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Turning Numbers into Knowledge:

Sensors for Safety, Health, Well-being, and Productivity

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Abstract

The industrial hygiene community has witnessed exponential growth in the use of sensors, especially by individuals. Remote wireless sensors are now monitoring worker health, the environment, agriculture, work sites, disaster relief, and "smart" buildings and facilities.

Sensors hold great promise for empowering workers and improving risk-informed management decisions. But how will we validate and apply the rapidly evolving sensor technologies, some of which have not yet been invented or even imagined?

Our community can take practical steps to transform the incredible promise of sensors into credible industrial hygiene practice. The vision discussed in this article describes how NIOSH is combining an informatics-based mindset with the industrial hygiene decision-making framework (anticipate, recognize, evaluate, communicate, control, and confirm) to apply a comprehensive life-cycle approach to sensor development, validation, and application. Effective partnerships will help us engage the community, inform the interested, reward the responsive, and understand and incentivize the reluctant to develop and apply sensors wisely.

AN INFORMATICS-BASED MINDSET

In a world saturated with information and data, we need to determine not only what can be measured, but what *should* be measured. Industrial hygienists have a rich and successful history of applying direct-reading instruments in the laboratory and the field. We also know the challenges of interpreting and converting "numbers" from such instruments into defensible and actionable decisions.

The concept of "informatics" can help us organize how we seek, create, curate, analyze, and apply modern information. Recent work described in *The Nanoinformatics 2020 Roadmap*, a publication of the National Nanomanufacturing Network, has resulted in a working definition of informatics that we have expanded and adopted for our purposes. We define sensor informatics as

> the science and practice of determining which information is relevant to meeting our measurement objectives; and then developing and implementing effective mechanisms for collecting, validating, storing, sharing, analyzing, modeling, and applying the information; confirming that appropriate decisions were made and that

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Additional information about the Center can be found at www.cdc.gov/niosh/topics/drst.

desired mission outcomes were achieved as a result of that information; and finally conveying experience to the broader community, contributing to generalized knowledge, and updating standards and training.

Successful missions apply all of the steps in the informatics process.

THE IH DECISION-MAKING FRAMEWORK

Our traditional industrial hygiene decision-making framework provides a robust approach to addressing any analytical problem. To determine sensible use of sensors, we can:

- **anticipate and recognize** specific situations where real-time monitoring might contribute to improved assessment of exposures, hazards, and resulting risks
- **evaluate and communicate** options for the development, validation, and use of methods, including considerations for the temporal and spatial deployment of monitors and the collection, quality assurance, and interpretation of associated data
- **control and confirm** the effective implementation of all aspects of the sensor life cycle to meet critical objectives from research to routine practice and regulatory compliance

SENSOR DEVELOPMENT AND USE

The recent launch of the NIOSH Center for Direct Reading and Sensor Technologies has created a home for NIOSH's longstanding work in the area of exposure assessment devices—work that has historically been performed across the Institute. In addition, the National Research Council's 2012 report *Exposure Sciences for the 21st Century* identifies direct-reading methods and monitors as important drivers for the future of the exposure sciences. And AIHA has indicated that it will prioritize research in sensor technologies as part of its new content portfolio (for more information, read Barry Graffeo's article "Six Priorities for IH Content Development" in the November issue at http://bit.ly/graffe01114).

Both the NIOSH Center for Direct Reading and Sensor Technologies and the National Nanotechnology Initiative are applying a life-cycle approach to sensor development and use (see Figure 1). The life cycle encompasses twelve distinct phases throughout an instrument's journey through concept development, testing, training, maintenance, and evaluation.

Mission evaluation is the first step of the life cycle. This step serves the role of "problem formulation" as described in the National Research Council's 2009 publication *Science and Decisions: Advancing Risk Assessment.* Mission evaluation for sensors defines the objective and context of the measurement, including constraints such as size, cost, the user's abilities, and the setting (where and when the instrument will be used). What concentrations must candidate technologies be able to measure? What interferences must be dealt with? If there is an "incumbent" technology, why is it no longer deemed adequate? Clear thinking and analysis at the mission evaluation step make the science and business case for the instrument.

The **research and development** step investigates the ability of a specific technology or instrument design to meet the mission requirements. If a new "lab-on-a-chip" technology has been demonstrated for one family of chemicals, can it be adapted for other applications? Is the technology likely to meet the required level of detection and the needed duration of performance? Understanding such requirements and opportunities can enable manufacturers to produce a sensor that is likely to meet the engineering requirements set in the mission evaluation step.

