United States Environmental Protection Agency

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# DRAFT Roadmap for Next Generation Air Monitoring

U. S. Environmental Protection Agency

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**Request for Comments on This Draft Roadmap**

EPA would like your comments on this document. Specifically, do you have thoughts on

- The characterization of findings, recommendations and gaps?
- The overall EPA goals, near and longer-term objectives?
- The contributions you and your organization could make to help achieve the goals and objectives, including areas for potential collaborative efforts?

Please send your comments to viens.matthew@epa.gov by April 19, 2013.

Thank you.

## PURPOSE

This Draft Roadmap is intended to summarize major findings from literature reviews, workshops, and discussions with experts about the Next Generation of Air Monitoring (NGAM), particularly sensor technology. It identifies key issues in need of EPA leadership and an ambitious set of priority objectives for EPA and other partners to address. The findings specified in this report make clear that monitoring technology is changing rapidly in the US and internationally. EPA plans to be actively involved on the front end to work with States and its regional programs to: help interpret what data from new technologies mean; set reasonable expectations for use of different technologies; engage communities interested in using new technologies; respond to inquiries from concerned citizens; and prepare for managing very large sets of data. EPA is helping guide sensor developers to produce technology that most effectively measures air pollutants. This Draft Roadmap was developed to share EPA's early thinking about how best to support the successful development and use of new monitoring technologies. It is also meant to serve as a framework for engaging other agencies and organizations interested in similar goals, coordination and collaboration.

## INTRODUCTION

Recent technological advances are quickly changing the landscape of air quality monitoring. The trend is that monitors are becoming smaller in size (many of them using sensors), are requiring less support infrastructure than equipment currently used in air monitoring stations, and are capable of operating autonomously. Many of these technologies are lower in cost (both in terms of up front purchase and operating cost of the instrument). This evolution in air monitoring has the potential to supplement regulatory air pollution monitoring networks, provide information on operating processes to facility managers and inspectors, promote community engagement, and support air pollution research studies.

As federal and state budgets for air pollution monitoring continue to be constrained, fewer resources are available to meet current and future air pollution monitoring needs. This climate is ripe for innovation, and the results of literature reviews and a series of workshops reveal a growing field of players from academicians to Do-It-Yourselfers (DIYers) engaging in this rapidly growing field of environmental monitoring/sensing. While not a technology developer in the traditional sense, EPA is keenly interested in this area and would like to facilitate development of lower cost, powerful air quality monitors including these sensors. At the same time, EPA and the States are working to prepare for these technological changes given many uncertainties about the quality of the data and how it will be used. The goal is for EPA to assist developers in quantifying the potential and limitations of their monitors, while also helping to set expectations for the types of uses best suited to different kinds of technologies. Currently, most new monitors/sensors do not produce data that is on par with the data generated from Federal Reference Methods or their equivalents. However, the new technologies will improve with time and become more reliable. For now, users of monitoring data are beginning to consider what the future holds: how more, but less precise, air quality measurements can supplement the measurement data from established monitoring stations.

## Benefits

Technology and software developed as part of the "next generation of air monitoring" (NGAM) can lead to better protection of public health and the environment, provide communities with better data on pollution in their neighborhoods, help regulated entities better manage their facilities, create business opportunities, and reduce the costs of air pollution monitoring for public agencies, regulated entities and researchers. It can provide new educational tools and graphics that make data easy to understand for students of all ages. New monitoring technologies have the potential to provide greater temporal and geographic coverage of air pollution measurements for use in research studies.

For example, infrared cameras can reveal emissions of harmful air pollutants that may be coming from tanks and other equipment but are invisible to the naked eye. In addition to providing helpful information for government inspectors, these tools can help regulated entities become more aware of pollution, including lost product, which may be coming from their facilities. Remote and fence line monitoring can reveal pollution around the perimeter of a facility that may be impacting communities. These tools can be used to engage communities and citizen scientists, giving the most vulnerable communities real time information about nearby air pollution exposures.

In the not too distant future, environmental sensors will be a key component of health care, connecting personal health measurements with personal environmental measurements to better inform medical decisions. And of increasing importance to EPA is a future network of low cost monitors (likely incorporating sensors) that can both supplement ambient air monitoring stations and provide source compliance information.

## EPA Goals

Given the breadth of scientific and technological possibilities, EPA proposes to focus NGAM efforts on the following three goals in the near term:

- Promote development of affordable, near source, fenceline monitoring technologies and sensor network-based leak detection systems for selected hazardous air pollutants and black carbon, to support new regulatory strategies and enforcement and compliance purposes.
- Supplement air quality monitoring networks through development of low cost, reliable air quality monitoring technology for measuring criteria air pollutants, such as nitrogen dioxide, carbon monoxide, ozone and particulate matter (PM).
- Support environmental justice communities and citizen science efforts to measure air pollution in local areas.

EPA's Office of Research and Development (ORD) is committed to ensuring that its research focuses on priority issues for EPA's goals and mission. EPA's Office of Enforcement and Compliance Assurance (OECA) has repeatedly requested ORD assistance in finding a more affordable, reliable method for measuring benzene. In addition, the monitoring needs of EPA's Office of Air and Radiation (OAR) have far outstripped the resources available to meet them. Increasing budget pressures on EPA and the States make the need for innovative, low-cost, alternative approaches for measuring pollutants a necessity. Along with technology costs are those associated with powering the equipment, analytical procedures and data quality processes. The EPA Administrator has made very explicit priorities clear in the EPA Strategic Plan (2011-2015). Expanding the conversation about the environment and supporting environmental justice and children's health efforts are cross-cutting fundamental strategies for meeting the Agency's goals. By getting low-cost environmental measurement technology into the hands of students and community residents, NGAM provides a way to do both. As ORD and other parts of EPA are working together, the Agency also places a high priority in working closely with the interagency community and private sector to help reach common goals.

## Organization of this Roadmap

The rapid development and deployment of NGAM, along with the wide spectrum of potential uses, has a broad range of both environmental policy and research implications. These fall into three general areas:

- Technology Development, Testing, and Integration
- Technology Demonstration, Outreach and Communication Strategies
- IT infrastructure and New Data Streams.

This Roadmap proposes research and other activities in each of these three areas, and describes the following:

A. Major findings and conclusions from literature reviews, workshops, and discussions with experts and other stakeholders

B. Recommendations and gaps that need to be addressed – without identifying <u>who</u> should address them. In some cases it may be appropriate for EPA to act; in other cases it will be more appropriate for others to lead.

