NIOSH Exposure Assessment Program:

Evidence Package for 2006-2016

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Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Executive Summary

Exposure Assessment Program Overview

Development of tools and strategies for conducting exposure assessment has been a fundamental part of the National Institute for Occupational Safety and Health (NIOSH) since its establishment in 1970. Exposures to hazards at worksites have evolved over time. NIOSH researchers have developed and evaluated exposure assessment methods and direct-reading monitors and methods to address these evolving exposures.

The NIOSH Exposure Assessment Program (EXAP) is distributed across both intramural programs (work conducted by NIOSH researchers) and extramural activities (grants and cooperative agreements funded by NIOSH). In recent years, the intramural component of the program has received an average of approximately $12 million in funding and the extramural component have received approximately $14 million in funding.

EXAP priorities are largely driven by available workplace and worker health surveillance data and related stakeholder needs. The EXAP priorities have been articulated in two strategic goals: (1) fostering research and providing guidance to develop or improve exposure assessment strategies and (2) developing or improving specific tools or methods to assess exposures of workers to critical occupational agents and stressors. Two of the most emphasized areas of work over the last 10 years have focused on methods development including the enhancement and expansion of the NIOSH Manual of Analytical Methods (NMAM) and on direct-reading exposure assessment methods and sensors. The ultimate goal of the EXAP is to reduce the exposures of workers to hazards.

Methods Development

The primary purpose of EXAP methods development activities is to develop methods to accurately measure occupational exposures to chemical, biological, and physical agents. Over the past decade (2006-2016), more than 235 NIOSH-developed advances in methods have been published in the NMAM and peer-reviewed publications. NIOSH grantees have additionally published more than 80 methods-related developments during that time period. NIOSH intramural and extramural peer-reviewed journal articles in that 10-year period have been used to advance and apply the current body of knowledge in this area as evidenced by the more than 4,300 open literature citations of those publications.

The NMAM, a signature product of NIOSH, is a collection of validated sampling and analytical methods used around the globe for exposure assessment purposes. NIOSH methods have been adopted by government agencies, employers and consensus standard bodies. In fact, the NMAM webpage is the second most visited webpage on the NIOSH website. Adoption of NIOSH methods by both domestic and international entities ensures harmonization and data comparability at different times and places.

The most recent NMAM edition includes 19 new methods, 40 revised methods, 9 revised chapters, and one new chapter. A number of additional new chapters are in development. These recent additions include the development of critical methods for evaluating worker exposures.

Direct-Reading Methods and Sensors

Although NIOSH has a long history of evaluating, developing, and using direct-reading monitors and methods, in 2008 NIOSH established a dedicated intramural initiative on direct-reading exposure assessment methods (the DREAM initiative) as part of an effort to improve the coordination of these activities across the Institute and with our external partners. The DREAM initiative ultimately led to the creation of the NIOSH Center for Direct Reading and Sensor Technologies in 2014.

The occupational safety and health community has recognized the importance of direct-reading methods and sensors and supports the need for research aimed at answering fundamental questions such as, do these sensors accurately measure what they are supposed to be measuring? In order to effectively answer such questions, the EXAP communicates and collaborates with other groups and organizations to ensure that sensors are developed, validated, and applied in ways that advance hazard evaluations and exposure science.

Over the past 10 years, NIOSH has worked with partners from across the spectrum of industry sectors. Successes in those collaborations are particularly notable in the mining and public safety sectors. Coal miners can now measure coal dust exposures in real-time to assist in the prevention of pneumoconiosis. Law enforcement officers now have a means of detecting methamphetamine residue on surfaces to help prevent injuries and injuries from exposures in illicit methamphetamine laboratories. NIOSH will continue to advance its sensor development work in these and other industry sectors to evaluate new and existing sensor technologies and to foster their application in occupational safety and health research and practice.

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Chapter 1: Exposure Assessment Program Overview

Program History

Exposure assessment research has been a focal area within the National Institute for Occupational Safety and Health (NIOSH) since its inception under the Occupational Safety and Health Act of 1970. In its infancy, exposure assessment work at NIOSH primarily focused on risks to workers from chemical, physical, psychological, and biological hazards, with a recognition that the nature of the U.S. workplaces and its workforce are constantly changing. As the health risks and challenges facing U.S. workers and employers have evolved over the decades, NIOSH researchers across the Institute have developed and applied effective exposure assessment methods that have made it increasingly possible to anticipate, recognize, evaluate, control, and confirm protection of workers from those hazards.

The abilities of NIOSH researchers to develop and apply exposure assessment methods has historically played important roles in the development of NIOSH guidance, including creation of the first *Toxic Substances List* [NIOSH 1971] and creation of the first published NIOSH Criteria Document entitled *Criteria for a Recommended Standard: Occupational Exposure to Asbestos* [NIOSH 1972], both published in the early 1970s. During the mid-1970s, the growing availability and application of practical and effective exposure assessment methods enabled an extensive series of NIOSH Current Intelligence Bulletins for a range of materials such as chloroprene, trichloroethylene, and ethylene dibromide [NIOSH 1975a, b, 1978]. Additionally, in 1975, NIOSH published the first edition of its *NIOSH Manual of Analytical Methods* (NMAM) [NIOSH 1975c], which researchers and industrial hygienists continue to use as a foundation for their practice in the protection of workers from occupational hazards and exposures. NIOSH experts were instrumental in reducing exposures to environmental tobacco smoke in the workplace [NIOSH 1991] and developing guidance to control, reduce, and prevent hazards such as asphalt paving fumes [NIOSH 2001], natural rubber latex allergic reactions [NIOSH 1997], and job-related stress [NIOSH 1999].

Exposure assessment formally became one of 21 priority research areas in 1996 as part of the first decade of the National Occupational Research Agenda (NORA). With the start of the second decade of NORA (2006-2016), exposure assessment was once again recognized as essential to worker protection and it was included as one of 24 NIOSH cross-sector programs in the NIOSH program portfolio.

Over the last two decades of NORA, exposure assessment strategies and methods have expanded from identifying the gaps and challenges to the development of new strategies and tools. As the third decade of NORA begins, the EXAP continues to develop new strategies and methods for relevant and reliable exposure assessment, including direct-reading sensors, across all industry sectors and health outcome cross-sectors.

Program Resources

Funding and Personnel

The NIOSH EXAP is currently managed by Dr. Gayle DeBord, Interim Director of the NIOSH Division of Applied Research and Technology (DART), in Cincinnati, OH. Dr. DeBord has been involved in the Program since the beginning of NORA, serving as a member of the Exposure Assessment Team during the first decade of NORA, the EXAP assistant coordinator from 2006-2010 in the second decade of NORA, and the manager of EXAP since 2010. The coordinator for the Program is Dr. Mark Hoover, Senior Research Scientist in the Respiratory Health Division (RHD), in Morgantown, WV. Dr. Hoover has also been involved in the Program since 2001, including serving as coordinator of the Mixed Exposures Team from 2004 to 2006 during the first decade, and as coordinator of the EXAP since 2006. The assistant coordinator for the Program is Dr. Cynthia Striley, Research Chemist in DART. Dr. Striley stepped into the EXAP assistant coordinator role in 2010 when Dr. DeBord became manager of the Program. Each of these individuals are directly involved in exposure assessment-related activities within their divisions, and serve part-time in their leadership roles for the EXAP. The EXAP leadership also benefits from the input and guidance of an internal steering committee made up of representatives from across NIOSH.

Exposure assessment activities are an integral part of the mission of NIOSH and its divisions as well as the NIOSH extramural research program. NIOSH funding in the EXAP is distributed across a combination of intramural and extramural activities, with slightly more funding going to support the work of NIOSH extramural activities (Table 1). This funding is directed towards projects and activities that contribute towards EXAP goals of developing *new* strategies and *new* methods and tools. It does not include *routine* applications of exposure assessment (such as using an existing NMAM method), although the disctinction between new and routine exposure assessment work is not always clearcut.

EXAP-related funding data are not available for FY 2006 or FY 2007 because at that time the EXAP was a Tools and Emphasis Area within the NIOSH Program Portfolio and, as such, NIOSH did not track expenditures of project funds related to EXAP. However, beginning in FY 2008 when NIOSH leadership restructured the Portfolio, the EXAP became a cross-sector program and NIOSH began attributing exposure assessment-related expenditures to the EXAP. Between FY 2008 and FY 2009 the criteria for the tracking of EXAP-related funds were further adjusted to focus on projects that create new exposure assessment capabilities. That adjustment in coding criteria removed a number of projects that were *routinely* applying exposure assessment methods, but not directly contributing to specific advancements of those methods and tools or to the development of new exposure assessment strategies.

Table 1. Exposure Assessment Program Funding (in millions) and Staff 2006-2016

Fiscal Year	Intramural	Extramural	Total	FTE
2006	NA	NA	NA	NA
2007	NA	NA	NA	NA
2008	$23.8	$19.7	$43.6	190
2009	$13.0	$17.6	$30.1	94
2010	$14.0	$16.6	$30.1	98
2011	$13.4	$13.4	$26.9	104
2012	$12.9	$16.0	$28.9	88
2013	$11.5	$15.5	$27.0	79
2014	$11.8	$15.5	$27.3	82
2015	$12.1	$14.2	$26.2	79
2016	$12.9	$7.3	$20.2	79

The number of full-time equivalent (FTE) NIOSH staff for the EXAP from 2006-2016 is also shown in Table 1. Approximately 62% of FTE working in the EXAP are chemists, physical scientists or health scientists (epidemiologists, industrial hygienists and environmental health specialists). Engineers and biologists are also well represented within the EXAP consisting of approximately 22% of the FTE in the Program.

Facilities

Cincinnati, OH

The **Division of Applied Research and Technology (DART)** conducts research in three primary areas: 1) exposure sciences to identify and measure chemical, physical, biological, and organizational hazards, 2) interventions and controls to reduce exposure to hazards and 3) human and social factors including work organization to address musculoskeletal disorders and other health related outcomes. EXAP scientists in DART utilize space and equipment in laboratories located in the NIOSH Taft facility and in the NIOSH Hamilton facility to conduct exposure assessment and methods development research. Within these laboratories, DART scientists have access to specialized equipment including high performance liquid chromatography/mass spectrometry, scanning and transmission electron microscopes, and vapor and aerosol generation systems for the comprehensive characterization of hazardous materials.

The **Division of Surveillance, Hazard Evaluations, and Field Studies (DSHEFS)** conducts and coordinates surveillance activities and performs health hazard evaluations and industry wide health and exposure studies to detect and prevent work-related illness. DSHEFS has dedicated exposure assessment and industrial hygiene facilities including the NIOSH Field Evaluations and Response Vehicle.

The **Education and Information Division (EID)** develops and transfers information and provides authoritative recommendations in Criteria Documents, Current Intelligence Bulletins, and other document formats to foster prevention of occupational injuries and diseases. This is done through targeted information development and dissemination, training research, and the development of qualitative and quantitative risk assessments. EID risk assessments provide the basis for establishing recommended exposure limits (RELs) and other emerging approaches for controlling exposures including occupational exposure banding guidance. EID is also home to the NIOSH Nanotechnology Research Center, which was established in 2004 and is a leader in the federal government nanotechnology initiative.

Morgantown, WV

The **Division of Safety Research (DSR)** conducts activities aimed at preventing the leading causes of traumatic injuries and fatalities in the workplace. DSR operates three laboratories for research related to exposure assessment. The division's human factors laboratory allows DSR researchers to conduct work in the areas of biomechanics, applied physiology, and industrial psychology. DSR's high bay laboratory includes a 37-foot high ceiling with an overhead catwalk and a manikin that has the capability to measure biodynamic forces. The DSR virtual reality laboratory contains a fully immersive simulation space, which is a computer-generated projection that gives users the illusion of being fully immersed in a three-dimensional world.

The **Health Effects Laboratory Division (HELD)** conducts basic and applied laboratory research to establish the causes of occupational disease and injury and contributes to the development of valid strategies of intervention and prevention. HELD has laboratories for exposure assessment research on a wide range of toxic agents and stressors. These laboratories provide the division's scientists with the ability to conduct toxicity studies with biological media and to develop new methods for identifying potential biomarkers for assessing exposures to hazardous agents and stressors. HELD includes an Exposure Assessment Branch with the mission of researching novel and improved techniques for assessing the exposure of workers to principally chemical, but also physical and biological hazards.

The **Respiratory Health Division (RHD)** seeks to protect workers against work-related hazards and exposures that cause or contribute to respiratory illness, injury, and death and to promote workplace-based interventions that improve respiratory health. As part of its field work, RHD operates a mobile surveillance laboratory that is equipped with interview stations, digital X-ray equipment, pulmonary function testing areas, and other medical test capabilities. Spirometry laboratories provide support to the NIOSH field-based pulmonary function and medical testing activities.

Pittsburgh, PA

The **National Personal Protective Technology Laboratory (NPPTL)** conducts timely scientific research on personal protective technology (PPT), including developing guidance and authoritative recommendations, disseminating information, and responding to requests for workplace health hazard evaluations related to the important role of PPT in keeping many workers within various industries safe while performing their professional duties. This research includes exposure assessments of both the need for and the effectiveness of PPT. EXAP resources at NPPTL include the human factor and ergonomics test laboratory to assess the wearability and performance of self-contained breathing apparatus, closed circuit escape respirators, and closed circuit self-contained breathing apparatus. NPPTL also has approval and research laboratories which includes capabilities for assessing the effectiveness of personal protective equipment in preventing exposures to hazardous agents.

The **Pittsburgh Mining Research Division (PMRD)** conducts exposure assessment-related research in support of its mission to eliminate mining fatalities, injuries, and illnesses through research and prevention. The PMRD exposure assessment laboratories include a work physiology laboratory, a motion analysis laboratory, two noise assessment laboratories, two laboratories used for testing diesel emissions sampling and monitoring approaches, three laboratories used for assessing and improving the performance of dust samplers and monitors, a proximity detection laboratory, a mine electrical laboratory, and a virtual immersion and simulation laboratory.

Spokane, WA

The **NIOSH Spokane Mining Research Division (SMRD)** conducts mine health and safety research on catastrophic failure detection and prevention, mining injury and disease prevention, and mining surveillance and statistical support. Specialized exposure assessment capabilities at SMRD include laboratories for industrial hygiene sample weighing and analyses, scanning and electron microscopy, and aerosol generation and optical microscopy.

Anchorage, AK / Denver, CO / Spokane, WA

The **NIOSH Western States Division (WSD)** addresses a broad range of workplace safety and health issues being faced by workers in western states, including unique hazards and issues associated with climate variations, working at altitude, long distance commutes, remote locations, oil and gas extraction, and wildland forest fires. WSD facilities in Spokane, WA; Anchorage, AK; and in Denver, CO have exposure assessment equipment for monitoring chemical and physical hazards, including portable sensors and direct-reading equipment. Plus, WSD operates a mobile industrial hygiene laboratory that enables a field-ready capability for both routine and emergency response.

Program Planning

In conjunction with the first decade of NORA, the EXAP developed and published a comprehensive document on the research needs and priorities for exposure assessment [NIOSH 2002]. In preparation for the second decade of NORA, the EXAP developed a program logic model to illustrate the relationships among its program inputs, activities, outputs, technology transfer and translation, intermediate outcomes, and end outcomes. The current version of the EXAP logic model can be found in Appendix B.

Goals from the first decade of NORA were developed from a white paper written by the Exposure Assessment Methods Team, which consisted of NIOSH staff and external experts. The white paper was peer and stakeholder reviewed [NIOSH 2002]. At the beginning of the second decade of NORA, EXAP leaders drafted a formal set of EXAP goals based on the NORA Exposure Assessment Methods Team's white paper.

The first strategic goal is to "foster research and provide guidance to develop or improve exposure assessment strategies," which includes updating the NMAM, creating guidance documents for appropriate use of methods and new strategies for exposure assessment, and discussing the ethical concerns of exposure assessment. The second strategic goal is to "develop or improve specific methods and tools to assess worker exposures to critical occupational agents and stressors," which includes developing new methods, creating field-deployable sensors and direct-reading instruments and refining the concept of the exposome and its impact on occupational safety and health research and practice.

These goals were vetted by a formal EXAP steering committee comprised of researchers from divisions across the Institute. The steering committee has been instrumental in identifying and articulating specific areas that serve as the priorities or flagship activities of the EXAP. Additionally, the EXAP leadership initiated an informal Exposure Assessment Interest Group to provide an Institute-wide forum for sharing of needs, capabilities, and experiences of exposure assessment researchers and practitioners across NIOSH. NIOSH EXAP goals are annually reassessed and updated by the EXAP steering committee. Appendix C provides a one page fact sheet on EXAP priorities, activities, accomplishments, and upcoming work at the current juncture between the second and third decades of NORA.

In addition to the EXAP overview contained in this first chapter of the EXAP evidence package, chapters two and three of this document describe the activities and impacts of the top two EXAP priority areas: 1) methods development and 2) direct-reading methods and sensors. As presented in chapter two, the activities and impact of methods development during the second decade of NORA placed a major focus on the revitalization of the NMAM by adding new or revising existing methods and developing new or updating existing 4th edition guidance chapters. That effort culminated in the release of the 5th edition of the NMAM in 2016. As presented in chapter three, NIOSH EXAP work related to direct-reading exposure assessment methods and sensor technologies during the second decade of NORA included completion of the NIOSH Direct-Reading Exposure Assessment Methods (DREAM) Initiative and the creation of a new NIOSH Center for Direct Reading and Sensor Technologies.

Other EXAP Activities

In addition to the two focus area examples of methods development and sensors that are highlighted in this package, the EXAP addresses other issues and has other efforts that are variable in nature and less extensive, but nonetheless important for our 21st century stakeholders. As described in the following examples, activities involving a range of research and service topics and activities involving collaboration with other occupational safety and health organizations and federal agencies are particularly notable.

Research and Technical Assistance

The promotion of **biomonitoring in occupational health studies** has been an interest of the EXAP since the inception of the program. These studies include the development of new methods, as well as foundational work like when biomonitoring should be considered and the ethics of measuring certain biomarkers in occupational health practice and research. With respect to the latter, NIOSH wrote the guidance document *Genetics in the Workplace: Implications for Occupational Safety and Health* [NIOSH 2010]. This document describes the implications of using genetic information in the workplace and has been downloaded from the NIOSH website over 1000 times. It has also been used by the Centers for Disease Control and Prevention Genomics Office as part of their basis for advancing genomics in public health.

NIOSH EXAP experts have been providing **technical assistance during national emergencies** such as Hurricane Katrina and the BP oil release (Deep Water Horizon). During these two national disasters, the NIOSH EXAP was consulted about which biomarkers might be appropriate for the hazards being encountered by workers. To more quickly decide whether to perform biomonitoring during future disasters, NIOSH subsequently published guidance on factors to consider when performing biomonitoring during a disaster [Decker et al. 2013].

An EXAP activity that involves both biomonitoring and other exposure assessment methods is the development of **the concept of the exposome**. First proposed by Christopher Wild [Wild 2005], the concept of the exposome is the totality of exposures over a lifetime and how those exposures affect health. Understanding how exposures from our environment (diet, lifestyle, etc.) interact with our own unique characteristics (genetics, physiology, epigenetics, etc.) impact our health is how the exposome is articulated. NIOSH efforts focus on improving our understanding of occupational exposures and resulting work-related diseases. The Institute's ongoing contributions to occupational epidemiology, the development of sensitive analytical methods, characterization and validation of biomarkers, improvement of sampling strategies and development of exposure databases will advance the field of occupational exposomics. EXAP planning and activities during the second decade of NORA included special emphasis on the occupational exposome in intramural research and publications, including describing biomarkers of response (omics technologies) and their use in occupational exposure limit setting [DeBord et al. 2015]. Our subsequent publication of an article that serves as a primer on the exposome for the practice of epidemiology [DeBord et al. 2016] clarified the overarching concept of the exposome as a guide and tool for comprehensive EXAP planning for research and activities.

An EXAP research and technical assistance activity has been to develop a new NIOSH tool called **occupational exposure bands (OEBs)** to predict worker exposure and to determine appropriate control methods [McKernan and Seaton 2014; McKernan et al. 2016]. The tool includes a process of quickly assigning chemicals into specific categories based on a chemical's potency and the adverse health effects associated with exposure to the chemical. Each of these bands corresponds to a range of exposure concentrations that is expected to be protective of worker health. External peer review and a public comment period are underway of a draft document that describes the application of the occupational exposure banding methodology to a broad spectrum of occupational settings. The draft NIOSH occupational exposure banding process uses limited toxicological data to determine a potential range of chemical exposure levels that can be used as targets for exposure controls to reduce risk among workers. To complete the NIOSH process, users must collect data on various health endpoints and compare the data to NIOSH criteria. The output of this process is an OEB that can be used as a target for control measures.

Although there are many exposure assessment tools available to predict worker exposure, most tools are not fully evaluated to be adopted by users. A tiered approach to obtain quantitative occupational exposure estimates, recommended for use under the 2006 European Union regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), requires a comprehensive evaluation using independent datasets not used to calibrate the tools. In support of improving the scientific basis for the OEB tool, NIOSH has conducted several evaluation studies through active collaboration with international researchers [Lee et al. 2009, 2011]. NIOSH exposure assessment scientists also contributed to the development of American Industrial Hygiene Association (AIHA) Guideline 9 on Guidance for Conducting Control Banding Analyses [AIHA 2007].

Advancement of Occupational Exposure Assessment Strategies

The NIOSH EXAP has a long history of engaging with other leaders in occupational safety and health organizations to define and advance exposure assessment strategies. A recent NIOSH contribution has been to shift the traditional industrial hygiene decision-making framework from a less risk-informed focus on **simply controlling hazards** to a more risk-informed paradigm of **confirming protection from hazards** [Hoover et al. 2011]. This emphasis on the confirmation of protection was conducted through an AIHA-NIOSH partnership on Anticipate, Recognize, Evaluate, Control, and Confirm (ARECC) and has elevated the role of health-relevant measurements during all phases of the assessment and management of hazards, exposures, and resulting risks. To train worker protection professionals to implement that process, AIHA has developed a Body of Knowledge on how ARECC works within occupational exposure assessment. The emphasis on ARECC has also provided a more formal recognition and place for the health screening and surveillance of potentially exposed individuals.

In a further refinement of the industrial hygiene paradigm, NIOSH EXAP scientists have worked with AIHA and other partners to emphasize the need for a stronger integration between the assessment of hazards and the assessment of exposures. ***Hazard-informed exposure assessment*** ensures that the relevant exposures are assessed in the appropriate locations and at the appropriate times. ***Exposure-informed hazard assessment*** ensures that realistic information about actual workplace exposure compositions, concentrations and conditions are factored into any laboratory-based studies that are conducted to understand the exposure-response relationships of those workplace hazards. Erdely et al. [2016] have published insights about the need to better link the understanding of hazards and exposures based on the NIOSH experience with carbon nanotube studies to bridge the gap between exposure assessment and hazard assessment experiments involving inhalation toxicology. Figure 1 shows how the modern industrial hygiene decision-making framework and process combines ARECC with a comprehensive approach to risk assessment and risk management [Jahn et al. 2015].

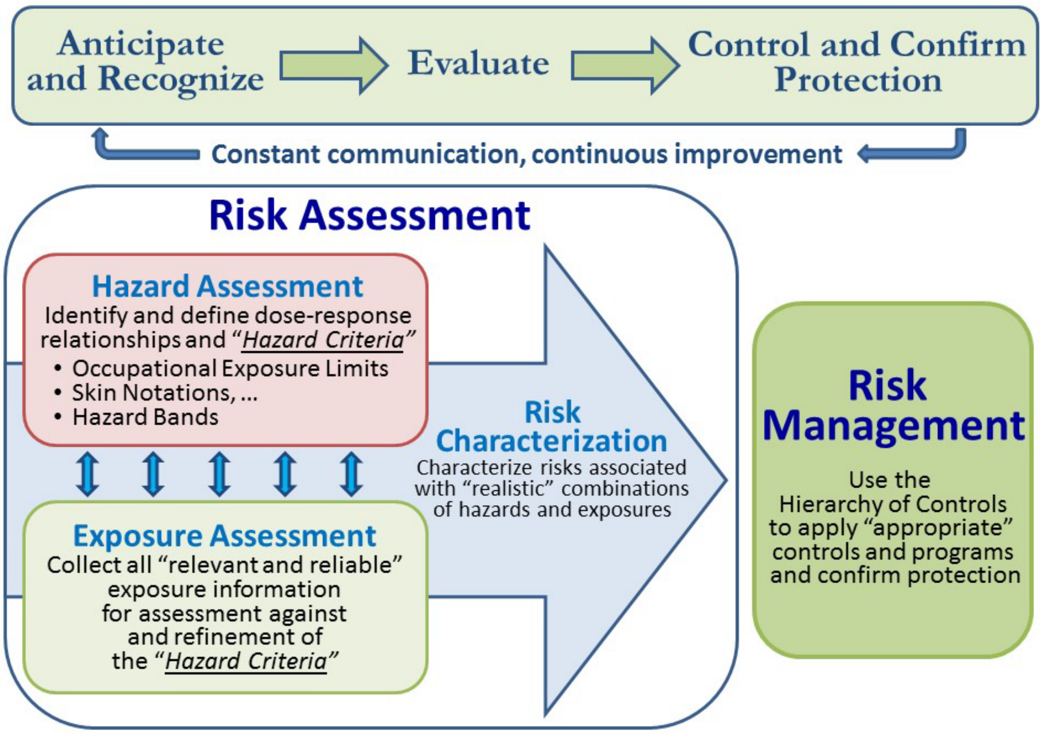

Figure 1. The modern industrial hygiene decision-making framework and process

Collaboration with Federal Agencies

The NIOSH EXAP also engages in **collaboration with other federal agencies** to improve exposure assessment strategies. The National Research Council (NRC) [2012] released a report on Exposure Science in the 21st Century which delineated important areas for improved exposure assessment and called for a federal working group to identify ways to increase collaboration and be more efficient with resources [NRC 2012]. Following a federal workshop that was held in December 2012 to refine and implement the vision for exposure science among the different agencies, the Exposure Science in the 21st (ES21) Century Federal Working Group was initiated. The Environmental Protection Agency led the workshop and serves as chair of the ES21, with NIOSH serving as the co-chair. ES21 is chartered by the Toxics and Risk Subcommittee of the White House National Science and Technology Council Committee on Environment, Natural Resources and Sustainability. ES21 is a forum for federal agencies to collaborate and advance the field of exposure science and optimize agency resources by identifying and coordinating ongoing and planned exposure science research and development activities. The following executive departments are part of ES21 membership: Department of Agriculture, Department of Commerce, Department of Defense, Department of Energy, Environmental Protection Agency, Department of Health and Human Services, Department of Homeland Security, Department of the Interior, Department of Labor, Department of Transportation, National Aeronautics and Space Administration, and National Science Foundation. Five crosscutting topic areas are the focus of E21 work: modeling, biomonitoring, sensor technologies, managing data, and community engagement/citizen science. NIOSH collaborations with other federal agencies also includes work with the National Toxicology Program.

Future Plans

During the second decade of NORA, the EXAP focused on the two flagship areas: the NMAM and sensors. During the third decade of NORA, the EXAP will place continued emphasis on the NMAM, sensors development and guidance for sensor use, and the occupational exposome. Additionally, the EXAP is developing an update of the historically significant and widely used *Occupational Exposure Sampling Strategy Manual*, which was developed by NIOSH exposure assessment scientists [NIOSH 1977].

External Factors

While great strides have been made in the development and evaluation of exposure assessment methods and direct-reading monitors and methods/sensors, continued efforts to expand and improve the body of knowledge in these areas are subject to changes in funding, research priorities and the availability of knowledgeable and experienced researchers.

