INDUSTRIAL HYGIENE

1. Introduction

Industrial hygiene is devoted to the anticipation, recognition, evaluation, and control of environmental factors or stresses arising in or from the workplace that may cause sickness, impaired health and well-being, or significant discomfort and inefficiency among workers or among the citizens of the community. It is a profession practiced by >11,000 industrial hygienists in the United States and many more worldwide. U.S. industrial hygienists are typically members of the American Industrial Hygiene Association (AIHA), which is the largest industrial hygiene organization, the American Conference of Governmental Industrial Hygienists (ACGIH), and the American Academy of Industrial Hygiene (AAIH). Many are certified industrial hygienists (CIH) as a result of meeting the requirements of the American Board of Industrial Hygiene (ABIH). Outside the United States, industrial (also called occupational) hygienists are members of such professional associations as the British Occupational Hygiene Society (BOHS) and the International Occupational Hygiene Association (IOHA).

Industrial hygienists work closely with members of several other professions concerned with workplace health and safety, eg, occupational medicine, occupational health nursing, and safety engineering. All of these groups are involved in the implementation of the laws that regulate workplace health and safety. In the United States the principal law is the Occupational Safety and Health Act (OSHA) (1) enforced by the U.S. Department of Labor (U.S. DOL). Similar laws are in place in almost every country in the world and are proposed by such international organizations as the World Health Organization (WHO) and the International Labor Organization (ILO).

It is common in the modern chemical industry for the industrial hygiene function to be grouped with safety and environmental control in a department under the control of a senior executive. These functions should not be seen as separate from other management responsibilities, but a integral parts of an over quality operation. To accomplish this, many companies employ a an intergrated safety, health, and environment management system that uses the quality principles of feedback and continuous improvement. Special skills not typically available at a plant such as toxicology or hygiene laboratory analyses may be located in a central skill pool.

Since 1988, the U.S. chemical industry, through the American Chemistry Council, has implemented Responsible Care, a voluntary program to achieve improvements in environmental, health and safety performance beyond levels required by the U.S. government. The program has resulted in significant reductions in releases to air, land and water, major improvements in workplace and community safety, and expanded programs to research and test chemicals for potential health and environmental impacts.

Program enhancements adopted by the American Chemistry Council include:

1. A Responsible Care Management System;
2. An independent third party certification of the management system to ensure appropriate actions are taken to improve performance;

3. Tracking and publicly reporting performance based on economic, environmental, health and safety, societal and product related metrics;
4. A Security Code that helps protect people, property, products, processes, information and information systems by enhancing security throughout the chemical industry value chain.

A partial list of the hazards or conditions arising from the workplace (see also PLANT SAFETY) and with which industrial hygienists are concerned includes.

Chemical	microwave radiation
carcinogens	extremely low frequency
acute poisons	
reproductive hazards	vibration
corrosives	magnetic fields
irritants	ulraviolet radiation
pneumoconiosis producing	infrared radiation
laser radiation	
neurotoxins	
nephro (kidney) toxins	*Ergonomic*
	repetitive strain injury (RSI)
Physical	carpal tunnel syndrome
noise	back injury
heat	lifting hazards
cold	visual display units
ionizing radiation	human/machine interaction

Industrial hygienists must be able to anticipate what workplace materials or events may give rise to any of these hazards, to recognize the hazards that occur, to evaluate a hazard to determine the degree of risk it presents, and to control hazards so as to reduce risk. The most cost-effective way to deal with workplace hazards is to anticipate them and if possible prevent their occurrence (see HHAZARD ANALYSIS AND RISK ASSESSMENT). The industrial hygienist's job begins when a new chemical or process is conceived. Based on data from animal experiments and/or human epidemiology relating to a substance or an analogous chemical it is possible to estimate the toxicity of the substance (see TOXICOLOGY). Many chemicals (lead, benzene) have a long history of health effects and much is known about them. For others, we only have the results of tests on animals, usually rodents, done by the chemicals manufacturer or by the government. Both the United States and the Europe have requirements for testing chemicals although they are quite different. Some substances are benign, others are potent carcinogens, and most are in between. Whenever possible, it is best to avoid using potentially dangerous chemicals. Similarly, potentially hazardous processes that produce excessive noise, heat, or other stress-related situations should be anticipated and avoided. However, the industrial hygienist can usually devise ways to use potentially dangerous chemicals safely (2).

2. Recognition of Potential Hazards

The process of recognition of potential hazards is based on extensive knowledge of what kinds of hazards may occur in any industry, process, or job activity. Table 1 summarizes the kinds of chemical hazard exposure sources typically found in the chemical process industry. A rating system for each source type determining the degree of exposure to be expected is also given. The recognition process typically proceeds by looking for sources of worker exposure to harmful chemicals and physical agents.

2.1. Fugitive Emissions. Fugitive emissions or leaks occur wherever there are breaks in a barrier that maintains containment. Whereas flange and seal leaks are individually small, these can cumulatively amount to the main source of loss from a unit. Even when these emissions are very small and cannot be detected as losses in a material balance, high local concentrations of contaminants can result and lead to overexposure. Furthermore, some leak sources, such as valve stem leaks, tend to gradually increase over time and can become large if not corrected. Other leaks, such as pump seal leaks, which are usually small, can become very large in the event of total seal failure. Overall, in most well-maintained plants, pumps and valves are more important sources of leakage than flanges. For that reason, leak detection and repair efforts usually focus on pumps and valves unless there is reason to suspect flanges. Fugitive emissions, even without catastrophic seal failure, are the origin of a continuous background exposure for workers. Whereas this source of exposure may not, by itself, result in overexposure, its presence reduces the margin within which other exposures may vary and still remain under the accepted limit (see MAINTENANCE).