C. Short- and Longer-Term Priorities for EPA – this section proposes priorities for EPA action, including collaborative efforts with partners. Additional work is needed to determine which activities are the highest priorities and which are achievable given budget constraints.

D. Implementation Strategy- A table summarizes ongoing and planned EPA activities which address the Priorities identified in Section C.

# 1. TECHNOLOGY DEVELOPMENT, TESTING, AND INTEGRATION

A revolutionary aspect of new monitoring technology is the change in who is measuring air pollution and the purpose for which it is being measured. Until now, air pollution measurement has primarily been left to trained scientists and technicians employing sophisticated instruments for the purposes of evaluating air quality compliance and conducting air pollution research. New breakthroughs in sensor technology and inexpensive, portable methods are now making it possible for anyone in the general public to measure air pollution and are expanding the reasons for measuring air pollution. Depending on the purpose, current lower cost monitors/ sensors may not achieve the level of rigor needed to perform certain tasks. However, the technology is advancing very rapidly and with it comes greater capabilities. Although some currently available monitors/ sensors are not advanced enough to perform the most sophisticated applications, engineers insist it is just a matter of time. NGAM may have any of the following applications:

- classroom purposes – Science, Technology, Engineering, and Mathematics (STEM) Education
- screening to determine if more extensive monitoring is needed
- personal monitoring
- community-based monitoring
- fenceline/emission source measurements for industry and enforcement officials
- individualized medicine
- air pollution research
- accurate measurement of ambient air exposures for regulatory purposes

There are vastly different data quality requirements for these applications. Figure 1 shows the range of required data quality for these applications.

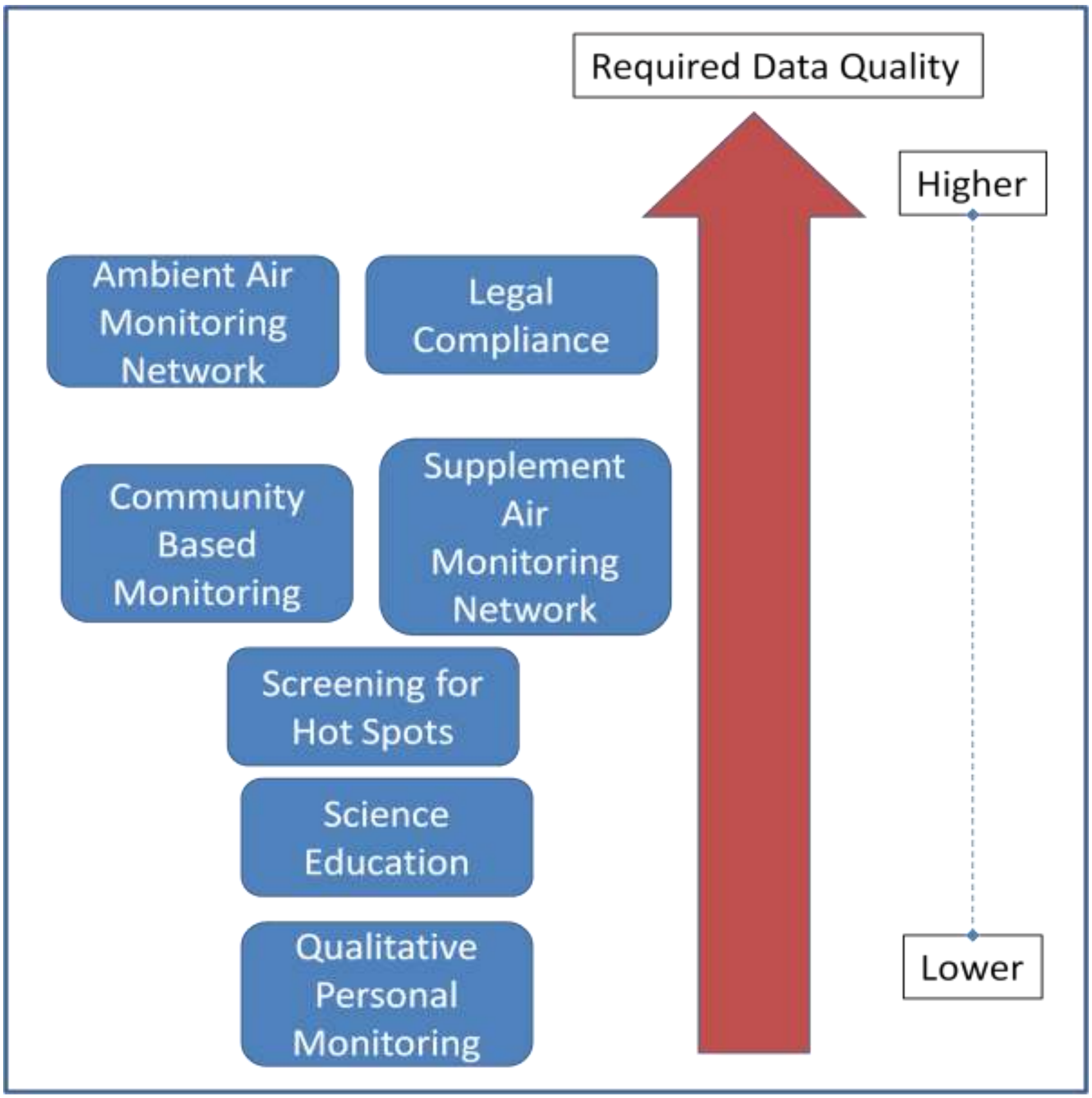


Figure 1. Data quality requirements for the range of NGAM applications.

To facilitate the discussion of the sensor cost throughout the Roadmap we will define the cost of potential technologies in Tiers. This is done because the concept of low cost is relative (e.g. low cost to the research community is considered high cost to the general public). Table 1 outlines these definitions and some anticipated users of the technologies.