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Chapter 2: Methods Development

The first strategic goal of the NIOSH Exposure Assessment Program (EXAP) is to develop exposure assessment strategies, which requires developing recommendations or guidance on methods and sampling. An example of this type of guidance is the NIOSH Manual of Analytical Methods (NMAM) which is a compendium of analytical and sampling methods that includes guidance chapters on a number of topics that support the development and use of methods.

The second strategic goal of the EXAP is to develop or improve specific methods and tools to assess worker exposures to critical occupational agents and stressors. Relevant and reliable occupational exposure assessment methods enable the effective anticipation, recognition, and evaluation of workplace hazards so that they can be effectively controlled and so that protection from those hazards can be confirmed.

Figure 2 is a logic model illustrating the theory of change by which the EXAP has moved its methods development and validations activities into practice. Elements of the logic model – Inputs, Activities, Outputs, Transfer/Translation, Intermediate Outcomes, and End Outcomes – are described in further detail in the following subsections.

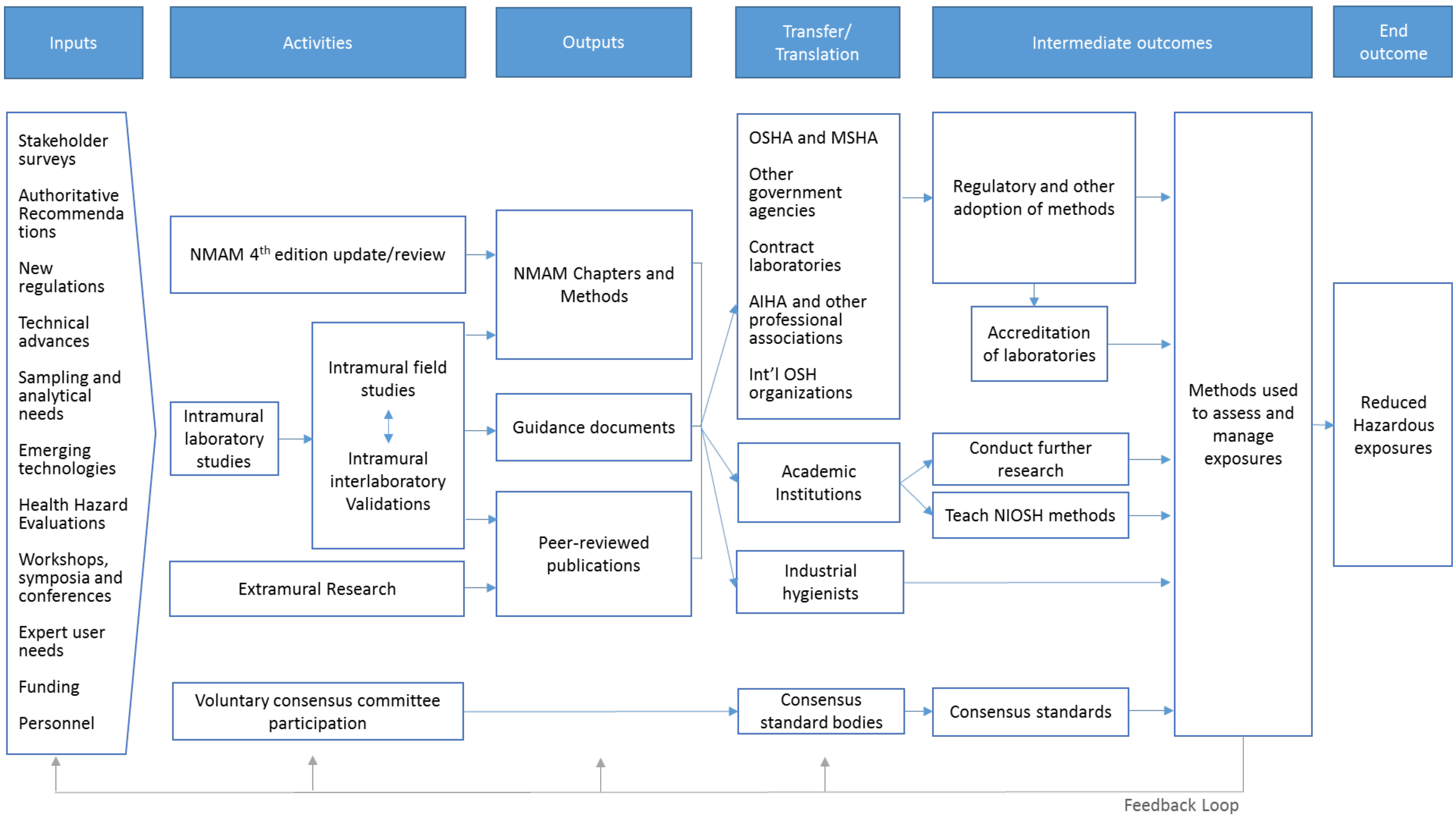

Figure 2. Logic model for the methods development initiative of the NIOSH Exposure Assessment Program

Inputs

Sampling and analytical methods published in the NMAM and in the associated NIOSH-conducted or NIOSH-funded scientific literature address the second EXAP strategic goal to "develop or improve specific methods and tools to assess worker exposures to critical occupational agents". A number of specific drivers provide impetus to NIOSH methods development efforts, as listed in the far-left side of Figure 2 and as described in more detail below. Each of those drivers plays a role in prioritizing NIOSH work to provide the tools necessary for accurate measurement of occupational exposures to chemical, biological and physical agents.

Stakeholder surveys have been conducted in order to obtain ideas and feedback on published methods as well as on needs for new or updated sampling and analytical protocols [Schlecht and Cassinelli 1997; Schlecht et al. 2011]. Inputs and feedback from those who rely on NIOSH methods are especially important for coordinating and prioritizing future methods development and validation efforts. In 2013-14, NIOSH in partnership with the American Industrial Hygiene Association (AIHA) sought feedback on the NMAM through an evaluation survey (approved by the Office of Management and Budget in accordance with the Paperwork Reduction Act of 1980). The survey targeted NMAM users and was posted on the AIHA and NIOSH websites. AIHA invited AIHA-accredited laboratories to take the survey via email and put several notices about the survey in the AIHA monthly publication, *The Synergist*. NIOSH also publicized the survey using the NIOSH Science Blog to ensure that information about the survey would reach users of the NMAM beyond those affiliated with AIHA. Respondents were asked to evaluate the NMAM for ease of use and utility of the methods and chapters. Respondents were also asked to suggest changes that would improve the NMAM and to provide new methods or chapters that they would find useful. Two hundred and fifty seven individuals completed the survey. Survey results indicated that a variety of new methods are needed in specific areas such as nanoparticles, carcinogens, and direct-reading and sensor technologies. Additional guidance was requested on biomonitoring, real world sampling and the calculation of limit of detection and limit of quantitation. Respondents expressed a desire for a mobile mechanism such as an e-book or smart phone/tablet application.

Authoritative recommendations such as NIOSH Current Intelligence Bulletins and Criteria Documents are drivers of NMAM content as they provide scientific background on the health burdens of workplace chemical hazards and how those burdens may be measured and mitigated. For example, the publication of an updated NIOSH Criteria Document on hexavalent chromium (Cr (VI)) established a revised NIOSH Recommended Exposure Limit (REL) for Cr (VI) [NIOSH2013a]. This reduced NIOSH REL called for improvements in analytical methodology, particularly a lower method detection limit and relative freedom from Cr (VI) analytical interferences [Ashley et al. 2003]. Other important considerations for Cr(VI) measurement were method equivalency to an existing Occupational Safety and Health Administration (OSHA) procedure [Boiano et al. 2000] and portability for applications in workplaces and industries such as construction [Marlow et al. 2000; Hazelwood et al. 2004]. Another notable example is the NIOSH Current Intelligence Bulletin on asbestos and related fibers [NIOSH 2011], which has spurred applied research [Harper et al. 2015] and associated studies in support of improvements to asbestiform fiber measurement methods [Harper et al. 2012; Lee et al. 2011; 2015].

NIOSH method validation efforts are also driven by the need to help employers comply with **new regulations** such as those promulgated by OSHA. Frequently after a new rule is implemented, new or revised sampling and analytical methods are needed so that employers can comply. For instance, the final new rule on occupational exposure to beryllium [OSHA 2017] establishes an OSHA Permissible Exposure Limit (PEL) that is at least tenfold lower than the previous limit and also includes a short-term exposure limit (STEL) for beryllium. NIOSH has been working with stakeholders to develop or evaluate methods that allow industry to comply with the lower standard. During this process, stakeholders from the Department of Energy (DOE) and a small business approached NIOSH and requested validation of a draft methodology for analysis of beryllium which had originated at Los Alamos National Laboratory [Minogue et al. 2005]. This tripartite collaboration ultimately resulted in the publication of two new NIOSH methods for on-site and/or fixed-site laboratory-based measurement of workplace beryllium at ultra-trace levels [NIOSH 2016a]. The availability of ultra-trace sampling and analytical methods for beryllium, as provided by recently-developed NIOSH methods, assists stakeholders in complying with established lower Occupational Exposure Limits (OELs) for this highly toxic element [Ashley 2011].

Another example is the newly-promulgated rule on respirable crystalline silica (RCS) [OSHA 2016]. This regulation reduced the OSHA PEL for RCS and sparked NIOSH research efforts to improve RCS sampling and analysis by, e.g., infrared spectrometry [Lee et al. 2016]. As another example, the work of Lee et al. [2016] included a new, improved design for a respirable cyclone sampler. The performance of the new sampler is being validated so that the sampler can be included in the revised NIOSH methods for respirable dust and RCS.

Technical advances in measurement methods often serve as catalysts for work on new or modernized NIOSH methods. For example, new sampler designs have resulted in improved sample collection methods for aerosols and gases/vapors, thereby enabling improvements in NIOSH methods for analytes such as nuisance dust [O'Connor et al. 2014], metals/metalloids [Andrews et al. 2016; Harper and Ashley 2013], inorganic acids [Breuer and Ashley 2014], and gases and vapors [Coffey et al. 2011; LeBouf et al. 2011, 2012]. New NIOSH policy on samplers used to collect aerosol particles [NIOSH 2016b] serves as an impetus for revising many of the aerosol sampling methods published in the NMAM. As another example, the availability of high-flow respirable samplers [Lee et al. 2010] has spurred a flurry of research activity in exposure assessment of respirable crystalline silica [Lee et al. 2012; Harper and Lee 2013]. This work will result in significant technical updates to NIOSH methods for respirable dust and respirable crystalline silica.

Sampling and analytical needs for field surveillance or assessment of intervention effectiveness often spur the development of NIOSH methods for specific agents and/or work conditions. Requirements for field portability of methods to measure airborne and surface concentrations of lead served as the driver for the development of on-site procedures for the determination of lead [Lawryk et al. 2009; Harper et al. 2007] as well as other metallic analytes [Ashley 2010]. Methods for analyses of titanium dioxide (TiO_2) were also advanced [LeBouf et al. 2011, 2013]. Surface sampling methods are often used to assess the effectiveness of engineering controls that are put in place for intervention purposes, and several examples of such sampling methods can be found in the NMAM [Brisson and Ashley 2011; Connor et al. 2016]. Sampling and analytical requirements for intervention evaluations and field studies have resulted in the development of a large number of the methods (mainly for air monitoring) that have ultimately been published in the NMAM [NIOSH 2016a]. Other federal agencies, for example the National Toxicology Program, have supported NIOSH methods development and evaluation research for specific toxic substances. It takes a significant amount of time and effort to address all the performance characteristics and sampling conditions that are included in the NMAM methods. Not all

NIOSH methods are published in the NMAM for a variety of reasons, and are instead published in the scientific literature. For instance, the enzyme-linked immunosorbent assay (ELISA) methods developed for biomonitoring are adapted from commercially available kits and their components are considered sensitive business information [Smith et al. 2011, 2014].

The **NIOSH Health Hazard Evaluation (HHE) Program**, which investigates occupational exposures at worksites all over the country in response to employee, union and/or employer requests, also provides input on needs for new or improved methods. The NIOSH HHE Program relies on the NMAM sampling and analytical protocols for chemical and biological agents to investigate worker exposures and the utility of control technologies such as local exhaust ventilation. In a recent case study [Broadwater et al. 2016], NIOSH HHE experts used NIOSH methods for volatile organic compounds and metalworking fluids in an investigation of persistent odor in a manufacturing operation.

Emerging technologies are additional drivers for developing NIOSH methods. NIOSH receives requests to evaluate the overall safety of new manufacturing processes and products. Nano-engineered materials provide one such example. NIOSH researchers have applied filter based carbon analysis, electron microscopy (EM), and direct-reading methods to monitor workplace exposure to carbon nanotubes and nanofibers (CNT/CNF). A NIOSH REL for CNT/CNF was established at 1 $\mu g/m^3$ as elemental carbon [NIOSH 2013b]. Elemental carbon was used to quantify exposures, while a new EM approach, based on a modified NMAM 7402, was used to confirm the presence of CNT/CNF particles and provide a CNT/CNF structure count [Birch et al. 2016]. This combination of methods [Birch et al. 2016] has been adopted as the approach of choice for these materials and has led to the drafting of a NMAM guidance chapter that is currently in review.

Workshops, symposia, and conferences can spur methods research and development efforts. A good example is the NIOSH-sponsored workshop on direct-reading exposure assessment methods [NIOSH 2008], which outlined needs for on-site exposure assessment methods. Screening techniques in particular, whether using direct-reading instruments or an analytical method, are useful to obtain a general understanding of the exposures in the environment so that an appropriate exposure assessment strategy can be developed. Critical issues for further work involving real-time measurement tools that were highlighted by the workshop participants included a wide range of needs for monitoring occupational hazards of concern including aerosols, gases/vapors, surface sampling, biomonitoring, etc. Some methods for these applications were present in previous editions of the NMAM [NIOSH 1995] but there are a desire and need for many more.

Expert user needs and expert user groups also provide opportunities for NIOSH scientists to understand and help meet new needs for sampling and analytical methods. An example in this area was the creation of the reference textbook on Radioactive Air Sampling Methods [Maiello and Hoover 2010], which was co-edited and co-authored by the EXAP coordinator, Dr. Mark Hoover. This authoritative reference provides 18 chapters on sampling objectives, safety issues, standards, and the NIOSH life-cycle approach to sampling; fundamentals of radioactivity, radioactive aerosols, and sampling systems; sampling in both routine and emergency situations; and 11 detailed sampling and analytical methods for airborne radioactivity.

Activities and Outputs

As illustrated in the following examples, the methods development activities and resulting outputs of the EXAP are focused on improving existing methods or creating and validating new methods through work by NIOSH researchers, both intramural and extramural and through NIOSH researchers' participation on voluntary consensus standards bodies.

NIOSH Manual of Analytical Methods

The *NIOSH Manual of Analytical Methods* **(NMAM)**, one of the premier NIOSH products shown in the logic model, is a compilation of validated sampling and analytical methods that are used globally for occupational exposure assessment in the industrial (occupational) hygiene field and related professions [NIOSH 2016a]. The methods that are published in the NMAM are evaluated and validated in consideration of their fitness-for-purpose for exposure monitoring in work areas [NIOSH 1995]. NIOSH methods primarily address workplace air sampling and analysis, but the NMAM also includes protocols for biological, surface, dermal, and bulk samples. Now in its fifth edition, the NMAM is continuously updated as new or revised methods are evaluated and their performance verified. NIOSH methods are intended to promote accuracy in exposure assessment [Kennedy et al. 1996] and, where applicable, they are harmonized with relevant international voluntary consensus standards [Ashley 2015]. The NMAM is available online on the NIOSH NMAM web site free of charge.

NIOSH exposure monitoring methods that are published in the NMAM are key instruments for assessing potential health risks to workers. Industrial hygienists are often responsible for assessing the effectiveness of measures taken to minimize and control worker exposures to airborne toxins and toxicants, and this is normally achieved by monitoring workplace air quality [DiNardi 2003; Hathaway and Proctor 2004; Kulkarni et al. 2011]. Air monitoring is vital because inhalation is ordinarily the most likely route of exposure in work areas [Hathaway and Proctor 2004; Rose and Cohrssen 2011]. However, other routes of workplace exposure, notably dermal contact with chemical and biological agents [Semple and Cherrie 2003; Behroozy 2013], often require consideration. Accordingly, surface sampling and analysis are widely used by occupational hygienists for functions such as contamination monitoring, dermal exposure prevention, and assessing the cleanliness of work areas [Brisson and Ashley 2011]. Complementary biomonitoring methods are also often used to assess occupational exposures to toxic chemical compounds via measurement of specific analytes, e.g., metabolites and/or biomarkers in body fluids (typically urine and/or blood) or tissues [Angerer and Greim 2006].

Within the NMAM, but separate from the methods themselves, are explanatory chapters that provide background and guidance on a number of topics. The chapters include information regarding quality assurance, sampling guidance, method development and evaluation, aerosol collection, etc., and provide valuable information to users of NIOSH methods [NIOSH 2016a]. Also linked to the NMAM are guidance documents on sampling and analytical procedures for conventional laboratory-based analysis [NIOSH 1995], direct-reading monitors [NIOSH 2012a] and diffusive sampling [ISO 2007; ASTM 2013].

NIOSH approved and published 19 new sampling and analytical methods during the previous decade (since publication of the 4th edition and its subsequent supplements) and approved nearly 40 revised methods. These new and revised methods appeared in the 5th edition of the NMAM, which was formally released in April 2016. The NMAM 5th edition differs from earlier editions of the manual in the following ways:

1. It includes primarily fully-validated methods. Partially-validated methods were not brought forward into the 5th edition except in special cases (e.g., methods for methamphetamines on wipes, which are workable for current needs as method improvement continues).
2. It is available online only (no printed version) and is routinely updated as new methods and guidance documents are approved. Additionally, all newly-posted NIOSH methods are readily

accessible to people with disabilities as required by the Section 508 amendment to the United States Workforce Rehabilitation Act of 1973 [U.S. Government 1998].

3. It includes additional methods developed by partners outside of NIOSH, notably the German Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA) with which NIOSH has a formal memorandum of understanding. The development of methods through outside partnerships saves NIOSH resources, prevents duplication, and increases global harmonization.

4. Obsolete or outdated methods have been given the designation as historical and have not been included in the 5th edition (e.g., inorganic acids method 7903 which has been replaced by NIOSH methods 7906, 7907, and 7908 and similarly, historical methods for lead in blood and urine by flame atomic absorption spectrometry which have been updated).

5. Biomonitoring methods are now included to a greater extent than past editions.

A list of the NIOSH developed methods published over the last 10 years is shown in Table 2. Of these recently published methods, here are a few illustrations of their applicability:

- NIOSH Method 0501 - *Particulates Not Otherwise Regulated, Total* uses a polyvinyl chloride (PVC) internal capsule for gravimetric analysis of collected aerosol particles for accurate measurement of nuisance dust. Construction and manufacturing sectors, in particular, may have increased levels of dust during cutting, grinding, machining, polishing, and sanding operations. Method 0501 represents an improvement over NIOSH Method 0500 in that it accounts for all material that enters the sampler [O'Connor et al. 2014]. Method 0500, a filter-only weighing procedure, suffers from inaccuracy due to non-inclusion of material deposited on the inside walls of the sampler.

- NIOSH Method 2027- *Ketones* is a fully validated method that relies on sorbent-based collection and gas chromatographic analysis for several ketones in workplace atmospheres. Ketones are used in several industries as solvents and polymer precursors and in the manufacturing of pharmaceuticals. This method uses a safer alternative to solvent desorption with carbon disulfide (which is hazardous) [Breuer and Eisenhardt 2013]. This method also provides a prime example of the result of the successful partnership with the German IFA described on page 30. It provides NIOSH a way to leverage resources with other partners to adopt critical analytical methods or replace outdated ones.

- NIOSH Method 5100 – *Carbon Black* was revised in 2015 to improve the accuracy of the measurements by using an internal capsule when sampling. The prior method may have underestimated the actual amount collected due to the depositing of the particles on the walls of the sampler. Using an internal capsule covers the walls so that the total amount of particulates can be weighed. NIOSH 5100 is used to measure diesel soot or oxidation products in the air. Multiple industrial sectors have exposures to diesel from construction, mining, oil and gas extraction and transportation and warehouse to name a few.
- NIOSH Method 7302 and NIOSH Method 7304 – *Elements by ICP (microwave digestion)* were developed to measure elements using Inductively-coupled argon plasma (ICP), atomic emission spectroscopy. Both methods are applicable for the analysis of metal and nonmetal dust that might occur in manufacturing, construction, or mining worksites. They entail simultaneous elemental analysis using a microwave digestion procedure. The difference is in the sampling media. NIOSH 7302 uses mixed cellulose ester (MCE) filters, while 7304 uses polyvinyl chloride (PVC) filters. Industrial hygienists would select PVC filters if they want to combine gravimetric and metals analysis. However, the PVC method provides less accurate results due to substantial deposits on the sampler wall. MCE filters are preferred because the entire filter can be microwave digested.
- NIOSH Method 7306 - *Elements by Cellulosic Internal Capsule Sampler* offers a significant improvement over Method 7300 and other aerosol sampling and analytical methods that are based on filter-only analysis [Harper and Ashley 2013; Andrews et al. 2016]. Method 7306 calls for the use of an acid-soluble internal capsule and, like Method 501 above, this procedure accounts for all particles entering the sampler. Thus, analytical accuracy is maximized since potential losses from internal wall deposits are appropriately addressed through application of the aerosol collection scheme that utilizes an internal capsule.
- NIOSH Method 7704 - *Beryllium in Air by Fluorometry* is a revised method for total beryllium that was first published in 2007. The revision allows for ultra-trace analysis to aid stakeholders

in complying with OSHA and DOE lowered OELs for beryllium [Ashley 2011]. Beryllium is used in defense, aerospace, telecommunications, automotive electronics, and medical specialties.

- NIOSH Method 7907 – *Volatile Acids by Ion Chromatography* is a revision of an older, less accurate NIOSH method for volatile inorganic acids such as hydrogen chloride, hydrogen bromide, and nitric acid. The revision was accomplished through a partnership with the German IFA laboratory. Volatile acids can be found in many sectors but are used primarily in manufacturing.
- NIOSH Method 7908 - *Non-Volatile Acids (Sulfuric Acid and Phosphoric Acid)* uses an inert filter for the collection of aerosols containing H_2SO_4 and/or H_3PO_4 [Breuer and Ashley 2014]. The procedure replaces NIOSH Method 7903 for the determination of H_2SO_4 and H_3PO_4 in workplace air samples by ion chromatography. While method 7903 specified sorbent tubes for sampling of airborne inorganic acids, the use of sorbent tubes (meant for gas/vapor sampling) for collecting acid mists is not appropriate nor fit-for-purpose. An advantage of Method 7908 is that it can allow for the collection of the inhalable fraction of nonvolatile acid aerosols in situations where an inhalable sampler is employed and wall deposits are included. Non-volatile acids are found in many industries such as petroleum refining and in the manufacture of fertilizers, paints, pigments, dyes, and explosives. This method is another example of the partnership with the German IFA laboratory to update older NMAM methods.
- NIOSH Method 8007 - *Toluene in blood* was added in 2013 as part of the EXAP effort to increase the number of biomonitoring methods found in the NMAM. Toluene is a commonly used solvent in paints, paint thinners, adhesives, resins, cleaning agents, and inks. It is also used in the synthesis of many organic chemicals including benzene, phenol and xylene and as a raw material in the production of explosives. Over the last 10 years, NIOSH has received nine HHE requests, including one specifically for toluene exposure in primarily manufacturing facilities [NIOSH 2017]. This method represents progress in the NMAM intention to include more biomonitoring methods.
- NIOSH Method 8319 - *Acetone and Methyl Ethyl Ketone in urine* is a new biomonitoring method that measures biomarkers of exposure to a variety of chemical agents that are used in many industrial processes [Perbellini et al. 1984; Pezzagno et al. 1986; Kawai et al. 1990]. This

biomonitoring method serves as a complement to air monitoring methods for ketones, alcohols and other agents for which acetone and methyl ethyl ketone in urine can be measured as biomarkers. One of the drivers for the NMAM 5th edition was to include more biomonitoring methods. This method was initially developed for an HHE before becoming an NMAM method [Tapp 2006].

- NIOSH Method 8321 - *ortho-Cresol* in urine was added to the NMAM in 2016 for the determination of total ortho-cresol in urine specimens. Cresols are excreted in urine primarily as conjugates. This method uses an acid hydrolysis step to convert the conjugates to free ortho-cresol. Cresols are precursors or synthetic intermediates to other materials including plastics, pesticides, pharmaceuticals and dyes. This is another example of adding biomonitoring methods into the NMAM.
- NIOSH Method 8322 – *Trichloroacetic Acid in Urine* measures the metabolite, trichloroacetic acid (TCAA) in urine specimens. TCAA is one of several metabolites detected after exposure to a variety of chlorinated compounds. The method was originally developed for an HHE request for trichloroethylene, a widely used industrial solvent.
- NIOSH Method 8324 - *3-Bromopropionic Acid in Urine* measures a possible metabolite of 1-bromopropane (1-BP) using laboratory calibration standards. The method was developed as a result of several HHE requests in furniture manufacturing facilities. 1-BP was being used as a substitute for methylene chloride in spray adhesives, used to assemble furniture cushions. The use of 1-BP has increased over the last 20 years [NIOSH 2013b]. Besides being a component of spray adhesives, it is also used as a degreaser and in the textile dry cleaning industry.
- NIOSH Method 8326 - *s-Benzylmercapturic acid and s-phenyl mercapturic acid in urine* was developed to measure the metabolites of toluene and benzene in urine. Initially developed for an exposure assessment study to evaluate toluene exposure for workers in nail salons, the method has been used to assess benzene exposure at oil and gas extraction sites [Esswein et al. 2014].
- NIOSH Method 9106 - *Methamphetamine and Illicit Drugs, Precursors and Adulterants on Wipes by Liquid-Liquid Extraction* was developed for the analysis of selected drugs and

precursors on surfaces in clandestine drug laboratories and to test for potential exposures to methamphetamine to first responders and emergency room personnel. This method screens for a larger number of illicit drugs than just methamphetamine, but is labor intensive due to the liquid-liquid extraction step.

- NIOSH Method 9109 - *Methamphetamine and Illicit Drugs, Precursors, and Adulterants on Wipes by Solid Phase Extraction* was developed to improve on Method 9106. The use of solid phase extraction reduces the time and effort. Similar to Method 9106, it still screens for a larger number of illicit drugs.
- NIOSH Method 9110 - *Beryllium in Surface Wipes by Fluorometry* enables accurate measurement of trace beryllium on surfaces [Agrawal et al. 2006; Ashley et al. 2007]. Workers exposed to this element through dermal contact may become sensitized and, if this is followed by subsequent inhalation exposure to beryllium, it can lead to chronic beryllium disease [Maier et al. 2006; OSHA 2015]. Thus monitoring surface contamination of beryllium in dust is essential to preventing dermal exposures to this element and consequent sensitization.
- NIOSH Method 9111 - *Methamphetamine on Wipes by Liquid Chromatography/Mass Spectrometry* was developed to focus only on measuring methamphetamine. This is the method that industrial hygienists prefer because it is directed only at methamphetamine and the sensitivity of this method is better than 9106 and 9109. When the methamphetamine work began, the researchers were unsure of what to measure since other drugs might be present at illicit drug laboratories. The two screening methods were devised, first 9106 and then 9109, until exposure assessment studies could be conducted [Fent et al. 2012; Snawder et al. 2011]. Two HHEs have also been conducted to assess worker exposures to illicit drugs [Fent et al. 2011; King et al. 2013].