2.2. Process Operations. The operation of a modern chemical plant is typically computer controlled and does not involve any routine operator contact with the feedstock, intermediates, or product (see PROCESS CONTROL). There are, however, a few actions the operators may need to take which can involve contact with process materials. Sampling of process streams is one such task. Whereas use of on line analyzers has substantially reduced the need for operator-collected samples, the latter are necessary to check the on line analyzer or wherever on line analyzers are not used. Exposure during sampling can be very high if the sampling line is flushed by running a quantity of a volatile liquid out on the pad. On the other hand, exposure can be very low where the sample is collected in a bomb from a closed loop. Worker care in following prescribed practices is important.

Many filters in chemical process units are either changed very rarely or are back-flushed automatically so there is hardly any exposure. Some filters, however, require frequent manual changing or cleaning and significant exposure may occur unless operators follow the proper procedure. The filter container should be drained of any toxic material and then flushed and purged as needed so that when it is opened there is only minimal exposure. Zero exposure is difficult to achieve in situations where a disposable paper filter cartridge may retain and slowly release a material that cannot be removed by multiple flushes and purges.

Gauging is often done automatically, but there are occasions where gauging needs to be carried out using a tape dropped through a hatch on the top of a tank. Even where automatic systems are installed, manual gauging may be used as a check. Depending on the nature of the liquid in the tank, vapors can be released more or less actively while the ullage hatch is open. Short of using respiratory protection, the only exposure control applicable to open-hatch gauging is the work practice of standing upwind if the platform at the hatch permits.

Vents and flares are intended to take contaminants released from safety valves away from work areas. However, if an elevated vent is at the level of an occupiable platform on the same or an adjacent unit, a worker may, under certain wind conditions, be subject to the nearly undiluted effluent of a vent. Whereas such elevated platforms may rarely be occupied, a heavy exposure from a vent could incapacitate a worker or cause a fall. Tanks that vent only when being filled are common causes of this concern. The usual solution is to raise the vent above any occupiable platform or, at greater cost, to scrub the vent effluent.

Extrusion is a common way for solid products such as plastics to emerge from closed manufacturing systems. Normally a polymer is hot when extruded and may contain additives and oligomers that are volatile at elevated temperatures. The result is fuming at the extruder head. These fumes can result in employee annoyance, housekeeping problems, and, at worst, depending on composition, health hazards.

In all of the process operations except venting and flaring, exposure is related to worker activity, and to some extent is dependent on worker behavior and the work practices applied. The distinction between those exposures that are impacted by worker behavior and those that, barring the use of respirators, are not is important. The types of control methods to be applied and the methods of exposure measurement to be used are influenced by this difference.

2.3. Material Handling. The continuous movement of materials through a process unit does not in itself result in opportunities for release and consequent exposure. However, some material-handling steps are difficult to accomplish with total containment. Wherever quantities of material are allowed to build up and be drawn from tankage or at temporary or permanent storage points, the possibility of release needs to be considered. Liquids entering fixed tanks displace air, which must be vented to avoid overpressuring the vessel. Control of liquid-transfer operations can be achieved by variable volume vessels, such as those having floating roofs, which do not require venting, scrubbing, flaring, or recovering the vented gas stream (see TANKS AND PRESSURE VESSELS).

In drumming and the filling of tank cars and trucks, where the vessel is initially empty, the amount of material being transferred that could be released by displacement depends on how much evaporates during the filling. Rarely does a material evaporate so quickly that the entire volume of displaced gas is saturated. More likely the initial release at the start of filling contains only a small amount and the concentration increases toward saturation as the filling proceeds. How quickly the concentration in the vented gas increases depends on the temperature and volatility of the material and on the loading mode. Splash loading, where the material leaves the filling spout at the top of the tank and free-falls to the bottom, results in much more evaporation of a volatile material

than bottom loading or submerged spout loading where the liquid level rises gently without splashing. Some very volatile liquids and gases that are liquids under pressure are allowed to autorefrigerate by controlled evaporation during transit. Vapors vented from liquid transfer can be collected and sent to an elevated vent or flare, returned to the discharging vessel head space, reliquefied by refrigeration, and returned to storage. One other opportunity for vapor release in material handling is air open mixing. In batch blending or production operations it may be the practice to add liquids or solids to an open vat that already contains some liquid. As the liquid evaporates and as the gas in the lead space of the vat is displaced by material addition, some vapor may escape out of the hatch or vat top. The amount of release depends on the temperature, volatility of the liquid, degree of mixer agitation, rate of addition of material, and openness of the vat top or hatch. Control is usually accomplished by local exhaust ventilation systems that maintain a negative pressure in the vat or collect vapors as they escape from the vat, or by closed addition systems such as rotary valves (see MIXING AND BLENDING).

Solids handling is often done by open means both because the hazard is perceived to be less and because it is more difficult to design totally closed solids handling systems (see POWDERS, HANDLING, BULK POWDERS). Where solids are handled in closed systems, often as fluids in pneumatic conveying (qv) systems, the potential release problems are similar to those for liquid transfer. Air displaced from hoppers and silos as these are filled may contain dust. Also, the conveying air must be released from the vessel where the conveyed material is deposited. These streams are sometimes sent to an air cleaning system such as a baghouse or other filter or an electrostatic precipitator. Whereas such devices are effective in removing particulates from the air, maintenance of the air cleaner itself sometimes results in a secondary exposure.