**Table 1: Tier definitions by cost and anticipated users**

| Tier | Cost Range | Anticipated User |
|---|---|---|
| **Tier V (most sophisticated)** | 10 – 50 K | Regulators (supplement existing monitoring –ambient and source) |
| **Tier IV** | 5 to 10 K | Regulators (supplement existing monitoring –ambient and source) |
| **Tier III** | 2 to 5 K | Community groups and regulators (supplement existing monitoring – ambient and source) |
| **Tier II** | 100 dollars to 2 K | Community Groups |
| **Tier I (more limited)** | Less than 100 dollars | Citizens (educational and personal health purposes) |

## A. Major Findings/Conclusions

This section summarizes major findings and conclusions from literature reviews, workshops, and discussions with experts and other stakeholders, related to technology development, testing and integration:

- Environmental sensors are being developed, deployed and used to report data at an increasing rate and this trend is expected to continue in coming years.
- The use of sensors for personalized medical, lifestyle and other decisions is being reported in the media regularly.
- Technologies that were the gold standard are being miniaturized and made cheaper. An example of this is the technology employed in the PAMS[1] network (on-line laboratory GC) that monitors volatile organic compounds, like benzene and 1,3-butadiene – it is being transformed into a rack mounted fieldable auto GC that can also measure these same compounds.
- Most air sensor development is focused on criteria pollutants.
- Pollutants most frequently reported in sensor research include CO, $CO_2$, $NH_3$, $NO_2$, and $SO_2$.
- Current sensor research efforts are mostly applied to the use and/or modification of sensors employing metal oxide semiconductors, followed by the application of spectroscopy techniques, and single-wall carbon nanotubes.
- Electrochemical and solid-state metal oxide semiconductor sensors are commercially available but have a range of performance capabilities.

[1] The Photochemical Assessment Monitoring Stations (PAMs) conduct monitoring for ozone, oxides of nitrogen and volatile organic compounds.

- Current sophisticated, expensive ambient air pollution monitoring technology is not economically sustainable as the sole approach and cannot keep up with current needs, specifically new monitoring networks and special purpose monitoring[2] (where monitoring is done for a specific project or purpose, in contrast to a standing network). Sensors offer the opportunity to "do more - less well." This is a necessary and valuable change in approach that will expand our knowledge base. However, its success will depend on using a sensor technology appropriate for the application.
- There is a clear need for a categorization system that sets reasonable expectations for application of sensor technologies (e.g., appropriate for classroom activities; special purpose monitoring; and accurate measurement of ambient air levels).
- Many sensors have not been evaluated to understand how accurate they are, or how their measurement capability holds up over time or through a range of environmental conditions.
- There is no "broad spectrum" technique available yet to measure a wide range of pollutants.
- Many sensor developers have little-to-no air quality expertise, which can affect the quality of the data.
- Supplying adequate power for a widely dispersed network or portable sensors is a bottleneck (especially with the smart phone sensors).
- There is growing support for use of passive monitoring (through wearable sensors) to avoid bias in cell phone sensors.
- There is considerable interest in on-the-go calibration of sensors.

The next generation of air monitoring will address a number of problems associated with current technology including price points that are quite high, infrastructure burdens that are large (e.g., climate controlled shelters needed, gas cylinders) and substantial power requirements. At the same time, new technologies present new challenges of their own. As evident from recent changes in telecommunications, sometimes the shift in technology happens faster than anyone expects and fairly quickly, people adapt.

## B. Recommendations/Gaps

This section provides recommendations and gaps that need to be addressed – without identifying who should address them. In some cases it may be appropriate for EPA to act; in other cases it will be more appropriate for others to lead.

- **Provide summary tables of major pollutants that** let developers and users understand the pollutants of concern, health effects, concentration ranges, performance goals, acceptable detection limits, etc. Include the following:
    - summary and sources of pollutants of concern
    - frequency for monitoring and location of pollutants
    - limitations and near- and long-term performance goals for accuracy, precision, and minimum detection limit (may differ for different pollutants and applications)
    - applicability of mobile and/or stationary monitoring

[2] Under Title 40: Protection of Environment PART 58—AMBIENT AIR QUALITY SURVEILLANCE Subpart C—Special Purpose Monitors (SPM) § 58.20. An SPM is defined as any monitor that is included in an agency's monitoring network that the agency has designated as a special purpose monitor (in its annual monitoring network plan and in AQS) but the agency does not count when showing compliance with the minimum requirements of Subpart C for the number and siting of monitors of various types.

- **Fund new sensor and instrument development.** Use existing research funding mechanisms, such as SBIR (Small Business Innovation Research), STAR (Science to Achieve Results) grants with and without other Agency partners, Open Challenges to spur practical innovation in the following areas:
    - Tier I high-quality sensors for criteria pollutant gases
    - Tier II-III particulate matter sensor systems
    - Tier II-III air toxics sensors
- **Fund research on specific issues related to sensor performance, e.g., power/battery life**
- **Develop calibration and validation systems, methods, and standards.** The existing developer and DIY communities lack the knowledge, experience, and resources needed to develop methods to calibrate and validate data from low-cost sensor systems
    - Conduct validation studies to examine the current performance of existing uncharacterized Tier I to Tier III cost sensors and sensor systems
    - Create a way for EPA scientists to collaborate with sensor system developers
    - Develop new, low-cost, and scalable ways to calibrate and validate sensors
    - Investigate numerical methods to quality-control data with high temporal resolution (e.g., 1-second collection). Investigate "walk/drive by" methods for validating measurements (i.e. wireless calibration).
    - Determine levels of uncertainty/accuracy vs application using existing mobile data sets
    - Investigate ways to use peer or community ranking systems to determine confidence in the data
- **Conduct pilot projects in collaboration with regulators to test and evaluate different aspects of Tier II to Tier V cost monitoring:**
    - Characterize performance of existing sensors in real-world conditions
    - Establish and develop quality assurance and quality control methods for these sensors
    - Test hardware platforms for these sensors
    - Identify appropriate interfaces and ergonomic properties
- **Develop open-source sensor systems hardware.** Create hardware/software technologies that allow the academic and DIY communities to develop sensor systems. Similar to the open-source hardware community, this platform would provide common data processing and data sampling, as well as allow for easier sensor-to-sensor comparisons.
- **Reach out and facilitate communication with/among the sensor community**
    - Conduct a series of follow-on workshops and conferences that bring together developers; DIYers; public health officials and researchers; local, state, and federal agencies; the private sector; and sensor/instrument manufacturers
    - Determine how to engage the sensor and instrument manufacturers. In addition, closely link the environmental and health research communities with sensor system manufacturers to develop comprehensive, integrated personal health monitors.
    - Create a vocabulary that facilitates communication among the numerous communities (academic, private, manufacturing, government, advocacy and DIY).
    - Create a webspace that facilitates discussion, sharing, interactions and understanding among sensor developers and users. The webspace should promote open sharing of information and be facilitated by representatives of the broader community of developers and users.

