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Real-Time Exposure Assessment and Job Analysis Techniques to Solve Hazardous Workplace Exposures

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I. INTRODUCTION

This chapter discusses real-time exposure assessment techniques to solve workplace hazards. Two case studies illustrate useful equipment and techniques for controlling problems of dust and gas exposure in industry. These case studies also show how integrating ergonomic and industrial hygiene principles pinpoints exposure sources and provides effective solutions.

Industrial hygienists often measure a worker's exposure to industrial contaminants by sampling the air he or she breathes. A small, battery-powered pump draws a known flow rate of air through a filter or other collection medium for a measured period of time. The collection medium is analyzed to quantify the contaminant collected and to compute the average exposure for the sampling period. Although these results indicate the extent of exposure, integrated air sampling provides little insight into the specific causes of the worker's exposure. Recommendations for controlling air contaminant exposures are often based upon the industrial hygienist's judgment and can result in control measures that do not address the major air contaminant exposure sources. Direct-reading instruments and data-recording devices can overcome the problem by recording events and exposures in the workplace as a function of time. The data from such a system associates events and exposures, and promotes more effective and focused recommendations for controlling the air contaminant exposures.

Through studies conducted in a variety of industries, researchers with the National Institute for Occupational Safety and Health (NIOSH) have developed a systematic approach to identify the sources of workplace exposures and to provide an effective means for communicating these results to workers and management [2–5]. This system employs:

Direct-reading instruments and data-recording devices to monitor and store data characterizing worker exposures
Video cameras and recorders to document worker activities
Task analyses to evaluate work activities
Statistical techniques to develop predictive models and to summarize the results
Personal computers to perform analyses on the data and to combine the activity data and the exposure data into a presentable form

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This chapter is largely condensed from a NIOSH technical report [1].

The present system evolved from a series of studies, conducted either to evaluate the effectiveness of engineering controls or to identify characteristics of worker exposures. Direct-reading instruments permitted researchers to monitor exposure changes over short intervals (on the order of seconds). The output from these instruments was stored in an electronic recording device, rather than on a strip chart recorder, so that the data would not require rekeying for statistical analysis. Workers' activities were documented by video-recording systems to determine whether exposures were the result of particular work practices. Work activity data were combined with the real-time exposure data by determining both the exposure and the activity at any given time. Time series analysis of the combined real-time and work activity data set resulted in a model to predict worker exposures. After several studies, however, it became apparent that time series analysis could become a prohibitive task because of processing the tremendous amount of data that can be collected over a very short period. To ease this problem, several simplified analysis techniques were developed. Although these techniques were not as powerful as the time series analysis, they identified those activities that contributed the most to the worker's contaminant exposures.

During completion of the initial studies, a need became obvious: communication of the study results to workers and management. The consensus among the studies' researchers was to provide the facility with a video recording of the work activity, combined with a display of the real-time exposure measurement. The exposure data could be presented in two forms on the video screen: numerically, with the value of the exposure measure displayed, or graphically. Both options were exploited by displaying both the numerical exposure concentration and a bar representing the relative magnitude of the exposure. To place the bar and number on the video screen, a computer program read the exposure data file and generated and updated the bar with time. The system required the use of consumer-quality video and ordinary personal computer equipment; the only specialized equipment required was a special graphics card for the personal computer. The result was a video recording that graphically showed how exposure to a particular substance was affected by activities of the worker.

II. VIDEO EQUIPMENT

Two types of video equipment were used: conventional video equipment for documenting the worker's activities and infrared video equipment for visualizing specific air contaminant plumes. Conventional equipment is used for conducting video exposure monitoring; infrared equipment is used with direct-reading instruments to characterize workplace contaminant concentrations.

A. Conventional Video Equipment

The conventional video recording system consists of a video camera and a videotape recorder. A camcorder, having both capabilities, provides better portability. Mounting the video camera onto a tripod eliminates the need to hold the camera throughout the process. The tape format (Beta, VHS, 8 mm) is not important, and many consumer-quality video recording systems are suitable for video exposure monitoring. There are, however, two important requirements. First, the video system must have a National Television System Committee (NTSC) standard video output signal—a signal used by the video overlay system described in Section V in this chapter. This standard is used by most home video equipment. Second, an on-screen clock or timer is needed—one that can be synchronized with the real-time clock of the data-recording device. Synchronizing the data-recording device with the video camera can be as simple as starting the timer in the camera at the same time the data logger is turned on.

The clock or timer should have a resolution of at least 1 second. The on-screen clock permits an exposure to be coordinated with an associated activity. The video recording of the work cycle or process can then be reviewed while simultaneously tracking the worker's exposure from a printout or plot of the real-time exposure data.

B. Infrared Video Equipment

Effective control of air contaminants depends on understanding the characteristics of their release. It is important to know not only the concentration but also the source and path of the emission. Although some gasses and vapors are visible, most are not. Infrared (IR) imaging is a technique that can provide a real-time picture of some otherwise invisible emissions.
A schematic of such an infrared imaging system is presented in Figure 1. An IR scanner (Thermovision 782) [6] detects changes in absorption of infrared radiation by contaminant gases or vapors. Two versions of the scanner may be used, depending on the range in which the gases absorb infrared radiation: a shortwave band (2–5.6 microns) and a longwave band (8–12 microns). The images received by the scanner are transmitted to a display unit and may be converted from the normal infrared gray-scale image to a colored scale. This image is then simultaneously transmitted to a monitor and video recorder for real-time viewing and recording.

The system uses a flat, black panel as an infrared radiator. The panel is a square, 2-in.-thick, aluminum tank filled with water. A flat-sheet electrical heater is glued to the back surface of the tank; the front surface is painted black. An electronic temperature controller maintains the tank at a constant temperature (120°F). The water in the tank is circulated by a laboratory stirrer to inhibit the formation of a temperature gradient across the panel surface.

The radiant panel and the infrared scanner are positioned so that the emission source is between them. The scanner sees the panel as a constant temperature source and displays it as a uniform image. As a contaminant gas passes between the scanner and the heat source, it absorbs some of the radiated infrared energy. The scanner detects the gas as a lower temperature, which is then displayed as a different color or shade of gray and recorded.