Semiclosed systems for handling solids often involve the use of big bags or tote bins. In these systems the solid is shipped in a large ($\geq$1t) container that is then lifted into place over a closed hopper or feed mechanism and a sealed connection is made. It is sometimes necessary to rap or agitate the big container to keep the solid moving and this action can result in deterioration or damage to the container or seals with consequent leaks. Also, there is some release of solids when containers are connected or disconnected as well as opportunities for dust generation.

Solids handling in small containers such as bags and drums can be either automated or manual. Automated bag- and drum-filling machines can position the container, fill it using a weighed amount of product, seal it, and label it. Some bag-filling machines exhaust dust generated inside the bag during filling. Dust generation and dispersion during bag and drum filling depend on the dustiness of the solid, the rate and manner of container filling, the degree of care taken in the filling process, the maintenance of machinery, and the cleanup of spills. Bag dumping can be done in open or closed systems. In open bag dumping there are potential releases when bags rupture during handling, when bags are dumped, and when the empty bag is collapsed for disposal. In manual bag handling operations, spills from ruptured bags damaged by fork lifts and other traffic can be a significant source of exposure. Blowing dust off machinery and clothing using compressed air adds to the problem. A means of control is frequent

cleaning using wet sweeping or vacuuming with heavy-duty installed systems. Automatic bag dumping can be done by machinery that conveys the bag into a closed chamber where it is split open and dumped. The empty bag is then transported to a compactor. The whole system is enclosed and exhausted so that all leaks are inward ones.

Handling of small quantities of solids may be altogether manual. Materials may be scooped out of drums, weighed on scales, and dumped into mixers entirely by hand. Exposure may be insignificant or a large concern depending on the toxicity and dustiness of the material. Some users of small quantities of solid additives may arrange for the supplier to package the material in preweighed batches packed in a bag so that the whole prepackaged container can be added to the mix. Mixing of solids by means of a banbury, muller, calender, or mill is either an open or incompletely enclosed process. Except for the loading of a mixer, there is usually little opportunity for dust created by the escape of powders because the mixing solids are generally wet or tacky. However, mixing of solids often requires considerable energy and generates heat which results in fumes of evaporated and condensed particulate. Local exhaust ventilation is effective in removing these fumes and close manual handling may still result in exposure.

2.4. Maintenance. Closed systems contain process materials except for leaks and fugitive emissions or when opened for maintenance. Open system maintenance can add to exposure by disturbing and dispersing deposits of materials in equipment. Most maintenance (qv) is done while the plant is in operation. Thus the maintenance workers are in close proximity to operating equipment for long periods of time. Local contaminant releases and physical hazards such as noise or thermal radiation need to be considered. In addition, the valves or other barriers blocking off the operating parts of the plant may leak into the maintenance work area. There is also the possibility of failure of the barrier. The piece of equipment being maintained should be cleaned as necessary to reduce exposure before it is opened and repaired. Where highly toxic process materials are present, it may be necessary to flush using a low toxicity stream, strip with steam, and purge with nitrogen. Where this is necessary, the equipment design should include the special fittings needed for the flush and purge line connections. Even when cleaning prior to opening is done as completely as possible, it may be necessary to use respirators at least for the initial opening to guard against overexposure resulting from trapped toxic substances. Proper cleaning and opening of equipment lines and vessels where toxic material may be present is complex and requires careful planning and attention to detail in execution.

Turnarounds, or significant periodic overhauls of chemical plant units, are a special case of plant maintenance. Because units are shut down during turnarounds, some risks are avoided, but because the unit is out of production there is also time pressure to complete the work. Contractors and other workers who may not be familiar with the unit may be brought in so that many maintenance activities proceed simultaneously. In this environment, there is the potential for disorganization and mishap resulting in unanticipated releases of chemicals. To conduct a safe turnaround, it is necessary to plan the event carefully in advance. Contingencies should be anticipated to the extent possible and plans made to

deal with them. All of the workers involved should be specially instructed in their duties and closely supervised during the entire turnaround from shutdown through startup and back to normal operation. The materials and operations used in maintenance may present a set of hazards quite separate from the hazards of the feedstocks, intermediates, and products of the chemical unit.

Welding. Any of the metals in the rod or the alloy being welded can become airborne in the welding (qv) fume. Zinc and some other metals can cause metal fume fever, a frequent problem for welders. Other metals such as cadmium can produce systemic effects. Chromium, under certain conditions, can be released in the potentially carcinogenic hexavalent form. In addition to these metal fumes, the welding process produces oxides of nitrogen, ozone, and ultraviolet (uv) radiation. All of the emissions can be controlled by general or local ventilation or by respirators if necessary. The welder's face mask provides only slight respiratory protection. Welding in confined spaces is particularly hazardous owing to the difficulty in delivering clean air to the site of the welding and in exhausting welding fumes.

Painting. Whereas leaded paints are no longer used for domestic painting, these paints are occasionally used in industry. Frequently, surfaces being prepared for painting may have remnants of old lead or chrome coatings that could become airborne during scraping or grinding. The solvents used in paints are not highly toxic, but can reach excessive concentrations in poorly ventilated spaces. Low rates of paint application as from brushing produce lower solvent release rates than intermediate rate application by roller or high rate spraying (see COATING PROCESSES, SURVEY). Certain modern coatings (qv), such as polyurethanes and epoxies, present special toxic hazards (see EPOXY RESINS; URETHANE POLYMERS).