- **Technology evaluations – research on issues related to NGAM performance in real world conditions.**
    - Test and evaluate performance of new sensor technologies in chambers that can simulate real world conditions
    - Develop test methods for calibration and validation

**C. Short- and Longer-Term Priorities**

This section proposes priorities for EPA action, including collaborative efforts with partners, in the area of Technology Development, Testing, and Integration. Additional work is needed to determine which activities are the highest priorities and which are achievable given budget constraints.

**EPA – Short Term Objectives (1-2 years):**

**Encourage development of autonomous, low maintenance, robust monitors/sensors that can detect pollutants at environmentally relevant concentrations. For some applications, integrated meteorological measurements would also be required.**

- Tier I real time monitors (indicative monitor) for ozone, nitrogen dioxide and carbon monoxide
- Tier III FEM real time monitors for ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide
- Tier III nitrogen dioxide sensor for the near roadway network
- Tier III real-time black carbon
- Tier IV real time butadiene monitor
- Tier III, fenceline sentry system - nonspeciating monitor volatile organic compounds (VOCs) and /or hazardous air pollutants (HAPs)
- Tier IV benzene real time monitor

**Develop summary tables of major pollutants**

- Provide succinct summary tables that let developers and users understand the pollutants of concern, concentration ranges, performance goals, acceptable detection limits, and typical sources. *Completed - table titled "Examples of Air Pollutants and Relevant Measurement Levels" (see Attachment A).*

**Develop calibration and validation systems, methods, and standards**

- Develop low cost scalable ways to calibrate and validate sensors, such as Wireless Air Quality Delivery – Data from federal reference monitors could be delivered by wireless phone applications such that sensor developers could evaluate how a sensor system is performing relative to the nearest reference monitor in near real-time. While this does not constitute a rigorous calibration program, it could nonetheless prove very useful to sensor developers.

**Evaluate technology through research and pilot projects, provide guidance on quality of sensors appropriate for different uses, and form a working group focused on issues related to monitor/sensor performance in real world conditions.**

- Conduct pilot projects with OECA and OAR employing Tier I to Tier IV sensors for criteria pollutants and priority HAPs
- Conduct evaluations of Tier I and II systems for measurement of criteria pollutants at various environmental conditions using exposure chambers and field studies
- Develop a means of categorizing sensors that indicate the various levels of quality and appropriate uses (e.g., education, screening, research, supplementing networks, etc)
- Convene a local, state, federal working group to address issues related to NGAM technology use, quality of data, and keeping current with new evaluation data about new technologies

**Reach out and facilitate communication with/among the sensor community and users**

- Create a webspace that facilitates discussion, sharing, interactions and understanding among sensor developers and users (independent group developed citizenair.net).
- Facilitate collaboration between technologists (sensor developers and evaluators) and community end users to promote the development of sensor technologies.

**EPA – Long Term Objectives (3-5 years):Support the development and commercialization of newly developed sensor technologies --autonomous, low maintenance, robust monitors/sensors) that can detect pollutants at environmentally relevant concentrations. For some applications, integrated meteorological measurements would also be required.**

- Tier II real time monitors (indicative monitor) for PM and black carbon
- Tier II real time monitor for total hydrocarbons (indicative monitor)
- Tier III federal equivalent method (FEM) real time monitor for PM
- Tier III real time benzene monitor
- Tier V real time monitor for metals
- Tier III real time 1,3 butadiene monitor
- Tier II (<0.5k per node) In-plant sensor networks to support advanced LDAR

## D. Implementation Strategy:

EPA has a number of ongoing and planned activities which address the priorities identified in Section C. Several mechanisms are available to help foster technology development and evaluation. In addition, the Agency can actively leverage these investments through partnerships with other Federal agencies. Existing and future planned efforts are summarized in Table 2.

| Table 2. TECHNOLOGY DEVELOPMENT, INTEGRATION, & TESTING: Existing and Planned Efforts | | | | |
|---|---|---|---|---|
| **Time Frame** | **Objectives** | **Specific Subobjectives** | **Existing Efforts** | **Potential Future Efforts** |
| **Short Term** | Develop autonomous, low maintenance, robust sensors that can detect pollutants at environmentally relevant concentrations | Tier I real time monitors (indicative monitor) for $O_3$, $NO_2$ and CO | 1)EPA Open Source Challenges: My Air, My Health<br>2) SBIR emphasis on low cost monitoring technology development | Funding for sensor development |
| | | Tier III FEM real time monitors for $O_3$, $NO_2$, $SO_2$, CO | ORD Village Green Project | |
| | | Tier III nitrogen dioxide sensor for the near roadway network | | |
| | | Tier III real-time black carbon | | |
| | | Tier IV real time butadiene monitor | | |
| | | Tier III, fenceline sentry system: non-speciating VOC/HAP | | |
| | | Tier IV benzene real time monitor | Field test potential benzene sensor | |
| | Summary tables of major pollutants | Succinct summary tables to connect pollutants and levels of detection for sensor developers | Table prepared by OAR (OAQPS & DC) 10/24/12 | Make available to public webspaces |
| | Systems, standards, & methods for calibration & validation | Low-cost scalable ways to calibrate and validate sensors | ORD Workshop March 2013 | Continued development of calibration tools |
| | Technology Evaluations | Conduct pilot projects with OECA and OAR employing Tier I to Tier IV sensors for criteria pollutants and priority HAPs<br><br>Field study evaluation of Tier I and II systems<br><br>Develop categorization of sensors according to levels of quality and appropriate uses (e.g., education, screening, research, supplementing networks, etc)<br><br>Convene a local, state, federal working group to address issues related to NGAM technology | ORD Benzene Field Testing<br><br>Drafting application-based recommendations for sensor performance criteria | |