This system is useful for detecting certain process emissions because it provides a real-time image that identifies both the source and path of the emissions. Medical processes, such as the release of nitrous oxide (N_2O) during dental surgery, and industrial processes can be monitored. Also, the IR imaging system, using tracer gas, can determine flow patterns around
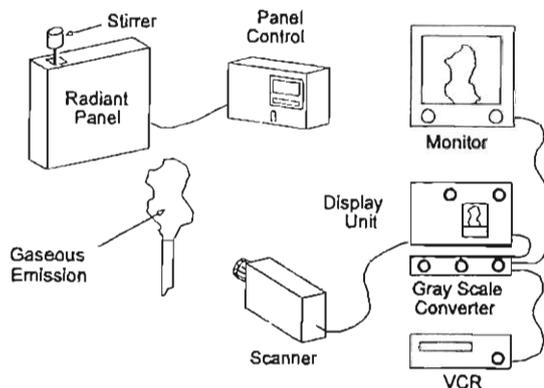

Figure 1 Infrared imaging system.

exhaust openings. This technique has the advantage that the effect of specific work activities or changes in control configuration can be determined immediately.

The most important limitation of this system is sensitivity. The absorption of the emission cloud is related directly to the concentration of the emission and the path length through the cloud. Thus, lower concentrations must be present in greater quantities to be visualized. For example, the sensitivity for N_2O is on the order of 200 ppm meter, i.e., a cloud of nitrous oxide having a concentration of 200 ppm must be more than 1 m in diameter to be detected. System sensitivity can be increased by the use of narrow band pass filters that filter radiation falling outside the narrow band containing the absorption peak of the monitored contaminant. The high concentrations typical of the emission generation point can generally be visualized using this system. Detection of contaminants at lower concentrations typical of the range recommended by occupational health standards is, however, limited. Another limitation of the system is lack of portability. Because the radiant panel is a water-filled tank, it is quite heavy ($\sim$55 lbs) and not easily positioned. Although this is not a severe limitation for laboratory use, it does make field operation difficult.

Some of these limitations are addressed by recent advances in thermal imaging technology. A system that uses a laser in combination with the infrared scanner to detect changes in energy is now available. The laser scans the viewed object, thus eliminating the need for a radiant panel, greatly increasing portability, and making the system much more convenient for field use. This system also has a sensitivity approximately one order of magnitude greater than the one previously described.

III.   MONITORING EQUIPMENT

Any air contaminant-monitoring instrument that produces an output signal of the concentration measurements can predict real-time assessments of a worker's exposure to an air contaminant. The usefulness of a specific instrument will vary with the situation. To evaluate the utility of an instrument, consider: (1) the nature of the analog or serial output, (2) the response time of the instrument, (3) specificity for the contaminant of interest, and the instrument's (4) portability and size.

A.   Output

The collection of real-time concentration data to evaluate the relationship between events in the workplace and air contaminant concentrations generally must to be recorded automatically. For a monitor to be useful, it should produce a digital or analog output, the latter often being voltage that is proportional to concentration. Techniques for recording analog data are given in Section VI, "Data Acquisition." Some instruments also provide a digital output that is periodically updated. The frequency of these concentration measurements is usually a function of the instrument and normally cannot be adjusted by the user.

B.   Response Time

The total system response time (for the monitor and the setting being evaluated) can be defined as the sum of (a) the time required for the air contaminant to be transported to the worker's breathing zone and begin to accumulate and (b) the time required for the instrument to respond to a change in concentration in the worker's breathing zone. To conduct video exposure-monitoring studies of air contaminant concentrations, the total system response time

must be less than that of the events of interest. As a result of the response time delays, the instrument output lags behind work events in the workplace.

Monitoring instruments often measure some general parameter that is proportional to concentration. For example, aerosol photometers respond to any aerosol that scatters light. Such a limitation requires either that the monitor be calibrated for the specific air contaminant being measured or that the results be reported as a relative concentration.

C. Portability

To allow for worker acceptance, the monitoring equipment should be light enough to be worn comfortably. The equipment should be battery-operated and should weigh as little as possible. If workers cannot wear the equipment, tubing can transport the air contaminant from a worker's breathing zone to the instrument. This arrangement, however, adds some complications. The monitoring system's response time will increase because of the time needed to transport the air contaminant through the tube to the monitor. In addition, aerosols and contaminants can be lost to the tubing walls and other collecting surfaces. If the tubing is later struck or vibrated, these contaminants can be released and may contribute to the instruments' signal. Organic vapors can be adsorbed onto the tubing walls during periods of high concentration and desorbed during periods of low concentration.

Users need to consider the limitations and capabilities of the direct-reading instruments when designing and conducting studies to yield useful information about exposure sources. Background information on these instruments can be obtained from *Air Sampling Instruments*, by the American Conference of Governmental Industrial Hygienists (ACGIH) and the NIOSH Manual of Analytical Methods (NMAM) [7,8].

IV. PERSONAL COMPUTER SOFTWARE

Several types of software collect and analyze real-time exposure data. Control software operates an analog-to-digital converter card, and communications software downloads portable data loggers. Spreadsheets are valuable for manipulating real-time exposure data, as well as for performing some simple analyses. For more sophisticated data analyses, full-function statistical analysis packages may be required. In addition, if the exposure data are to be combined with a work activity video recording, a customized computer program can be used to generate a graphical representation of the worker's exposure.

Control software operates the analog-to-digital converter that is either a card located in the computer or a stand-alone system with an interface to the computer. These software packages usually require special device drivers for the particular hardware system in use. Many of these control packages can process the real-time data during collection, and some packages provide limited data analysis capability. Besides collecting data from an analog source (a direct-reading instrument, for example), control software can also instruct the computer to send out signals, although this function is beyond the scope of this chapter.

Configuring the analog-to-digital system is normally done by menu-driven software. Many of the software packages allow readings—graphical or tabular—to be displayed on the computer screen as the data are being collected. Once data collection is complete, the readings are stored in a data file. Some programs link directly with a spreadsheet program, making it possible to save the data in a spreadsheet file. For other programs, the data are stored in file formats that can be imported into the spreadsheet. There are several different control programs with many different functions and capabilities. Two specific packages are Labtech

Notebook (Laboratory Technologies Corporation, Wilmington, MA) and ASYST (MacMillan Software Company, New York, NY). Both of these programs work with a variety of analog-to-digital converter cards.