Sandblasting. Whereas some modern corrosion-resistant treatments do not require the removal of all rust, sandblasting to clean metal surfaces prior to coating is very common. In addition to the metal dust, the very fine fragments broken off from the abrasive particles may be respirable, that is, capable of reaching the deep lung where these may cause damage. The degree of risk depends greatly on the type of abrasive used. Steel balls and walnut shells produce relatively nontoxic dust, as does aluminum oxide. On the other end, fine dust from sand, which is typically composed of silicon dioxide, is very toxic and can produce a serious lung disease. The degree of dust exposure from sandblasting depends on the degree of enclosure and the use of personal protective equipment. Small pieces can be cleaned in fully enclosed blast cabinets having local exhaust ventilation to maintain negative pressure. Large objects, such as truck bodies, which are too large to be done in cabinets, are often cleaned in large booths using down draft local exhaust ventilation. For structures and fixed piping, sandblasting is done out in the open. When blasting in either the booths or in the open, the operator should be protected by a special sandblaster's supplier-air hood. A common problem occurs when the operator uses the hood for physical protection but does not connect the hood to a supply of clean air. When a hood is used in this manner, fine dust can enter the worker's breathing zone under the hood, and the hood does not provide respiratory protection.

Insulation. It is common for workers replacing insulation at older plants to encounter asbestos (see INSULATION, ELECTRIC; INSULATION, THERMAL). The composition

of both old and new insulation should be known to be certain that proper procedures are followed. The removal of asbestos-containing insulation is a complex and difficult process requiring personal protective equipment, monitoring, containment, special disposal procedures, stringent work practices, and record keeping (3). Many companies elect to have asbestos removal done by specialized contractors.

Modern nonasbestos insulation frequently incorporates synthetic mineral fibers for strength at high temperatures. These glass or rock wool fibers are usually silicates that are large compared to asbestos, ie, too large to be inhaled into the deep lung. Also, these fibers do not split the long way and thus do not produce as many fine fibers. For these reasons, even if the synthetics are as potent as asbestos fiber for fiber, the synthetics are less hazardous because fewer respirable fibers result. Ceramic fibers, however, are made in respirable size ranges and are, therefore, more hazardous. Also, when ceramic fibers are used inside high temperature furnaces, they may be converted to christobalite which is more toxic than quartz.

Chemical Cleaning. Removal of deposits from inside vessels and pipes is often done using acids, caustics, or strong solvents, the handling of which can cause a number of hazards. Transfers and mixing of small quantities is usually done manually from drums or tank trucks. Application involves pumping materials through hoses or temporary piping. Sometimes strong cleaners are applied as a pressure spray or jet with consequent spattering. The reaction of the chemical with the deposit materials and the metal of the pipe or vessel can produce dangerous gaseous air contaminants. Even when cleaning is done *in situ*, removal and disposal of the cleaner and flushing fluid can cause exposure. Because these operations are infrequent, installed control equipment is rarely used. In most cases workers rely on personal protection equipment plus detailed handling precautions.

Catalyst Handling. A great many chemical manufacturing reactions are made possible by the use of catalysts such as those listed in Table 2 (see CATALYSIS). Catalysts may be divided into two categories: homogenous catalysts, which are dispersed in the reactant mix so that the entire reaction takes place in a single phase, and heterogeneous catalysts, where catalysis occurs at phase interfaces. Homogeneous catalysts are added to reaction streams the same as any other process chemical and are removed by the usual finishing separations process. From the point of view of industrial hygiene, these chemicals are no different than any other additive. Heterogeneous catalysts, on the other hand, are often used in the form of fixed beds, which must periodically be regenerated or removed and replaced (see FLUID CATALYTIC CRACKING (FCC) UNITS, REGENERATION). These latter tasks must be considered as worker exposure opportunities.

Catalyst charging and topping is an occasional task typically done at the top of a reactor using temporary handling facilities. For this reason, local exhaust ventilation is rarely used even when the operation may be dusty and the catalyst toxic. Scrupulous use of personal protective equipment and adherence to work practices is essential to minimize exposure. Respiratory protection can be so critical as to require air-line respirators; skin protection may include full protective suits. When catalysts are dumped from a reactor these may be very dusty because of particle size reduction occurring in the reactor and because of

handling. Dumping is often done via chutes, which do a poor job of containing the dust. In addition to protecting the workers, it may be necessary to erect a temporary enclosure to prevent contamination of adjacent work areas. Some catalysts being dumped are pyrophoric. Water sprays used to prevent fires also help control the dust. When catalyst beds are rendered inert, the danger of a release into the work area of large amounts of the inerting gas, which may cause asphyxiation, exists. Most catalyst removal operations are carried out by experienced contractors using special equipment and techniques. It is important that plant personnel not undertake this or any job for which they are not properly trained or equipped. The hazard from what comes out of a reactor may be quite different and much more severe than that from the catalyst that went into the reactor.

2.5. Waste Handling. Housekeeping procedures in general can have a significant impact on employee exposure, and certain waste handling procedures can result in very serious exposure if proper precautions are not taken. The best way to keep a plant clean is to not spill in the first place. Management reviews of the origins of spills and accumulated debris not only keep the plant cleaner but prevent loss of valuable material, save cleanup labor, and reduce fire and other safety hazards. Spilled materials in aisles and on walkways can become airborne by redispersion and can be spread onto surfaces and result in skin contact. Dry powders are best cleaned up with either installed or portable industrial vacuum cleaners. Liquid spills can be soaked up using a number of available solvents, and scraped or shoveled into containers. Careful consideration should be given to the methods used to clean floors. Serious worker overexposures have resulted from the use of volatile solvents on large floor areas inside buildings.