| | | | | |
|---|---|---|---|---|
| | Technology evaluations – research on issues related to sensor performance | Exposure chamber evaluation of Tier I and II systems under a broad range of conditions (temperature, humidity, etc) | ORD Test Sensor Chamber | |
| | Reach out and facilitate communication with/among the sensor community | Create a webspace that facilitates discussion, sharing, interactions and understanding among sensor developers and users. | Launched: www.CitizenAir.net (note: not an EPA site).<br><br>Share information on new developments in sensor technology and calibration approaches | March 2013 ORD workshop in RTP; other avenues for communication |
| | | Facilitate collaboration between technologists and community end users | | |
| **Long Term** | Develop autonomous, low maintenance, robust sensors that can detect pollutants at environmentally relevant concentrations | Tier II real time monitors (indicative monitor) for PM and black carbon | (FY11 ) STAR Grants 1.) A Compact, Low-cost, Network Accessible, Optical Particle Counter for the Real Time Measurement of Submicron Aerosol Particle Size Distributions, and 2.)Development of Cost-effective, Compact Electrical Ultrafine Particle (eUFP) Sizers and Wireless eUFP Sensor Network | |
| | | Tier II real time monitor for total hydrocarbons (indicative monitor) | | |
| | | Tier III real time benzene monitor | (FY13) Included in SBIR Solicitation | |
| | | Tier V real time monitor for metals | | |
| | | Tier III real time 1,3 butadiene monitor | (FY13) Included In SBIR Solicitation | |
| | | Tier II (<0.5k per node) In-plant sensor networks to support advanced LDAR | | |
| | Promote the commercialization of these newly developed sensor technologies | NA | 9 MCRADAS established for Sensor Calibration Workshop | Use SBIR and CRADAS to commercialize developed sensors |

**Additional Information on Existing EPA Efforts and Plans**

i. EPA Open Source Challenges - Currently a challenge for a Tier IV or lower priced, portable field sensor for Benzene has been completed. In addition, EPA announced a joint challenge with the Department of Health and Human Services to develop personal air pollution and health sensors (My Air My Health).

ii. EPA SBIR – The Small Business Innovation Research program's current year solicitation includes components for lower cost field grade instruments under $10,000 as well as new technologies for community based monitoring that include sensor technologies. SBIR's annual budget of roughly 5 million dollars per year may yield about 7-8 phase I awards in air pollution of $80,000 each. New laws that allow SBIR grantees from any government SBIR phase I program to apply to any SBIR phase II is a constructive move allowing easier access to funding resources.

iii. ORD National Exposure Research Laboratory's Sensor Test Chamber – ORD is providing a local test chamber for sensor developers interested in gaining an understanding of the sensitivity, range and basic operating parameters of their devices. This collaboration with sensor developers was launched in September 2012 at the EPA lab in Research Triangle Park, NC, using one of the existing chamber systems and focuses on sensors for $NO_2$ and ozone (Tier I to Tier II costs).

iv. EPA STAR Grants – Through the STAR program the Agency can continue to fund innovative air monitoring work while refining the request for proposals (RFPs) in accordance with developments in the field of sensors and apps and the resulting needs. The opportunity for collaboration with other agencies is a priority.

v. ORD National Risk Management Research Laboratory - Field Testing of Benzene Sensors – NRMRL is field testing one to two benzene sensors (Tier III to IV) alongside gold standard monitoring technologies to assess instrument capabilities.

vi. ORD – Sponsoring a workshop in 2013 to share information on new developments in sensor technology with a focus on approaches for improving data quality.

vii. ORD Village Green project is developing a Tier III to Tier IV cost, solar-powered stationary monitor to continuously measure PM, black carbon, and ozone using non-regulatory methods to both supplement existing ambient data sets and to provide the public with an educational experience, supporting EPA's STEM efforts.

iv. EPA particpates in online forums, such as CitizenAir.Net and others, which help the growing sensor community.

v. ORD's Sustainable and Healthy Communities Research Program is involved in efforts related to citizen sensing.

vi. ORD and OAR have completed a pollutant table (list of pollutants, detection limits, and sources) and this information will be posted on public webspaces, such as CitizenAir.Net and others.

vii. National Science Foundation (NSF) – ORD is also involved in a new interdisciplinary NSF program on Wireless Intelligent Sensor Networks. An NSF grant was recently awarded to Duke University, and a Memorandum of Understanding has been developed to guide interactions between Duke and EPA. EPA can select topics related to sensor networks for air monitoring and Ph.D. students can do research to aid in the development of these sensor networks.

## 2. OUTREACH AND COMMUNICATION STRATEGIES

The findings specified in this report emphasize the rapidly changing landscape for air monitoring technology, both here in the US and internationally. With the likelihood that air monitoring technology is quickly moving from the arena of trained technicians and scientists to the general public, EPA needs to be prepared for how best to engage citizens in the use of these technologies and how best to respond to their concerns. As a result, there are numerous implications for building trust, understanding privacy issues, communicating risks, and reaching common ground on expectations for what different technologies can reliably achieve.

### A. Major Findings, Conclusions

This section summarizes major findings and conclusions from literature reviews, workshops, and discussions with experts and other stakeholders, related to outreach and communication strategies. These strategies fall into two general areas: 1) Involving communities in pilot projects demonstrating new monitoring technologies; and 2) responding to concerns raised by communities related to data from new sensor monitoring technologies.

1. Involving communities in pilot projects demonstrating new monitoring technologies

- Technology development is only the first step – there are many greater challenges including effective outreach to, and sensitivities in working with, various local communities. Each local community is different and cookie cutter approaches will not work. State and local monitoring agencies are the primary entities interfacing with these communities.
- Community interaction requires lead time and trust building but has great benefits. The ultimate goal is for participants to continue to engage even after training is completed, leading to self-sustaining community efforts. Examples of activities that can help build this trust:
    - Training scientists, government agencies, and others in working with communities, listening to their views first
    - Involve local communities in planning of citizen science activities upfront
    - Provide training to local community members on participatory research, use of sensors and technical data
    - Jointly set expectations for the interpretation of data from various types of sensors
- Partnerships between academia and local community groups can be very powerful.

- Engaging students in sensors for air pollution has spillover benefits.  Parents and siblings also become engaged and invested in air quality awareness.  Participation in the sensing activity makes a much larger impact on students than passive activities (such as reading assignments).
- Students not only wear sensors and collect data but they can also build sensors from kits.
- There is still a lot to learn about interpreting the data once collected. What does it mean for the community?  How can sensor data help communities with chemical exposures of concern, while not making them feel completely discouraged about involuntary exposures?
- Given some lack of comfort with technology (e.g., generational issue in local communities) – the role of the community advocate and the public library becomes critical.
- Selection of software for sharing the data is important decision. Want user friendly systems for newcomers to social networking; customizable too.