   If a portable data-recording device (data logger) records the real-time exposure data, control software is not needed. Instead, a program to download the data logger to a personal computer is required. Downloading software either comes complete with most data loggers or is available for an additional cost. After the data logger is downloaded, some programs allow simple data analysis to be performed. Many of these programs store the data in a file that can then be imported into a spreadsheet program. In addition to the programs supplied with the data loggers, there are communications programs such as Crosstalk (Crosstalk Communications, Roswell, GA) and Procomm (Datastorm Technologies Inc., Columbia, MO) that can download some data loggers through the computer's asynchronous communications port. Communications programs may require nonstandard use, since the format of the data from the data logger may vary with the device.

   After the data have been collected and stored in a file, spreadsheet programs can manipulate data and do simple data analysis. Lotus 1-2-3 (Lotus Development Corporation, Cambridge, MA) and Microsoft Excel (Microsoft Corporation, Redmond, WA) are examples of two spreadsheet programs. If the data are to be analyzed by worker activity, a spreadsheet is useful for keying activities with the real-time exposure data: a researcher must determine the time a particular reading was recorded and then observe the worker's activities for that time on the video recording of the work activity. Spreadsheets not only sort data and perform elementary statistical analysis but also format data sets for analysis in a statistical analysis program, or combine the work activities and the real-time exposure data onto videotape.

   To combine the real-time exposure data with the video recording of the worker's activities, NIOSH researchers have written a program for IBM-compatible computers that generates a graphical representation of the worker's exposure [1,9,10]. This IBM-compatible program reads a real-time data file, generates a bar to represent the magnitude of the exposure, and then displays the bar on the screen. When this program is run through a video overlay system, a video recording graphically shows how a worker's exposure is influenced by the work activity. The video overlay system is discussed in Section V, "Personal Computer Hardware." The bar is updated with each time interval of readings in the data set. The program allows either one or two bars to be displayed on the screen at one time. Two bars can be displayed if the exposures of two workers are to be compared, or if one worker is monitored with two different instruments. To use the program, the real-time exposure data must be stored in a properly formatted ASCII file. For the program to display one bar, the format of the data file must have three columns of data: two columns for the time the reading was recorded (minutes and seconds) and one column for the exposure measurements. For the program to display two bars, the data file format must have an additional column for the second exposure measurement. The first data set is displayed on the left side of the screen, whereas the second data set is displayed on the right. The time interval between the readings must be constant. The spreadsheet program arranges the data file into the proper format. and generates a bar that is overlaid onto the work activity video recording by a video overlay system.

V.   PERSONAL COMPUTER HARDWARE

The computer hardware required for collecting and presenting real-time data is fairly basic. Specialized equipment is required only for combining the graphical exposure bars with the video recordings of the work activity or for running a computer-based analog-to-digital con-

verter system. The basic computer system used by NIOSH researchers is an IBM PC–compatible personal computer. The computer should have sufficient memory (i.e., 4 megabytes) and a hard disk drive. Additional memory (i.e., 4–12 megabytes) may be desirable to improve performance if unusually large data sets (i.e., 1200 readings) are to be manipulated in a spreadsheet. If the real-time exposure data are not going to be combined with the video recording of the work activity, then the type of graphics card is not critical. If data loggers are to be downloaded to the computer, an asynchronous (serial) communications port is required (most computers are sold with this port as standard equipment).

Computer-based analog-to-digital converters are special cards that fit into an expansion slot of the computer. Special software drivers and control programs may be required to operate this board. Section VI, "Data Acquisition," contains more detailed descriptions of the analog-to-digital converter systems.

To overlay the real-time exposure data with the video recording of the work activity, the computer will need either an enhanced graphics adapter (EGA) card and a video overlay board, or a variable graphics array (VGA) card with the overlay features built in. A monitor appropriate for the graphics card also is needed. Both VGA and EGA are high-resolution color graphics adapters, with VGA having slightly higher resolution.

If an EGA card is used, it must be combined with a video overlay system. One such system, the Video Charley (Progressive Image Technology, Folsom, CA), consists of a single computer card. The Video Charley requires the EGA card to have a standard features connector (most EGA cards do). The features connector links the video overlay board with the computer. The video overlay board converts the computer's graphics signal to an NTSC signal and overlay the graphics onto the activity video recording. Besides the features connector, most EGA cards also have a DB9-pin connector for the EGA monitor and two RCA-type connectors. Under normal circumstances (without the Video Charley), the two RCA connectors serve no function. With the Video Charley board installed, however, one RCA connector inputs the activity video signal, and the other outputs the video signal with computer graphics overlaid.

When overlaying computer graphics using the Video Charley, signal differences require the computer display system to operate at a resolution of 640 × 200 pixels, rather than at the typical EGA resolution of 640 × 350 pixels. To combine the activity video signal with the computer graphics signal, the two signals must have the same synchronization frequencies. In the case of the video signal, an NTSC signal, the horizontal sync frequency is 15.7 kHz and the vertical sync frequency is 60 Hz. In the 640 × 200 pixels mode, the horizontal and vertical sync frequencies are also 15.7 kHz and 60 Hz, respectively. In the 640 × 350 pixels mode, the vertical sync frequency is 60 Hz; however, the horizontal sync frequency is 21.8 kHz. To get both signals at the same horizontal sync frequency, the computer graphics card must operate at the lower resolution mode. Depending on the type of EGA card used, either software drivers or hardware switches can set the resolution.

If the VGA option is chosen, an appropriate VGA card is required. Two such cards are the USVideo VGA/NTSC Recordable® graphics card with the Genlock Overlay Module (USVideo, Stamford, CT) and the Willow Peripherals VGA-TV GE/O® (Willow Peripherals, Bronx, NY). These two systems allow computer graphics to be overlaid onto video images at a higher resolution than does the EGA system with the Video Charley. To overlay on VGA systems, only one setting needs to be changed to direct the card's output to the video monitor: on the USVideo card, this is done with a hardware switch; on the Willow Peripherals card, a software program is run. Both cards have two RCA-type ports, one for video-in and one for video-out. The cabling setup, shown in Figure 2, is the same for both the EGA/Video Charley and the VGA systems. Operation of the VGA overlay system is similar to the normal use of the computer, except that the video monitor (connected to the video-out RCA-type port) is the primary monitor.
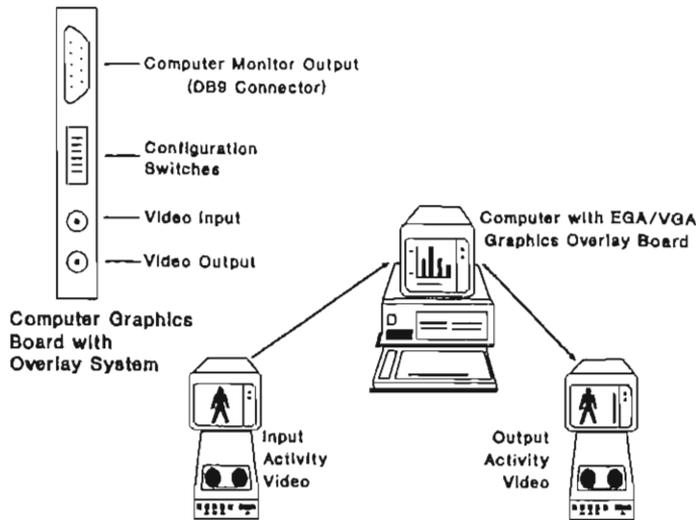
Figure 2 Diagram of personal computer system equipment and connections needed to overlay exposure data with work activities.