Air cleaning systems are often used to remove dust or vapors from plant or process exhaust streams. Dust collecting systems such as filters or electrostatic precipitators that handle heavy loads of dust are usually designed to be self-cleaning, but it is still necessary to enter the air cleaner periodically for inspection or repair. Dust deposits inside the equipment are likely to be stirred up and inhaled by unprotected workers. Baghouses are particularly likely to cause exposure because large amounts of dust may be retained in the cloth and released when the bags are handled.

Wastewater treatment facilities may receive chemical process wastes and spills. These wastes may volatize on emerging from a closed sewer system into open waste treatment tanks particularly if hot streams have heated the tank. These releases can occur without warning and result in unexpected employee exposure. Covering reduces the hazard and can also reduce air emissions but does require careful design to avoid creating an explosion hazard. Toxic substances trapped in separator or biological oxidation sludge may be released when sludge is filtered, and skin contact can result from sludge handling.

3. Hazard Evaluation

The evaluation phase of industrial hygiene is the process of making measurements on some set of samples which permits a conclusion about the risk of harm resulting from exposure to a hazardous substance. Before conducting an

evaluation, it is necessary to make a number of choices of what and where to sample, when to sample, how long to sample, how many samples to take, what sampling and analytical methods to use, what exposure criteria to use in the analysis of the data, and how to report the results. These choices as a whole constitute the evaluation plan. The object is to find if one or more workers have an unacceptable probability of being exposed in excess of some established limit.

The discussion that follows deals with air sampling since inhalation is the most common route of exposure for chemicals. However, workers may also be harmfully exposed by skin contact, injestion or even injection by a high velocity jet. These other routes of exposure need to be considered in evaluating the risk of harm.

3.1. Sampling Strategy. A sampling strategy is a careful plan or method to collect exactly those samples which enable required decisions regarding control to be made at the required level of confidence and minimal cost and effort. The basic choices of sampling strategy are where, when, how long, and how many. A detailed discussion of the statistical basis for sampling strategy and the design of sampling programs are covered elsewhere (4–7) (see SAMPLING).

The origin of the complexity of sampling strategy is the great variability of occupational exposure. The concentration of an air contaminant in the space of a workplace varies with time over both short and long periods. Moreover, workers move in varying patterns through an environment where the contaminant concentration varies with location, and the actions of the workers themselves may cause the concentration to vary. All of these sources of variability lead to an exposure distribution which is usually best described statistically by the log normal distribution (5) and that typically has geometric standard deviations from two to five or more. This means that the upper seventeenth percentile may be as much as from two to five times the mean. This variability is compounded by the problem of estimating the exposure of a group of workers having differing exposures to find the most exposed workers. Compared to this environmental variability, the variability introduced by the sampling and analytical error is small, even for those methods such as asbestos counting, which are relatively imprecise.

Who to Sample. The objective is to find out if one or more workers may be overexposed, then if it is clear who the most exposed workers are, only those workers need be sampled. If their exposure is acceptable, then all those who are less exposed are also within the limits. If the high risk group is overexposed, further evaluation is necessary to find out if anyone else is overexposed. This high risk sampling technique depends on clear knowledge of how exposure is distributed among a group of workers. Lacking that knowledge or lacking confidence in it, it is necessary to discover the exposure distribution among workers by sampling. The exposure of all exposed workers could be measured or some fraction using statistical tables that produce the probability of finding the highest exposure in a population with various numbers of samples. The population of workers who may be over exposed includes employees but also contractors and others who have been invited into the plant.

Where to Sample. Measurements of the concentration of a contaminant in the general air or at a fixed location are often easier than measurements in a breathing zone of a moving worker. Larger, line powered pumps (qv) can be used to collect bigger samples yielding greater sensitivity. Size selective samplers,

such as cascade impactors, can be used to give aerodynamic size distribution data. Fixed monitors tied in to computer data acquisition systems are also possible. The problem is that health effect depends on dose, which depends on exposure. The breathing zone measurement, which most closely approximates exposure, is most often not the same as the general air measurement. This is because of the variability of concentration in the space through which the worker moves and the effect of the workers own activities, eg, welding, grinding, smoking, etc, on the concentration. Consequently, personal or other breathing zone sampler measurements are needed for comparison to specific exposure criteria. However, area measurements may still be useful for a number of purposes such as control system evaluation.

When to Sample. Smoothly repetitive operations are likely to be homogeneous over time so that the choice of sample period is not likely to bias the result. Less smooth day to day variation and cyclical operations can be accommodated by random sampling. Some experts have found that systematic sampling can be as free of bias as random sampling even in cyclical operations as long as the sampling period does not match the process period (6). An advantage of systematic sampling, in addition to convenience, is that by making use of information from observation, it is possible to decrease the variance of the sample set. Another advantage is that sampling can be directed at high risk events that might be missed by random sampling.