Prototype testing and **type testing** define and document the actual performance and limitations of the sensor. Input from field industrial hygienists during mission evaluation can specify realistic test requirements for these steps. The major difference between prototype testing and type testing is that type testing involves formal requirements for the sensor to meet performance or procedural specifications set by national or international standards. Few existing instruments or methods have formal ANSI, ASTM International, AIHA, governmental, or other testing procedures. Additional guidance is needed.

Production control testing ensures that manufactured sensors meet requirements for enhanced reliability and performance in accordance with documented procedures for quality management and assurance. Do all sensors and sensor features need to be tested at the manufacturing stage, or will testing a representative sample suffice?

Training is a crucial cross-cutting step conducted at each phase of the life cycle. This step is a consideration for both instrument developers and instrument users. Effective stakeholder engagement from field industrial hygienists and managers about the realities of instrument use and interpretation is essential to ensuring that training is both relevant and reliable.

An organization that is using a new instrument will conduct **acceptance testing** upon receipt of the instrument. Did it arrive in an undamaged state, with all appropriate documentation? Appropriate attention at the mission evaluation step should ensure that the details of instrument configuration and operation are compatible with the capabilities of those who will actually use the instrument.

Initial calibration may be performed as part of production control testing, but is generally performed after acceptance testing and before initial use of the instrument. How does the instrument work at the temperatures, pressures, humidity, and interferences of actual use? Are relevant calibration conditions or atmospheres available, affordable, and reliable?

Functional checks determine that an instrument is operational and capable of performing its intended function at the actual time of use. Many modern software and firmware packages have automatic diagnostics and self-checking features. Such features are especially valuable for single-use sensors. Unfortunately, many single-use sensors have limited or no self-checking capability and may require extensive quality assurance testing.

Operational experience involves careful tracking and evaluation of actual measurement experience to ensure proper instrument operation and interpretation of results. Are measurements consistent? Do concentrations for similar activities vary by time of year, possibly indicating unwanted influences of seasonal environmental conditions? How can the deployment of more sensors with faster response times improve both the control of hazards as well as the assessment of worker exposure and the characterization of cumulative risk for both workers and members of the public? How can brief temporal peaks or varying spatial concentrations be interpreted and responded to in a manner that reflects actual health and safety considerations? What advances in modeling and understanding will be required to translate "more numbers" into "more knowledge and wisdom"?

Maintenance and calibration ensures that sensor components, including replacement parts or alterations, have been successfully integrated in the supply chain and are equivalent to those specified by the manufacturer. Modified sensors, in particular, would require additional performance tests and documentation prior to issuance for field use, unless the modifications are shown not to affect the instrument performance or intended use for regulatory purposes.

Periodic performance testing ensures that the sensor continues to provide adequate performance under intended and actual conditions of use, including the hazards' changing composition or concentrations and associated exposures. Have process or environmental conditions changed in ways that can render the sensor unworkable or the measurement irrelevant?

PARTNERING FOR SENSOR SUCCESS

Our community must keep abreast of new sensor technology advancements and adapt those developments for the workplace. One of NIOSH's core missions is to establish and maintain leadership in all aspects of worker exposure assessment, including direct-reading and sensor technologies. The initial activities of the NIOSH Center for Direct Reading and Sensor Technologies focus on coordinating a national research agenda, developing guidance documents such as validation and performance characteristics, developing training protocols, and establishing partnerships to collaborate in the Center's activities.

A recent example of sensor-related work at NIOSH involved the evaluation of smartphone sound measurement apps. The potential to turn every smartphone into a sound-level meter or dosimeter can have tremendous influence on noise research and noise control in the workplace. The study, published in the *Journal of the Acoustical Society of America*, found that the quality of the smartphone microphone makes a significant difference in the accuracy of these apps. (Further details are available from the NIOSH Science Blog at http://bit.ly/noiseapps). NIOSH researchers have expanded the study to examine the performance of smartphone sound measurement apps with external microphones that comply with the OSHA minimum requirements for general purpose noise measurements (that is, microphones that are ANSI Type-2 compliant, or accurate within 2 dB). Results of the expanded study will be published shortly. In addition, NIOSH is developing its own sound measurement app and will make it available to the public.

Another recent sensor development example is related to concerns about respirable dust in mining. The personal dust monitor (PDM) is a real-time dust monitor developed by NIOSH over the last decade. Extensive NIOSH testing has demonstrated that the PDM is an accurate dust sampler, and MSHA has specified that the PDM will be used for compliance dust sampling in its new respirable dust regulations, which have just completed the final stages of the rulemaking process. The PDM is a success story for research-to-practice efforts and for sensor technology. Additional information about the PDM can be found at http://bit.ly/respirabledust.