Table 2. New NMAM Methods Published in the Past 10 Years

Method Number	Method Name
0501	Aerosol particles - Polyvinyl chloride (PVC) internal capsule (gravimetric analysis) [2015]
2027	Ketones [2016]
5100	Carbon black – PVC internal capsule (gravimetric analysis) [2015]
7302	Elements by inductively coupled plasma (ICP) (mixed cellulose ester filter microwave digestion) [2014]

Table 2. New NMAM Methods Published in the Past 10 Years	
Method Number	**Method Name**
7304	Elements by ICP (PVC filter microwave digestion) [2014]
7306	Elements by ICP (cellulosic internal capsule) [2015]
7704	Beryllium in air by fluorometry [2007; updated 2015]
7907	Volatile acids (HCl, HBr, HNO3) by ion chromatography [2014]
7908	Non-volatile acids (H2SO4, H3PO4) by ion chromatography [2014]
8007	Toluene in blood [2013]
8319	Acetone and methyl ethyl ketone (MEK) in urine [2014]
8321	o-Cresol in urine [2016]
8322	Trichloroacetic acid in urine [2015]
8324	3-Bromopropionic acid in urine [2014]
8326	s-Benzylmercapturic acid and s-phenyl mercapturic acid in urine [2014]
9106	Methamphetamines and other drugs on wipes (liquid-liquid extraction) [2011]
9109	Methamphetamines and other drugs on wipes (solid phase extraction) [2011]
9110	Beryllium on wipes by fluorometry [2007; updated 2015]
9111	Methamphetamines and other drugs on wipes (liquid chromatography-mass spectrometry) [2011]

Validating Methods

Research involving laboratory, field and inter-laboratory studies has been undertaken in the course of method development, evaluation, and validation. These labors are necessary in the course of NIOSH method development and, as a result of these efforts, NIOSH has published numerous peer-reviewed papers, monographs, and allied reports.

Draft methods require validation in the laboratory and through NIOSH field investigations. All fully-validated methods must undergo rigorous independent tests to ensure that they are sufficiently rugged and will provide accurate, reproducible, and defensible data [NIOSH 1995]. To fully validate a method it must be demonstrated that other laboratories can perform the method and obtain similar results. NMAM methods are validated using at least one other laboratory, usually a contract laboratory, but sometimes other federal, state, or academic laboratories assist with the validation of a method.

A more comprehensive way to ensure a method is accurate and reproducible is to conduct an inter-laboratory or round robin test. This testing process can involve multiple independent scientists performing the method in their own laboratories. The samples being analyzed by each laboratory are prepared and provided by a designated laboratory in a manner that does not reveal information to the participating laboratories about the concentrations or contents of the samples. When NIOSH performs an inter-laboratory evaluation, it calls upon partners in federal or state laboratories, academic institutions and even foreign laboratories to participate. Prior to finalizing NIOSH methods and/or complementary voluntary consensus standards, inter-laboratory evaluations have been carried out to validate methods for numerous chemical agents. Examples include: amphibole asbestos [Harper et al. 2012], Be [Agrawal et al. 2006; Ashley et al. 2007, 2011; Cronin et al. 2008; Oatts et al. 2012], RCS [Harper et al. 2014; Stacey et al. 2014] and multi-element analysis [Ashley et al. 2012; Harper and Ashley 2013; Andrews et al. 2016].

In the last ten years NIOSH has conducted field investigations to further evaluate draft exposure assessment methods on soluble silver [Drake et al. 2006] and RCS [Harper and Lee 2013]. Field and inter-laboratory studies are key to evaluating prototypes such as nanoparticle samplers [Cena et al. 2015] and cassette sampler inserts [Andrews et al. 2016; Harper and Ashley 2013] under challenging yet realistic conditions.

Evaluations and validations of test protocols are necessary to ensure that the applied sampling and analytical methods are capable of providing the desired outcomes. Establishing the "fitness-for-purpose" of candidate sampling and analytical methods requires application of rigorous tests to assess their performance under realistic conditions. For example, research to evaluate a test protocol on the suitability of sampling pumps for size-selective sampling [Lee et al. 2014a, b; Soo et al. 2014] has investigated the influence of pump pulsation on sampler performance.

Guidance Documents

Guidance documents are often published in support of NIOSH methods and those who use the methods in a range of applications. In the last decade, NIOSH has published NMAM recommendations on cassette sample collection of aerosols, new and revised chapters, and protocols for evaluating direct-reading instruments. Examples include:

1. Sampling guidance for consideration of sampler wall deposits – Inclusion of material adhering to internal cassette surfaces during sampling and analysis of airborne particles [NIOSH 2016b].
2. Protocols that apply NIOSH methods for the evaluation of direct-reading instruments:
    - Components for evaluation of direct-reading monitors for gases and vapors [NIOSH 2012a].

- Addendum to components for evaluation of direct-reading monitors for gases and vapors – Hazard detection in first responder environments [NIOSH 2012b].

3. NMAM 5th ed. Chapters (2016a; all chapters from the 4th edition are updated, plus one new chapter):

- Purpose and scope
- Factors affecting aerosol sampling
- Monitoring diesel particulate exhaust in the workplace
- Measurement of fibers
- Filter pore size and aerosol sample collection (New)
- Glossary
- Development and evaluation of methods
- General considerations for sampling airborne contaminants
- Sampling and analysis of soluble metal compounds
- Measurement uncertainty and NIOSH method accuracy range

In the last 10 years, NIOSH scientists have developed or improved methods and published that work in over 235 papers in the scientific literature. These methods have enabled NIOSH to evaluate occupational exposures and to improve the accuracy of sampling. For example, Pretty et al. [2012] developed a method to assess exposure to antineoplastic drugs for healthcare workers. Liquid chromatography/ mass spectrometry methods were developed for individual analysis of five antineoplastic drugs (cyclophosphamide, ifosfamide, paclitaxel, doxorubicin, and 5-fluorouracil) in surface wipe media and air sample media. These methods were used in the analysis of samples in a large exposure assessment study that found contamination at three cancer centers [Connor et al. 2010]. In a second example, Cauda et al. [2014] compared two prototype cyclone samplers to sample for diesel particulate matter in mining environments. The Mine Safety and Health Administration (MSHA) requires monitoring of diesel particulate matter in non-coal mining operations. The purpose of this research was to evaluate samplers to eliminate the interference from mine dust and thus improve the accuracy of the monitoring.

Voluntary Consensus Standard Committees

NIOSH scientists participate on voluntary consensus standards committees that produce and validate methods. Standards/methods are developed by ASTM International (ASTM) (originally known as the American Society for Testing and Materials) and by the International Organization for Standardization (ISO) and are often based on NIOSH methods [Lee et al. 2016; Ashley 2015]. NIOSH scientists participate as chairs, secretaries, and reviewers on not only ASTM and ISO committees but also American National Standards Institute (ANSI) and International Electrotechnical Commission (IEC) consensus standard committees.

Extramural Research

Many of the extramural research projects on exposure assessment methods are funded through investigator-initiated research awards that leverage innovation and expertise from the extramural community. Some of the NIOSH programs including EXAP with respect to its sensor work, have been able to provide the NIOSH Extramural Grants Program with general guidance on the needs of the program.

NIOSH grantees have published over 80 methods development-related peer-reviewed research papers from 2006-2016. The methods development research that is funded extramurally by NIOSH ranges from developing job matrices to assess exposure to developing methods to measure exposure to physical hazards and/or chemical exposure [Fischer et al. 2017; Kim et al. 2012; Mostafaei et al. 2015]. For example, Fischer et al. [2017] developed an improved job exposure matrix that includes work practices, job conditions and quality of data while Mostafaei et al. [2015] developed a method to measure fluorine in bone. NIOSH grantees have also focused on improvement of methods for sample collection and analysis [Su et al. 2012 a, b; Tolchinsky et al. 2010]. Some more detailed examples of extramural methods development research follows.

Aerosol Samplers

Researchers at Rutgers, the State University of New Jersey received awards in 2006, 2010, and 2016 to develop and field-test **a novel bioaerosol sampler** capable of improving the ability to measure exposures to airborne microorganisms, especially at low concentrations. A liquid-based electrostatic precipitator with superhydrophobic surface (EPSS, Mark I) for bioaerosol sampling was developed [Han and Mainelis 2008; Han et al. 2010, 2011]. Details of the sampling protocol have been shown to be important to preserve the structural integrity of cell membrane, and the amount of cell damage during bioaerosol sampling and the resulting release of DNA can be substantial which should be taken into account when analyzing bioaerosol samples [Zhen et al. 2013].The EPSS has been modified and optimized to Mark II, so it could measure higher concentrations, and the sampler has shown satisfactory collection efficiency and high concentration rate [Han et al. 2015a]. Based on this sampler, the field-deployable electrostatic precipitator with superhydrophobic surface was developed so that it could be operated as a stand-alone device in the field. The studies with the new standalone device demonstrated the ability to rapidly detect airborne microorganisms using an adenosine triphosphate (ATP)-based detection method; it also detects their presence faster than the other two tested samplers (i.e., BioSampler and Button sampler). Researchers concluded that the ATP-based detection method could be integrated into bioaerosol detection systems, particularly where concentrations are low and time is critical [Han et al. 2015b].

Lovelace Biomedical and Environmental Research received NIOSH funding in 2007 to design, construct, and test **a personal bioaerosol sampler** incorporating a re-circulating liquid cyclone collection medium. Researchers developed two liquid-cyclone-based personal bioaerosol samplers, PAS-4 and PAS-5. In studies that evaluated their performance, the results showed that these two samplers are able to perform high efficiency aerosol sampling (with cutoff diameters of approximately 0.7 µm for both samplers), and to provide adequate survival for the collected bioaerosols [Tolchinsky et al. 2011]; although the PAS-5 was considered a better personal bioaerosol sampler than the PAS-4 [Su et al. 2012].

Researchers at Colorado State University received NIOSH funding in 2007 to develop a more powerful exposure assessment tool involving **a respiratory deposition-based sampler** that directly measures the estimated deposition of inhaled particles within the human lung. Researchers used a semi-empirical model to design a sampler made from porous, polyurethane foam that can reproduce the size-specific (but not region-specific) deposition of aerosol in the human respiratory system. The sampler provides a better estimate of aerosol dose than penetration-based samplers [Koehler et al. 2009]. However, since the sampler does not give any indication of where the particles deposit in the respiratory system, researchers developed and tested a multistage sampler to estimate regional deposition of aerosol [Koehler and Volckens 2013].

In 2012, a different team of researchers at Colorado State University received NIOSH funding to develop and test **new size-selective samplers** to characterize workplace aerosol size distributions of large inhalable particles (up to 100 µm). Two samplers capable of size-selective sampling were developed; however, the second sampler produced higher sampling efficiencies and sharper cut points compared to the simpler elutriator design. These samplers could be valuable to exposure assessment scientists and industrial hygienists since there has been a lack of measurement technology for large, inhalable particles [Anderson et al. 2015].

In 2006, NIOSH funded researchers at the West Virginia University to characterize the size and quantity of **aerosol droplets produced by humans while coughing**, and then to use this information to better understand the mechanisms by which influenza is transmitted from infected individuals to others. A NIOSH-designed and validated two-stage bioaerosol cyclone personal sampler was used in this work to collect bioaerosols [Lindsley et al. 2006]. Airborne influenza and respiratory syncytial virus (RSV) viral particles were collected in a hospital emergency department and in an urgent care medical clinic using mobile and stationary samplers. Some of these researchers continued this work in well-controlled laboratory studies at NIOSH facilities. Findings from the study in the emergency department provided evidence that influenza virus may spread through the airborne route [Blachere et al. 2009] and a NIOSH study in the urgent care medical clinic unit supported the possibility that influenza and RSV can be transmitted by the airborne route [Lindsley et al. 2010]. A mathematical model was also developed by the grantee to predict the viability of airborne viruses [Posada et al. 2010].

Researchers at the University of Minnesota received NIOSH funding in 2008 to assess the sizes of particles that are associated with **viruses in occupational environments**. A study was conducted to develop methods for size-selective sampling of viral aerosols and to determine the best method for maximizing recovery of viable viruses. An eight-stage non-viable Andersen cascade impactor (ACI) and a micro-orifice uniform deposit impactor (MOUDI) were compared in a study; even though both impactors were capable of size-selectively sampling viral aerosols, the ACI achieved higher relative recoveries of virus than the MOUDI [Appert et al. 2012]. Another study evaluated the survivability of airborne viruses and sampling performance of the ACI in an environmental chamber, which simulated a typical indoor environment. Male-specific bacteriophage and avian influenza virus showed higher survival at lower temperature, absolute humidity was found to be a better predictor of virus survival than relative humidity, and the interaction between absolute humidity and temperature was not significant [Ge et al. 2014].

Other Types of Exposure

In 2012, NIOSH provided extramural funding to researchers at Purdue University to develop and validate a novel **neutron activation analysis (NAA) system** to noninvasively quantify bone manganese (MnBn) in vivo (Liu et al. 2014; Liu et al. 2013]. Occupational exposure to manganese commonly takes place during mining and steel operations, welding, and other settings (Crossgrove and Zheng 2004). Based on a feasibility study [Liu et al. 2013], a deuterium-deuterium neutron generator–based NAA system was developed and validated that quantifies metals, including MnBn in vivo. Researchers concluded that this system is promising for in vivo bone Mn quantification in humans [Liu et al. 2014]. They also conducted a study to determine the acceptable doses to apply the technology for a manganese toxicity in human population [Sowers et al. 2015].

Researchers at the University of Washington received NIOSH funding in 2007 to evaluate the suitability of **methoxyphenols as urinary biomarkers** of exposure to woodsmoke. Researchers assessed occupational exposure to wildland fire smoke in 14 wildland firefighters working at prescribed burns at the Savannah River Site, SC, by measuring the urinary concentrations of nine hydroxylated metabolites of polycyclic aromatic hydrocarbons (OH-PAHs) [Adetona et al. 2017]. Personal monitoring of exposure to particulate matter with median aerodynamic diameter of 2.5 µm (PM2.5), levoglucosan, and carbon monoxide was conducted [Adetona et al. 2013]. The results of this work suggest that OH-PAHs may be useful biomarkers of wildland fire smoke exposure [Adetona et al. 2017].

Researchers at the University of Wisconsin - Madison received funding in 2012 to investigate the feasibility of automatically evaluating the American Conference of Government Industrial Hygienists (ACGIH) **Hand Activity Level** using digital video processing [Akkas et al. 2015]. Researchers used a marker-less 2D video algorithm to measure hand kinematics for varying hand activity levels. The approach is automatic, repeatable, objective and unobtrusive, and is suitable for evaluating repetitive exertions, muscle fatigue and manual tasks [Akkas et al. 2016].

Transfer/Translation

NIOSH-developed methods are transferred or translated into practice in a number of ways. **Federal agencies** including OSHA, MSHA, DOE, the Department of Defense (DOD), and the Environmental Protection Agency (EPA) use NIOSH methods once validated, to compare measured worker exposures to established standards like OELs. NIOSH is part of the the National Toxicology Program (NTP), which is administered by the National Institute for Environmental Health Sciences. Part of the role of the NTP is to determine toxicity testing needs of chemical and biological hazards. The NTP often comes to NIOSH to perform work-place exposure assessments for nominated chemicals to determine the need. To perform these exposure assessments requires NIOSH to develop methods for the nominated chemicals.

State programs, international organizations, and safety and health professionals in the private sector also rely on NIOSH methods to conduct their exposure monitoring activities. **Contract laboratories** implement NIOSH NMAM methods into their testing list as they are used by industrial hygienists. **AIHA and other national and international occupational safety and health organizations** recommend the use of NIOSH methods to their members.

Academic institutions use NMAM methods as part of their course content in measuring exposures. **Industrial hygienists** use NIOSH methods to assess hazardous exposures. **Consensus standards organizations**, particularly ASTM International and ISO, have used NIOSH methods as a foundation for standards development. The use of consensus standards by federal agencies and international organizations ensures harmonization and data comparability at different times and places [Ashley 2015]. Partners who have engaged in these activities can be found in Table 3.

Table 3. Example list of partners to whom NIOSH methods have been transferred / translated
Domestic
American Industrial Hygiene Association (AIHA)
American Conference of Governmental Industrial Hygienists (ACGIH)
Department of Defense (DOD)
Department of Energy (DOE)
Environmental Protection Agency (EPA)
Mine Safety and Health Administration (MSHA)
National Center for Environmental Health, Division of Laboratory Science (NCEH-DLS)

Table 3. Example list of partners to whom NIOSH methods have been transferred / translated
National Aeronautics and Space Administration (NASA)
Occupational Safety and Health Administration (OSHA)
U.S. State Public Health Laboratories
International
ASTM International
Health and Safety Laboratory (HSL) in the United Kingdom
Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST) in Canada
Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA) in Germany
Instituto Nacional de Seguridad e Higiene en el Trabajo (INSHT) in Spain
Institut National de Recherche et de Sécurité (INRS) in France
International Organization for Standardization (ISO)
Japan National Institute of Occupational Safety and Health (JNIOSH)
Ministerio de Salud, Programa de Salud Ocupacional in Chile
World Health Organization (WHO)

Intermediate Outcomes

The intermediate outcomes that result from EXAP sensor-related activities and outputs include actions taken by stakeholders in response to NIOSH products or efforts, and are intended to ultimately result in end outcomes that are improvements in safety and health in the workplace that can be attributed to NIOSH efforts. Those intermediate outcomes include measurable applications of NIOSH products like the NMAM in occupational safety and health practice.

Reach of the NMAM

NMAM has been the second most visited site on the NIOSH website in recent years. In 2015 the NMAM was viewed approximately 300,000 times and the individual methods were downloaded an average of 622 times each. In 2010-2016, the NMAM methods and chapters were downloaded approximately 2.16 million times, with an average of 308,581 downloads per year (Figure 3). For the new 5th edition, almost 46,000 web views and 15,000 downloads have occurred since it was published in April 2016. The most downloaded method is NMAM 7302 [Elements by ICP (Microwave Digestion)]. The 4th edition of the NMAM was downloaded over 295,000 times in 2016 alone. Other related resources have also been accessed online: sampler wall deposit guidance has been viewed more than 14,500 times.

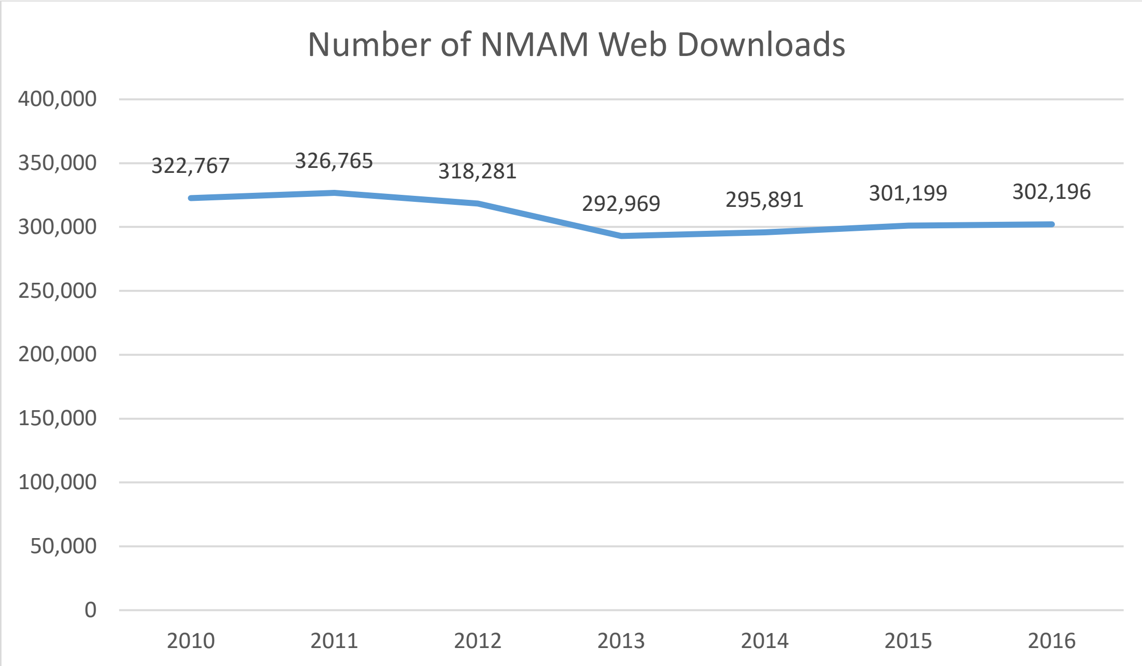

Figure 3. Number of web downloads of the NIOSH Manual of Analytical Methods (NMAM) for the years 2010 through 2016.

Use of NMAM Methods by Accredited Laboratories

Numerous **laboratories have adopted NIOSH NMAM methods**. Air Force, Army and Navy laboratories are accredited by the AIHA Industrial Hygiene Laboratory Accreditation Program, LLC (AIHA IHLAP) for multiple NIOSH methods. State public health or industrial hygiene laboratories in the U.S. depend upon NIOSH methods for their workplace exposure monitoring activities and responsibilities. For instance Iowa, Kentucky, Oregon, California, Michigan, Wisconsin, and Washington have adopted NIOSH methods and are accredited by the AIHA IHLAP for these methods [AIHA 2017].

Professional organizations like the AIHA and the ACGIH often recommend the use of NIOSH methods to their members and other professionals in the occupational health field. For example AIHA recommends several NIOSH methods to measure titanium dioxide in their Nanoparticle Sampling and Analysis Fact Sheet [AIHA 2016]. Contract laboratories point to their use of NIOSH methods, which supports laboratory accreditation relating to analysis of workplace samples (collected by, e.g., industrial hygienists). The AIHA IHLAP certifies proficiency of commercial laboratories, as well as some State and Federal laboratories, to run NIOSH and other methods. Currently, there are over 170 laboratories accredited by this program and approximately 150 of them use NIOSH methods. A list of the laboratories can be found in Appendix E, and Appendix F has a table of number of labs accredited for each NMAM method.

Use of NIOSH Methods by Federal Agencies

The Occupational Safety and Health Act of 1970 (Public Law 91-596) charged NIOSH with developing and recommending occupational health standards (i.e., NIOSH (RELs)) that OSHA can use at its discretion to develop PELs. To support **occupational exposure limits** such as NIOSH RELs and OSHA PELs, requisite sampling and analytical methods must be made available so that occupational exposure monitoring can be done. The methods, once validated, enable comparisons of measured worker exposures to established standards like OELs. The NMAM was born out of this need for workplace exposure monitoring methods. For example, the recent EXAP output (see page 26) of the published NIOSH Criteria Document on Cr (VI) [NIOSH 2013], improved NIOSH sampling and analytical methods for Cr (VI) are cited in the promulgation of a revised NIOSH REL for Cr (VI) compounds. NIOSH method 7605 for Cr (VI) was developed in parallel with international consensus standards [ASTM 2002; ISO 2005], which have supported regulatory exposure assessment activities for this agent in the U.S. and Europe. NMAM analytical methods for Cr (VI) have been used extensively in investigations of control technologies, risk assessments and specific work tasks [NIOSH 2013a].

Numerous NIOSH methods have been adopted for use by OSHA and MSHA for their **regulatory purposes**. For example, the MSHA revised method for measuring silica and cristobalite in mine dust references NIOSH Method 7500 [MSHA 2013]. NIOSH methods are also relied upon by other federal agencies, such as the DOE, DOD, and EPA. In a recent OSHA rulemaking concerning occupational exposures to beryllium, NIOSH [2016a] and ASTM [2015] ultra-trace monitoring methods were cited in support of the newly-established OSHA PEL and STEL for Be [OSHA 2017]. These methods are widely used by laboratories within the DOE [Oatts et al. 2012] and should soon see extended applications elsewhere [Ashley 2011; Ashley et al. 2011]. In conjunction with that work, NIOSH collaborated with National Institute of Standards and Technology and DOE to develop a new standard reference material for use in laboratory calibration and validation studies to apply the methods [Winchester et al. 2009].

In another OSHA rule, NIOSH methods for RCS were cited in support of setting a lower PEL for RCS [OSHA 2016] in order to provide better protection to exposed workers. Currently, NIOSH methods for RCS and asbestos are undergoing revision so that higher-flow sampling devices can be incorporated into the methods. These improvements are necessary in view of scientific advances regarding samplers for respirable particles and airborne fibers. Once finalized, the revised methods will support the new OSHA PELs for RCS and asbestos.

NIOSH partnered with DOD and others to conduct a study that evaluated **JP-8 jet fuel exposure** for military personnel. NIOSH developed a method for 2-methoxy(ethoxy)ethanol that was used in the study as a surrogate for JP-8 jet fuel exposure [B'Hymer et al. 2005]. The composition of JP-8 jet fuel varies with lot number. However, 2-methoxy(ethoxy)ethanol, a deicing agent, is added to each lot in a known percentage, thus serving as an indication of exposure over multiple lots [B'Hymer et al. 2012].

Also of note is the use by NASA of a very compact and **portable air quality sampler** created by Dr. John Volckens and his team at Colorado State University (CSU) with NIOSH extramural funding and designed collaboratively by Pittsburgh's RJ Lee Group and CSU. The sampler is designed to characterize aerosol size distributions of large inhalable particles (up to 100 µm). This sampler could be valuable to exposure assessment scientists and industrial hygienists since there has been a lack of measurement technology for large, inhalable particles [Anderson et al. 2015]. NASA has adopted the new sampler for use in the International Space Station to measure air quality in the station.

Use of NIOSH Methods in Voluntary Consensus Standards

The National Technology Transfer and Advancement Act directs federal agencies to (a) rely on applicable voluntary consensus standards in lieu of procedures and documents developed in-house, and to (b) participate in the development of pertinent consensus standards that are related to the agencies' activities [U.S.Government 1996]. Therefore, in terms of a hierarchy of sampling and analytical methods for exposure assessment, consensus standards are, in fact, at the apex [Ashley 2015; Lee et al. 2016]. Consensus standard organizations such as ASTM and ISO commonly incorporate NIOSH methods into their standards. The following subsections provide examples.

ASTM International Subcommittee D22.04 on Workplace Atmospheres

ASTM has developed a number of standards that cite NIOSH studies, publications and/or methods (Table 4).