2. Responding to concerned communities based on data from new sensor monitoring technologies

- Interpreting data from sensors, including what they mean for health, is a new and complex area requiring immediate attention.
- Conversations with concerned citizens will need to address the type of instrument used to collect the data and what can reasonably be expected from various technologies and data outputs. These can be difficult conversations without upfront efforts to develop trust, understanding, and agreement on expectations.
- EPA and other agencies need to consider how to take advantage of community measurements to help inform where more sophisticated monitoring may be a higher priority
- EPA Regions, State and local monitoring agencies are concerned about how to respond to citizens reporting data from these new sensor technologies while information on data quality may not be known.

**B. Recommendations/Gaps (apply to both pilot studies and response to concerned communities)**

This section identifies recommendations and gaps that need to be addressed – without identifying who should address them. In some cases it may be appropriate for EPA to act; in other cases it will be more appropriate for others to lead.

- **Understand health implications –** Local communities need to understand the health implications, if any, from exposures measured by air sensors.
    - Develop understanding of how to interpret short-term measurements, what they mean for possible health implications
    - Develop flexible, simple language for exposure mitigation and behavior change
    - Improve action/mitigation recommendations among federal agencies (for example, work with the Centers for Disease Control and the National Oceanic and Atmospheric Administration)
    - Develop individualized recommendations based on personally collected data
- **Develop a citizen monitoring toolkit**
    - List of devices
    - Sampling methodologies

    - Generalized calibration/validation approaches
    - Measurement methods
    - Data interpretation
    - Education and outreach
- **Engage social scientists to assist with the trust and local community engagement issues** that drive participation by citizens and organizations in monitoring efforts and help with communication in responding to communities.
- **Address privacy issues and challenges** surrounding personal participatory sensing by reviewing existing research, conducting new privacy-focused research related to pollutant and health data, and developing new technological approaches to address privacy issues.
- **Conduct pilot projects to test and evaluate different aspects of low-cost (Tier I to Tier II) monitoring in local communities. Different pilots could:**
    - Establish a cooperative, participatory collaboration among government, non-governmental organizations and citizens
    - Update existing and develop new software, systems, and tools to facilitate collaboration and participation
    - Identify approaches that make participation in environmental sensing of value to all
    - Test a toolkit of air quality monitoring principles and methods for small sensors
    - Create and test education curriculum and materials
- **Identify critical issues for regulatory entities related to the potential widespread use (both by individuals and community groups) of these Tier I - III sensors as well as other advanced monitoring technologies and develop strategies for tackling these complex issues. These issues include:**
    - How will the regulatory world respond / take into consideration non-regulatory data?
    - What communication strategies should be used for this type of monitoring? These should be consistent with other decisions about the uses of data.
- **Promote science, technology, engineering, and mathematics educational efforts using air sensors.**

### C. Short- and Longer-Term Priorities

This section proposes priorities for EPA action, including collaborative efforts with partners, in the area of Outreach and Communication Strategies. Additional work is needed to determine which activities are the highest priorities and which are achievable given budget constraints.

**EPA – Short Term Objectives (1-2 years):**

- Begin to address major challenges/issues associated with advanced monitoring that has been identified in the workshops and literature reviews. EPA Regions and State and local monitoring agencies have specific concerns on how this monitoring affects existing policy. The perspectives of all of these groups need to be represented.
- Begin to address privacy issues that are raised when collecting data from wearable sensors on individuals.
- Begin to address questions of how EPA might use data collected by citizens.
- Begin to address how sensor users try to interpret the air pollution data and what it means for health

- Promote science, technology, engineering, and mathematics educational efforts using air sensors.

**EPA –Long Term Goals (3-5 years):**

- Develop strategy (mechanism) for evaluating the accuracy of low cost sensor measurements and integration of these data streams into publically-accessible portals
- Establish a mechanism to share information on devices and information needed to help citizens and community groups choose technology for their intended application.
- Engage social scientists, community leaders and government officials to address perceptions of trust, communication and expectations for participating in crowd sensing.
- Conduct pilot projects with communities. Specifically pilot projects that engage the community while conducting low cost, low power, community/neighborhood level monitoring.

**D. Implementation Strategy:**

The EPA has a number of ongoing and planned activities which address the priorities identified in Section C. For example, ORD has a research program focused on sustainable and healthy communities that may offer opportunities for outreach and communication related to new monitoring technologies. Existing and future planned EPA efforts are summarized in Table 3.

**Table 3. OUTREACH AND COMMUNICATION: Existing and Planned Efforts**

| Time Frame | Objectives | Specific Subobjectives | Existing Efforts | Potential Future Efforts |
|---|---|---|---|---|
| Short Term | Address major challenges/issues associated with NGAM<br><br>Address new opportunities associated with NGAM | | | Establishment of a work group to address issues with advanced monitoring and its impact on regulatory monitoring (Regions, OAR, OECA, State and local monitoring agencies, ORD) |
| | Address privacy issues related to data collection | | | Establishment of a work group to address privacy (OEI, OGC, OAR, ORD, OECA) |
| | Interpretation of data and implications for health | | | Develop approaches for assessing and communicating risk (ORD and OAR) |
| | Address how EPA might use citizen collected data | | November 2012 Interagency Meeting (EPA participation in DTRA- lead effort) | |

| | | | | |
|---|---|---|---|---|
| | Conduct pilot studies with communities, leveraging existing monitoring efforts | | | |
| | Promote STEM educational efforts | | EPA/ Air Force Research Institute's Wright Brother's Institute students are working to develop sensors and apps for air pollution (Tier II). | ORD Village Green Project |
| **Long Term** | Develop strategy for evaluation of low-cost sensors. | Helps set expectations for what sensors can reasonably measure | | Creation of a sensor evaluation guide to help improve sensor quality and accuracy |
| | Approaches for sharing information on different devices and how to choose appropriate technology | Integrate data streams into publically-accessible portals | Develop data visualization tools for mobile sensor data | Integrate real time sensor data into appropriate models: e.g.,Community-Focused Exposure and Risk Screening Tool (CFERST), Air Now, ATLAS, etc |
| | | | | Creation of a citizen monitoring toolkit |
| | Address issues of trust and interest in participating in air pollution sensor activities | | Participating in online forums (i.e. CitizenAir.net), Village Green Blog | Pilot projects/ workshops to promote partnerships among communities, scientists, tech developers , local, regional officials<br><br>Other outreach approaches |
| | Conduct local community-level pilot projects for experimental neighborhood monitoring | | | Pilot projects to work with communities, scientists, tech developers , local, regional officials |