VI. DATA ACQUISITION

Many direct-reading monitors have analog output capability, usually in the form of a DC voltage signal, typically on the order of 1–10 V, full scale. Before the proliferation of the personal computer, this analog output typically drove a strip chart recorder. To perform data analysis with a computer, the data from the strip chart was keyed into the computer—a tedious process. With advances in personal computers, the analog output from these monitors can now be stored digitally, allowing the data to be transferred to the computer in just a few easy steps.

Data-recording devices generally fall into two categories: portable data loggers and computer-based analog-to-digital (A/D) converter systems. Both types of devices have a limited resolution over their working voltage range. Depending on the type, the device has either a fixed voltage range (0–2 V, for example) or a working range that can be chosen with hardware switches or control software. This working range is then broken down into intervals. Resolution of a data-recording device is usually given in bits. For example, the working range of 0–2 V for an 8-bit data logger consists of 256 intervals. The number of intervals is determined as follows:

$$\text{Number of intervals} = 2^{\text{bits}} \tag{1}$$

The magnitude of these voltage intervals is calculated from

$$V_I = \frac{V_U - V_L}{N} \tag{2}$$

where
V_I = Interval, V
V_U = Upper working range, V
V_L = Lower working range, V
N = Number of intervals

For the example of an 8-bit, 0- to 2-V working range, there must be a difference of at least 0.008 V for the data-recording device to detect a difference between two voltage readings. In most instances, an 8-bit device should be sufficient. Data loggers are typically 8-bit devices, whereas A/D converters range from 8 to 16 bits; 12-bit boards are very common.

Computer-based systems store the data directly onto the computer's hard drive or onto a disk drive. These systems require software programs to control the parameters. Depending on the program, the exposure measurements can be displayed on the computer screen as the data are being collected. Computer-based A/D converter systems are more flexible than portable data loggers. Computer-based systems are usually more expensive; A/D boards can cost $1000 or more and the control software can cost another $1000.

Portable data loggers store the data in a built-in bank of memory. After data collection, the data logger must be downloaded to the computer, typically through the computer's communication port. A general communications program or a program written specifically for downloading a particular data logger can control the downloading procedure. Most data loggers have parameter-setting programs built in and require no additional control software and most display only limited amounts of data while recording. Since the data logger is likely to be fastened to a worker, observation of the data as it is being generated is not feasible. Portable data loggers, including downloading software, can be purchased for as little as $500.

A hybrid of the A/D systems and the portable data loggers is a telemetry system. Telemetry systems use a transmitter and receiver to transfer data from an instrument to a base unit for storage. The base unit may include a personal computer and may allow the data to be displayed as it is being generated. As with portable data loggers, telemetry systems do not require a worker to be tethered to a computer. Unfortunately, most commercially available telemetry systems tend to be expensive (i.e., > $10,000) [11].

VII. WORKER ACTIVITY ANALYSIS

Activity analysis is an important step in video exposure monitoring because such an analysis helps catalog work activities. This systematic method breaks a complex job into its elements, permitting study of and improvements in a specific task. More importantly, these elements can be sorted so those contributing most to a worker's air contaminant exposure can be dealt with first.

The first phase of activity analysis is a time-and-motion study, which determines the work content of the job. Time-study and production records, as well as timed observations, provide the necessary interval data. Managers, supervisors, and workers can provide job descriptions and demonstrations from which to determine tasks. A job is described as a set of tasks, with each task consisting of a series of steps or elements [12], that is, the fundamental movements or acts (reaching, grasping, moving, positioning, using, etc.) required to perform a job. Groups of elements making up a task (or an activity) are usually performed in the same sequence to accomplish a common end. Examples of tasks might include the following: "turn on machine," "operate machine," and "cleanup." By observing the job or slow-motion video recordings of that job, the researcher identifies the elements composing a task. Gilbreth suggested that formal element definitions are arbitrary in that one can increase or decrease detail as necessary. For example, "get" adequately describe the process of "reach-grasp-move," and "put" works well for "move-position-release" [12].

The second phase of activity analysis is an actual review of the job for recognized occupational risk factors that may cause excess exposure to air contaminants. If a trained investigator can record the risk factors as the worker is performing the job, this analysis can

be done at the worksite. A more thorough analysis can be done, however, by viewing the video recording of the worker's activities. The clock or timer in the video camera documents the time it takes the worker to perform the various activities. The clock or timer also allows activities to be studied as changes occur in the air contaminant exposure as measured by direct-reading instruments. When evaluating air contaminant data, the researcher needs not analyze the job in more detail than what the real-time exposure data can reveal. For example, if the response time of the instrument measuring the air contaminant exposure is longer than the time required to complete a set of tasks being video-recorded, then analysis of those individual activities is of little value, and they should be combined into a "principal" activity. This principal activity can then be studied with regard to air contaminant exposure.

VIII. DATA ANALYSIS

To perform data analysis, researchers must combine worker exposure measurements and descriptions of events in the workplace into a single data set. Descriptive statistics describe the contribution of workplace events to a worker's air contaminant exposure. In addition, statistical analysis evaluates whether workplace events significantly affect exposure. The findings of the data analyses help to focus control measures upon actual sources of worker air contaminant exposure.