Table 4. ASTM Standards that Cite NIOSH Methods and NIOSH Methods-Related Publications		
ASTM Standard	**Year**	**Citations of NIOSH Products**
D3686-13 Standard Practice for Sampling Atmospheres to Collect Organic Compound Vapors (Activated Charcoal Tube Adsorption Method)	2013	NIOSH [1994]
D3687-07 Standard Practice for Analysis of Organic Compound Vapors Collected by the Activated Charcoal Tube Adsorption Method	2012	NIOSH [1994]
D4490-96 Standard Practice for Measuring the Concentration of Toxic Gases or Vapors Using Detector Tubes	2016	Colen [1972]; McCammon et al. [1982]; NIOSH [1977a]; Roper [1974]
D4532-15 Standard Test Method for Respirable Dust in Workplace Atmospheres Using Cyclone Samplers	2015	Bartley et al. [1983, 1984, 1994]; Bowman et al. [1984]; Lee et al. [2010; 2012; 2014]; NIOSH [1994]; Soo et al. [2014a, b]; Stacey et al. [2014]
D4597-10 Standard Practice for Sampling Workplace Atmospheres to Collect Gases or Vapors with Solid Sorbent Diffusive Samplers	2015	Cassinelli et al. [1987]
D4599-14 Standard Practice for Measuring the Concentration of Toxic Gases or Vapors Using Length-of-Stain Dosimeters	2014	Bartley [1986]
D4766-98 Standard Test Method for Vinyl Chloride in Workplace Atmospheres (Charcoal Tube Method)	2014	Hill et al. [1976]
D4844-16 Standard Guide for Air Monitoring at Waste Management Facilities for Worker Protection	2016	NIOSH [1985, 1994]
D4856-11 Standard Test Method for Determination of Sulfuric Acid Mist in Workplace Atmospheres Collected on Mixed Cellulose Ester Filters (Ion Chromatographic Analysis)	2016	NIOSH Contract CDC-99-74-45
D4913-00 Standard Practice for Determining Concentration of Hydrogen Sulfide by Direct Reading, Length of Stain, Visual Chemical Detectors	2016	NIOSH [1977b]
D5337-11 Standard Practice for Flow Rate Adjustment of Personal Sampling Pumps	2016	NIOSH [1994]
D5578-04 Standard Test Method for Determination of Ethylene Oxide in Workplace Atmospheres (HBr Derivatization Method)	2015	NIOSH [1994]

Table 4. ASTM Standards that Cite NIOSH Methods and NIOSH Methods-Related Publications		
ASTM Standard	**Year**	**Citations of NIOSH Products**
D5836-08 Standard Test Method for Determination of 2,4-Toluene Diisocyanate (2,4-TDI) and 2,6-Toluene Diisocyanate (2,6-TDI) in Workplace Atmospheres (1-2 PP Method)	2013	NIOSH [1973, 1978]
D5932-08e1 Standard Test Method for Determination of 2,4-Toluene Diisocyanate (2,4-TDI] and 2,6-Toluene Diisocyanate (2,6-TDI) in Air (with 9-(N-Methylaminomethyl) Anthracene Method) (MAMA) in the Workplace	2013	NIOSH [1973]
D6061-01e1 Standard Practice for Evaluating the Performance of Respirable Aerosol Samplers	2012	Baron [1983]; Bartley [2001]; Bartley et al. [1982, 1984; 1994]; Bowman et al. [1984]; Busch and Taylor [1981]; Gunderson and Anderson [1980]; NIOSH [1977c]; Soderholm [1989]
D6062-07 Standard Guide for Personal Samplers of Health-Related Aerosol Fractions	2012	Bartley et al. [1994]; NIOSH [1994, 1995a]; Soderholm [1989]
D6246-08e1 Standard Practice for Evaluating the Performance of Diffusive Samplers	2013	Bartley [2001; 2008]; Bartley and Irwin [2002]; Cassinelli et al. [1987]; Gunderson and Anderson [1980]; NIOSH [1995b]
D6494-99 Standard Test Method for Determination of Asphalt Fume Particulate Matter in Workplace Atmospheres as Benzene Soluble Fraction	2015	NIOSH [1994]
D6552-06 Standard Practice for Controlling and Characterizing Errors in Weighing Collected Aerosols	2016	Smith and Bartley [1999]; Chen and Baron [1996]; Busch [1977]; Kennedy et al. [1995]
D6561-06 Standard Test Method for Determination of Aerosol Monomeric and Oligomeric Hexamethylene Diisocyanate (HDl) in Air with (Methoxy-2–phenyl-1) Piperazine (MOPIP) in the Workplace	2016	Chen and Baron [1996]; NIOSH [1995b]
D6562-12 Standard Test Method for Determination of Gaseous Hexamethylene Diisocyanate (HDI) in Air with 9-(N-methylaminomethyl) Anthracene Method (MAMA) in the Workplace	2012	NIOSH [1973]

Table 4. ASTM Standards that Cite NIOSH Methods and NIOSH Methods-Related Publications		
ASTM Standard	**Year**	**Citations of NIOSH Products**
D6785-13 Standard Test Method for Determination of Lead in Workplace Air Using Flame or Graphite Furnace Atomic Absorption Spectrometry	2013	Ashley [1995]; Ashley et al. [1998a]; Ashley and Harper [2013]; NIOSH [1994, 1995b]; Schlecht et al. [1996]; Harper and Ashley [2013]; Harper and Demange [2007]
D6832-13e1 Standard Test Method for the Determination of Hexavalent Chromium in Workplace Air by Ion Chromatography and Spectrophotometric Measurement Using 1,5-diphenylcarbazide	2013	Ashley [2001]; Ashley et al. [2009]; Ashley and Harper [2013]; Boiano et al. [2000]; Harper and Demange [2007]; Marlow et al. [2000]; NIOSH [1981, 1994, 1995b]; Wang et al. [1997]
D6877-13e1 Standard Test Method for Monitoring Diesel Particulate Exhaust in the Workplace	2013	Birch [1998, 2002]; Birch and Carey [1996a, b]; Birch et al. [1999]; Birch and Noll [2004]; NIOSH [1988]; Noll and Birch [2004]
D7035-16 Standard Test Method for Determination of Metals and Metalloids in Airborne Particulate Matter by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES	2016	Andrews et al. [2016]; Ashley [2001]; Harper and Ashley [2013]; NIOSH [1994, 1995]; Oatts et al. [2012]
D7049-04 Standard Test Method for Metal Removal Fluid Aerosol in Workplace Atmosphere	2010	NIOSH [1994]
D7144-05a Standard Practice for Collection of Surface Dust by Micro-vacuum Sampling for Subsequent Metals Determination	2016	NIOSH [1994]
D7200-12 Standard Practice for Sampling and Counting Airborne Fibers, Including Asbestos Fibers, in Mines and Quarries, by Phase Contrast Microscopy and Transmission Electron Microscopy	2012	Harper et al. [2012]; NIOSH [1994]; Schlecht and Shulman [1986]
D7201-11 Standard Practice for Sampling and Counting Airborne Fibers, Including Asbestos Fibers, in the Workplace, by Phase Contrast Microscopy (with an Option of Transmission Electron Microscopy)	2011	NIOSH [1994]; Schlecht and Shulman [1986]; Taylor et al. [1984]
D7202-15 Standard Test Method for Determination of Beryllium in the Workplace by Extraction and Optical Fluorescence Detection	2015	Agrawal et al. [2006]; Ashley et al. [2005, 2007, 2011]; Goldcamp et al. [2009]; NIOSH [1994]; Oatts et al. [2012];

Table 4. ASTM Standards that Cite NIOSH Methods and NIOSH Methods-Related Publications		
ASTM Standard	**Year**	**Citations of NIOSH Products**
D7439-14 Standard Test Method for Determination of Elements in Airborne Particulate Matter by Inductively Coupled Plasma–Mass Spectrometry	2014	NIOSH Methods 7013, 7024, 7027, 7029, 7030, 7048, 7082, 7105, 7300, 7303, 7901; Kennedy et al. [1995]; Ashley [2001]; Harper and Demange [2007]; Ashley et al. [2012]
D7659-10 Standard Guide for Strategies for Surface Sampling of Metals and Metalloids for Worker Protection	2015	Ashley et al. [2002]; Day et al. [2007]; NIOSH [1994]; Song et al. [2001]
D7822-13 Standard Practice for Dermal Wipe Sampling for the Subsequent Determination of Metals and Metalloids	2013	Brouwer et al. [2000]; Esswein et al. [2011]; NIOSH [1994]
D7948-14e1 Standard Test Method for Measurement of Respirable Crystalline Silica in Workplace Air by Infrared Spectrometry	2014	Lee et al. [2012]; Miller et al. [2012, 2013]; NIOSH [1994]; Shulman et al. [1992]; Song et al. [2001]
E1370-14 Standard Guide for Air Sampling Strategies for Worker and Workplace Protection	2014	Harper and Demange [2007]; NIOSH [1975, 1977]
E2864–13 Standard Test Method for Measurement of Airborne Metal and Metal Oxide Nanoparticle Surface Area Concentration in Inhalation Exposure Chambers using Krypton Gas Adsorption	2013	Baron [2002]; Chen et al. [2006]; Ku and Maynard [2005]; LeBouf et al. [2011];
E3025 – 16 Standard Guide for Tiered Approach to Detection and Characterization of Silver Nanomaterials in Textiles	2016	Stefaniak et al. [2013]; Tulve et al. [2015]

International Standards Organization (ISO)

ISO has developed a number of standards that cite NIOSH studies, publications and/or methods (Table 5).

Table 5. ISO Standards that Cite NIOSH Methods and Information		
ISO Standard	**Year**	**NIOSH Citations**
ISO 8672 Air quality -- Determination of the number concentration of airborne inorganic fibres by phase contrast optical microscopy – Membrane filter method	2014	Harper et al. [2012]; Lee et al. [2010, 2011]; Pang and Harper [2008]
ISO 13138 Air quality -- Sampling conventions for airborne particle deposition in the human respiratory system	2012	McCawley [1999]; Bartley and Vincent [2011]; Lidén and Harper [2006]

Table 5. ISO Standards that Cite NIOSH Methods and Information		
ISO Standard	**Year**	**NIOSH Citations**
ISO/TR 14294 Workplace atmospheres -- Measurement of dermal exposure --Principles and methods	2011	Bartley and Lidén [2008]; Day et al. [2007, 2009]; Maynard et al. [2004]
ISO 15202-1 Workplace air – Determination of metals and metalloids in airborne particulate matter by inductively coupled plasma atomic emission spectrometry – Part 1: Sampling	2012	Harper and Demange [2007]
ISO 15202-2 Workplace air – Determination of metals and metalloids in airborne particulate matter by inductively coupled plasma atomic emission spectrometry – Part 2: Sample preparation	2012	Ashley [1998b]; Ashley et al. [2001]; Drake et al. [2006]; Harper and Demange [2007]
ISO 15767 Workplace atmospheres -- Controlling and characterizing uncertainty in weighing collected aerosols	2009	Chen and Baron [1996]; Smith et al. [1998]
ISO 16107 Workplace atmospheres -- Protocol for evaluating the performance of diffusive samplers	2007	Bartley et al. [1983, 1988]; NIOSH [1994]
ISO 16258-1 Workplace air -- Analysis of respirable crystalline silica by X-ray diffraction -- Part 1: Direct-on-filter method	2015	Baron et al. [2002]
ISO 16258-2 Workplace air -- Analysis of respirable crystalline silica by X-ray diffraction -- Part 2: Method by indirect analysis	2015	Baron et al. [2002]
ISO 17735 Workplace atmospheres -- Determination of total isocyanate groups in air using 1-(9-anthracenylmethyl) piperazine (MAP) reagent and liquid chromatography	2009	Bello et al. [2002]; England et al. [2000]; Streicher et al. [1996, 2000]; Tucker [2007]
ISO 17736 Workplace air quality -- Determination of isocyanate in air using a double-filter sampling device and analysis by high pressure liquid chromatography	2010	England et al. [2001]
ISO/TR 19716 Nanotechnologies -- Characterization of cellulose nanocrystals	2016	Stefaniak et al. [2014]
ISO 21438-2 Workplace atmospheres -- Determination of inorganic acids by ion chromatography -- Part 2: Volatile acids, except hydrofluoric acid (hydrochloric acid, hydrobromic acid and nitric acid)	2009	NIOSH [1995]

Table 5. ISO Standards that Cite NIOSH Methods and Information		
ISO Standard	**Year**	**NIOSH Citations**
ISO 24095 Workplace air -- Guidance for the measurement of respirable crystalline silica	2009	Bartley et al. [2007]
ISO/TR 27628 Workplace atmospheres -- Ultrafine, nanoparticle and nano-structured aerosols -- Inhalation exposure characterization and assessment	2007	Antonini [2003]; Maynard [2003a, b]; Maynard and Kuempel [2005]; Wallace and Keane [1993]
ISO/TS 4869-5 Method for estimation of noise reduction using fitting by inexperienced test subjects	2006	Murphy [2004]
ISO/DIS 4869-2: Estimation of effective A-weighted sound pressure levels when hearing protectors are worn	2006	Murphy [2004]

American National Standards Institute (ANSI)

ANSI has developed a number of standards that cite NIOSH studies, publications and/or methods (Table 6).

Table 6. ANSI Standards that Cite NIOSH Methods and Information		
ANSI Standard	**Year**	**NIOSH Citations**
ANSI-ASA S3.44: Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment	2016	man et al. [2010, 2012]
ANSI-ASA S12.6: Methods for measuring the real-ear attenuation of hearing protectors	2015	Berger et al. [1996, 1998]; Royster et al. [1996]; Murphy et al. [2004, 2006]
ANSI-ASA S12.68: Methods for estimating effective A-Weighted sound pressure levels whem hearing protectors are worn	2012	Kroes et al. [1975]; Murphy et al. [2002, 2004, 2006]
ANSI N13.56: Sampling and Monitoring Releases of Airborne Radioactivity in the Workplace	2012	Maiello and Hoover [2010]
ANSI N323AB: Radiation Protection Instrumentation Test and Calibration, Portable Survey Instruments	2013	Hoover and Cox [2004]
ANSI N323C: Radiation Protection Instrumentation Test and Calibration – Air Monitoring Instruments	2009	Hoover and Cox [2004]

Use of NIOSH Methods Internationally

The reach and impact of the NMAM and other NIOSH methods are not limited to domestic applications. NIOSH NMAM methods have been adopted by many other occupational safety and health organizations around the world. Just a few examples of organizations in other countries that have incorporated NIOSH methods for their own use include the Instituto Nacional de Seguridad e Higiene en el Trabajo (INSHT) in Spain, the Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST) in Canada, the Japan National Institute of Occupational Safety and Health (JNIOSH) in Japan and the Ministerio de Salud, Programa de Salud Ocupacional in Chile. In some cases, with support from entities such as the World Health Organization (WHO), NIOSH researchers have assisted professionals in other countries in the technical transfer of NIOSH methods to their occupational health laboratories. Such technical assistance endeavors by NIOSH experts have taken place in nations like Chile, Colombia, Ecuador, El Salvador, Mexico, Peru, South Africa and Zambia.

Use of NIOSH Methods by Academc Institutions

The use of NIOSH sampling and analytical methods is **taught to aspiring occupational health professionals** in universities throughout the U.S., notably in nearly twenty NIOSH-supported Education and Research Centers. University faculty use NMAM methods as part of their course content in measuring exposures. Examples of such universities are Southeastern Oklahoma University, the University of Utah, the University of Iowa, and the University of Arizona, all of which use a number of NMAM methods in their course contents.

NIOSH methods are frequently **used by researchers** to investigate the effectiveness of interventions meant to reduce worker exposures to chemical and biological agents. For instance, in a recent study, NIOSH methods for RCS were used in evaluating the performance of a prototype control technology for **airborne dust control** in work operations involving large amounts of sand [Alexander et al. 2016]. RCS exposures in oil and gas operations such as hydraulic fracturing can be extremely high [Esswein et al. 2013]. Stakeholders, including industry, desire new sampling techniques to comply with the new OSHA airborne RCS concentrations in occupational settings.

The NIOSH-developed two-stage bioaerosol cyclone sampler [Lindsley et al. 2006], as described on page 39, has been used by other researchers both within and outside of NIOSH in a growing number of different studies. For example, in several extramural studies, it was used for **particulate size separation** to characterize bioaerosols from dairy barns [Lecours et al. 2012]; for size-selective analysis of aerosolized glucan and endotoxin to examine the aerosolization of culturable and total fungi, (1-3)-β-D glucan, and endotoxin from eight flood affected floor and bedding materials collected in New Orleans homes after Hurricane Katrina [Adhikari et al. 2009]; for size-selective collection of airborne fungi and fungal fragments to assess the personal exposures of agricultural workers to airborne fungi and fungal fragments [Lee and Liao 2014] and for collecting air samples to compare the effects of aerosolization and sampling on the infectivity of five tail-less bacteriophages and two pathogenic viruses [Turgeon et al.2014].

The findings and techniques developed by extramural researchers such as Zuo et al. 2013 at the University of Minnesota have been applied in other studies. For example, the findings from the study by Zuo et al. 2013 were cited by Guha et al. 2015 to support aerosol selection in a study to determine the **effectiveness of facemasks** meant for pediatric population. The findings, as described on page 42, of Appert et al. 2012 that compared the eight-stage non-viable ACI and a MOUDI have been cited in different studies that used the ACI for size-differentiated air sampling:

- The ACI was used in a study that investigated the plausibility of aerosol transmission of H5N2 highly pathogenic avian influenza virus during the 2015 spring outbreaks that occurred in the U.S. Midwest [Torremorell et al. 2016].
- The ACI was also used in a study that evaluated an electrostatic particle ionization technology for decreasing airborne pathogens in pigs; based on the study findings, the reduction in infectious agents in the air by the EPI technology may decrease the microbial exposure for pigs and people in confinement livestock facilities [Alonso et al. 2016].

Findings and techniques tested or developed through the study by researchers at Rutgers, the State University of New Jersey have been used in diverse studies by other researchers. For instance, Benami et al. 2016, Gauthier-Levesque et al. 2016, and Therkorn et al. 2017 followed sampling procedures to address **reduction in bacterial viability or cell damage** during collection that were supported by the findings from the study by Zhen et al. 2013.

Use of Methods by Employers

Results from NIOSH research can change the methods that companies use to assess exposures. For example, NIOSH publications and engagement with wood product manufacturing companies have helped advance exposure assessment methods in that industry. NIOSH published a paper that evaluated the methods available for the collection of wood dust samples (Lee et al. 2011a). NIOSH subsequently sponsored a conference entitled “Wood Dust 2011”, along with an anonymous survey of wood products manufacturing companies conducted by the research institute of the American Forest & Paper Association. In response to a survey question, respondents articulated the need for “[r]esearch on types of sampling devices that adequately quantify inhalable dust exposures, yet also address sampling issues unique to wood dust.” Conference participants from two U.S. companies and a Canadian company (representing 10,500 and 400 employees potentially exposed to wood dust, respectively) reported that they found the information presented at the conference to be useful for informing future industry decisions on assessing worker exposure to wood dust. In addition, conference attendees from the two U.S. companies reported that they were considering adopting an assessment method that measures the “inhalable fraction,” due both to changes in non-legally binding guidelines and to new research findings by NIOSH on worker health or exposure assessment.

End Outcomes

The desired end outcome of NIOSH method development, evaluation, and validation efforts is the reduction of hazardous exposures to chemical, biological, and physical hazards. Determination of the presence of a biological, physical, or chemical agent and the level of exposure, cannot be determined without the availability of reliable, validated sampling and analytical methods. Currently, no metrics exist to show the impact of NIOSH methods on the desired outcome. However, with adoption of NMAM methods by NIOSH partners and customers around the world, expanded exposure assessment has been carried out on a global scale. As regulations change, stakeholders and partners come to NIOSH to request assistance in complying with any new rules. This can drive applications of the NMAM nationally as tools for employers to use to ensure compliance with new rules. Adoption of NIOSH methods and translation into consensus standards extends the reach of the NMAM internationally. NIOSH methods and specifically the NMAM, is a singularly invaluable global resource in occupational health.

Alternative Explanations

While NIOSH has contributed substantially to the development and validation of methods used in the occupational safety and health community, there are other federal agencies such as OSHA and EPA with regulatory authority that impacts methods development. Commercial entities also develop methods to meet their internal needs. The European Union's REACH regulations also influences the adoption of methods by U.S. firms to be compliant with these regulations. While there have been attempts to harmonize regulations, the European Union does have different OELs than the U.S. Since many companies are global in nature, they must follow not only REACH regulations but also U.S.regulations. Between the two systems, occupational exposure limits may be different and the methods used to measure exposure may also differ.

Future Plans

NIOSH staff continue to work on the development and evaluation of new and improved methods for exposure assessment purposes. The methods used to assess and manage occupational exposures often require revision/updating. For instance, as OELs are lowered and as the science of sampling and analysis advances, new techniques may need to be accommodated by means of new or revised NIOSH methods. When unknown hazardous agents are encountered in the workplace, new methodologies may be required for their sampling and measurement.

Hence there is constant feedback from the application of methods as tools and products regarding considerations such as: (a) the development of new methods, (b) performance evaluation in ongoing laboratory studies, (c) evaluation of new prototypes, (d) investigation of health effects, (e) industrywide studies, and (f) toxicological studies. The NMAM is a living document that is continuously undergoing revision, updating, and improvement in response to countless drivers from myriad industrial hygienists, engineers, scientists, and other professionals in the occupational health field. Methods development, in general, is a critical aspect of the NIOSH mission.

The internal capabilities of NIOSH experts to understand and meet Institute needs enables NIOSH to be highly responsive to changing analytical needs. Additionally, NIOSH's continued involvement with consensus standards organizations will help target priorities for promulgating harmonized, high-quality sampling and analytical methods. Reliance on external resources and collaborations will also be crucial in maintaining the relevance of the NMAM over the long-term. A list of NMAM planned efforts is presented in Table 7.

Table 7. NIOSH Development Plans for Future Methods, NMAM Chapters and Other Activities	
Methods	
Total isocyanates	New NMAM method. Total isocyanate are important for a variety of worksites such as spraying foam insulation
Combined GC Method for Solvents	New NMAM method. Combines a number of existing NMAM methods into one. This was requested by commercial laboratories that are charged per method for accreditation.
Butyltin chlorides in urine	New NMAM method. A priority for the 5th edition was the inclusion of biomonitoring methods
Respirable Particulates not otherwise regulated [Update]	Revision of existing method. New sampling method improves the accuracy of the measurement of the respirable fraction.
Organophosphorus pesticides [Update]	Revision of existing method. Improves sensitivity of method.
Elements in tissue	New NMAM method based on recent publications of the method
New methods development	Driven by revised NIOSH carcinogen policy requiring better sensitivity
NMAM Chapters	
Application of Biological Monitoring Methods for Chemical Exposures in Occupational Health	Update of 20-year old chapter
Analysis of Carbon Nanotubes and Nanofibers on Mixed Cellulose Ester Filters by Transmission Electron Microscopy	New NMAM chapter in support of ongoing epidemiological studies
Direct-reading Instruments for Gases and Vapors	New NMAM chapter to address stakeholder request for additional guidance on the calibration, validation and interpretation of information obtained for gases and vapors using direct-reading instruments
Monitoring Diesel Exhaust in the Workplace	Revision of existing NMAM chapter to update health-relevant information and add a section on carbon nanomaterials
Quality Assurance/Quality Control	Revision of existing NMAM chapter to update 20-year old chapter
Other Activities	
NMAM Web e-book updates	The NMAM Web e-book was recently posted as requested by stakeholders during the NMAM survey
NMAM Videos on how to sample	Requested by stakeholders during NMAM survey
Update of Occupational Exposure Sampling and Strategies Manual	Requested by NIOSH stakeholder to update the 40-year old manual

Table 7. NIOSH Development Plans for Future Methods, NMAM Chapters and Other Activities	
Closed-System Transfer Device (CSTD) for hazardous drugs – evaluation protocol revision	Needed to be inclusive of both barrier type devices and air filtering type devices
Peracetic acid – measurement methodology and exposure assessment	Congressional request

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Chapter 3. Direct-Reading Methods and Sensors

Direct-reading methods and sensors are being used more frequently in many different settings ranging from personal monitoring of individual health to applications in research and occupational health practice. Wireless data transfer based on cell phone networks and smart phone technology is enhancing the adoption of sensors, and allowing integration of geographically disperse sensors to produce comprehensive exposure pictures. The term “direct-reading” is commonplace in the field of occupational safety and health, referring to immediate or near-immediate feedback about the presence or magnitude of hazards in the workplace. “Sensor” is used more broadly in environmental health and in the technological world to refer to a wide variety of devices or components that measure attributes of a situation. NIOSH has adopted the term “sensor” to include instruments that are direct-reading or field-portable along with the mobile devices and other platforms and applications that enable sensor functionality and use.

Although NIOSH has a long history of evaluating, developing, and using direct-reading monitors and methods, in 2017 the NIOSH Director, Dr. John Howard, identified sensors as one of the occupational health issues in the U.S. that needs greater attention to address lessons learned and advances in technology [Howard 2017]. The impetus for the Director’s message, at least in part, stemmed from an evolution that began in 2008 with an intramural initiative to place higher emphasis on direct-reading exposure assessment methods and monitors. Lessons learned during the formulation of that initiative were used as a basis for the creation of the NIOSH “virtual center” on direct-reading and sensor technologies. The leadership and activities are not concentrated in a single geographic location and are instead coordinated across NIOSH using communications technologies.

In 2014 NIOSH established the virtual NIOSH Center for Direct Reading and Sensor Technologies (“the Center”) to focus on the continued need to develop new sensors and to develop guidance on the use of sensors in occupational safety and health practice. The Center serves as the home for NIOSH’s longstanding work in the area of exposure assessment devices—work that is done across the Institute and through an array of national and global partnerships. It is part of the EXAP and the EXAP leaders serve as co-directors for the Center. The activities of the Center are driven by EXAP’s two strategic goals: development of new strategies/guidance and development of new methods or tools. The Center has outreach as an additional focal area. This approach recognizes that increased understanding, guidance, and scientific exchange are needed to keep pace with the ever expanding uses and demands for reliable and cost-effective sensors in myriad settings from occupational health and safety research to practice. Appendix D provides a one page fact sheet on Sensor Center priorities, activities, accomplishments, and upcoming work.

As noted in the National Research Council report *Exposure Science in the 21st Century: A Vision and a Strategy* [NRC 2012], direct-reading methods and monitors are important drivers for the future of exposure sciences. Research is needed to answer fundamental questions: Do these methods accurately measure what they are supposed to be measuring? How can they be adequately calibrated and validated? When are they limited to use for screening; and when can they provide an accurate characterization of specific hazards? How can those data be feasibly analyzed and interpreted given the large amounts of data that may be collected from such technologies? In support of effectively answering those questions, EXAP and the Center welcome partnerships and collaborations to ensure that sensors will be one of the technologies that advances exposure sciences in all industry sectors.

Figure 4 is the logic model for the sensor technologies portion of the NIOSH EXAP. The logic model illustrates key relationships characterizing how EXAP and the Center contribute to the field of sensor technologies as it applies to occupational safety and health. Elements of the logic model – Inputs, Activities, Outputs, Transfer/Translation, Intermediate Outcomes, and End Outcomes -- are described in further detail in the following sections.

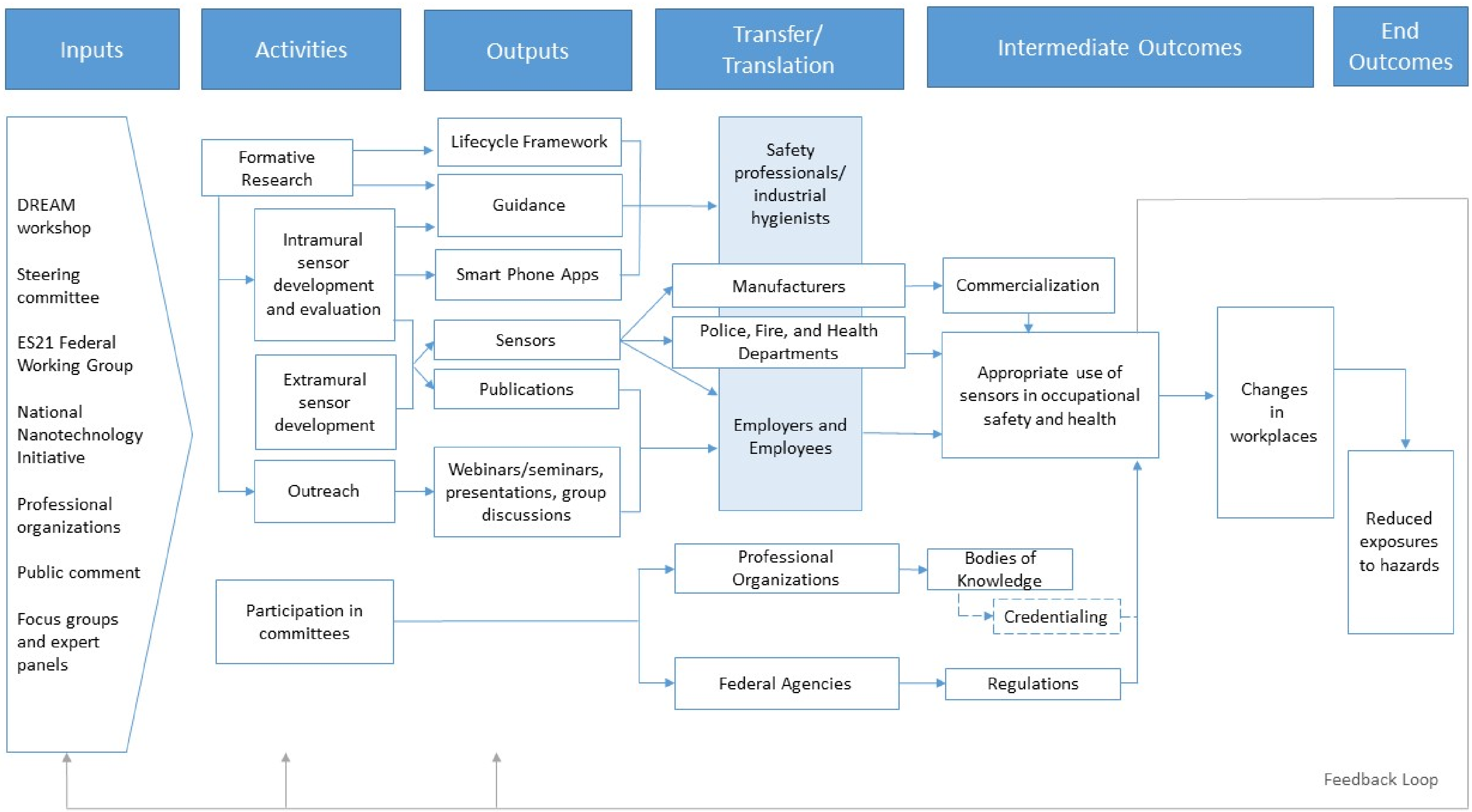

Figure 4. Logic model for the sensor technologies initiative of the NIOSH Exposure Assessment Program

Inputs

The principal aim for NIOSH work on sensor technologies is to provide the strategies and tools necessary for accurate and actionable measurement of occupational exposures to hazards. As listed in the far-left side of Figure 4, a number of drivers provide impetus to NIOSH sensor development efforts.