How Long to Sample. The period of the sample should be matched to the period of the exposure criteria. Most standards are referred to as 8-h time weighted averages (TWAs). These standards are for the average exposure >8 h. Various combinations of individual samples can be used to obtain the equivalent of what would have been measured by one sample of 8-h duration, as shown in Figure 1. When the standard applies to a shorter period, as, eg, a short-term exposure limit (STEL), which is a 15-min average, samples should be taken to measure over this shorter averaging time. Some limits are supposed to apply to instantaneous concentrations but because there are no truly instantaneous measurement methods (all have some response time) and because peak concentration is known to be a function of averaging time, these limits are somewhat undefined. The best solution when these limits are to be applied is to make a very short ($\geq$1 min) period measurement.

How Many Samples. A first step in deciding how many samples to collect is to divide what constitutes an overexposure by how much or how often an exposure can go over the exposure criteria limit before it is considered important. Given this quantification of importance it is then possible to calculate, using an assumed variability, how many samples are required to demonstrate just the significance of an important difference if one exists (5). This is the minimum number of samples required for each hypothesis test, but more samples are usually collected. In the usual tolerance limit type of testing where the criteria is not more than some fraction of predicted exceedances at some confidence level, increasing the number of samples does not increase confidence as much as in tests of means. Thus it works out that the incremental benefit above about seven samples is small.

3.2. Measurement Method Selection. A measurement method should meet sampling strategy requirements to the degree that the data can be used for

decision making. This does not mean that it must be the optimum method with respect to all requirements. The range of methods available is limited and it is often necessary to select a method deficient in one or more attributes, but which can yield data from which conclusions can be drawn with the desired degree of confidence. Some of the attributes to be considered in selecting a method follow.

Duration of Sample. When measuring a substance having an 8-h averaging time, a single 8-h sample or several consecutive samples adding up to 8 h is best (see Fig. 1). Short period grab samples are the least satisfactory. For a STEL, the method should be able to collect enough material to provide adequate sensitivity.

Sensitivity. The sampling and analytical method together should ideally have a limit of detection much less than the exposure limit. Less sensitive methods are still usable, however, as long as the limit is easily within the range of the method.

Freedom from Interferences. To avoid spurious results it is necessary that other substances present in the air being sampled do not bias the result so as to make it unusable. Some error owing to interferences is acceptable if the outside limits of likely error are known and can be taken into account in using the data.

Time to Result. The time required to submit samples to a laboratory, have the samples analyzed, and receive the results is not usually a critical health issue, although promptness in reporting the results of an evaluation adds credibility and impact. On the other hand, some evaluations of acutely acting substance may require immediate results such as a direct on the spot reading.

Intrusiveness. Workers are likely to alter their behavior, consciously or unconsciously, when they are observed. To the extent that a worker's exposure is related to the worker's actions, this change can distort the representativeness of the evaluation. Measurement methods which require the close presence of the person collecting the sample are more likely to influence the result than samples collected with unobtrusive devices worn by the worker.

Proximity to Breathing Zone. Whereas all exposure measurement methods attempt to sample from air that is likely to be inhaled, some methods do so better than others. A sampler fixed some distance away from a breathing area is not usually accurate in measuring exposure. Even using mobile samplers that move with the worker, the few centimeters in distance from the nose and mouth to the position of the sampler, has been found to make a difference.

Accuracy. The more accurate the sampling method the better. Given the very large environmental variability, however, sampling and analytical imprecision is rarely a significant contribution to overall error, or width of confidence limits, of the final result. Even highly imprecise methods, such as dust count methods, do not add much to overall variability when the variability between workers and overtime is considered. An undetected bias, however, is more serious because such bias is not considered by the statistical analysis and can, therefore, result in gross unknown error.

Summary. The technology of air sampling and analysis in the occupational environment makes it possible to take many more samples more conveniently than ever before. Whereas detailed descriptions of specific measuring

systems are beyond the scope of this article, the basic systems may be rated. Ratings given in Table 3 are based on the usual or most common systems and devices used in each class. Not all direct reading instruments are insensitive, however, and not all substances can be measured by short period pump–sorbent–type systems. There is considerable variation in the attributes of the specific sampling and analytical system within each class. However, the central or typical performance of various management systems is described to illustrate the use of the selection criteria and to provide benchmarks by which to compare methods.

3.3. Information Gathering. The planning of an evaluation should be complete before any actual measurements are made. The plan should include the sampling strategy element, the choice of sampling and analytical method, and how the data are to be analyzed and tested to arrive at a decision. This last is critical to the planning because weak data cannot support a decision whereas some decisions require no data at all. Once the evaluation plan is set, it should be followed to the extent possible because divergences may bias the result and even compromise the integrity of the conclusion. However, if planning assumptions turn out to be incorrect, it may be necessary to revise the plan. For example, when it is obvious that the sampling and analytical method is not working because of interferences, it would be useless to continue until a new method is found and the strategy altered accordingly. Also, some plans have built-in decision points, such as phased sampling schemes, which decide on a second sequential set of samples based on the results of a first set.

Management of Employee Cooperation. Before beginning to collect data, the cooperation of the managers involved, including the first line supervisor, and of the workers should be secured. Management needs to be informed so that they can be confident that surveillance activities will not upset production or lead to injuries. Workers need to know what the valuation means to them and how the results are to be reported. Everyone needs to know how the measurement is to be conducted so that the actual measurement causes as little disruption as possible.

Sample Integrity. In order to be able to rely on the results of measurements, it is necessary to be sure that the sample as analyzed is the same as it was when collected, and that it is properly identified in the field, in the laboratory, and in the report. Transit times and temperatures should be within the limits allowed for the type of sample and analysis. A series of documents that establish a chain of custody should exist so that it is possible to be sure that the right result goes with the right sample.