**Additional Information on Existing EPA Efforts and Plans**

i. Citizen monitoring toolkit –At EPA's March 2013 workshop, participants will develop a template for an information clearinghouse on air sensors. The clearinghouse will help citizens and community groups choose technology for their intended purposes and help air quality officials have a better sense of how to interpret the reported measurements. This information could be posted on an established website that is populated with recent products including sensor evaluation information.

ii. ORD is supporting development of an informational guide to (1) enable the development of appropriate sensor systems for intended purposes and (2) provide guidance so users can select sensors that are appropriate for specific purposes.

iii. Air Force Research Institute/Wright Brother's Institute (AFRI/WBI) – EPA is also partnering with AFRI/WBI student intern program to develop innovative solutions to challenges within the area of sensors and apps for air pollution. In addition to providing technical guidance on the specific challenges, the EPA also provides mentors to help these students complete these projects.

## 3. INFORMATION TECHNOLOGY (IT) INFRASTRUCTURE AND NEW DATA STREAMS

As new monitoring technologies are developed and used, we will face challenges presented by the ever increasing amounts of sensor-generated data, the analytics needed to translate data into knowledge, and how to make sensor data available for discovery and integration with data from other allied disciplines.

**A. Major Findings/Conclusions**

This section summarizes major findings and conclusions from literature reviews, workshops, and discussions with experts and other stakeholders, related to IT Infrastructure and New Data Streams:

- When using sensors/monitors that are under development (or even commercially available sensors) there is a struggle to understand the quality of the data generated by the sensors (especially in the field). Also unsure how to communicate the quality of the data.
- Several developers are focused on geo-spatial enabled applications – easier visualization of results for non-technical users
- Sensors/monitors can generate data every 10 seconds such that questions abound. Specifically: 1) What do the data mean? 2) Where are the data stored? 3) How do we communicate the data to the community (related to interpreting the data in topic 2)?
- Data are coming in with all different formats (even different time stamps etc.). Inputting into data display systems (like Air Now) will then be very difficult. Some systems transmit on military time, some on EST, etc.
- There is a lack of statistical thinking. As we move towards this technology, statistical methods are needed to analyze new types air quality data – more data of lower quality, and data from instruments that are moving rather than stationary.
- It is still unclear how local communities, environmental and public health agencies will use the data.

**B. Recommendations/Gaps**

This section identifies recommendations and gaps that need to be addressed – without identifying who should address them. In some cases it may be appropriate for EPA to act; in other cases it will be more appropriate for others to lead.

- **Develop Data Schema –** Create data schema and standards to help guide and unify the developer communities:
    - Create data or environmental data schema (e.g., AQCSV, environmental XML, or sensor XML); investigate real-time data standards developed by other organizations.
    - Develop metadata standards to unify the characteristics and attributes of the data, sensors, sensor systems, etc
    - Develop a classification scheme that relates performance goals to use/applications

- **Conduct research (including statistical) on the usefulness and benefits of new data source**
    - Perform geostatistical research to quantify the value of many low-quality measurements vs fewer mid- or high-quality measurements ("Do More Less Well").
    - Perform research to relate personal pollutant data to personal health data and develop interfaces for individualized messages
- **Improve and build upon existing data management systems** to manage the increase in data type, volume of data, and organizations making measurements
    - Use the AirNow or some other framework to create a sensor community data system for ingesting, storing, quality-controlling, and displaying data collected by community groups, citizens, and sensor system developers.
    - Update & improve or develop the quality control algorithms used to handle data with high temporal resolution
    - Evaluate methods for storing vast amounts of data
    - Ensure visualization and data management features excel for community use (see below)
    - Explore data links to Google and Internet database systems.
- **Develop new visualization techniques and applications.** With the deluge of data making it harder to extract understanding and context, the following efforts could help improve data usability:
    - Create new ways to visualize data (stationary and mobile, high resolution and sparse, and multi-pollutant)
    - Create methods and approaches that make data explorable and understandable
    - Create open Application Programming Interfaces to promote widespread use of air quality sensor data
    - Conduct events and challenges to explore data use, develop visualizations, and create new applications.
- **Conduct Pilot Projects to test and evaluate IT infrastructure and data requirements for low-cost monitoring (Tier I to Tier II) in local communities. Pilot could:**
    - Identify and test the range of application/uses
    - Test data distribution methods
    - Create and test new visualization techniques
    - Establish and test toolkits, best practices, and guidance
    - Establish and evaluate data governance and policies

## C. Short- and Longer-Term Priorities

This section proposes priorities for EPA action, including collaborative efforts with partners, in the area of IT Infrastructure and New Data Streams. Additional work is needed to determine which activities are the highest priorities and which are achievable given budget constraints.

### EPA – Short Term Objectives (1-2 years):

- Determine how to use lower quality (high uncertainty) measurements to ascertain air pollution concentrations (statistical approaches)
- Develop IT infrastructure that is capable of conveying QA assessment of sensors including the uncertainties associated with their data.

- Create new ways to visualize data (stationary and mobile, high resolution and sparse, and multi-pollutant)
- Work with others on developing suggested data standards to help sensor users manage and display results, all the while protecting privacy. These standards include:
    - Data formats
    - Metadata
    - XML standards
    - Data visualization

**EPA – Long Term Goals (3-5 years):**

- Determine how to use EPA "official" AQ measurements to support calibration/validation needs of Tier I cost sensor community.
- Determine if EPA can legally use data from personal sensors (including stationary sensors on people's property) and what EPA will do with the data.

## D. Implementation strategy:

The EPA has a few ongoing and planned activities which address the priorities identified in Section C. EPA has existing infrastructure for communicating air pollution data (AirNow) and develops data standards within various aspects of their programs. Existing and future planned efforts are summarized in Table 4.