In 2007, NIOSH solicited informal input from stakeholders and partners regarding the future of direct-reading monitors or sensors in occupational safety and health research and practice. In response to this input and deliberations of an internal NIOSH working group, NIOSH decided to sponsor an Institute-wide intramural initiative on direct-reading exposure assessment methods and monitors, also referred to as the DREAM Initiative. The primary purpose of the initiative was to identify research needs, gaps, and challenges with respect to the use of sensors in occupational health and safety. The various sources from which the EXAP has identified these areas are outline below.

The direct-reading exposure assessment methods (DREAM) workshop [NIOSH 2009] held in 2008 was co-sponsored by NIOSH and 11 other organizations, attracting over 175 participants. The purpose of the workshop was to gather input from academia, labor, management, developers, governmental agencies, and equipment manufacturers on the research needs in the area of direct-reading methods for assessing occupational exposures. The opening general session included state-of-the-art plenary presentations that addressed direct-reading exposure assessment methods for workplaces and issues relevant to the broad range of industry sectors and occupational hazards. Key issues such as validation, data handling and interpretation were discussed. The general session was followed by six concurrent, hazard-specific breakout sessions including: aerosols, gases/vapors, ergonomics, noise, radiation, and surface sampling/biomonitoring. Key concepts discussed in each session were 1) comprehensive and contemporary information about the state-of-the-art/state-of-the-science regarding real-time assessment of worker exposure, 2) availability of direct-reading methods for the hazards and exposures of interest, 3) gaps in the currently-available technology for real-time exposure methods and 4) specific needs for direct-reading method research by occupational agent hazard class.

When the Center was created in 2014, EXAP initiated an **internal steering committee** consisting of scientists from across the Institute who utilize or conduct research or field surveillance and have interest and expertise in sensor technologies. This steering committee is separate and distinct from the

EXAP steering committee described in Chapter 2. The role of the Center steering committee is to review progress on initiatives, determine gaps and needs, and identify pertinent priorities/issues that can be addressed in the Center strategic plan. This group also coordinates Institute-wide training and communication so that NIOSH field and laboratory researchers share information and are aware of the latest available technologies, novel innovations, and field methods, which allows for greater collaboration among staff. The leaders of the EXAP/Center communicate and work closely with NIOSH programs to share and maintain awareness of how direct-reading instruments are used, identify needs, and promote the development of sector and cross-sector goals to address their needs.

The **Exposure Science in the 21st Century (ES21) Federal Working Group**, which was described on page 18, includes a Sensors/Dosimeters Subgroup in which NIOSH participates. This subgroup is currently reviewing the recommendations of the National Research Council [NRC 2012]; taking inventory of current and emerging tools and gaps; and developing options for new approaches that may enhance or replace older technologies. New challenges and new scientific advances mean that an expanded, integrated vision of exposure science is necessary — one that considers exposures from source to dose, over time and space and accounts for multiple stressors from molecular to ecosystem levels. Advanced sensor and dosimeter technology is an important part of this expanded vision. Information from this ES21 subgroup has been used to drive the development of a number of NIOSH outputs.

National Nanotechnology Initiative (NNI) is a U.S. Government research and development initiative within the White House Office of Science and Technology Policy created in 2000. The NNI involves 20 departments and independent agencies working together toward the shared vision of "a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society" (NNI 2017a). The NNI brings together the expertise needed to advance this broad and complex field—creating a framework for shared goals, priorities, and strategies that helps each participating federal agency leverage the resources of all participating agencies. In support of the overall NNI, a number of "signature initiatives" have been developed to advance several areas that are essential to success of the overall initiative. Two of these signature initiatives are entitled "Nanotechnology for Sensing and Sensing for Nanotechnology: Improving Safety, Health, and the Environment" (NNI 2017b) and "Nanotechnology Knowledge Infrastructure: Enabling National

Leadership in Sustainable Design" (NNI 2017c). Both of these signature initiatives have been informed by and continue to inform NIOSH sensor work. The NIOSH Nanotechnology Research Center was established in 2004 and is an active participant and a leader in the federal NNI.

Professional organization meetings provide an opportunity to present findings and get input from attendees. For instance, a sensor fair held during the 2015 International Society of Exposure Science annual meeting provided sensor developers with the opportunity to showcase their sensors and receive feedback from other attendees. NIOSH showcased four of its technologies including the chemical exposure monitor with indoor positioning (CEMWIP) system, the Helmet-CAM with EVADE software, the antineoplastic lateral flow assay, and the NIOSH Sound Level Meter. The EXAP also communicated with sensor users and developers at a number of other professional society meetings. Feedback from these venues resulted in valuable design alterations such as incorporation of location information and a field notes section in the NIOSH Sound Level Meter application.

The **American Industrial Hygiene Association (AIHA)** wrote a report on "The Future of Sensors: Protecting Worker Health Through Sensor Technologies" as part of the AIHA initiative to create industrial hygiene-related bodies of knowledge (AIHA 2016a). The EXAP is using input from the document as background information for the development of NIOSH guidance on sensor use in emergency response. NIOSH scientists have also played a lead role in the revision of the main product of AIHA's Real-Time Detection Systems Committee [AIHA 2016b].

A NIOSH Request for Information entitled "Request for Information on NIOSH Center for Direct Reading and Sensor Technologies: Sensors for Emergency Response Activities" was published in a January 2016 Federal Register notice to seek input regarding specific issues on the availability, capability, suitability, barriers, limitations, and opportunities for current or future direct-reading devices and sensor technologies that can be utilized for emergency response. Responses can be found at https://www.regulations.gov/docket?D=CDC-2016-0002. The EXAP is also using input from this Request for Information as background information for the development of NIOSH guidance on sensor use in emergency response.

Focus groups were also convened in 2016 by the Center after approval by the NIOSH Institutional Review Board. Three separate focus groups with individuals from different emergency response roles covering emergency response workers, emergency response managers, and sensor experts were assembled via teleconference to provide input to NIOSH on sensor use in incident responses. A contractor identified the participants and facilitated the focus groups, which each had five to seven participants. The EXAP and the Center are using input from this activity as background information for the development of NIOSH guidance on sensor use in emergency response.

Input and feedback related to sensors and Occupational Exposure Limits are key aspects of the NIOSH mission and will only become more prominent as new sensors are needed or marketed that have a role in occupational health and safety practice. There is constant feedback from the application of these tools to considerations such as: (1) the development of new sensors, (2) evaluation of existing sensors, (3) improving existing sensors, and (4) improving sensor strategies.

Activities and Outputs

As illustrated in the following examples, the sensor-related EXAP activities and outputs are grounded in advancing a life-cycle framework for sensor development and use and include a wide range of formative research, sensor development and evaluation, educational outreach, and participation in professional and consensus standards committees.

Lifecycle Framework

The **NIOSH life cycle approach for sensor development and use** (Figure 5) is perhaps one of the most significant outputs developed by the EXAP. Originally developed in 2004 for use in emergency response situations [Hoover and Cox 2004], it was subsequently revised in 2010 for radioactive air sampling and instrumentation [Hoover and Cox 2010] and further applied in 2015 to emerging needs for sensor technologies [Hoover and DeBord 2015]. The approach was also adopted as a systematic way to organize the framework of the White House's signature initiative white paper on *Nanotechnology for Sensors and Sensors for Nanotechnology* [NNI 2012]. The lifecycle approach for the development and application of direct-reading and sensor technologies is an example of a NIOSH tool to ensure the relevance and reliability of measurements to protect workers. The cycle begins with a clear and complete identification of what needs to be measured, under what conditions it needs to be measured, and how well it needs to be measured. It also guides research and development, prototype testing, type testing, production control testing, and training needed to develop the instrument. The life cycle approach defines procedures for acceptance testing, initial calibration, functional checks, conduct and evaluation of operational experience, maintenance and recalibration, and periodic performance testing to confirm continued successful use of the instrument. Effective prototype testing ensures that the final instrument will work as intended under realistic conditions. Documentation and continuous improvement are essential at each step.

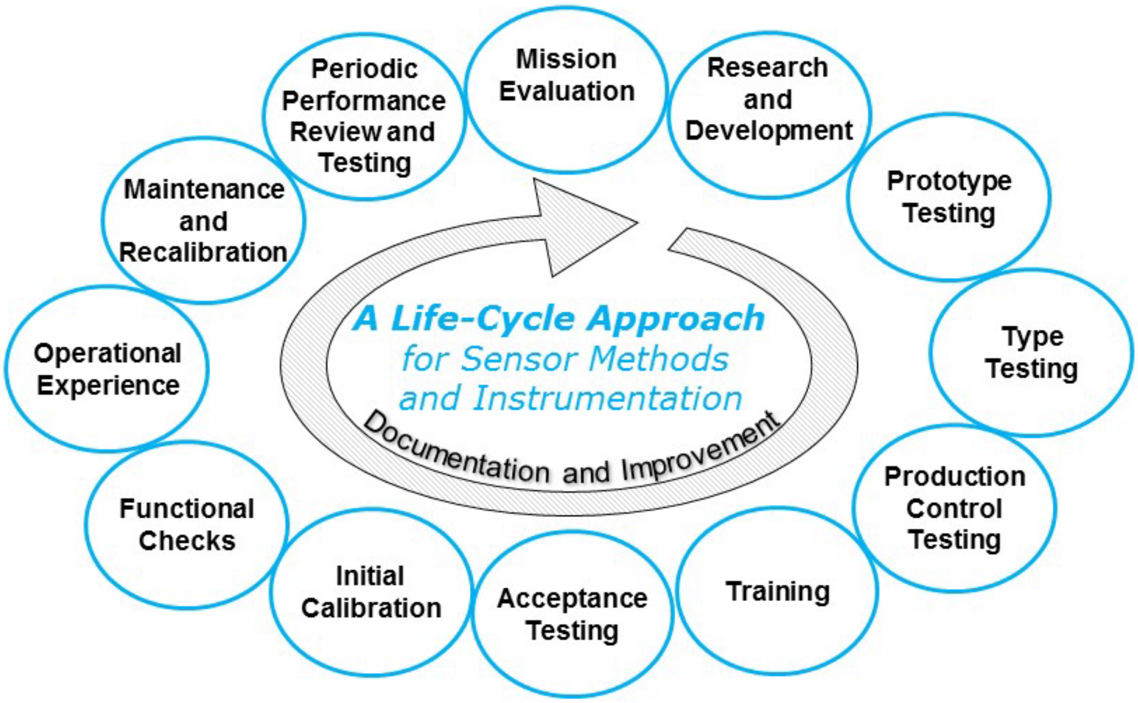

Figure 5. The NIOSH life cycle approach for sensor methods and instrumentation

Guidance and Publications

The development of guidance on sensor selection [NIOSH 2012a, b] has been a critical piece of NIOSH's efforts to address the use of sensors in occupational safety and health. The first document, *Components for Evaluation of Direct-Reading Monitors for Gases and Vapors,* provides discussion of the physical, operational, and performance characteristics for direct-reading monitors. Guidance is provided for experiments to evaluate response time, calibration, stability, range, limit of measurement, impact of environmental effects, interferences, and reliability of direct-reading monitors [NIOSH 2012a]. Also included are evaluation criteria for the experiments and details for the calculation of bias, precision and accuracy, and monitor uncertainty. The second document is an *Addendum to Components for Evaluation of Direct-Reading Monitors for Gases and Vapors: Hazard Detection in First Responder Environments* [NIOSH 2012b].This Addendum expands the applicability of the *Components* document by presenting methods to be used in evaluating direct-reading monitors for hazard detection in first responder environments, including those related to incidents involving weapons of mass destruction. The Addendum contains a standardized test protocol and performance acceptance criteria for evaluating commercially available, direct-reading monitors in a style similar to the Components document.

Other **publications and communications** have been issued by NIOSH staff that discuss the role of sensors in industrial hygiene applications. *The Future of Industrial Hygi*ene [Howard et al. 2014] and *Turning Numbers into Knowledge: Sensors for Safety, Health, Well-being, and Productivity* [Hoover and DeBord 2015] are two examples of articles that discuss how sensors are likely to revolutionize industrial hygiene practice. Further guidance has been developed in a 2016 webinar entitled *Wearable Sensors: An Ethical Framework for Decision-Making* and in a NIOSH Science Blog with the same title in 2017. The purpose of both, the webinar and science blog was to begin a discussion on the ethics of wearable sensors. Because innovation tends to move ahead of ethical discussions, issues of personal privacy, security and data accuracy and ownership are important considerations. In the last 10 years, NIOSH has published over 55 sensor-related journal articles. NIOSH grantees have contributed over 30 peer-reviewed articles. These publications have been cited over 1,600 times by other researchers.

NIOSH-Developed Sensors

NIOSH scientists have been developing sensors since the Institute was established. The drivers behind NIOSH sensor development are varied. The occupational safety and health market is relatively small so many companies do not invest their research and development resources in developing sensors. NIOSH scientists have specific occupational expertise which allows them to develop sensors for a specific industry or worksite. To date, NIOSH has also been successful in getting companies to market NIOSH-developed sensors for the field. Examples of NIOSH-developed sensor systems are provided in Table 8 and described in detail below.

Table 8. NIOSH-developed Sensor Technologies

Developed Sensor	References
Coal dust explosibility meter (CDEM)	NIOSH 2012c
Continuous personal dust monitor (CPDM)	NIOSH 2006
MethChek and MethAlert	Smith et al. 2009; Snawder et al. 2011

Table 8. NIOSH-developed Sensor Technologies	
Developed Sensor	**References**
Portable aerosol mobility spectrometer (PAMS)	Qi and Kulkarni 2012a, b
CEMWIP	Brown et al. 2016
Respirator end-of-service life indicator	Greenawald et al. 2015, 2016
Proximity detection systems	Ducarme et al. 2013
Portable assessment system for slips, trips and falls	Pan et al. 2012a, b

Coal dust explosibility meter (CDEM) is a simple-to-use handheld device that provides a pass/fail assessment of coal mine dust samples [NIOSH 2012c]. Accumulations of combustible dust can lead to large-scale explosions with multiple deaths and injuries. There have been 15 explosion-related mine disasters since 1970 with 201 miners losing their life [MSHA 2017a]. Explosions can be prevented by continuously monitoring combustible gases and dusts, and applying rock dusts (like limestone) to make the coal dust inert [NIOSH 2011].

For decades, coal miners had been able to monitor the concentrations of oxygen, methane and other combustible gases using handheld, direct-reading gas detectors; however, gas concentrations are only one of the variables that contribute to the ignition of explosions [NIOSH 2012c]. Thus, the previously available devices only served as indirect measures of explosibility. Morevover, managers and workers had two options for deciding how effective the existing rock dust was and when to add more: conduct a subjective visual inspection of the mine entry, or collect and send mine dust samples to a laboratory for analysis, which could take days or weeks [NIOSH 2011].

To address this gap, researchers at NIOSH, in collaboration with the Mine Safety and Health Administration (MSHA) developed the CDEM real-time dust explosibility measuring instrument to provide instant feedback to miners on the relative hazard of coal dust accumulations in the mine and the effectiveness of rock dusting practices. In 2010, NIOSH upgraded the device software to include ambient methane in the hazard determination and revised the calibration procedures to address issues identified in an earlier MSHA field study.

As a final step before commercialization, NIOSH conducted a cooperative study in 2009-2010 with MSHA. Samples of coal and rock dust mixtures were collected by MSHA field inspectors, who used the CDEM to test for explosibility on the spot in mines in 10 bituminous coal districts. The samples were also sent to an MSHA lab for analysis using traditional methods. NIOSH found that for 97% of samples, the explosibile/non-explosible determination of the CDEM correlated with the laboratory findings. This strongly supported the use of CDEM [NIOSH 2012c].

The **continuous personal dust monitor (CPDM)** was developed through the efforts of a partnership between NIOSH, MSHA, industry, and labor [NIOSH 2006]. The approximately 23,000 coal miners in the U.S. breathe in coal dust as they work, putting them at risk of developing coal worker's pneumoconiosis, frequently called "black lung disease" [NIOSH 2016a; Mischler and Coughanour 2017; MSHA 2016]. This disease causes lifelong and irreversible breathing problems that lead to premature death [NIOSH 2016a]. The U.S. Department of Labor's Black Lung Program has paid over $43 billion in compensation to black lung sufferers since 1970, and over $289 million in 2015 alone [Mischler and Coughanhour 2017]. MSHA has a special initiative entitled "End Black Lung Now" that in part includes their Respirable Dust Rule that was released in 2014. [MSHA 2017b].

Black lung disease is a continuing hazard for coal miners. In 2016 NIOSH researchers documented an upward trend progressive massive fibrosis, the most serious form of pneumoconiosis, in the Center for Disease Control and Prevention (CDC)'s *Morbidity and Mortality Weekly Report* [Blackley et al. 2016]. That same week, NPR's "All Things Considered" confirmed the resurgence in progressive massive fibrosis with cases from 11 black lung clinics [Berkes 2016]. Coal dust exposure remains a serious health concern in underground mining.

The CPDM detects hazardous coal mine dust in the miner's breathing zone, reporting this information on a frequently updated digital readout. Miners can wear the portable CPDM for their entire shift. The device specifically measures respirable dust particles capable of embedding in lung tissue and causing black lung. Although dust sampling has been mandated by MSHA since 1969, mine operators and workers were previously unable to tell if dust had reached hazardous levels during a shift. Historically, dust samples were collected in a filter and sent to a lab for analysis, a process that could take weeks. The CPDM, by comparison, takes only minutes and delivers the information directly to the miner. Workers and employers can use this information to take immediate steps to either move to a less dusty location or to adjust dust controls at the source [Mischler and Coughanour 2017].

The CPDM was designed to integrate the power supply of the cap lamp that all underground coal miners utilize with an advanced real-time respirable dust sampling device. NIOSH worked with Rupprecht and Patashnick Co., Inc. and its successor company, Thermo Fisher Scientific, as well as with labor unions, employers, and government partners to adapt its existing fixed-site environmental particulate mass monitor into a smaller sampling device that could be safely worn underground [Mischler and Coghanour 2017]. The real-time CPDM provides continuous information about the concentration of respirable coal mine dust within the breathing zone of a miner for the previous 30 minutes. Data are displayed on a digital screen on the miner's belt pack and recorded for later analysis. It can also be uploaded to an MSHA database used to monitor compliance with respirable dust exposure limits [Mischler and Coughanour 2017].

NIOSH has been instrumental in the development of electromagnetic-based **proximity detection systems (PDS)** for use on mining equipment. In 2015, MSHA promulgated a rule to require PDSon continuous mining machines and proposed a regulation that would require the use of PDSon other mobile haulage equipment. NIOSH collaborations on electromagnetic PDS have been at the forefront of scientific research to enhance the technology used in commercially available systems. NIOSH has also developed guidelines and recommendations to help mine operators to effectively utilize the available technologies to prevent machine related pinning and striking accidents and improve safety around mining machinery [Bartels et al. 2009; NIOSH 2007].

NIOSH involvement in PDS collaborations consists of a number of partnerships and workgroups focused on conducting research and development of PDS safety technology. NIOSH has historically been involved in a number of special emphasis work groups, in different capacities, to evaluate commercially available proximity detection systems and develop features to enhance reliability and accuracy of the system performance. One example is NIOSH's involvement in the West Virginia Mine Safety Technology Task Force. NIOSH's role was to develop a field evaluation protocol to scientifically quantify effectiveness of the systems based on a number of scenarios and conditions typically experienced in underground coal mines. The task force consisted of system manufacturers, mine operators, health and safety professionals, and academia partnering to promote the use of the safety technology. Through these efforts, NIOSH was able to obtain critical access to mines to evaluate existing technologies, identify research gaps, and develop research plans designed to enhance the systems based on real world findings. The results from the field evaluations also yielded valuable information used by mine operators and system manufacturers to overcome integration challenges, improve system performance, and expedite the development of the systems.

NIOSH also formed the Proximity Detection System Workgroup, an industry-wide partnership designed to promote the use of proximity detection systems, expedite the accessibility of findings to end users, identify critical research areas, and provide a direct forum for stakeholders to discuss their experiences with commercially available proximity detection systems. NIOSH hosted the first Proximity Detection System workgroup meeting on June 22, 2016 at the NIOSH laboratory in Pittsburgh, PA. The meeting was attended by representatives from NIOSH, MSHA, academia, PDS manufacturers, United Mine Workers of America, and mine operators. It proved crucial in the advancement of the lifesaving technology. The workgroup is designed to facilitate industry interactions that will promote the rapid development of the technology and provide the industry with accessibility to research findings disseminated through a number of workshop presentations and publications.

NIOSH is developing guidelines that the industry and regulatory agencies can use in the design and implementation of proximity detection technology for mobile haulage equipment in underground coal mines. These guidelines will focus on design considerations including: detection range required to prevent an accident, deceleration rates required to prevent injury to equipment operators, effectiveness of in-cab and other warnings, environmental conditions that influence the performance of the systems, and alternative technologies that may enable additional protections for miners working in close proximity to mobile mining equipment.

The enhanced video analysis of dust exposures (EVADE) software program and the Helmet-CAM assessment system were initially developed in partnership with Unimin Corporation, a leading industrial mineral producer, to assess exposures of workers to respirable dust in mining**.** The EVADE software processes data from several commercially available dust monitors in conjunction with a video camera that was attached to a miner's helmet (known as the Helmet-CAM) to provide information about a worker's environment [NIOSH 2014].The Helmet-CAM procedure is a technique that utilizes a video camera and a real-time data logging aerosol monitor worn by the worker to provide visual record of the worker's activities while concurrently monitoring aerosol levels. TheEVADE software program merges video files and logged data files, allowing the user to view them simultaneously to help identify exposure sources. Efforts are also underway to assess exposures to other airborne contaminants such as diesel exhaust, chemicals and welding fumes. NIOSH has also partnered with Vulcan Materials Co. to be the first to test and evaluate the Helmet-CAM system for noise assessment at its Havre De Grace mining operation near Baltimore, MD. The system included a video camera attached to the worker's hardhat, as well as a dosimeter and a respirable dust monitor for a combined noise and dust assessment to be made simultaneously. The launch of this new health contaminant assessment was extremely positive for Vulcan's corporate health and safety staff, for the plant's management team, for the miners who actually wore the Helmet-CAM system, as well as for NIOSH personnel involved in this study [Cecala et al. 2015]. NIOSH made the EVADE software available to other researchers to test and use. Based on the utility of EVADE 1.0 and feedback from the EVADE user community, EVADE Version 2.0 was released in December 2016. Improvements include the expansion to other sensors beyond just dust exposure, playback of any video stream against any logged data stream, and multiple video and logged data channels can now be created for a single project. Other enhancements make it easier to design, edit and share the project.

MethAlert and MethChek technologies are NIOSH-developed, commercially available, real-time sensors for the detection of methamphetamine residues. Police, fire fighters, first responders, emergency responders, and industrial hygienists had indicated the need for real-time surface detection methods for methamphetamine, based in part on results of a 2006 NIOSH-funded research study on real-world conditions of exposure [McFadden et al. 2006]. The concern was that dermal exposure was occurring when law enforcement entered an illicit drug laboratory or if drug residue was being transferred to emergency medical service and emergency room personnel during the transport and treatment of patients who may have been exposed to methamphetamine.

Two methods to address this need for detection of methamphetamine were developed and evaluated: a colorimetric wipe method and a more sensitive immunochemical surface wipe detection method. The development and testing of the methods involved a number of partners who allowed NIOSH access to clandestine methamphetamine laboratories to evaluate and validate sensors. NIOSH provided data to partners about the extent of surface contamination within structures of concern, where exposures to the contamination were most likely to occur in the structures, and when the structures were safe to reoccupy after remediation. The commercial sampling technologies company SKC, Inc. worked with NIOSH to commercialize the two licensed products that were released to the commercial market at the American Industrial Hygiene Conference and Exposition in 2006. This work on the conception, development, and rapid commercialization of two novel surface wipe detection methods for methamphetamine was recognized for its technical achievement.

NIOSH developed an inexpensive **end-of-service life indicator** [Greenawald et al. 2015, 2016] for use with respiratory protective equipment. Previously, healthcare workers, emergency responders and other workers that use respirators had no way of knowing when their respirator needed to be replaced, putting them at risk for excessive exposures. The inexpensive red, green, blue (RGB) color sensor is capable of detecting low ppm concentrations of hydrogen cyanide gas, and could serve as the first realtime end-of-service-life alert for hydrogen cyanide gas. The end-of-service life indicator functions by means of a piece of glass fiber filter paper containing monocyanocobinamide [CN(H2O)Cbi] being positioned directly above the RGB color sensor and an on-chip Light Emitting Diode (LED). Light reflected from the paper was monitored for RGB color change upon exposure to hydrogen cyanide at concentrations of 1.0–10.0 ppm as a function of 25, 50, and 85% relative humidity. A rapid color change occurred within 10 s of exposure to 5.0 ppm hydrogen cyanide gas, which is near the NIOSH REL.

The **chemical exposure monitor with indoor positioning (CEMWIP) system**, developed by NIOSH scientists, combines a sensor for measuring volatile organic compounds (VOCs) with geographic-locating sensors [Brown et al. 2016]. VOCs evaporate into the air and diminish indoor air quality, contributing to work-related asthma. These compounds are used as solvents in “green” or “natural” cleaning products and in manufacturing processes, among other industrial uses [Wells 2009]. The benefit of combining location or video sensors with other sensors that measure a hazard is that one can identify what the worker is doing or where the worker is located when they experience an exposure to VOCs. This allows for an evaluation of the work so that controls can be instituted to reduce exposures. The CEMWIP system, which is small enough to be worn on the outside of a shirt pocket, was designed to use a commercial photoionization detector in combination with a commercially obtained radio frequency identification positioning sensor. The proprietary nature of the CEMWIP is the software that allows worker location and hazard location to be demonstrated together. The original intent was for use in manufacturing facilities in which solvents were being used. The utility of the CEMWIP has been expanded and is currently being evaluated by the NIOSH investigators as a laboratory safety tool to assess exposures to laboratory workers.