A. Transportation Lag and Autocorrelation

As a prolog to data analysis, an appreciation is needed of how events in the workplace affect the contaminant concentration measured by an instrument. Consider a worker standing at a workstation. Turbulence in front of the worker transports the air contaminant from a source at the workstation into the worker's breathing zone. If it takes 2 sec for the air contaminants to travel from the source to the worker, the concentration in the worker's breathing zone does not start to change until 2 sec after the event has occurred. In statistical terms, the concentration is said to lag behind the workplace events. This can be referred to as transportation lag. The actual magnitude of this lag can be estimated by observation and measurement, or it can be addressed in the selection of a statistical modeling and data analysis package.

After the air contaminant has been transported into the worker's breathing zone, the direct-reading monitor begins to respond to the changing concentration. A monitor with a time constant of 1 sec would require 3 sec to complete 95% of the change in response to an abrupt change in concentration. Because of the dynamics of the monitor's response, the measured concentration at any moment in time is a function of the concentration in the preceding time intervals. This phenomenon is called autocorrelation.

B. Assembling the Data Set

Concentration measurements from a direct-reading instrument are recorded and stored by data-logging devices. Because the software written for controlling or downloading data-logging devices has limited data analysis capabilities, real-time concentration data can be imported into a spreadsheet program for manipulation and data analysis. Many of the downloading or control programs include utilities for storing the real-time concentration measurements in a *print file*

that can be imported into the spreadsheet. (A print file is a text file in ASCII format that can be printed directly by the operating system's print command.) The interval between the concentration measurement readings is set either before the data are recorded by the data-logging device or when the data are stored in the print file.

The real-time exposure data are loaded into the spreadsheet using the "import" command. (The name of this command may vary from program to program, but the command loads a print file.) The print file loaded into the spreadsheet may contain several columns of numbers, depending on the type of data-logging device used. These columns may include several time columns (elapsed time, clock time, etc.), event markers, and concentration measurements. The data can be manipulated in the spreadsheet to create a data set that includes only two columns, one for the real-time concentration measurement and one for the time the readings were recorded. This time reading can be elapsed time or clock time, depending on how the data-logging device was synchronized with the video camera's clock or timer.

After the time and concentration readings have been isolated, work activity variables can be added to the spreadsheet. The video recording of the work activities can be viewed while tracking the worker's exposure in the data set. From this recording, the worker's activities can be defined in two different ways: so that only one activity can occur at any given time, or so that any one of several activities can occur at any given time. For each concentration measurement, the activity can be coded into the data set in one of several ways, depending on how the activities were defined and on the type of data analysis to be conducted. Two methods are frequently used: (1) to enter the activity as a single variable with a different value for each activity, or (2) to enter each activity as a separate variable, with one value if the activity occurs, and another value if it does not occur ("1" and "0," for example). If the activities are defined such that only one activity can occur at a time, the single-variable method is usually more appropriate since it will result in a smaller data set than if each activity were to be entered as a separate variable. If, however, several activities can occur at a time or if data analysis involves using a spreadsheet program to perform multiple regression, then each activity is usually entered as a separate variable. If the activities were entered using the single-variable method, a different value would be needed for every combination of activities.

As discussed earlier, the air contaminant concentration lags behind the causal activities because of the time required to transport the air contaminant from the source to the monitor. If the transportation lag is not addressed by a statistical analysis package, the air contaminant concentration measurements can be "slipped" with respect to the worker activity variables, after the researchers estimates the magnitude of the lag. The lag time matches the worker's activities with the associated air contaminant concentration measurements.

C. Data Analysis Techniques

After the data set is assembled as a time series, it can be analyzed to determine the effect of workplace activities on changes in worker air contaminant exposures. Autocorrelation considerably complicates (1) statistical analysis for modeling worker exposures and (2) examination of whether the worker's activities are affecting the air contaminant exposures. When conducting statistical analysis, researchers should compare the extent of the changes in exposure attributing to a worker's activities with the variability of the exposure data. When the changes in exposure are large with respect to the exposure data variability, one can conclude that the activities significantly affect the exposure. Autocorrelation can cause the variability of the exposure data to be underestimated during regression analysis and analysis of variance. Thus, autocorrelation can cause these two data analysis techniques to overstate the level of

confidence in the conclusion that workplace events affect the worker's exposure. Special techniques, called time-series analysis, have been devised to deal with autocorrelated data.

A variety of techniques are available to analyze real-time data and deal with autocorrelation, but because of the time and complexity required to deal with autocorrelation, descriptive statistics are commonly used instead. For a quantitative evaluation of whether activities are causing air contaminant exposures, autocorrelation in the data can be addressed either by censoring the data to remove autocorrelation or by performing time-series analysis. At times, too much information is lost when the data are censored to remove autocorrelation. Time-series analysis methods can evaluate the relationship between the worker's activities and air contaminant concentrations without censoring the data set [13]. Because time-series analysis can be very complicated, the assistance of a statistician may be needed.

Descriptive statistics can aid exploratory data analysis. In such an analysis, the identity of workplace activities causing differences in the worker's exposure is investigated. If there are no differences or if the differences are greater than an order of magnitude, conclusions can usually be based on the findings of the descriptive statistics. However, when the observed differences in concentration are less than an order of magnitude, statistical analysis should be performed. In conducting statistical analysis, the effect of autocorrelation on the analysis must be evaluated.

Real-time data are frequently analyzed to evaluate whether specific workplace activities affect worker exposures. When a workplace activity occurs and the worker's exposure increases, one can conclude that the activity has contributed to the exposure. Because many activities can occur simultaneously in an industrial environment, the change in the worker's exposure may be due to some unrecognized activity. Thus, judgment must be exercised when interpreting the results of the data analysis. After one analyzes the real-time data, control measures can be focused on actual exposure sources.

IX. PRACTICAL APPLICATION OF VIDEO EXPOSURE MONITORING

Video exposure monitoring is effective for identifying those specific activities that contribute most to a worker's exposure to an air contaminant. Integrated monitoring, such as sorbet tube or filter sampling, is normally conducted to determine the extent of the worker's exposure (averaged over the sampling period) before video exposure monitoring. After determining the extent of the exposures, the researcher can apply the techniques for video exposure monitoring. A typical video exposure monitoring evaluation might proceed in the following manner.

1. With the worker activity and contaminant of concern identified, the appropriate direct-reading monitor must be chosen. The monitor should be appropriate for the contaminant, e.g., an aerosol photometer to monitor for aerosols. It should have a minimal time constant so that activities of short duration can be evaluated, and it should be as portable as possible. The monitor should be set to zero and calibrated according to the manufacturer's instructions.