An exciting current partnership funded through the NIOSH extramural grant program is development at the University of Michigan of a belt-worn monitor to detect volatile organic compounds. Current extramural research grants in the area of sensors include biosensors for different chemical exposures, wearable monitors for a variety of work sites, monitors that can be used in exposure characterization for ultrafine and nanoparticles, and noise dosimeters. Information about funding opportunities provided by the NIOSH Grants Program can be found at http://bit.ly/nioshgrants.

We invite you to partner with us to identify gaps in our knowledge and to create research strategies for reliable development, validation, use, and interpretation of direct-reading and sensor technologies. These technologies can better characterize cumulative risks and empower employers and workers to help reduce harmful exposures and become active partners in preventing occupational illnesses and injuries.

Biographies

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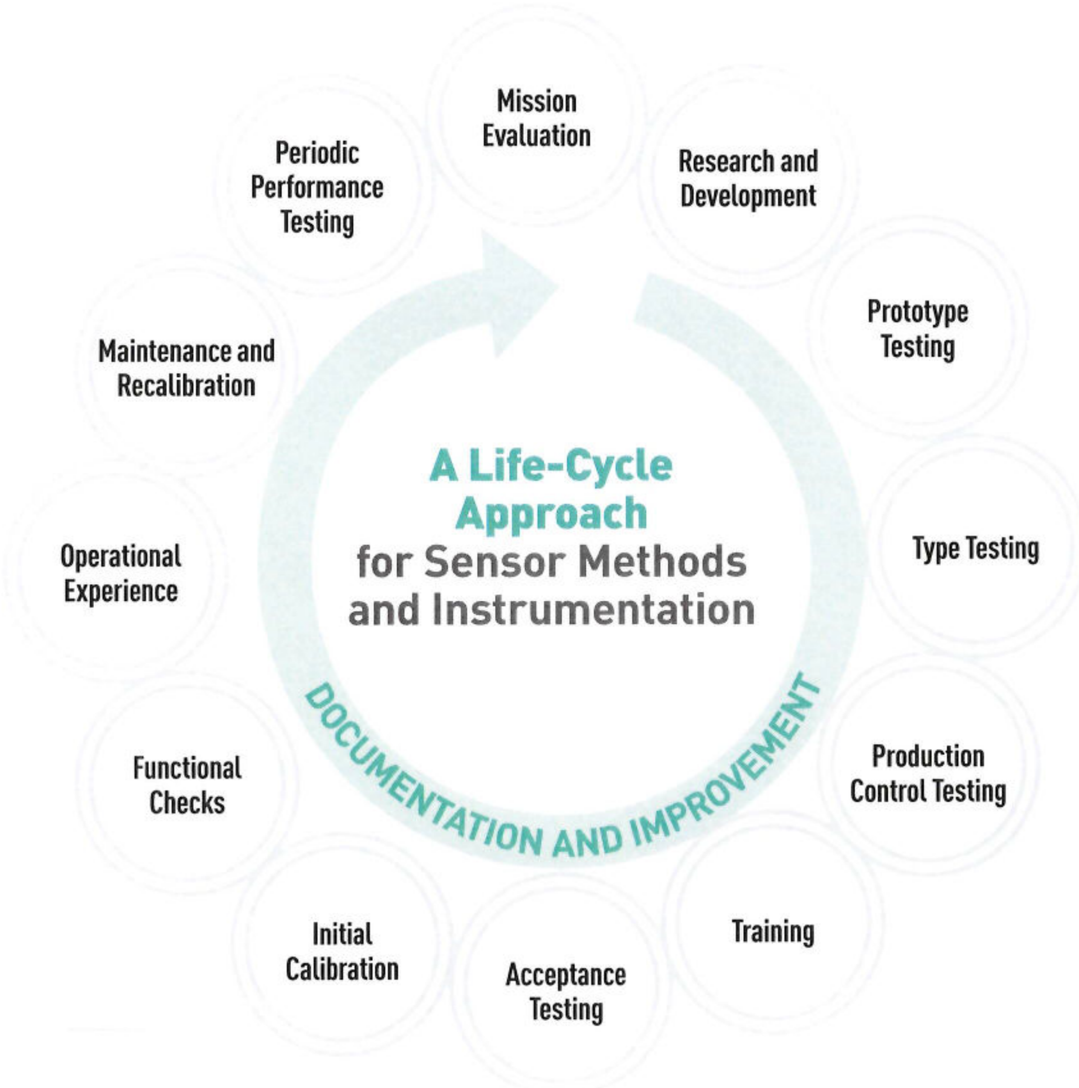

Figure 1.

Life-cycle stages for development and application of sensors.

Source: A Life-Cycle Approach for Development and Use of Emergency Response and Health Protection Instrumentation.