The Portable Aerosol Mobility Spectrometer (PAMS) was developed by NIOSH investigators to address measurement needs in emerging areas related to nanoparticle and ultrafine aerosol exposure assessment [Kulkarni et al. 2016; Qi and Kulkarni 2012]. PAMS measures the number-weighted size distribution of submicrometer aerosol, including the nanoparticle fraction. Monitoring exposure to nanoscale aerosols is a recognized measurement need because of the harmful respiratory effects associated with particles in this size range. Current state-of-the-art bench-top instruments, called Electrical Mobility Spectrometers (EMS), were designed for measurement of the size distribution of airborne nanoparticles and are mainly research instruments intended for laboratory use. NIOSH investigators addressed two critical limitations of the existing technology: 1) poor suitability for field work due to prohibitive size, weight, and cost, and 2) use of a radioactive source for particle charge conditioning, which seriously limits field application due to regulatory restrictions on transport and use of radioactive sources.

To address these limitations, NIOSH investigators developed an innovative miniature non-radioactive charger, which allows unrestricted access to sampling sites [Qi and Kulkarni 2012; Kulkarni et al. 2016]. The investigators also developed a new miniature differential mobility analyzer, which allows significant reduction in size, weight, and cost of the PAMS, and allows particle size measurement over a very wide range: from 5 nm to 1000 nm [Qi and Kulkarni 2016]. A new technology has also been developed for detection of particles using condensation growth [Kulkarni et al. 2016]. These innovations have led to significant advantages of PAMS with respect to the current EMS instruments: reductions in size (by a factor of 20), weight (factor of 10-15), and cost (factor of 4). The PAMS instrument has been commercialized through licensing of NIOSH technologies and technology transfer to Kanomax, Japan, Inc. And it is now available through Kanomax, USA, Inc. (http://www.kanomax-usa.com/product/pams/). The availability of the PAMS eliminates a long-standing impediment to field measurement of nanoscale through submicrometer aerosols, for on-person or area sampling. The innovative instrument offers major design improvements with respect to analytical performance, unrestricted field access, size, weight, and cost, to allow mobile aerosol measurement for environmental, occupational, and public health applications.

Extramurally-developed Sensors

NIOSH has also **extramurally funded** the development of 9 sensors, all of which have been patented. A list of these sensors can be found in Table 9 and several are discussed below.

Table 9. Sensor Development supported by NIOSH Extramural Funding

Institution	Sensor
Colorado State University	Electrochemical paper device for metals
Michigan State University	Protein-based electrochemical array
University of Washington	Software to assess hand fatigue
University of Michigan	Micro gas chromatograph
Virginia Polytechnic Institute and State University	Minaturized gas chromatograph
Synkera technologies, Inc	Sensor to detect volatile hydrides
Oakland University	Ionic liquid-based methane sensor

An **electrochemical-based microfluidics device** was developed at Colorado State University to investigate metal contamination [Cate et al. 2015]. Exposure to metal-containing aerosols has been linked with adverse health outcomes for almost every organ in the human body. Epidemiological studies have found that individuals in metalworking, construction, transportation, and mining are at risk of metal exposure [Pope et al. 1995]. Commercially available techniques for quantifying particulate metals are time-intensive, laborious, and expensive; often sample analysis exceeds $100. A simple technique was devised for quantifying metal concentrations of nickel, copper, and iron in airborne particulate matter using microfluidic paper-based analytical devices. Paper substrates were used to create sensors that are self-contained, self-timing, and require only a drop of sample for operation. Results of this work suggest that these methods are a faster and cheaper yet reliable alternative to traditional analytic methods to assess potential exposure of workers to welding fumes [Cate et al. 2015].

Researchers at Colorado State University also developed a new method for measuring aerosol oxidative activity that uses silver nanoparticle aggregation coupled to glutathione oxidation in a paper-based analytical device [Dungchai et al. 2013]. By increasing the efficiency and economy of hazard monitoring, industrial hygienists might find it easier to identify, evaluate, and control workplace hazards, which could lead to improved worker health [Cate et al. 2014]. In addition, paper-based analytical devices represent a step towards the idea of people being able to monitor their personal exposure to harmful pollutants and identify sources of pollution for further scientific evaluation and remediation [Cate et al. 2013].

NIOSH funded researchers at Michigan State University to develop a **protein-based electrochemical biosensor array platform** using different classes of proteins [Huang et al. 2013]. This protein-based biosensor array has utility to detect drugs, neurotransmitters, hormones, and toxins. It may also be useful in monitoring metabolites of occupational chemicals. Projected detection limits are in the parts per trillion range for most compounds, assuming a 1 liter sample volume. This sensor platform has the potential to be used in biomonitoring.

Researchers on **muscle fatigue** at the University of Washington received funding in 2008 to conduct research aimed at creating software to continually monitor the digital signals from the mouse and keyboard in order to determine whether small, systematic changes in mouse button-click and keystroke durations occur. These changes may be associated with objective fatigue-related changes in the muscle. In a repeated measures experimental design, 18 subjects participated in four different 8 hour conditions: a control (no exposure) condition and three exposure conditions (keyboard, mouse, and combined keyboard and mouse use) comprised of 6 hours of computer use followed by 2 hours of recovery. In each condition, eight temporal measurements were collected to evaluate the fatigue state of the right middle finger flexor digitorum superficialis muscle before, during, and after computer use. Researchers concluded that muscle fatigue did result from intensive mouse, keyboard use and combined mouse and keyboard use; intensive mouse use was associated with the greatest levels of muscle fatigue when comparing mouse and keyboard use which may explain why mouse use has a greater association with computer-related injuries [Kim and Johnson 2014]. The study results indicated that electrical stimulation of the muscle had the sensitivity to measure muscle fatigue resulting from computer work and was able to characterize diverse levels of muscle fatigue between the three modes of computer use evaluated.

A **second generation micro gas chromatograph** (GC) was designed at the University of Michigan to detect trace-level determinations of complex mixtures of VOCs [Zhong et al. 2009]. The laboratory characterization of a novel, second-generation portable GC prototype design uses response patterns in conjunction with chromatographic retention times to identify eluting mixture components. Scrubbed ambient air is used as the carrier gas. Enhancements in design relative to a previously reported first-generation prototype instrument have led to significant reductions in limits of detection as well as improvements in resolution, reliability, flexibility, and convenience. The ultimate purpose of a micro GC is to have a wearable instrument that can be taken into the field to identify unknown hazards.

In more recent work through a subsequent NIOSH-funded study, the researchers developed and tested the design of a microfabricated preconcentrator focuser for integration into a wearable microfabricated GC currently under development [Bryant and Zellers 2015]. Results from mock field tests of the developed wearable GC prototype have demonstrated successful monitoring of concentrations of three VOCs during a solvent handling task [Wang et al. 2016]. This device would provide real-time identification of occupational hazards.

Researchers at Virginia Polytechnic Institute and State University received a three year NIOSH award in 2012 for a project that aimed at the development of a **miniaturized GC** system to identify hazardous air pollutants found in transportation-related and other workplaces. The research resulted in a fabricated prototype GC system that leverages micro-machined components to achieve low power consumption (2.75 watts) and fast analysis time (4.4 minutes). A limit of detection of ~1 ng was achieved, which enables monitoring of hazardous air polutants at sub-100 parts per billion by volume concentrations. The fabricated prototype was functionally characterized and compared with a conventional system for real gasoline samples [Garg et al. 2015].

Researchers at Synkera technologies, Inc received NIOSH funding in 2006 to continue the development of new **gas sensor arrays**. The goal of the project was to develop improved sensors to detect volatile hydrides for protection of chemical worker and emergency responders from lung injury. Key accomplishments of this project addressed steps toward commercialization: 1) maximized the performance of individual sensors for detection of hydrides to achieve parts per billion detection, 2) demonstrated reliable, sensitive and selective detection of hydrides using a sensor array and 3) built a prototype instrumentation module based upon the unique sensor array. The project resulted in a designed, developed and commercialized unique nanoceramic platform (trademarked MikroKera) that can be used to detect toxic industrial chemicals [Sinkera Technologies 2010].

NIOSH funded researchers at Oakland University in 2009 to investigate ionic liquids as new sensing materials for **methane sensors** using real-time, portable and low cost orthogonal electrochemical and Quartz Crystal Microbalance transducers for readout. Researchers integrated an ionic liquid electrolyte with electrochemical transducers to introduce an innovative and high-performance methane sensor that is small, involves low power consumption, and is low cost [Wang et al. 2014]. Improved detection of methane, such as in situations involving its presence in natural gas, can reduce hazards to workers from explosions or asphyxiation.

Evaluation of Commercially Available Sensors

NIOSH scientists also evaluate commercially available sensors in a variety of field and laboratory studies to assess their value in measuring occupational exposures. Using or adapting commercially available sensors whenever possible demonstrates NIOSH's commitment to good stewardship of taxpayer investment.

In 2015, NIOSH researchers evaluated the efficacy of an **in-vehicle monitoring system (IVMS)** designed to reduce risky driving behaviors**.** Motor vehicle crashes are the leading cause of worker fatalties, affecting not just "professional drivers" (bus and truck drivers) but rather a wide range of workers who operate many types of vehicles, including passenger cars [NIOSH 2017]. Researchers combined an IVMS with forward-and driver-facing cameras which recorded driver behaviors, and accelerometers that detected vehicle maneuvers such as hard braking, acceleration, and speeding [Bell et al. 2015]. When a vehicle event was triggered by a harsh maneuver, the IVMS saved a 30-second video/audio clip, 15 seconds before and after the triggering event. The videos were viewed by the IVMS vendor's trained observers and coded for approximately 60 different risky driving behaviors of varying severity. Two types of feedback to the drivers were evaluated; instant feedback from lights on the dashboard that flashed yellow or red to denote harsh vehicle maneuvers and one-on-one coaching between supervisor and driver, consisting of viewing the recorded video events involving the driver and discussing safe driving behaviors. The purpose of the study was to evaluate whether telematics could be useful to reduce risky driving behaviors that may lead to collisions and injuries. The largest decline in the rate of risky driving behaviors occurred when feedback included both supervisory coaching and lights [Bell et al. 2017].

Smart Phone Applications

NIOSH scientists also develop smart phone applications to assist workers and employers in the assessment and control of exposures to a variety of hazards. The **NIOSH Ladder Safety app** was the first NIOSH smart phone application [Simeonov et al. 2012a, b, 2013]. In the U.S. more than 500,000 people are treated, and more than 300 people die from ladder-related injuries each year. The estimated annual cost of ladder injuries in the U.S. is more than $24 billion. Improper ladder angle positioning leading to slide-out at the ladder base has been identified as a major cause (>40%) for extension and straight ladder falls. To help prevent positioning errors, the Ladder Safety application includes a multimodal inclination indicator (i.e., angle measuring tool) that uses the accelerometers and gyroscopes in modern smart phones to determine the spatial orientation of an object aligned with the smart phone. The inclination indicator was developed to assist ladder users in positioning extension and straight ladders at an optimal safe angle of approximately 75 degrees. The tool has a graphic color-coded display as well as digital indication for quick and easy checking and verifying the safety of the ladder inclination in the field.

Furthermore, the tool can provide sound and vibration feedback signals for fast and accurate adjustment and positioning of the ladder when the smart phone is held against the ladder rail. The inclination indicator tool is self-intuitive, easy to use, and can be instantly deployed within the Ladder Safety application on a smart phone. The concept and technology behind the multimodal inclination indicator in the Ladder Safety application was first developed, tested, and patented by the NIOSH researchers through human studies [Simeonov et al. 2012a, b]. The studies compared a prototype device using the new technology with the existing ladder positioning methods and demonstrated that using the new multimodal indicator is faster and more accurate than the existing methods, and thus it may help improve both the safety and productivity of extension and straight ladder use [Simeonov et al. 2013]. The researchers then partnered with the American Ladder Institute, ATL International, and DS Federal to develop the Ladder Safety application for smart phones with the inclination indicator as its signature feature. In addition to the ladder angle measuring tool, the application contains easy-to-use, graphic-oriented safety tools, including ladder selection and inspection guidelines and extension ladder accessory information. In 2015, based on user feedback, the application was updated to include an enhanced angle measuring tool and information on the safe use of step ladders.

NIOSH has also developed a **portable assessment system for slips, trips and falls** [Pan et al. 2012a, b]. This field-based, remotely deployed tool is capable of monitoring and providing early warning of working conditions that have a high likelihood of musculoskeletal injury. The system is noninvasive, real-time, and instrument-based system. Sensor technology simultaneously measures and collects data regarding the body loads and awkward postures imposed by package handling as well as driving-related, low-frequency vibrations. Wireless technology establishes communication links between the sensors and a data logger and between the data logger and a smart phone with positioning and text messaging capabilities. The data logger records the body weight, posture, and vibration data over time and transfers the data to a databank for archiving and further data analysis. During data recording, the data logger detects the data that either exceed the lifting index limit defined by the NIOSH Lifting Equation or the human whole-body vibration exposure limit defined by the ISO-2631-1 Human Exposure to Whole-Body Vibration standard. The data logger wirelessly transmits the data segment, which contains the marked out-of-limit data, to the smart phone in real-time. The smart phone then automatically dials a predefined number and sends an alert text message and alarm detailing the exposure/safety data, the GPS location of the occurrence, the date/time stamps, and a corresponding safety message. Additionally, the smart phone stores the sent text message for archiving and further data analysis.

NIOSH has also evaluated several **smart phone applications for measuring noise levels** [Kardous 2016; Kardous and Shaw 2014]. Smartphone developers offer many sound measurement applications using the devices' built-in microphone (or through an external microphone in more sophisticated applications). The use of smartphone sound measurement application can have a tremendous and far-reaching impact in the areas of noise research and noise control in the workplace as every smartphone can be potentially turned into a dosimeter or a sound level meter [Maisonneuve et al. 2010; Williams and Sukara, 2013]. Such a tool would be especially beneficial for the manufacturing, construction and mining industries, where the prevalence of hearing loss was 20% or higher in 2015 [Mastserson et al 2012].

However, in order for smartphone applications to gain acceptance in the occupational environment, the applications must meet certain minimal criteria for functionality, accuracy, and relevancy to the users, specifically the worker. NIOSH noise researchers received numerous requests from stakeholders, safety professionals, and the public to assess the accuracy of the many sound measurement applications available for smartphones and determine whether they can be relied upon to provide an accurate assessment of the ambient environment. NIOSH successfully and cost-effectively developed its own sound level meter application to address gaps in the existing available applications such as lack of ability to calibrate the meter. The NIOSH Sound Level Meter application was approved in 2016 and released in January 2017. It is available for free download from the Apple Store.

Wrist-watch style sensors provide an additional opportunity for health and safety-related applications to gain acceptance and use in the workplace. A recent NIOSH project on “Development of a Human Vibration Wrist Watch” has developed a wearable, non-intrusive, convenient, and reliable device to monitor hand-transmitted vibration exposure at workplaces [Xu et al. 2014, 2015, 2016]. The device measures and stores the frequency content, vibration magnitude, and exposure duration of hand-transmitted vibration. Additionally, the project evaluated the performance of a number of commercially available that may be able to perform such measuring tasks, including a finger-set data-logging adapter and a glove encased accelerometer. The NIOSH prototype wrist watch sensor included a software package that was developed for post analysis of the massive long-term vibration data. The challenges of collecting and assessing so-called “big data” situations are a continuing concern for exposure assessment.

Outreach

Conducting educational outreach to the occupational safety and health community regarding sensor use is one of the focal areas of the EXAP. It provides a mechanism to disseminate guidance related to topics like sensor use, data interpretation, and discussion on issues such as the ethical concerns of sensor use. NIOSH scientists have developed educational webinars/seminars, presentations, and initiated group discussions at meetings and professional development courses.

The existence and availability of NIOSH expertise and science-based guidance information is one reason why NIOSH scientists are invited to present on the topic of sensor use at meetings and to participate in a variety of activities. Staff have been invited to present on sensors at various professional organization meetings such as regional AIHA chapter meetings and the University of Cincinnati Sensor Community Meetings. Staff have also participated in developing scientific sessions that focus on sensors at national and international meetings like the American Industrial Hygiene Conference and Exposition (AIHce), the International Society for Exposure Science (ISES) and the American Chemical Society. The session at the 2016 AIHce on wearable sensors was selected as one of only four science symposia by AIHA from all the applications submitted, chosen based on the merit of the topic and scientific value of the session. Also in 2016, NIOSH along with other government, industry, and manufacturing representatives participated in the AIHA Sensor Summit. The Sensor Summit was conceptualized at a NIOSH-AIHA partnership meeting held in 2014. The purpose of the summit was to engage the community in identifying needs of industrial hygienists in the use of sensors in their practice.

NIOSH has provided subject matter expertise and technical review assistance to a number of **committees and workgroups** as a mechanism for outreach (Table 10). One such example is NIOSH involvement in the AIHA Real-Time Detection Systems Committee, one of AIHA's workgroups. NIOSH subject matter experts were involved in the original development of a body of knowledge (BoK), competency assessment criteria, and training curriculum on 4-gas meters, including development of the AIHA Four-gas Gas Meter and Photoionization Detector Operator Registry. The professional development course, Theory of Operation and Applications for Use of 4-gas monitors and photoionization detectors that arose from these efforts has been offered at every AIHce since 2013 as well as several invited offerings to regional AIHA chapters, fire departments, hazmat teams and industry. In 2016, a version specific to the oil and gas industry was offered at the OSHA Oil and Gas Safety and Health Conference in Houston. Since the development of the original Registry, NIOSH has since participated in the development of the BoK for Field Use of Direct-Reading Instruments for Detection of Gases and Vapors.

In the area of instrumentation and sensors for airborne radioactivity, Center co-director Dr. Mark Hoover served as chair for development of the National Council on Radiation Protection and Measurements (NCRP) Report 176 on Radiation Safety Aspects of Nanotechnology [NCRP 2017]. He also helped lead the development of the American National Standards Institute (ANSI) N42.37 standard on Training for the Radiological/Nuclear Detection Mission [ANSI 2016].

Table 10. List of Sensor-Related Committees and Work Groups with NIOSH Participation
Exposure Science in the 21st Century
Exposure Science in the 21st Century Sensors Subgroup
NNI and its signature initiatives
AIHA Book of Knowledge: Field use of direct-reading instruments for detection of gases and vapors
AIHA Real-Time Detection Systems Committee
ANSI instrumentation standards

Table 10. List of Sensor-Related Committees and Work Groups with NIOSH Participation
NCRP guidance documents, including sensor-related information in the new NCRP Report 176 on Radiation Safety Aspects of Nanotechnology

Finally, NIOSH has contributed to **training** and promotion of sensors in occupational safety and health research. Professional development courses on four-gas meter use were conducted at AIHA and various regional AIHA chapters. A similar course was presented to participants in the National Service, Transmission, Exploration and Production (STEPS) Network, which is an all-volunteer organization involving oil and gas activities that partners with NIOSH, OSHA, and other groups and educators across the country. General training on sensors was also presented at nearly 20 regional AIHA meetings in the last three years. In 2016, NIOSH also initiated conversations about the ethical use of wearable sensors and state-of-the-art data visualization techniques. Both topics were made available through publically accessible webinars. Because sensors provide large datasets that are not easily interpreted from numbers in a spreadsheet, data visualization may be one technique to highlight important information for any decisional analysis.

Transfer/Translation

Many of the sensors that NIOSH develops have commercial appeal. Manufacturers either purchase rights to provisional patents or work with NIOSH scientists to commercialize the sensor. NIOSH also partners with a number of organizations and companies to evaluate the field ruggedness of sensors. For instance, NIOSH worked with a number of police and fire departments in the Cincinnati area during the development of methamphetamine sensors. Table 11 lists some of the partner organizations to which sensors or guidance have been transferred/translated.

Table 11. NIOSH Sensor Technologies Partners List
Government
Boone County, Kentucky Sheriff's Department
Colerain, OH Fire Department
Consumer Product Safety Commission (CPSC)
Corinth, KY Fire Department
Crittenden, KY Fire Department
Department of Defense (DOD)
Department of Energy (DOE)
Dry Ridge, KY Fire Department
Environmental Protection Agency (EPA)
Exposure Science in the 21st Century (ES21) Federal Working Group

Table 11. NIOSH Sensor Technologies Partners List
Fairfield, OH Fire Department
Ft. Thomas, KY Fire Department
Grant County Kentucky Sheriff's Department
Greater Cincinnati and Northern Kentucky Hazmat Team
Hamilton County Ohio Sheriffs' Department
Miami Township, OH Fire Department
Mine Safety and Health Administration (MSHA)
Mt Healthy, OH Fire Department
Occupational Safety and Health Administration (OSHA)
St. Bernard, OH Fire Department
U.S. Army Corps of Engineers (USACE)
U.S. Army Research Laboratory (ARL)
Williamstown, Kentucky Police Department
Williamstown, KY Fire Department
Professional Organizations
American Association for Aerosol Research (AAAR)
American Industrial Hygiene Association (AIHA)
Health Physics Society (HPS)
International Safety Equipment Association (ISEA)
International Society for Exposure Science (ISES)
Industry
Badger Mining Corporation
Barrick Gold Corporation
Becton Dickinson Medical
Block Engineering
Bruker
EA Labs
Fairmount Santrol Corporation
Flir
FocusMotion
Kanomax
Kinetics
Photon Systems
Sensidyne
SKC, Inc.
Thermo Fischer Scientific
TSI
Unimim Corp
U.S. Silica Company
Vulcan Materials Corporation
Zefon
Guidance Bodies
American National Standards Institute (ANSI)

Table 11. NIOSH Sensor Technologies Partners List
ASTM International
International Organization for Standardization (ISO)
International Electrotechnical Commission (IEC)
Academia
University of Cincinnati
University of Michigan
Colorado State University

Intermediate Outcomes

Commercialization

Many NIOSH sensors have a role in occupational health and safety practice. The fact that a number of NIOSH sensors have been commercialized by companies provides evidence of the importance of these sensors (Table 12). In the last 10 years, based on discussions with our commercialization partners, we estimate that over 35,000 NIOSH-developed sensors have been sold. This is an underestimation of the true impact because some companies do not share their sales information with NIOSH.

Table 12. Sensors and Commercialization Partners

Sensor	Commercialization Partner
Coal Dust Explosibility Meter (CDEM)	Sensidyne
Personal Dust Meter (PDM)	Thermo-Fisher Scientific
Portable Aerosol Mobilty Spectrometer	Kanomax, Inc
MethChek and MethAlert	SKC, Inc
MikroKera	Synkera Technologies, Inc (now IDT)

NIOSH sensor strategies and devices are key resources in the occupational safety and health communities. These strategies and devices are frequently adopted by stakeholders and partners in government, academia, and private commercial entities for the purposes of research, periodic or episodic exposure monitoring and investigation of interventions. For example, the **NIOSH-developed methamphetamine sensor** (discussed on pgs 88-89) is currently sold by SKC, Inc. under the MethAlert and MethChek brand names. The manufacturer reported that users of the MethAlert and MethChek technologies include first responders, industrial hygienists, site remediation technicians and state and local health departments. The methods have proven to be cost-effective ways to immediately detect methamphetamine residues [Snawder et al. 2011].

NIOSH has been told that the MethAlert has been used by public health departments in Ohio and Michigan to make decisions on when the structure (house, hotel room, etc.) can be reoccupied after it has been cleaned [Dietrich, 2016]. Before the cost-effective and easily used direct-reading detector became available, it was an expensive and time-consuming process to obtain actionable information about the amount of contamination in a home or building. Louisville Metro Police and several other police departments in Kentucky are using MethChek for presumptive tests and assessing contamination for decontamination decisions or to determine if they could do their own clean-up. Health Departments in Australia and New Zealand are also using the MethChek and MethAlert [Dietrich 2016]. In addition, SKC, Inc. reported to NIOSH that real estate agents and the general public are purchasing the products to test residential structures, signifying that the methods are having a public health, as well as an occupational health impact [Dietrich 2016].

Use of the **Continuous Personal Dust Monitor (CPDM)** (discussed on pgs 85-86) was mandated by MSHA as of February 1, 2017. It is part of a larger MSHA regulation that, among other things, lowers permissible dust in coal mines from 2.0 milligrams of dust per cubic meter of air (mg/m^3) to 1.5 mg/m^3 (79 FR 24813). The CPDM is certified and commercially available as the PMD3700 Personal Dust Monitor from Thermo Fisher Scientific [Mischler and Coughanour 2017]. Although only coal miners in specific occupations at high risk of over-exposure wear the CPDM, its use helps reduce dust levels for all coal miners. One of these high-risk groups are the tailgate shearer operations, who traditionally have shown the greatest percentage of samples that exceed the dust standard because they are positioned downwind from longwall cutting machines and are exposed to high levels of dust. NIOSH tracks the percentage of overexposures using a four-year rolling average. The average increased slightly from 15.4% for 2011-2014 to 15.6% for 2012-2015. NIOSH expects the number of overexposures to continue to decrease in future years as use of the CPDM increases as required by MSHA.

The mining industry is seeing the benefits of having this sort of information at workers' fingertips. Early data reported to MSHA indicate miners are using information from the CPDM to either move themselves to areas where dust levels are within safe limits or make ventilation adjustments to their workspaces to move the dust in a different direction [Mischler and Coughanour 2017]. Some miners are even competing with workers in other shifts to achieve lower CPDM dust readings [NIOSH 2016a].

The worker-empowerment aspect of the CPDM enables miners to take an active role in reducing dust exposures and prevent new cases from developing.

In April of 2011, the **Coal Dust Explosibility Meter (CDEM)** (discussed on pgs 84-85) was approved by MSHA for use in underground coal mines [NIOSH 2011]. It has been commercialized by Sensidyne LP of Clearwater, Florida as the CDEM-1000 Coal Dust Explosibility Meter. When it first entered the market in 2011, the President of Sensidyne, Howard Mills, said, "For the first time mine operators will have a real time device to help in identifying and mitigating the explosion hazards resulting from inadequate rock dust levels. Sensidyne is proud to offer a device which we believe can become an important tool to further improve the operations and safety of the coal mining industry and its miners." [IHSN 2011]. The significance of this innovation is evidenced by its election by the public as the 2012 "People's Choice" winner in the HHSinnovates contest [NIOSH 2012d] and its selection as one of Department of Health and Human Services (HHS) Secretary Sebelius' three "Secretary's Top Picks." The CDEM is marketed as a tool to help mines meet the requirements of the MSHA rule promulgated in 2011 that requires a minimum of 80% rock dust in all mined areas outside the return airway to prevent explosion propagation (76 FR 35968). In 2013, MSHA issued a Program Information Bulletin encouraging mine operators to purchase the CDEM [MSHA 2013].

Researchers at Synkera technologies, Inc (now IDT) have also produced and commercialized gas sensors for detection of ammonia, hydrogen, hydrogen sulfide, and chlorine on the developed and commercialized unique nanoceramic platform through a NIOSH funded project.

Industry Use of Sensors and Applications

In the area of **vehicle safety** (discussed on pg. 97), Houston-based FMC Technologies, a global provider of technology and services for the oil and gas industry, is in the process of deploying an IVMS-based safety program across its entire fleet of 1,300 vehicles [Huff 2015]. The decision to take that action was based on the success of a comprehensive study conducted by NIOSH and its partnering organization SmartDrive.

The **Ladder Safety application** (discussed on pg. 95) is available for free download in English and Spanish on both iOS and Android devices. It has received many positive reviews from ladder users and safety professionals, including the American Society of Safety Engineers and Industrial Hygiene and

Safety News. Since its release in 2013, the application has been downloaded more than 120,000 times. Because the tool can be readily accessed at the worksite, it is especially helpful for small construction businesses, which have limited safety resources. State officials, industry leaders, and safety professionals have promoted the application, and many companies have incorporated the use of the application as part of their safety practices. The application has also received considerable international attention.