2. In addition to the direct-reading monitor, an IR video system may prove useful, depending on the contaminant being sampled. Such a video system can visualize air contaminant plumes, identify contaminant sources, and identify work practices that may contribute to a worker's exposures.

3. The output of the direct-reading instrument should be recorded by a data acquisition system. Setup of this system consists either of programming the data logger or of running the control software of the analog-to-digital converter system. The clock on the video camera and the data-recording device should also be synchronized at this point.

4. Data collection begins by starting the data-recording device and the video camera, and continues for a period judged to be representative of the process being studied. After the data-collection period, the data must be stored in a data file. If a data logger has been used, the data must be downloaded to a computer for storage to a file.

5. After the data are collected and filed, they are imported into a spreadsheet program. Work activity is analyzed from the video recording of the work activities. The activity variables are entered into the spreadsheet to accompany the air contaminant exposure data. Data analysis can be conducted with the spreadsheet or by statistical analysis programs. The spreadsheet analyses can consist of simple descriptive statistics or regression analysis. Statistical analysis programs are used for more sophisticated analyses, such as time-series analysis.

6. If the exposure data are to be overlaid onto the video recording of the work activities, the video overlay system must be assembled and the exposure data stored in an ASCII file specifically formatted for use by the bar-generating program. To overlay the exposure data onto the video recording of the work activities, the bar-generating program is set up (inputs entered); the work activity videotape then is played back. When the time on the video image reaches the time of the initial reading from the data file, the program's display is started. This synchronizes the exposure data with the video recording. The overlaid signal can be displayed on a video monitor and recorded on a second video recorder.

7. In some situations, the real-time concentration data is useful for evaluating ventilation systems for contaminant dilution and for determining the contaminant generation rate for the process. In these instances, the spreadsheet's regression function or a statistical analysis program can be used to determine the room's mixing factor. With this factor, the generation rate can be estimated, and ventilation systems can be further evaluated.

A.   Case Study 1: Manual Material Weigh-out

This plant manufactures a variety of plastic and rubber materials. At the operation studied, powdered acrylic copolymer was weighed into batch lots at a weigh-out booth as diagrammed in Figure 3 [2]. The final manufactured product from this operation was vinyl wall covering. In the weigh-out booth, a hinged segment of the work platform could be raised to allow a drum of raw material to be placed inside the booth. An exhaust plenum formed the back wall of the booth. At the booth, the worker emptied 22.7-kg (50-lb) bags of powder into a fiber drum measuring 84 cm (33 in.) high and 55 cm (21.5 in.) in diameter. Then, using a scoop, the worker transferred the powder from the drum to a small paper bag. The bag was placed on the scale and the weight of powder in the bag adjusted. Usually, two scoops of the powder were required to achieve the proper weight. Finally, the filled bag was closed and placed in a bin behind the worker. This process was repeated until the required number of batches were filled or the fiber drum was emptied.

Methodology

Direct-reading monitors measured the effect of depth of material in the drum and the elements of the job cycle on dust exposure. The worker began with a full drum and weighed the powder into paper bags. An aerosol photometer, the Hand-held Aerosol Monitor (HAM) (PPM Inc., Knoxville, TN), showed the dust concentration in the worker's breathing zone. Every two seconds, the HAM's analog output was recorded by an Apple II Plus computer, equipped with an AI 13 analog-to-digital converter (Interactive Structures Inc., Bala Cynwyd, PA). The evaluation ended when the drum was nearly empty (about 22 minutes).
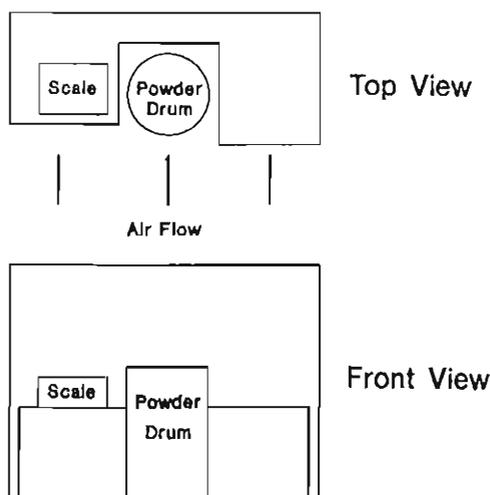
Figure 3   Diagram of a powder weigh-out workstation.

The voltage output was statistically analyzed to determine if the amount of powder in the drum affected worker dust exposure, and if it did, which activities contributed the most to this increase. The strategy for this analysis was to fit a regression model involving the relation of the variable "worker" (a time-dependent measure of dust exposure) to the independent variables "bagcount," "scooping," "weighing," and "turning." "Worker" was the voltage output of the direct-reading monitor mounted on the worker. "Bagcount" was the cumulative number of bags that were weighed. "Scooping" was the cumulative time during each cycle spent scooping material from the drum and into the bag. "Weighing" was the cumulative time during each cycle spent weighing the bag on the scale and adjusting the amount of powder in the bag. "Turning" was the cumulative time during each cycle spent placing the bag in the bin. The worker's exposure was modeled closely enough to provide a fair representation of its relationship to the variables. There was no attempt to continue to add terms to the model until the lack of fit was not statistically significant.

A key assumption in the data analysis was the independence of measurements. Successive readings from the instrument were not independent. When a dust-generating event occurred, dust concentrations did not increase immediately; time was needed for the air to transport the dust cloud from the point of generation to the inlet of the instrument. Also, the HAM was operated with a time constant of 1 second, and it required some time to respond to fluctuating concentrations. The total instrument response time appeared to be 2 to 5 seconds, meaning the instrument responded 2 to 5 seconds after a dust-generating activity occurred. As a result, autoregressive terms were used in the analysis.

The results of the regression analysis are shown in Figure 4, which shows that dust exposure during the scooping activity increased as the bag count increased. Bag count was a surrogate measure for the level of powder in the drum; a bag count of 0 corresponded to a full drum, and a bag count of 55 corresponded to an empty drum. During weighing and turning, the worker's dust exposure either remained constant or failed to increase as fast as the exposures during scooping.