Sample Analysis. It is possible to make quality decisions using imprecise methods as long as the imprecision is considered in the sampling statistics. Likewise, it is possible to make good decisions using biased methods if the bias is known and can be offset. In order to properly handle such error sources, it is necessary to know what analytical method is to be used and what its properties are. Further, even when a method is capable of an adequate level of accuracy, it must be demonstrated that the analytical laboratory's results are accurate. To do this, the laboratory must have a quality control program which includes analysis of both internal and external quality control samples. Typically, laboratories having acceptable quality control programs are accredited by the American Industrial Hygiene Association. As an additional check, some spiked samples

are usually submitted along with the collected samples and blanks. The usual practice is to subject blanks to all of the handling of a sample (opening cassettes, breaking tube ends), except for drawing the air through the blank.

Factors Influencing Results. Apart from deliberate tampering, which is usually easy to detect, there are other influences which affect sample representativeness and its usefulness in making decisions. The basic question, "What was measured?" must be answered to know if the result can be applied as intended. If, for example, the measurement represents an unusual event, it is probably not useful for characterizing the long-term average exposure of workers. However, it may be useful in deciding if engineering controls are needed to prevent an infrequent but excessive overexposure. If measurements are made in cold weather and all windows are closed, it should be remembered that ventilation is probably better and concentrations lower in the summer, ie, observation can be combined with measurement to understand how to interpret the results.

3.4. Decision Process. In many cases, the decision regarding the need for exposure reduction measures is obvious and no formal statistical procedure is necessary. However, as exposure criteria are lowered, and control becomes more difficult, close calls become more common, and a logical decision-making process is needed. A typical process is shown in Figure 2. The interpretation and decision step may be a simple comparison with a standard for a substance with a well defined threshold. For a carcinogen without a known threshold however it may be necessary to make a judgement about risk and risk acceptability and how low is "As Low As Reasonably Achievable" (ALARA). Even when decision making is easy it is useful to remember the process and the assumptions involved. Based on an evaluation, decisions are made regarding control. The evaluation and decision steps cannot be separated because the conduct of the evaluation, the strategy, measurement method, and data collection are all a part of the decision process.

Data Collection. A set of data is collected according to plans using the strategy and methods selected. At the same time, observations are made and recorded that aid in the interpretation of the data.

Data Analysis. First, the raw data must be converted to concentrations over an appropriate time span. When sample periods do not correspond to the averaging time of the exposure limit, some assumptions must be made about unsampled periods. It may be necessary to test the impact of various assumptions on the final decision. Next, some test statistics (confidence limit, etc) (Fig. 3) are calculated and compared to a test criteria to make an inference about a hypotheses.

Interpretation. Whereas statistical tests establish whether results are or are not different from (over) an exposure criteria, the generality of this outcome must be judged. What did the samples represent? May the outcome, which is inferred to cover both sampled and unsampled periods, be legitimately extrapolated into the future? In other words, is the usual assumption of a stationary mean valid? All of these questions are answered by judgment and experience applied to the observations made at the time of sampling, and the answers are used to interpret the quantitative results.

Conclusion. The quantitative measurements, their interpretation, the calculated statistics, and the exposure criteria all come together to arrive at a conclusion to be drawn with a known chance of being wrong. The data and

their interpretation give the extent of the conclusion. The exposure criteria, its origin and basis, define the impact of a conclusion that conditions are unsafe.

Decision. Whereas a conclusion that conditions are to some degree unsafe requires that something be done, what should be done depends on the range and impact of the conclusion. The problem may be easy to correct, or it may no longer exist. The data may describe past conditions that do not presently exist but may recur. It may be that the only possible decision is to undertake significant exposure reduction efforts at great cost. The possibility of each decision should have been anticipated when the evaluation was planned so that the data in hand support the decision that must be made.

4. Generic Exposure Assessment

The United Kingdom and, to an increasing degree, European governments are implementing less quantitative means of assessing and controlling workplace hazards, paritcularly for small and medium size establishments (SMEs). In the United Kingdom the Control of Substances Hazardous to Health Regulations (COSHH) requires employers to: assess the risks to health from chemicals and decide what controls are needed; use those controls and make sure workers use them; make sure the controls are working properly; inform workers about the risks to their health; train workers.

COSHH Essentials has been developed to help firms comply with COSHH. It provides a set of simple steps to arrive at what needs to be done to protect workers. It also includes "control banding" where process and chemical combinations fall into bands for which certain controls are recommended. These methods work well for common processes typically used by SMEs but may not be applicable to more complex chemical processes.

5. Other Agents

Evaluations of occupational exposure to physical agents such as noise, radiation or heat, biological agents, and multiple chemical agents are similar to the process for single chemical substances but have some key differences.

5.1. Noise. Technical differences exist between personal noise dosimeters and high accuracy sound level meters and these may alter the usual preference for personal monitors. But it is exposure to noise rather than general room noise that must be estimated for comparison with noise exposure criteria. the logarithmic expression and alternative means of summation (3 vs. 5 db doubling) complicate statistics. Exposure criteria for both dose and peak exposure must be evaluated, and space and time variability of noise intensity can be immense.

5.2. Radiation. Protection against high voltage and fixed isotope sources of radiation is usually a matter of shielding and the observance of strict work practices. Evaluation of potential exposure to radiation sources is analogous to safety surveys which look for events and incidents that show weaknesses in procedures. Absenting accidents, exposure should be near background. For some

free sources of radiation, such as radon in uranium mines, evaluation is a matter of sampling much as for a chemical substance, except the sampling and analysis can be theoretically and analytically much more complex.