**Table 4: Existing and Planned Efforts on IT INFRASTRUCTURE AND NEW DATA STREAMS**

| Time Frame | Objectives | Specific Subobjectives | Existing Efforts | Future Planned Efforts |
|---|---|---|---|---|
| Short Term | Effectively use lower quality measurements to ascertain air pollution concentrations | | | |
| | Develop IT infrastructure capable of conveying QA sensor assessments | | | |
| | Create new ways to visualize data (stationary and mobile, high resolution and sparse, and multi-pollutant) | | Ongoing ORD research project addressing data visualization (NRMRL) | |
| | Work on suggested data standards to help sensor users manage and display results, while protecting privacy | Data format standards | | Develop a suggested set of standards as part of the Quality Assurance Project Plan for the Mobile Monitoring and Air Quality Data Visualization & Processing Project |
| | | Metadata standards | | |
| | | XML standards | | |
| | | Data visualization standards | | |

| | | | | |
|---|---|---|---|---|
| **Long Term** | Determine how to use EPA "official" AQ measurements to support calibration/validation needs of Tier I cost sensor community | | | Design and develop a web service that provides real-time data for on-the-fly evaluation of sensor measurements |
| | Determine if EPA can legally ingest data from personal sensors, and what will be done with this data | | | |

**Additional Information on Existing EPA Efforts and Opportunities**

i. ORD will also design and develop a simple prototype web service through which users can directly access real-time data in the AirNow system (using their devices) for on-the-fly evaluation of sensor measurements near the monitoring stations.

## CONCLUSION

Sensor technology is developing rapidly, and it is conceivable that in the near future lower cost sensor technology (Tier I to Tier III) will meet the current requirements of regulatory monitoring. This draft Roadmap outlines the initial efforts needed to prepare for this changing landscape of air monitoring.

## APPENDIX A – List of Acronyms

AQCSV – Air Quality Comma Separated Values

CRADA – Cooperative Research and Development Agreement

FEM – Federal equivalent method

HAP – Hazardous air pollutant

MCRADAS – Material Cooperative Research and Development Agreement (for exchange of materials only)

NGAM – Next generation of air monitoring

OAQPS – Office of Air Quality Planning and Standards

OAR – Office of Air and Radiation

OECA – Office of Enforcement and Compliance Assurance

ORD – Office of Research and Development

SBIR – Small Business Innovation Research

STAR – Science to Achieve Results, EPA's research grants program

STEM – Science, Technology, Engineering, and Mathematics

VOC – Volatile organic compound

## APPENDIX B – EXAMPLES OF AIR POLLUTANTS AND MEASUREMENT LEVELS

| POLLUTANT GROUPS[3] | Air Pollutant of Interest (Click on Pollutant to obtain more information)[4] | Useful Detection Limits[5] | Examples of sources | Additional Notes |
|---|---|---|---|---|
| Criteria Pollutants | Ozone | 10 ppb | No direct emission sources | Secondarily formed when nitrogen oxides (NOx) and volatile organic compounds (VOCs) react in sunlight |
| | Carbon monoxide | 1 ppm | Mobile sources, fuel combustion, industrial processes | |
| | Sulfur dioxide | 10 ppb | Fuel combustion, industrial processes, mobile sources | |
| | Nitrogen dioxide | 10 ppb | Mobile sources, fuel combustion, industrial processes | |
| | Fine particle matter ($PM_{2.5}$) | 5 µg/m³ 24-hr | Dust, fuel combustion, mobile sources, industrial processes, agriculture, fires | Consists of both primary and secondarily formed pollutants |
| | Particulate matter ($PM_{10}$) | 10 µg/m³ 24-hr | Dust, fuel combustion, agriculture, industrial processes, mobile sources, fires | |
| | Lead (also an air toxic) | 0.05 µg/m³ 24-hr | Mobile sources, industrial processes, fuel combustion | Chemical analysis of collected particulate is required. Measurements typically collected by TSP or PM10 samplers. |
| Diisocyanates | Methylenediphenyl | 0.05 µg/m³ | | |
| | 2,4-toluene diisocyanate | 0.01 µg/m³ | Industrial processes (e.g., urethane foam production) | |
| | 1,6-hexamethylene diisocyanate | 0.001 µg/m³ | Polyurethane paints | |
| Carbonyls | Acetaldehyde | 0.1 µg/m³ | Mobile sources, combustion, industrial processes, tobacco | |

[3] All pollutant groups other than criteria pollutants are considered air toxics

[4] This column is hyperlinked to either the EPA Six Common Air Pollutants website (http://www.epa.gov/airquality/urbanair/) or the Technology Transfer Network Air Toxics website (http://www.epa.gov/ttn/atw/).

[5] Approximated for detection at the levels of the Air Quality Index (AQI) for the criteria pollutants, and at the levels of chronic human health benchmark values for the air toxics

| POLLUTANT GROUPS[3] | Air Pollutant of Interest (Click on Pollutant to obtain more information)[4] | Useful Detection Limits[5] | Examples of sources | Additional Notes |
|---|---|---|---|---|
| Metals | Arsenic compounds | $5.00 \times 10^{-5}$ - 0.005 µg/m³ | Combustion, industrial processes | |
| | Cobalt | 0.05 µg/m³ | Industrial processes (e.g., steel) | |
| | Manganese compounds | 0.01 µg/m³ | Industrial processes (e.g., iron & steel), fuel combustion | |
| | Nickel compounds | 0.0005-0.01 µg/m³ | Fuel combustion, industrial processes | |
| PAH (Polycyclic Aromatic Hydrocarbons) | Benzo (a) pyrene and other PAHs | 0.0001 µg/m³ | Fuel combustion, industrial processes, tobacco | |
| | Naphthalene | 0.005-0.05 µg/m³ | Fuel combustion, industrial processes, mothballs, tobacco | |
| VOCs (Volatile Organic Compounds) | Acrolein | 0.005 µg/m³ | Fuel combustion, mobile sources, industrial processes, tobacco | Significant monitoring challenges. At some concentrations an odor can be detected. |
| | Benzene | 0.01 -10 µg/m³ | Mobile sources, refineries and other industrial processes, tobacco | At some concentrations an odor can be detected. |
| | 1,3- butadiene | 0.01-0.5 µg/m³ | Mobile sources, industrial processes, forest fires, other combustion, tobacco | At some concentrations an odor can be detected. |
| Individual Pollutants | Chromium (VI) | $1.00 \times 10^{-5}$ -0.01 µg/m³ | Industrial processes (e.g., ore refining, chemical processing, cement production) | |
| | Formaldehyde | 0.01 - 1 µg/m³ | Mobile sources, industrial processes, incinerators, consumer products, tobacco | Significant amount is secondarily formed from biogenics |