Figure 5 illustrates the effect of job cycle upon dust exposure. During the scooping activity, the dust exposure increased. During the weighing and turning activities, the dust exposure decreased. This suggests that most of the worker's dust exposure was caused when
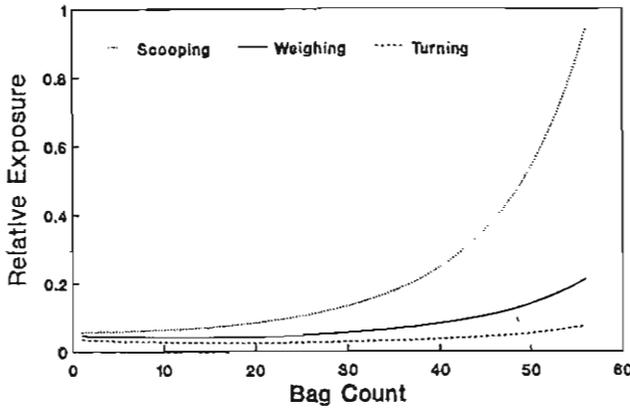
Figure 4   Modeled dust exposure of a worker as a function of bag count for scooping, weighing, and turning.

scooping the powder from the drum. Dust exposures caused by weighing and turning were much smaller than the dust exposures caused by scooping and may have been controlled by the ventilation system. The weighing activity appeared to be associated with higher dust exposure than did the turning activity. This difference, however, may be an artifact caused by the delay of the HAM's response to the high dust exposures during scooping.

Findings

Figure 4 shows that dust exposure increased with bag count, which is a surrogate variable for depth of scooping. The data were collected over approximately 20 minutes. This same conclusion was reached with the use of conventional short-term measurement of dust concentrations with pumps and filters. The filter data, which required three full shifts to collect, however, did not provide any insight into the relationship between job cycle and the worker's dust exposure. Knowledge of the specific task that elevated the worker's dust exposures was crucial to the redesign of the weigh-out booth.
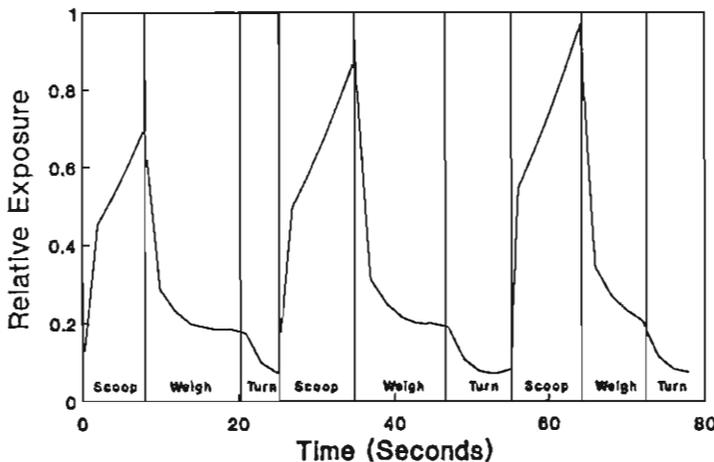

Figure 5   Modeled dust exposure of worker for filling bags 51 through 53.

Recommendations

Based upon the results presented in Figures 4 and 5, researchers recommend that the facility use shorter storage drums for bulk powder to reduce the dust generated by scooping. This case study clearly showed that direct-reading monitors can qualitatively and quantitatively measure sources of dust exposure during the work cycle—exposures too short with regard to time to be studied with integrated air sampling methods.

B. Case Study 2: Dental Administration of Nitrous Oxide

This study was conducted to evaluate how effectively scavenging systems reduce occupational exposure to waste nitrous oxide (N_2O) [14]. For more than 100 years, dentistry has used N_2O as a general anesthetic agent, analgesic, and sedative [15]. Today, N_2O is used primarily for psychosedation, to reduce fear and anxiety in the conscious patient [15]. N_2O scavenging systems typically have three principal components: an N_2O and oxygen (O_2) gas delivery system, a nasal cone for the patient from which to inhale the gases, and an exhaust system that carries the respired gas from the patient out of the building. A schematic of the nasal cone is shown in Figure 6. Although the studies show that scavenging systems significantly reduce N_2O concentrations, the systems do not reduce it to the NIOSH recommended exposure limit (REL) of 25 ppm during the time of administration [16]. In addition to evaluating the effectiveness of scavenging systems, this study was conducted also to determine why exposures exceeded 25 ppm.

Methodology

A dental facility that uses a commercial scavenging system during dental surgery was evaluated by NIOSH researchers. Ten dental operations (e.g., filling, extracting) were monitored by using a combination of sampling strategies: personal breathing zone sampling (dentist and dental assistant), general area sampling, and real-time sampling. A Miran 1A (Foxboro Instruments, Foxboro, MA) monitored the real-time N_2O concentrations. A sampling probe connected to the Miran 1A was placed approximately 12 in. above the patient's head. In addition, video and IR scanning equipment recordings monitored the dental practices (activities). Because N_2O is IR absorbing, it can be "visualized" by using IR thermography. Motion and time measurement techniques were used to document activities of the dentist, dental assistant, and patient during the operation [12]. These activities, listed below, were coded into a computer spreadsheet along with the associated N_2O concentration data.
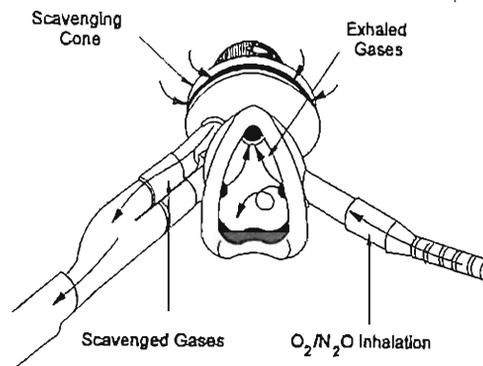

Figure 6   Diagram of a typical dental N_2O scavenging system.

injecting local anesthetic
extracting a tooth
filling a tooth
using the aspirator
using the water and air syringe
using the rubber dam (small rubber sheet that isolates the operative site)
using the curing light for restorative composite resin material
talking, coughing, and yawning of patient
turning on N_2O
turning off N_2O
adjusting N_2O flow rate

Statistical analysis of the N_2O concentration and changes in concentration were modeled as a function of these work elements from the spreadsheet [17].