Federal Agencies Use of Sensor Technologies

OSHA and NIOSH have identified nine deaths related to manually sampling storage tanks in oil and gas extraction work [NIOSH 2016b]. In response to the identification of this hazard by NIOSH and its partners, the American Petroleum Institute (API) using recommendations from NIOSH on remote sensing developed and published a new safety standard, the *Custody Transfer of Crude Oil from Lease Tanks Using Alternative Measurement Methods* [American Petroleum Institute 2016], contained in the API Manual of Petroleum Measurement Standards. This new standard describes alternative methods for measuring the quantity and quality of crude oil without opening the tank hatch, thus protecting workers from exposure to hydrocarbon gases and vapors. In October 2016, the Department of the Interior's Bureau of Land Management (BLM) issued the first major update of rules for oil measurement on federal and Indian leases in over 25 years [BLM 2016]. The new regulation incorporates API's standard on alternative measurement methods (remote sensing). Prior to the update, oil and gas companies had to apply for variances to use alternative measurement methods for gauging and sampling. The update to the rules allows companies to use measurement systems and automatic tank gauging systems without having to obtain variances from BLM. The rule also includes a more streamlined process for approving new technology as it is developed. Now, oil and gas companies can more easily implement safer alternatives for gauging tanks on these leases and reduce the risk for worker deaths from breathing an oxygen-deficit atmosphere.

Partner Initiatives

EXAP leaders have participated in the development of AIHA's "Body of Knowledge: Field use of direct-reading instruments for detection of gases and vapors" [AIHA 2015]. This book provides summaries of skills and competencies industrial hygienists are expected to demonstrate. The BoK outlines the knowledge and skills necessary for competent use of direct-reading instruments to measure gases and vapors. It also establishes a framework for the development of training programs, skill assessment tools, and credentialing.

An AIHA report on *The Future of Sensors: Protecting Worker Health Through Sensor Technologies* [AIHA 2016a] was developed as part of the AIHA initiative to create industrial hygiene-related bodies of knowledge. NIOSH scientists provided input to its development and also participated in an invited AIHA workshop on the results of the report. NIOSH scientists have also participated with AIHA in the development of reporting specifications for electronic real time gas and vapor detection equipment [AIHA 2016b].

End Outcomes

The primary end outcome of NIOSH sensor technology is the reduction of biological, chemical, or physical exposures. Sensors serve as a tool for rapidly measuring potential hazards at worksites so that actions can be taken in real-time to mitigate or reduce the exposure. While NIOSH cannot definitively prove the impact of its work on end outcomes, NIOSH-developed sensors are being used by a number of stakeholders as evidenced by the intermediate outcomes achieved. While great strides have been made in methods development and sensors research, continued efforts to expand and improve the body of knowledge in this area are necessary. Measurement of the achievement of desired end outcomes can be difficult. One success story is that since the CPDM was mandated, the percentage of samples exceeding the MSHA dust exposure limit have dropped by 90%, from 3.1% to 0.3%. One company indicated dust concentrations have fallen by 20% since the CPDM was implemented [NIOSH 2016a]. Moreover, efforts to market the CDEM to help mines meet the requirements of MSHA's 2011 rule regarding rock dust minimums (76 FR 35968) and MSHA's issuance of a 2013 Program Information Bulletin encouraging mine operators to purchase the CDEM [MSHA 2013] appear to be contributing to the desired results. The number of MSHA violations for both accumulations of combustible materials and improper ratios of combustible/non-combustible materials has declined in the past two years (Figure 6).

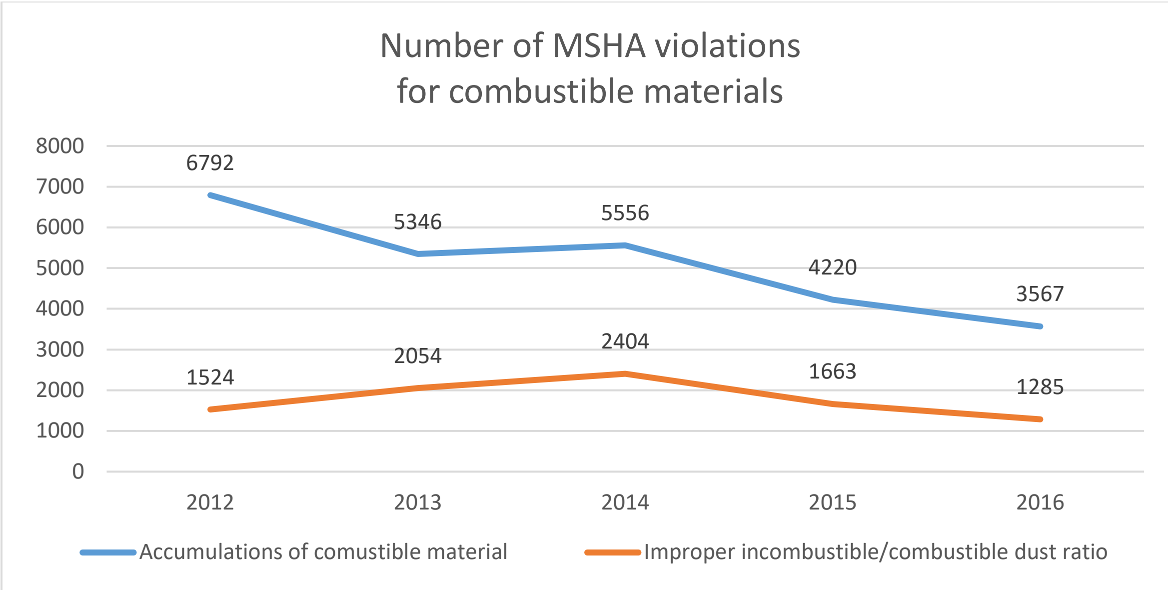

Figure 6. Number of MSHA violations for combustible materials for the years 2012-2016

Alternative Explanations

While NIOSH has contributed to development and validation of sensors used in the occupational safety and health community, there are other federal agencies such as the DOD, EPA, and the Department of Homeland Security (DHS) that possess regulatory authority that impacts sensor development. Sensor manufacturers will develop their devices to meet the specifications of these agencies. Since sensors are used in so many different industry sectors there are different governing bodies that can and do make recommendations on their applications and use. For instance, DHS and the Interagency Board are the primary groups that evaluate and recommend sensors for emergency response efforts. The BLM can also approve new technologies for tank gauging in the oil and gas sector.

Future Plans

The EXAP will continue to work on the development and evaluation of new and improved direct-reading and sensor technologies. The impact of automation and sensors is likely to have a major effect on how American worksites are structured and the hazards to which workers are exposed. The importance of research and development of sensor technologies and strategies will likely continue to grow. The NRC [2012] has stated that sensors will be key 21st century tools to improve exposure assessment. As was shown in Table 13, a number of NIOSH sensor technologies are currently under development. Additionally other sensors have been requested by stakeholders such as a sensor for drugs of abuse such as fentanyl. First responders are concerned about their exposure to this drug and other opiods.

Table 13. Status of NIOSH Sensors in Development

Field-based silica monitor	Miller et al. 2012; Cauda et al. 2016
Helmet-CAM and EVADE Software 2.0	NIOSH 2014; Cecala et al. 2013, 2014
Anticancer drugs	Smith et al. 2010, 2016a, b
Multi-elemental analysis	Diwakar and Kulkarni 2012; Diwakar et al. 2011
Biochip for silica exposure	Prototype developed in 2016
Hand portable silica analyzer	Prototype in development
Particulate carbon	Zheng et al. 2016

EXAP staff and the NIOSH Manual of Analytical Methods (NMAM) team are currently working together on a NMAM chapter on direct-reading of gases and vapors. This chapter will provide guidance on performance characteristics that are important for these sensors. In addition, the Center has received funding from CDC's Office of Public Health Preparedness and Response to develop a guidance document on sensor use during emergency response. Both the NMAM chapter and the emergency response guidance document are expected to be completed in 2018.

One area that NIOSH has not tackled to any degree is "big data" issues. Sensors give large amounts of data and how best to manage and interpret this information is a challenge. Along with the NIOSH Center for Workers' Compensation Studies, a webinar is planned for summer 2017 on harnessing sensors and big data for insurance risk characterization and control. This webinar will set the stage for a public meeting to be held in 2019 to discuss the research needs and gaps for big data analytics in occupational safety and health.

During the 2016 AIHA Sensor Summit and the NIOSH-AIHA leadership discussions, a number of issues were identified that clearly fall into the NIOSH mission. NIOSH plans to continue to collaborate with AIHA to address these. The ethical issues that surround sensors, in general, and wearable sensors, specifically, need to be brought into a wider discussion to ensure that worker privacy and confidentiality remain at the forefront of innovation.

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Appendix A: List of Abbreviations

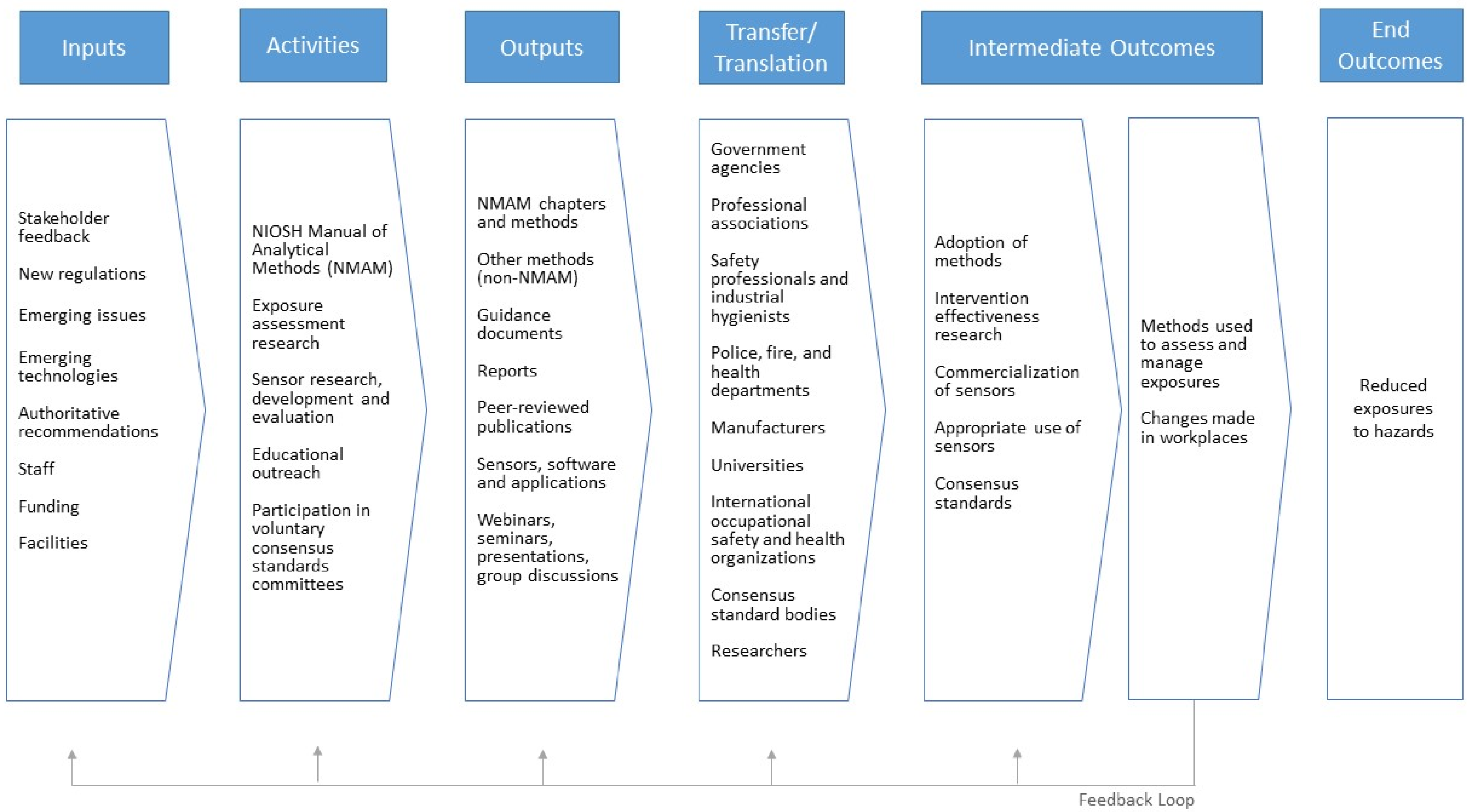
1-PB	1-bromopropane
AAAR	American Association for Aerosol Research
ACGIH	American Conference of Governmental Industrial Hygienists
ACI	Andersen Cascade Impactor
AIHA	American Industrial Hygiene Association
AIHA IHLAP	AIHA Industrial Hygiene Laboratory Accreditation Program, LLC
AIHce	American Industrial Hygiene Conference and Exposition
ANSI	American National Standards Institute
API	American Petroleum Institute
ARECC	Anticipate, Recognize, Evaluate, Control, and Confirm
ARL	U.S. Army Research Laboratory
ASTM	ASTM International (originally known as the American Society for Testing and Materials)
ATP	Adenosine triphosphate
Be	Berylium
BLM	Bureau of Land Management
BoK	Body of Knowledge
CDC	Centers for Disease Control and Prevention
CDEM	Coal Dust Explosibility Meter
CEMWIP	Chemical Exposure Monitor With Indoor Positioning
CNT/CNF	Carbon nanotubes and nanofibers
CPDM	Continuous Personal Dust Monitor
CPSC	Consumer Product Safety Commission

CR (VI)	Hexavalent chromium
CSU	Colorado State University
DART	Division of Applied Research and Technology
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DREAM	Direct-Reading Exposure Assessment Methods
DSHEFS	Division of Surveillance, Hazard Evaluations, and Field Studies
DSR	Division of Safety Research
EID	Education and Information Division
ELISA	Enzyme-Linked Immunosorbent Assay
EM	Electron Microscopy
EMS	Electrical Mobility Spectrometers
EPA	Environmental Protection Agency
ES21	Exposure Science in the 21st Century
EVADE	Enhanced Video Analysis of Dust Exposures
EXAP	Exposure Assessment Program
GC	Gas Chromatograph
HAP	Hazardous Air Pollutants
HELD	Health Effects Laboratory Division
HHE	Health Hazard Evaluation
HSL	Health and Safety Laboratory (in the United Kindgom)
ICP	Inductively Coupled Plasma
IEC	International Electrotechnical Commission

IFA	Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (in Germany)
INRS	Institut National de Recherche et de Sécurité (In France)
INSHT	Instituto Nacional de Seguridad e Higiene en el Trabajo (in Spain)
IRSST	Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (in Canada)
ISEA	International Safety Equipment Association
ISES	International Society for Exposure Science
ISO	International Organization for Standardization
IVMS	In-Vehicle Monitoring System
JNIOSH	Japan National Institute of Occupational Safety and Health
LED	Light Emitting Diode
MOUDI	Micro-Orifice Uniform Deposit Impactor
NCEH-DLS	National Center for Environmental Health, Division of Laboratory Science
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NNI	National Nanotechnology Initiative
MCE	Mixed Cellulose Ester
NAA	Neutron Activation Analysis
NMAM	NIOSH Manual of Analytical Methods
MnBn	Bone manganese
MSHA	Mine Safety and Health Administration
NORA	National Occupational Research Agenda
NPPTL	National Personal Protective Technology Laboratory
NRC	National Research Council
OEB	Occupational Exposure Bands

OEL	Occupational Exposure Limit
OH-PAH	Hydroxylated metabolites of polycyclic aromatic hydrocarbons
OSHA	Occupational Safety and Health Administration
PAMS	Portable Aerosol Mobility Spectrometer
PDS	Proximity Detection Systems
PEL	Permissible Exposure Limit
PMRD	Pittsburgh Mining Research Division
PPT	Personal Protective Technology
PVC	Polyvinyl chloride
RCS	Respirable Crystalline Silica
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
REL	Recommended Exposure Limit
RGB	Red, blue, green
RHD	Respiratory Health Division
RSV	Respiratory Syncytial Virus
SMRD	Spokane Mining Research Division
STEL	Short-Term Exposure Limit
STEPS	National Service, Transmission, Exploration and Production
TCAA	Trichloroacetic acid
USACE	U.S. Army Corps of Engineers
VOC	Volatile Organic Compounds
WHO	World Health Organization
WSD	Western States Division

Appendix B: Exposure Assessment Program Logic Model



NIOSH Exposure Assessment Program

May 2016

What are our priorities?

The National Institute for Occupational Safety and Health (NIOSH) Exposure Assessment Program works with partners in industry, labor, trade associations, professional organizations, and academia. The program focuses on promoting the use of 21st century exposure assessment sensors, methods, and processes.

What do we do?

- Develop guidance for how to conduct exposure assessments in all types of occupational settings. Exposure assessments help identify who is exposed, how they are exposed (air, water, skin contact), how much exposure occurs, how often, and the duration of exposure.
- Develop new or improved sensors for assessing exposure to make it easier and quicker to identify and measure exposures.
- Develop new or improved assessment methods to ensure that exposure measurements are accurate and able to detect lower levels of agents in the workplace.

What have we accomplished?

- Published NIOSH Manual of Analytical Methods (NMAM) Method 0501, "Particulates Not Otherwise Regulated," which accurately measures nuisance dusts.
- Published NMAM Method 5100, "Carbon Black," which more accurately measures the fine carbon powder that can be found in the air when petroleum products are not completely burned.
- Published NMAM Method 8319, "Acetone and Methylethyl Ketone in Urine." These two chemicals are used in a wide variety of industrial processes.
- Published NMAM Method 8322, "Trichloroacetic Acid in Urine," which detects a metabolite of trichloroethylene that occurs from inhaling this industrial solvent or swallowing trichloroethylene-contaminated water.
- Published a method on a new sensor for hazardous drug exposure. It enables rapid assessment of unknown spills of hazardous drugs in the pharmacy or treatment areas of healthcare facilities. Current methods to measure for spills can take weeks to analyze, but this new sensor checks for hazardous drugs in just a few minutes, so workers can be protected sooner.
- Published guidance on using biomarkers of effect to set occupational exposure limits. This is one of a series of NIOSH documents to understand factors that can or cannot be reliably used to assess risk and set standards.
- Published NMAM method 7306, "ELEMENTS by Cellulosic Internal Capsule Sampler and ICP-AES." It uses an analyzable filter insert to improve reporting accuracy for 33 elements by collecting material that may have adhered to the sampler wall and making that material available for analysis.

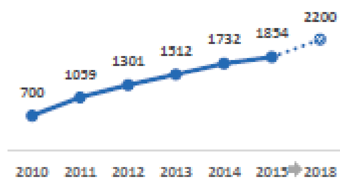
What's next?

- Refine the NMAM method for total isocyanates, at OSHA's request. Isocyanates are potent irritants and sensitizers which are increasingly used in the automobile industry, for auto body repair, and in insulation for buildings. Current methods underreport isocyanate levels, and a refined method will more accurately assess exposure levels.
- Publish guidance on exposome research to help epidemiologists understand the multitude of exposures an individual has over a lifetime, and how exposures may affect current or future health.
- Publish an update of the NIOSH Occupational Exposure Sampling Strategy Manual.

At-A-Glance

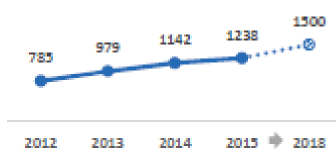
The Exposure Assessment Program provides national and international leadership in the development and use of effective exposure assessment tools to prevent work-related illness and injury. This snapshot shows recent accomplishments and upcoming work.

Cumulative web downloads of "Genetics in the Workplace" guidance document



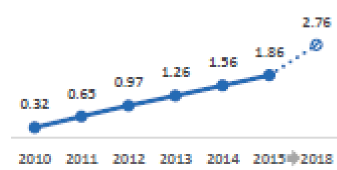
Source: NIOSH program records

Cumulative web downloads of "Direct-Reading Monitors for Gases and Vapors" guidance document



Source: NIOSH program records

Cumulative web downloads of *NIOSH Manual of Analytical Methods* (NMAM) (in millions)



Source: NIOSH Program Records

DHHS (NIOSH) Publication No. 2016-122

Appendix D: Center for Direct Reading and Sensor Technologies Fact Sheet

NIOSH Center for Direct Reading and Sensor Technologies

May 2016

What are our priorities?

The National Institute for Occupational Safety and Health (NIOSH) Center for Direct Reading and Sensor Technologies works with partners in industry, labor, trade associations, professional organizations, and academia. The Center focuses on fostering leaders, cultures, and systems to advance the development and use of sensors for occupational safety, health, well-being and productivity.

What do we do?

- Coordinate a national research agenda for direct reading methods and sensor technologies.
- Develop sensor-relevant guidance documents, including validation and performance characteristics.
- Develop training protocols to help others learn how to select, use, and interpret the data of direct reading methods and sensor technologies.
- Partner with other Federal agencies (such as the Environmental Protection Agency and U.S. Air Force), the American Industrial Hygiene Association, and with academics such as the University of Cincinnati to increase the development and use of sensors in occupational health research.

What have we accomplished?

- Published an article describing the NIOSH sensor development lifecycle and the Center. The article also invites others to partner with the Center on mutually important research and development projects.
- Collaborated as a key player in the National Nanotechnology Signature Initiative on Sensors for Nano and Nano for Sensors. The NIOSH sensor development lifecycle has been incorporated into the program activities and publications of the Signature Initiative and the Center is helping the Initiative explore ways that nanotechnology can protect and improve health, safety and the environment.
- Held three webinars on sensors and information sharing with the American Industrial Hygiene Association, the National Nanotechnology Coordination Office, and the Environmental Protection Agency.
- Hosted two seminars led by expert academic researchers on sensor use in occupational and environmental research. Each seminar was attended by approximately 50 individuals from within and outside of NIOSH.
- Developed outreach opportunities, including:
  - Participating in a "Sensor Fair" that demonstrated NIOSH-developed sensors to attendees at the International Society for Exposure Science.
  - Presenting at partner organizations, including the International Society for Exposure Science, the American Industrial Hygiene Association, the Health Physics Society, and the University of Cincinnati Sensors Community.
- Provided training to three American Industrial Hygiene Association Local Sections.

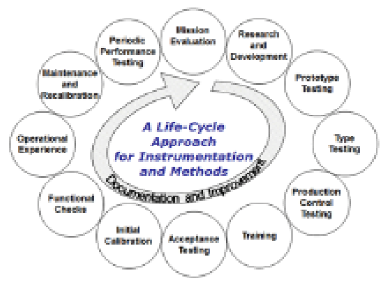
What's next?

- Hold at least two expert seminars on sensor applications open to NIOSH staff and outside partners.
- Publish a guidance chapter on direct reading meters for gases and vapors in the NIOSH Manual of Analytical Methods.
- Conduct three focus groups with emergency responders to gather information on current practices and limitations for the selection, use and data interpretation of sensors used to assess hazardous conditions.
- Coordinate a workshop to bring together experts on the use of sensors in emergency response to develop a framework for a guidance document on best practices.
- Hold a webinar on issues for the ethical and legal use of sensors to increase awareness of these issues for developers and users of sensors.

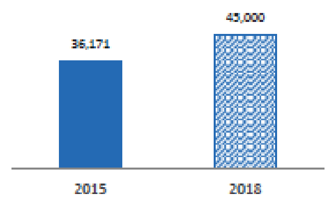
At-A-Glance

The Center for Direct Reading and Sensor Technologies is a virtual center that provides leadership to develop recommendations on the use of 21st century technologies in occupational safety and health. This snapshot shows recent accomplishments and upcoming work.

