, Suresh Dhaniyala, Mechanical and Aeronautical Engineering, Clarkson University; Phil K. Hopke, Chemical Engineering, Clarkson University

Advances in Instrumental Techniques for Air Analysis: Andrew Tipler, Frank DeLorenzo, Zoe Grosser, PerkinElmer Life and Analytical Sciences

Advantage of Independent Real-Time Perimeter Air Monitoring: Bruce Scamoffa, Environmental Affairs, South Jersey Industries; Adam Fasano, Industrial Hygiene, GZA GeoEnvironmental

An Approach to Data Validation of Air Toxics Data: Hilary Hafner, Steven G. Brown, Sonoma Technology, Inc.

A PCA and PMF Study on Speciation Data from Big Bend National Park: Johann P. Engelbrecht, Richard J. Tropp, Division of Atmospheric Sciences, Desert Research Institute

There will also be an all-day course on April 19 on **Optical Remote Sensing Advances for Air Monitoring Applications.**

VII. Appendix—Technology Descriptions

The table below is provided for the readers' reference. A description of key technologies is shown below.

Key Technologies	
Acronym / Name	**Description**
AMS (Aerosol Mass Spectrometry)	Basic AMS design consists of three main parts: an aerosol inlet, a particle sizing chamber, and a particle composition detection section. Each section is separated by small apertures and is differentially pumped. Particles are sampled from ambient pressure and focused by an aerodynamic inlet into a narrow beam (~1 mm diameter) as they enter into high vacuum. Particle aerodynamic diameter is determined by measuring particle velocity via particle time-of flight over a known flight path. Particle chemical composition is determined via flash vaporization (or other methods) followed by electron impact ionization mass spectrometry.
CIMS (Chemical Ionization Mass Spectrometry)	An air sample is mixed with an ionized reagent, and the resulting mixture is introduced directly into a mass spectrometer, where ions are focused with ion optics (magnetic lenses), analyzed by a magnetic quadrupole, and detected with an ion multiplier. The multiplier connects to a discriminator/preamplifier which converts ion signals into TTL pulses.
DIAL (Differential Absorption LIDAR)	The DIAL technique uses two LIDAR signals at slightly different wavelengths, one of which is chosen at the center of an absorption line of the gas under study, and the second one in a weakly absorbing spectral region. When the wavelength difference is sufficiently small the backscatter and extinction are the same except for the gaseous absorption. Differential absorption allows for detection of trace gases at several kilometers from the system.
DOAS (Differential Optical Absorption Spectroscopy)	The process whereby column abundances of trace-species are derived from measurements of electromagnetic radiation in a specified spectral interval. The main advantage of this technique over others is that it allows real-time measurements of several different trace-gas species with a single instrument. To perform DOAS, two spectra are necessary: one, referred to as the reference, in which the light has passed through little (ideally none) of the absorber in question and one in which the light has passed though a large amount of the absorber. The retrieved DOAS quantity is the apparent column density (ACD). When the instrument is pointed towards the sun the measured signal comes from direct sunlight. In this case the physical interpretation of the ACD is relatively straightforward: it represents the difference in the column density of the absorber between that along the line-of-sight and that in the reference. Often, however, the viewing direction is away from the sun and so the source of the measured signal is scattered light. The ACD no longer has a clear physical interpretation as the path of the light through the atmosphere is complex and the measured sunlight may have been scattered in the atmosphere or reflected by the surface several times.
FTIR (Fourier Transform Infra-Red Spectroscopy)	A method of obtaining infrared spectra by first measuring the interferogram of the sample using an interferometer, then performing a Fourier transform on the interferogram to obtain the spectrum.

Key Technologies	
Acronym / Name	**Description**
Inductively – coupled spectroscopy	Uses plasma as both an excitation and an atomization source.
LIBS (Laser-induced Breakdown Spectroscopy)	A pulsed laser beam (532nm) is focused with a lens to the target, which can be gas, liquid, or solid to induce a micro-plasma in the focal area. The induced plasma is of very high temperature (about 10,000K). Any material in the plasma is excited and it produces strong optical emission. Spectroscopy analysis of the emission gives information about the properties of the material present in the laser induced plasma.
LIDAR (Light Detection and Ranging)	Systems that use a light beam in place of conventional microwave beams for atmospheric monitoring, tracking and detection functions.
LIPS Laser-induced Plasma Spectrometer	An apparatus for detecting elements in an aerosol which includes an "aerosol beam focuser" for concentrating the aerosol into an aerosol beam; a laser for directing a laser beam into the aerosol to form a plasma; a detection device that detects a wavelength of a light emission caused by the formation of the plasma. The detection device can be a spectrometer having at least one grating and a gated intensified charge-coupled device. The apparatus may also include a processor that correlates the wavelength of the light emission caused by the formation of the plasma with an identity of an element that corresponds to the wavelength. Furthermore, the apparatus can also include an aerosol generator for forming an aerosol beam from bulk materials.
TDLAS (Tunable Diode Laser Absorption Spectrometer)	These laser spectrometers use for their light source laser diodes which are tunable to frequencies for particular gases of interest.
X-ray fluorescence	A method used in the analysis of artifact composition, in which the sample is irradiated with a beam of X-rays which excite electrons associated with atoms on the surface.

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