Findings

Average real-time N_2O concentrations for the 10 operations ranged from 206 to 770 ppm. The average real-time concentration over all 10 operations was 442 ppm. The average personal breathing zone (integrated sample) concentration over all 10 operations for the dentists was 487 ppm. There was no significant difference ($p < 0.68$) between the real-time and personal breathing zone concentrations for dentists. There was, however, a significant difference ($p < 0.014$) between the overall average real-time sampling concentration and the average personal breathing zone concentrations among dental assistants (150 ppm). The differences in dental assistant breathing zone concentrations and the real-time concentrations may have been because the sampling probe was placed closer to the patient's and the dentist's breathing zone than to the dental assistant's breathing zone. Thus, these real-time sampling results may be more representative of the dentists' exposure than that of the dental assistants. It also was determined that the dentists, by nature of the dental surgery, worked closer to the patient's breathing zone than did the dental assistants.

Real-time sampling results and work activities were combined to determine if changes in N_2O concentrations were related to these activities. From the video recordings, several dental surgery activities were selected for analysis. For data analysis, the real-time concentrations were matched with the identified dental activities. A plot of this relationship is shown in Figure 6. Based on this analysis, the only activities that showed significant N_2O concentration changes occurred: (a) when the dentist turned on the N_2O gas, (b) when the dentist adjusted the N_2O concentration during the operation, and (c) when the dentist turned off the N_2O gas, following the operation. Statistical analysis showed that 98% of the changes in N_2O exposure could be accounted for by the N_2O concentration of the gas delivered to the patient as opposed to the specific dental surgery activities (note the "sawtooth" pattern in Figure 7). Thus, the primary source of N_2O exposure was not from the work practices of the dentists, but from N_2O delivery and the inadequacy of the scavenging exhaust system.

During 2 of the 10 dental operations, an IR video camera qualitatively evaluated scavenging mask leakage. The infrared camera revealed N_2O leakage between the mask and face seal, indicating that the scavenging mask did not fit the patient's face properly. The off-gassing of N_2O during patient mouth breathing also affected exposure during these two operations. The IR video camera also revealed that a sudden increase in N_2O exposure could be traced to the patient's expired breath. This increase was corroborated by real-time data. When the patient inspired, the N_2O concentrations decreased. Synchronization of the real-time data with the IR video camera helped to confirm that patient's mouth breathing was also a source of N_2O exposure.
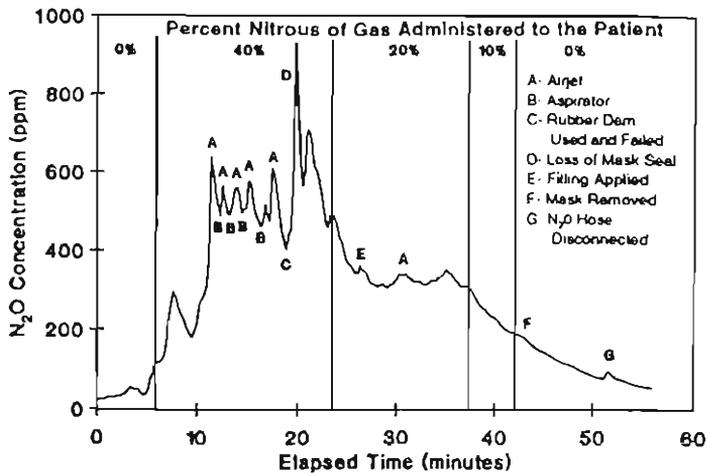
Figure 7   Plot of real-time N₂O concentration with activities and supply concentrations.

Recommendations

Scavenging mask leakage and an inadequate scavenging exhaust system caused most of the N₂O exposure in this study. Patient mouth breathing was a secondary source of exposure. If the scavenging system had been more efficient, the work practices, such as use of the aspirator, air and water syringes, and patient mouth breathing might have had a greater impact on the N₂O exposures of the dentists.

The IR video camera proved to be a valuable tool for detecting N₂O leakage from the patient's mask as well as from patient mouth breathing. By following the real-time data patterns, NIOSH researchers discerned when there was a mask leak, when the patient was mouth breathing, or both. This ability to determine these exposure sources helped provide recommendations for improving scavenging system mask design and work practices, and for reducing overall N₂O exposures.

X.   CRITICAL REVIEW OF CURRENT STATUS

Video exposure monitoring is a set of flexible techniques that can determine specific sources of a worker's exposure to air contaminants. However, there are a number of practical considerations when integrating real-time exposures with the worker's activities. The researcher has to make sure the changes in exposures match worker activities. Problems challenging the researcher are (1) instrument transportation lag, such as natural diffusion of chemical from their source to the detectors, (2) response time, such as the instruments' sensors responding to a contaminant once it has arrived, and (3) autocorrelation of data, which arises from instrument lag and response time. These challenges are equally matched by the difficulty of analyzing videotapes of worker activities and defining the work activity elements so that they correspond to changes in chemical exposure. For example, if the worker is performing several work activities in a short period of time, the changes in chemical exposure shown in the data may not match these activities. Therefore, the researcher has to take special precautions to collect enough data (i.e., videotape and real-time personal sampling) so that patterns of exposure emerge. This will guide the researcher to identify exposure sources, and from this

to devise effective controls. The key to successful integration of both real-time exposure assessment and job analysis techniques is to use both methods in such a way that patterns of exposure quickly emerge.

XI. FUTURE CONCERNS

Most of the integration of real-time direct-reading instruments with work analysis has been conducted by Federal and academic researchers [18–20]. For real-time exposure assessment and workplace job analysis techniques to succeed as a useful tool in industry, several things need to occur: (1) real-time instruments need to be more compact, portable, and easy to operate; (2) real-time instrument costs need to be in line with costs of traditional sampling instruments; (3) the availability and reliability of real-time sampling instruments need to be improved; (4) standards and guidelines need to be developed so that real-time data can be compared with traditional integrated sampling results; and (5) industry needs to invest in educating and training of its health and safety professionals to perform real-time sampling and work analysis assessments. The future of these sampling techniques may depend on a number of factors. The first is for government and academic researchers to continue applied research and development in this area; then to transfer this technology to industry to demonstrate the effectiveness of pinpointing exposure sources so that controls can be more effectively applied. The second is for industry to invest in this technology by training its own personnel to use these methods for cost-effective controls. We believe that if these factors occur, real-time sampling and work analysis will become a valued tool in evaluating and controlling hazardous chemical and physical agents in the workplace.

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