NIOSH Sensor Development Lifecycle

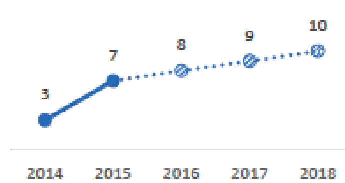


Total Number of NIOSH-Developed Sensors Sold by Manufacturers since 2012



Source: NIOSH Program Records

Outreach Presentations and Trainings



Source: NIOSH Program Records

DHHS (NIOSH) Publication No. 2016-132

Appendix E: Laboratories Accredited to use NIOSH Methods

Laboratory	State	Type
White Environmental Consultants, Inc.	AK	Company
Guardian Systems, Inc.	AL	Company
Safety Environmental Laboratories and Consulting, Inc.	AL	Company
Environmental Enterprise Group, Inc.	AR	Company
TestAmerica Laboratories, Inc.	AZ	Company
EMC Labs, Inc.	AZ	Company
Fiberquant Analytical Services	AZ	Company
Aerotech Laboratories, Inc	AZ	Company
AIH Laboratory	CA	Company
Micro Analytical Laboratories, Inc.	CA	Company
Forensic Analytical Laboratories, Inc.	CA	Company
LA Testing Huntington Beach	CA	Company
EMLab P&K, LLC.	CA	Company
Lawrence Livermore National Laboratory ASI Analytical Laboratory	CA	Federal laboratory
AT Labs, A Unit Of Assay Technology	CA	Company
SRI International, Industrial Hygiene Laboratory	CA	Company
Envirocheck, Inc.	CA	Company
Forensic Analytical Laboratories, Inc.	CA	Company
Environmental Health Laboratory (EHL), California Department of Public Health	CA	State laboratory
Navy Environmental Preventative Medical Unit	CA	Military laboratory
EMSL Analytical, Inc	CA	Company
LA Testing	CA	Company
EMLab P&K South San Francisco	CA	Company
Reservoirs Environmental, Inc.	CO	Company
ALS Environmental – Fort Collins	CO	Company
Johns Manville	CO	Company
DCM Science Laboratory, Inc.	CO	Company
ESIS Environmental Health Laboratory	CT	Company
Mystic Air Quality Consultants, Inc.	CT	Company
EnviroMed Services, Inc	CT	Company
Chemscope, Inc	CT	Company
The Hartford Risk Engineering Laboratory	CT	Company
TRC Environmental Corporation	CT	Company
Travelers Industrial Hygiene and Forensics Laboratory	CT	Company
Environmental Testing, Inc	DE	Company
Batta Laboratories, Inc.	DE	Company
Advanced Chemical Sensors Co.	FL	Company
EMLab P&K, LLC.	FL	Company
Analytical Environmental Services, Inc.	GA	Company
Bureau Veritas North America	GA	Company
Materials Analytical Services, LLC	GA	Company
Hawaii Analytical Laboratory, LLC	HI	Company
State Hygienic Laboratory at the University of Iowa (Ankeny)	IA	State laboratory

Laboratory	State	Type
TestAmerica Laboratories, Inc.	IA	Company
State Hygienic Laboratory at the University of Iowa (Coralville)	IA	State laboratory
STAT Analysis Corporation	IL	Company
Federal Occupational Health Environmental Laboratory	IL	Federal laboratory
Bureau Veritas North America	IL	Company
EMSL Analytical, Inc	IL	Company
AbbVie EHS Laboratory	IL	Company
AnalyticaLab, Inc.	IL	Company
ACT Environmental Services, Inc.	IN	Company
Micro Air, Inc.	IN	Company
EMSL Analytical, Inc.	IN	Company
Certified Environmental Management	KS	Company
KY Division of Laboratory Services, Dept. for Public Health, Cabinet for Health and Family Services	KY	State laboratory
EASI, LLC	LA	Company
Axiall Corporation	LA	Company
ARS International, Inc.	LA	Company
MIT Industrial Hygiene Lab	MA	University laboratory
Con-Test Analytical Laboratory	MA	Company
Liberty Mutual Insurance Industrial Hygiene Laboratory	MA	Company
Magellan Diagnostics, Inc.- Analytical Services Group	MA	Company
ProScience Analytical Services, Inc.	MA	Company
EMSL Analytical, Inc.	MA	Company
Army Public Health Center (Provisional)	MD	Military laboratory
EMSL Analytical, Inc.	MD	Company
AMA Analytical Services, Inc.	MD	Company
GPI Laboratories, Inc.	MI	Company
The Michigan Department of Licensing and Regulatory Affairs	MI	State laboratory
The Dow Chemical Company	MI	Company
Prism Analytical Technologies, Inc.	MI	Company
Bureau Veritas North America, Inc.	MI	Company
BASF Corporation Industrial Hygiene Laboratory	MI	Company
Techtron Engineering, Inc.	MN	Company
IEA, Inc.	MN	Company
Pace Analytical Services, LLC - IH Lab Minneapolis	MN	Company
LEGEND Technical Services, Inc.	MN	Company
EMSL Analytical, Inc.	MO	Company
CEI Labs, Inc.	NC	Company
EMSL Analytical, Inc.	NC	Company
Scientific Analytical Institute, Inc.	NC	Company
Sensors Safety Products, Inc.	NC	Company
RTI International	NC	Company
Optimum Analytical and Consulting LLC	NH	Company
EMSL Analytical, Inc.	NJ	Company
International Asbestos Testing Laboratories (IATL)	NJ	Company
Hillmann Consulting, LLC	NJ	Company
Forensic Analytical Laboratories, Inc.	NV	Company
Adirondack Environmental Services, Inc.	NY	Company

Laboratory	State	Type
EMSL Analytical, Inc.	NY	Company
SGS Galson Laboratories, Inc.	NY	Company
Eastern Analytical Services, Inc.	NY	Company
Laboratory Testing Services, Inc.	NY	Company
KAM Consultants Corporation	NY	Company
Airtek Environmental Corp.	NY	Company
ATC Group Services LLC	NY	Company
Atlas Environmental Lab	NY	Company
America Science Team New York, Inc. Dba AmeriSci New York	NY	Company
EMSL Analytical, Inc.	NY	Company
American Analytical Laboratories, Inc.	OH	Company
AT Labs, a Unit of Assay Technology	OH	Company
ALS Laboratory Group, Environmental Division, (Cincinnati)	OH	Company
American Electric Power	OH	Company
EA Group	OH	Company
Fluor-B&W Portsmouth, LLC, Portsmouth Analytical Laboratory	OH	Company
USAFSAM Occupational and Environmental Laboratory - Industrial Hygiene	OH	Military laboratory
QuanTEM Laboratories	OK	Company
Oregon OSHA Lab	OR	State laboratory
Criterion Laboratories, Inc.	PA	Company
Free-Col Laboratories, a Division of Modern Industries, Inc.	PA	Company
Eagle Industrial Hygiene Associates, Inc.	PA	Company
Clark Laboratories, LLC	PA	Company
Accredited Environmental Technologies	PA	Company
RJ Lee Group, Inc.	PA	Company
MSHA - Department Of Labor	PA	Federal laboratory
Covestro Industrial Hygiene Laboratory	PA	Company
PSI - Professional Service Industries, Inc.	PA	Company
PPG Corporate IH laboratory	PA	Company
Analytical Environmental Services International, Inc.	PR	Company
Savannah River Nuclear Solutions, LLC (SRNS)	SC	Company
Michelin Tire Corporation	SC	Company
NAS, LLC	TN	Company
TOSHA Laboratory	TN	Company
Materials And Chemistry Laboratory, Inc (MCLinc)	TN	Company
Consolidated Nuclear Security, LLC (CNS LLC)	TN	Company
Oak Ridge National Laboratory	TN	Federal laboratory
Pantex Industrial Hygiene Laboratory	TX	Company
Armstrong Forensic Laboratory, Inc.	TX	Company
Crisp Analytical Labs, LLC	TX	Company
Sea Harbor Laboratories	TX	Company
Golden Specialty, Inc.	TX	Company
Envirotest, Ltd.	TX	Company
J3 Resources, Inc.	TX	Company
A&B Environmental Services, Inc.	TX	Company
CHEMTEX	TX	Company
HIH LABORATORY, INC.	TX	Company

Laboratory	State	Type
Rio Tinto Kennecott Environmental and Industrial Hygiene Laboratory	UT	Company
ALS Environmental	UT	Company
OSHA Salt Lake Technical Center	UT	Federal laboratory
Dixon Information, Inc.	UT	Company
Analytics Corporation	VA	Company
Marine Chemist Service, Inc.	VA	Company
Newport News Shipbuilding	VA	Company
Navy Environmental and Preventive Medicine Unit Two CIHL Norfolk	VA	Military laboratory
SanAir Technologies Laboratory	VA	Company
Schneider Laboratories Global, Inc.	VA	Company
Environmental Hazards Services, LLC	VA	Company
Washington State Department of Labor and Industries, DOSH Industrial Hygiene Laboratory	WA	State laboratory
RJ Lee Group, Inc. – Columbia Basin Analytical Laboratories	WA	Company
WAI Hanford Laboratory	WA	Company
TestAmerica Richland	WA	Company
Advanced Technologies & Laboratories, International, Inc. - (TTC)	WA	Company
Environmental Health Laboratory, University of Washington, Seattle	WA	Company
NVL Laboratories, Inc.	WA	Company
Wisconsin Occupational Health Laboratory	WI	State laboratory
ACL Industrial Toxicology Laboratory	WI	Company

Appendix F: NIOSH Methods and the Number of Accredited Laboratories

Method Number	Method Name	Number of accredited laboratories
NIOSH 0500	PARTICULATES NOT OTHERWISE REGULATED, TOTAL	63
NIOSH 0501	PARTICULATES N.O.R., Total	1
NIOSH 0600	PARTICULATES NOT OTHERWISE REGULATED, RESPIRABLE	60
NIOSH 1000	ALLYL CHLORIDE	10
NIOSH 1001	METHYL CHLORIDE	11
NIOSH 1002	b-CHLOROPRENE	9
NIOSH 1003	HYDROCARBONS, HALOGENATED	47
NIOSH 1004	DICHLOROETHYL ETHER	9
NIOSH 1005	METHYLENE CHLORIDE	31
NIOSH 1006	FLUOROTRICHLOROMETHANE	13
NIOSH 1007	VINYL CHLORIDE	26
NIOSH 1008	ETHYLENE DIBROMIDE	8
NIOSH 1009	VINYL BROMIDE	5
NIOSH 1010	EPICHLOROHYDRIN	23
NIOSH 1011	ETHYL BROMIDE	1
NIOSH 1012	DIFLUORODIBROMOMETHANE	6
NIOSH 1013	PROPYLENE DICHLORIDE	4
NIOSH 1014	METHYL IODIDE	9
NIOSH 1015	VINYLIDENE CHLORIDE	17
NIOSH 1016	(1) 1,1,1,2-TETRACHLORO-2,2-DIFLUOROETHANE and (2) 1,1,2,2-TETRACHLORO-1,2-DIFLUOROETHANE	6
NIOSH 1017	TRIFLUOROBROMOMETHANE	6
NIOSH 1018	DICHLORODIFLUOROMETHANE	17
NIOSH 1019	1,1,2,2-TETRACHLOROETHANE	14
NIOSH 1020	1,1,2-TRICHLORO-1,2,2-TRIFLUOROETHANE	17
NIOSH 1022	TRICHLOROETHYLENE	29
NIOSH 1024	1,3-BUTADIENE	18
NIOSH 1025	1- and 2-BROMOPROPANE	7
NIOSH 1026	p-CHLOROBENZOTRIFLUORIDE	5
NIOSH 1300	KETONES I	34
NIOSH 1301	KETONES II	28
NIOSH 1302	N-METHYL-2-PYRROLIDINONE	17
NIOSH 1400	ALCOHOLS I	47
NIOSH 1401	ALCOHOLS II	27
NIOSH 1402	ALCOHOLS III	22
NIOSH 1403	ALCOHOLS IV	31
NIOSH 1404	METHYLCYCLOHEXANOL	6
NIOSH 1405	ALCOHOLS COMBINED	6
NIOSH 1450	ESTERS 1	35

Method Number	Method Name	Number of accredited laboratories
NIOSH 1451	METHYL CELLOSOLVE ACETATE	17
NIOSH 1452	ETHYL FORMATE	9
NIOSH 1453	VINYL ACETATE	20
NIOSH 1454	ISOPROPYL ACETATE	19
NIOSH 1457	ETHYL ACETATE	26
NIOSH 1458	METHYL ACETATE	19
NIOSH 1459	METHYL ACRYLATE	18
NIOSH 1460	ISOPROPYL ACETATE	5
NIOSH 1500	HYDROCARBONS, BP 36ø-216 øC	49
NIOSH 1501	HYDROCARBONS, AROMATIC	54
NIOSH 1550	NAPHTHAS	38
NIOSH 1551	TURPENTINE	17
NIOSH 1552	TERPENES	15
NIOSH 1600	CARBON DISULFIDE	5
NIOSH 1601	1,1-DICHLORO-1-NITROETHANE	5
NIOSH 1602	DIOXANE	19
NIOSH 1603	ACETIC ACID	17
NIOSH 1604	ACRYLONITRILE	21
NIOSH 1606	ACETONITRILE	25
NIOSH 1609	TETRAHYDROFURAN	19
NIOSH 1610	ETHYL ETHER	20
NIOSH 1611	METHYLAL	11
NIOSH 1612	PROPYLENE OXIDE	12
NIOSH 1613	PYRIDINE	18
NIOSH 1614	ETHYLENE OXIDE	11
NIOSH 1615	METHYL tert-BUTYL ETHER	22
NIOSH 1616	n-BUTYL GLYCIDYL ETHER	15
NIOSH 1617	PHENYL ETHER	10
NIOSH 1618	ISOPROPYL ETHER	8
NIOSH 1619	PHENYL GLYCIDYL ETHER	11
NIOSH 1620	ISOPROPYL GLYCIDYL ETHER	6
NIOSH 1622	CARBON DISULFIDE - DRAFT	1
NIOSH 2000	METHANOL	53
NIOSH 2001	CRESOL – WITHDRAWN METHOD	1
NIOSH 2002	AMINES, AROMATIC	19
NIOSH 2003	1,1,2,2-TETRABROMOETHANE	6
NIOSH 2004	DIMETHYLACETAMIDE	23
NIOSH 2005	NITROAROMATIC COMPOUNDS	15
NIOSH 2007	AMINOETHANOL COMPOUNDS I	11
NIOSH 2008	CHLOROACETIC ACID	6
NIOSH 2010	AMINES, ALIPHATIC	10
NIOSH 2011	FORMIC ACID	14
NIOSH 2012	n-BUTYLAMINE	9
NIOSH 2013	PHENYL ETHER-DIPHENYL MIXTURE	6
NIOSH 2014	p-CHLOROPHENOL	9
NIOSH 2015	CHLOROACETALDEHYDE	5
NIOSH 2016	FORMALDEHYDE	39

Method Number	Method Name	Number of accredited laboratories
NIOSH 2017	ANILINE, o-TOLUIDINE, AND NITROBENZENE	10
NIOSH 2018	ALIPHATIC ALDEHYDES	11
NIOSH 2500	METHYL ETHYL KETONE	31
NIOSH 2501	ACROLEIN 2501	5
NIOSH 2503	MEVINPHOS	1
NIOSH 2504	TETRAETHYL PYROPHOSPHATE	3
NIOSH 2505	FURFURYL ALCOHOL	17
NIOSH 2506	ACETONE CYANOHYDRIN	1
NIOSH 2507	ETHYLENE GLYCOL DINITRATE	8
NIOSH 2508	ISOPHORONE	18
NIOSH 2510	1-OCTANETHIOL	3
NIOSH 2513	ETHYLENE CHLOROHYDRIN	11
NIOSH 2514	ANISIDINE	7
NIOSH 2515	DIAZOMETHANE	3
NIOSH 2516	DICHLOROFLUOROMETHANE	10
NIOSH 2517	PENTACHLOROETHANE	6
NIOSH 2518	HEXACHLORO-1,3-CYCLOPENTADIENE	8
NIOSH 2519	ETHYL CHLORIDE	9
NIOSH 2520	METHYL BROMIDE	3
NIOSH 2521	METHYLCYCLOHEXANONE	8
NIOSH 2522	NITROSAMINES	3
NIOSH 2523	1,3-CYCLOPENTADIENE	8
NIOSH 2524	DIMETHYL SULFATE	4
NIOSH 2525	n-BUTYL MERCAPTAN	2
NIOSH 2526	NITROETHANE	12
NIOSH 2527	NITROMETHANE	8
NIOSH 2528	2-NITROPROPANE	8
NIOSH 2529	FURFURAL	8
NIOSH 2530	DIPHENYL	15
NIOSH 2532	GLUTARALDEHYDE	19
NIOSH 2533	TETRAETHYL LEAD (as Pb)	1
NISOH 2534	TETRAMETHYL LEAD (as Pb)	1
NIOSH 2535	TOLUENE-2,4-DIISOCYANATE	3
NIOSH 2536	VALERALDEHYDE	6
NIOSH 2537	METHYL AND ETHYL METHACRYLATE	23
NIOSH 2538	ACETALDEHYDE	8
NIOSH 2539	ALDEHYDES, SCREENING	7
NIOSH 2540	ETHYLENEDIAMINE	15
NIOSH 2541	FORMALDEHYDE	15
NIOSH 2542	MERCAPTANS, METHYL-, ETHYL-, and n-BUTYL	3
NISOH 2543	HEXACHLOROBUTADIENE	9
NIOSH 2544	NICOTINE	8
NIOSH 2545	ALLYL GLYCIDYL ETHER	11
NIOSH 2546	CRESOL (all isomers) and PHENOL	21
NIO2H 2549	VOLATILE ORGANIC COMPOUNDS (SCREENING)	5
NIOSH 2551	NICOTINE	9
NIOSH 2552	METHYL ACRYLATE	4

Method Number	Method Name	Number of accredited laboratories
NIOSH 2553	KETONES II	10
NIOSH 2554	GLYCOL ETHERS	7
NIOSH 2555	KETONES I	12
NIOSH 2556	ISOPHORONE	3
NIOSH 2557	DIACETYL	10
NIOSH 2558	ACETOIN	5
NIOSH 2559	DECABROMODIPHENYL OXIDE	3
NIOSH 2560	1-NITROPYRENE IN DIESEL PARTICULATES	1
NIOSH 2561	(1) 2-(DIMETHYLAMINO)ETHANOL, (2) 1-DIMETHYLAMINO-2-PROPANOL	4
NIOSH 2562	1,1,2,2-TETRACHLOROETHANE	4
NIOSH 3500	FORMALDEHYDE by VIS	10
NIOSH 3503	HYDRAZINE	2
NIOSH 3506	ACETIC ANHYDRIDE	1
NIOSH 3507	ACETALDEHYDE	5
NIOSH 3508	METHYL ETHYL KETONE PEROXIDE	4
NIOSH 3509	AMINOETHANOL COMPOUNDS II	5
NIOSH 3510	MONOMETHYLHYDRAZINE	2
NIOSH 3511	MONOMETHYLANILINE	5
NIOSH 3512	MALEIC ANHYDRIDE	6
NIOSH 3513	TETRANITROMETHANE	3
NIOSH 3514	ETHYLENIMINE	2
NIOSH 3515	1,1-DIMETHYLHYDRAZINE	1
NIOSH 3518	PHENYLHYDRAZINE	1
NIOSH 3600	MANEB	1
NIOSH 3601	MANEB Hand Wash	1
NIOSH 4000	TOLUENE (diffusive sampler)	7
NIOSH 5000	CARBON BLACK	15
NIOSH 5001	2,4,5-T	7
NIOSH 5002	WARFARIN	8
NIOSH 5003	PARAQUAT	8
NIOSH 5004	HYDROQUINONE	15
NIOSH 5005	THIRAM	9
NIOSH 5006	CARBARYL	1
NIOSH 5007	ROTENONE	4
NIOSH 5008	PYRETHRUM	8
NIOSH 5009	BENZOYL PEROXIDE	12
NIOSH 5010	(1) BROMOXYNIL and (2) BROMOXYNIL OCTANOATE	5
NIOSH 5011	ETHYLENE THIOUREA	1
NIOSH 5012	EPN	2
NIOSH 5013	DYES, BENZIDINE-, o-TOLIDINE-, o-DIANISIDINE	3
NIOSH 5014	CHLORINATED TERPHENYL (60% CHLORINE)	5
NIOSH 5016	STRYCHNINE	6
NIOSH 5017	DIBUTYL PHOSPHATE	2
NIOSH 5018	2,4,7-TRINITROFLUOREN-9-ONE	3
NIOSH 5019	AZELAIC ACID	4

Method Number	Method Name	Number of accredited laboratories
NIOSH 5020	DIBUTYL PHTHALATE	17
NIOSH 5021	o-TERPHENYL	10
NIOSH 5023	COAL TAR PITCH VOLATILES	3
NIOSH 5025	CHLORINATED DIPHENYL OXIDE	2
NIOSH 5026	OIL MIST, MINERAL	8
NIOSH 5027	RIBAVIRIN	7
NIOSH 5029	4,4'-METHYLENEDIANILINE	12
NIOSH 5030	CYANURIC ACID	5
NIOSH 5031	ASPARTAME	6
NIOSH 5032	PENTAMIDINE ISETHIONATE	4
NIOSH 5033	p-NITROANILINE	9
NIOSH 5034	TRIBUTYL PHOSPHATE	7
NIOSH 5036	TRIMELLITIC ANHYDRIDE	2
NIOSH 5037	TRIORTHOCRESYL PHOSPHATE	3
NIOSH 5038	TRIPHENYL PHOSPHATE	5
NIOSH 5039	CHLORINATED CAMPHENE	6
NIOSH 5040	DIESEL PARTICULATE MATTER (as Elemental Carbon)	6
NIOSH 5041	CAPSAICIN and DIHYDROCAPSAICIN	5
NIOSH 5042	BENZENE-SOLUBLE FRACTION AND TOTAL PARTICULATE (ASPHALT FUME)	17
NIOSH 5043	p-TOLUENESULFONIC ACID	6
NIOSH 5044	ESTROGENIC COMPOUNDS	3
NIOSH 5046	TETRAKIS(HYDROXYMETHYL)PHOSPHONIUM CHLORIDE	2
NIOSH 5100	CARBON BLACK	1
NIOSH 5500	ETHYLENE GLYCOL	2
NIOSH 5502	ALDRIN, LINDANE	4
NIOSH 5503	POLYCHLOROBIPHENYLS	24
NIOSH 5504	ORGANOTIN COMPOUNDS (as Sn)	3
NIOSH 5506	POLYNUCLEAR AROMATIC HYDROCARBONS by HPLC	24
NIOSH 5508	KEPONE	4
NIOSH 5509	BENZIDINE and 3,3’-DICHLOROBENZIDINE	8
NIOSH 5510	CHLORDANE	9
NIOSH 5512	PENTACHLOROPHENOL	6
NIOSH 5514	DEMETON	2
NIOSH 5515	POLYNUCLEAR AROMATIC HYDROCARBONS by GC	12
NIOSH 5516	2,4- AND 2,6-TOLUENEDIAMINE (in the presence of isocyanates)	4
NIOSH 5517	POLYCHLOROBENZENES	9
NIOSH 5518	NAPHTHYLAMINES, a and b	6
NIOSH 5519	ENDRIN	6
NIOSH 5521	ISOCYANATES, MONOMERIC	4
NIOSH 5522	ISOCYANATES	3
NIOSH 5523	GLYCOLS	27
NIOSH 5524	METALWORKING FLUIDS (MWF) ALL CATEGORIES	9

Method Number	Method Name	Number of accredited laboratories
NIOSH 5525	ISOCYANATES, TOTAL (MAP)	2
NIOSH 5526	METHYLTIN CHLORIDES	1
NIOSH 5600	ORGANOPHOSPHORUS PESTICIDES	7
NIOSH 5601	ORGANONITROGEN PESTICIDES	11
NIOSH 5602	CHLORINATED AND ORGANONITROGEN HERBICIDES (AIR SAMPLING)	6
NIOSH 5605	THIOPHANATE-METHYL IN AIR	1
NIOSH 5606	THIOPHANATE-METHYL IN AIR	1
NIOSH 5700	FORMALDEHYDE ON DUST (TEXTILE OR WOOD)	5
NIOSH 5701	RESORCINOL	6
NIOSH 6001	ARSINE	9
NIOSH 6002	PHOSPHINE	1
NIOSH 6004	SULFUR DIOXIDE	21
NIOSH 6005	IODINE	9
NIOSH 6006	DIBORANE	2
NIOSH 6007	NICKEL CARBONYL	5
NIOSH 6009	MERCURY	33
NIOSH 6010	HYDROGEN CYANIDE	11
NIOSH 6011	CHLORINE	19
NIOSH 6012	SULFURYL FLUORIDE	3
NIOSH 6013	HYDROGEN SULFIDE	20
NIOSH 6014	NITRIC OXIDE and NITROGEN DIOXIDE	9
NIOSH 6015	AMMONIA	6
NIOSH 6016	AMMONIA by IC	8
NIOSH 6017	HYDROGEN CYANIDE	2
NIOSH 6042	PHOSPHORUS TRICHLORIDE	3
NIOSH 6600	NITROUS OXIDE	1
NIOSH 6700	NITROGEN DIOXIDE (Diffusive sampler)	1
NIOSH 7013	ALUMINUM and compounds, as Al	3
NIOSH 7020	CALCIUM and compounds, as Ca	2
NIOSH 7024	CHROMIUM and compounds, as Cr	7
NIOSH 7027	COBALT and compounds, as Co	3
NIOSH 7029	COPPER (dust and fume)	5
NIOSH 7030	ZINC and compounds, as Zn	7
NIOSH 7033	CADMIUM and compounds, as Cd	1
NIOSH 7048	CADMIUM and compounds, as Cd	10
NIOSH 7056	BARIUM, soluble compounds	3
NIOSH 7074	TUNGSTEN (soluble and insoluble)	4
NIOSH 7082	LEAD by Flame AAS	44
NIOSH 7102	BERYLLIUM and cpds, as Be	6
NIOSH 7103	RHODIUM – WITHDARWN METHOD	1
NIOSH 7105	LEAD by GFAAS	8
NIOSH 7300	ELEMENTS by ICP (Nitric/Perchloric Acid Ashing)	54
NIOSH 7301	ELEMENTS BY ICP (AQUA REGIA ASHING)	8
NIOSH 7302	ELEMENTS by ICP (Microwave Digestion)	4
NIOSH 7303	ELEMENTS by ICP	38
NIOSH 7304	ELEMENTS by ICP Microwave Digestion	2

Method Number	Method Name	Number of accredited laboratories
NIOSH 7400	ASBESTOS and OTHER FIBERS by PCM	106
NIOSH 7401	ALKALINE DUSTS, NaOH, KOH, LiOH, and basic salts	6
NIOSH 7402	ASBESTOS by TEM	14
NIOSH 7500	SILICA, CRYSTALLINE, by XRD (filter redeposition)	27
NIOSH 7501	SILICA, AMORPHOUS	1
NIOSH 7502	ZINC OXIDE	2
NIOSH 7505	LEAD SULFIDE	1
NIOSH 7506	BORON CARBIDE	2
NIOSH 7600	CHROMIUM, HEXAVALENT	16
NIOSH 7601	SILICA, CRYSTALLINE, by VIS	1
NIOSH 7602	SILICA, CRYSTALLINE by IR (KBr pellet)	6
NIOSH 7603	QUARTZ in coal mine dust, by IR (redeposition)	4
NIOSH 7604	CHROMIUM, HEXAVALENT (IC)	2
NIOSH 7605	CHROMIUM, HEXAVALENT by Ion Chromatography	6
NIOSH 7607	INORGANIC CHLORAMINES BY IC - DRAFT	1
NIOSH 7701	LEAD BY PORTABLE ULTRASONIC EXTRACTION/ASV	1
NIOSH 7704	BERYLLIUM in Air by Field-Portable Fluorometry	5
NIOSH 7900	ARSENIC and compounds, as As (except AsH3 and As2O3)	1
NIOSH 7901	ARSENIC TRIOXIDE, as As	8
NIOSH 7902	FLUORIDES, aerosol and gas by ISE	9
NIOSH 7903	ACIDS, INORGANIC	36
NIOSH 7904	CYANIDES, aerosol and gas	7
NIOSH 7905	PHOSPHORUS	2
NIOSH 7906	PARTICULATE FLUORIDES and HYDROFLUORIC ACID by Ion Chromatography	13
NIOSH 7907	VOLATILE ACIDS by Ion Chromatography	7
NIOSH 7908	NON-VOLATILE ACIDS (Sulfuric Acid and Phosphoric Acid	6
NIOSH 9002	ASBESTOS (bulk) by PLM	19
NIOSH 9100	LEAD in Surface Wipe Samples	15
NIOSH 9102	ELEMENTS ON WIPES	9
NIOSH 9103	MERCURY ON WIPES, DRAFT	1
NIOSH 9106	METHAMPHETAMINE and Illicit Drugs, Precursors and Adulterants on Wipes by Liquid-Liquid Extraction	1
NIOSH 9109	METHAMPHETAMINE and Illicit Drugs, Precursors, and Adulterants on Wipes by Solid Phase Extraction	2
NIOSH 9110	BERYLLIUM in Surface Wipes by Fluorometry	4
NIOSH 9201	CHLORINATED AND ORGANONITROGEN HERBICIDES (PATCH)	1
NIOSH 9202	CAPTAN AND THIOPHANATE-METHYL in Handrinse	2
NIOSH 9205	CAPTAN and THIOPHANATE-METHYL on Dermal Patch	1
NIOSH P&CAM 205	Ammonia	1
NIOSH P&CAM 236	MOCA	3
NIOSH P&CAM 255	Thiophene	1

Method Number	Method Name	Number of accredited laboratories
NIOSH P&CAM 263	Hexamethylenetetramine	2
NIOSH P&CAM 302	Maleic anhydride	1
NIOSH P&CAM 304	OCBM	1
NIOSH P&CAM 333	Bisphenol A	5
NIOSH S-100	HEXACHLORONAPHTHALENE	1
NIOSH S-146	N-ETHYL MORPHINE	1
NIOSH S-150	MORPHOLINE	5
NIOSH S-155	TETRAMETHYLSUCCINITRILE	2
NIOSH S-166	DI-NITRO-o-CRESOL	1
NIOSH S-181	QUINONE	3
NIOSH S-188	RHODIUM, FUME AND DUST	1
NIOSH S-189	RHODIUM, SOLUBLE	1
NIOSH S-215	DI-NITROTOLUENE	1
NIOSH S-228	PICRIC ACID	2
NIOSH S-257	PHOSPHORUN PENTACHLORIDE	1
NIOSH S-264	ETHYL SILICATE	6
NIOSH S-274	DDT	2
NIOSH S-283	DIELDRIN	2
NIOSH S-347	AMMONIA	2
NIOSH S-385	HYDROGEN CYANIDE	2
NIOSH S-288	VANADIUM	3

Appendix G: NIOSH Methods Development Publications

The citations in black were published by intramural NIOSH scientists and the citations in blue were published by NIOSH grantees. The number of times a publication has been cited as of January 2017 is listed in parentheses at the end of each citation.

2017

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4. Fischer H, Vergara X, Yost M, Silva M, Lombardi D, Kheifets L [2017]. Developing a job-exposure matrix with exposure uncertainty from expert elicitation and data modeling. J Exp Sci Environ Epidemiol *27*:7-15. (2)
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Appendix H: NIOSH Sensor Technologies Publications

The citations in black were published by intramural NIOSH scientists and the citations in blue were published by NIOSH grantees. The number of times a publication has been cited as of January 2017 is listed in parentheses at the end of each citation.

2017

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