5.3. Heat. Personal monitoring of the environmental conditions which impose a heat stress on a worker is impractical, so fixed station measurement of such parameters as wet bulb globe temperature are usually made (see TEMPERATURE MEASUREMENT). These stations are carefully selected so that the results, plus worker location and workload data, can be combined to yield an overall heat stress estimate. Heat strain, the effect on the human, can be estimated from core body temperature, but this is usually only a research tool.

5.4. Biological Agents. Evaluation of occupational exposure to biological agents, such as those responsible for anthrax or Legionnaires' disease, is so difficult to do in any quantitative sense that exposure measurement may not be the best pathway to risk estimation. Inhalation is only one route of infection by organisms. Even where inhalation is the primary route, the measurement of exposure is thwarted by the enormous and largely unpredictable variation in exposure. When exposure measurements are made they are difficult to interpret because dose response relationships are not often known, and there are no quantitative standards. Organism variability and human susceptibility make it difficult to predict the consequences of the presence of an organism. Risk assessment is perhaps better based on observation of conditions which could lead to exposure and an observation of biological effect.

5.5. Control. The evaluation phase should be planned to yield the data needed to draw accurate conclusions about control needs. The need for certainty depends on how difficult it is to achieve control. If all that is required is a minor change in a work practice or a simple substitution, a reasonable likelihood that the control is necessary may be sufficient. It is much more likely that all the easy controls have already been implemented. Therefore, additional steps involve significant engineering, process, or product changes at considerable cost. In these cases, it is necessary to be very confident of the need to reduce exposure further; ie, it is worth spending considerable effort on data collection to achieve that confidence. There are techniques for calculating the value of information based on the decisions to be made. There is cost associated with being wrong.

Although the evaluation phase comes chronologically between the recognition and control phases, the control options play a considerable role in the extent or intensity of the evaluation phase.

5.6. Options. Traditional control options for overexposure are material substitution, process change, containment, enclosure, isolation, source reduction, ventilation, provide personal protection, change work practices, and improve housekeeping. A simple way of looking at selection of control options is to find the cheapest option that results in the desired amount of exposure reduction. It is not actually that simple, however, because the various options differ in ways other than cost and degree of control. Some of the other factors to consider in selection of control options are operability, reliability, and acceptability.

Operability. Hidden costs may result from changes in the way a process operates as a result of a control. For example, enclosure and isolation may diminish the ability of workers to observe the process. Upsets and disruptions

resulting from this loss of intelligence are expensive and generate resistance to the use of these controls, no matter how effective.

Reliability. Certain controls are only effective if carefully maintained. Whereas a substitution, if appropriately selected, may need monitoring, a control that depends on a sensor operating an alarm may cease to work after it is installed if it is not carefully checked, calibrated, and repaired. This procedure costs money, time, and supervisory effort, and increases risk.

Acceptability. Personal protection may seem to be the easiest and least expensive way of reducing exposure. Protective clothing such as gloves, aprons, etc, is in fact a necessary adjunct to release control in the prevention of dermal exposure. Respirators are also capable of providing significant protection, but these often have the problem of worker acceptability. Given strong management commitment and supervisor emphasis, it is possible to achieve effective protection using respirators for short periods of use. Long, routine use is almost universally resisted and, as a consequence, actual exposure reduction may not be achieved even when respiratory use is theoretically required. The difficulties of maintaining an effective respirator program are so great that exposure controls which do not rely on worker behavior are easier and more reliable. The same is also true of work practice controls. Wherever difficult, time-consuming work practices are introduced to reduce exposure, there is a tendency to revert to the easy way of doing the job, especially if supervisor emphasis is relaxed.

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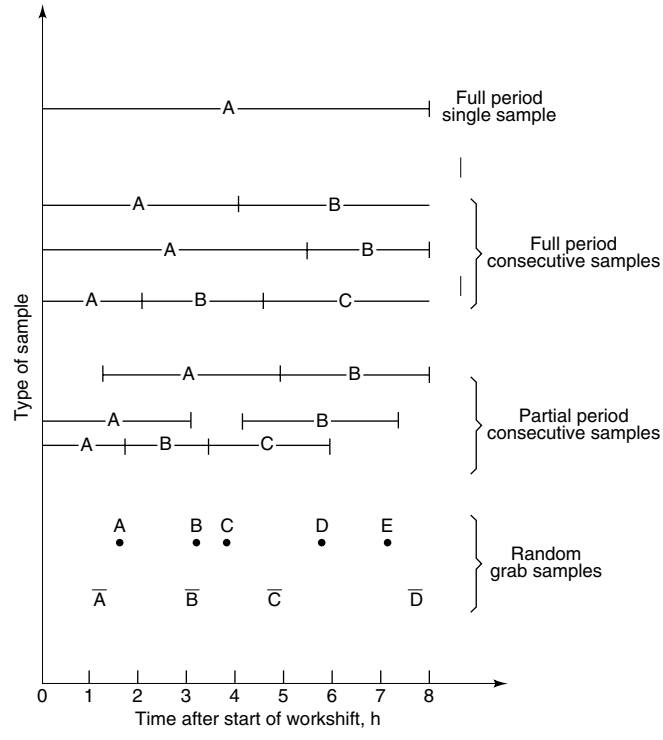

Fig. 1. Sample period options, where each letter, A through E, represents a separate sample.

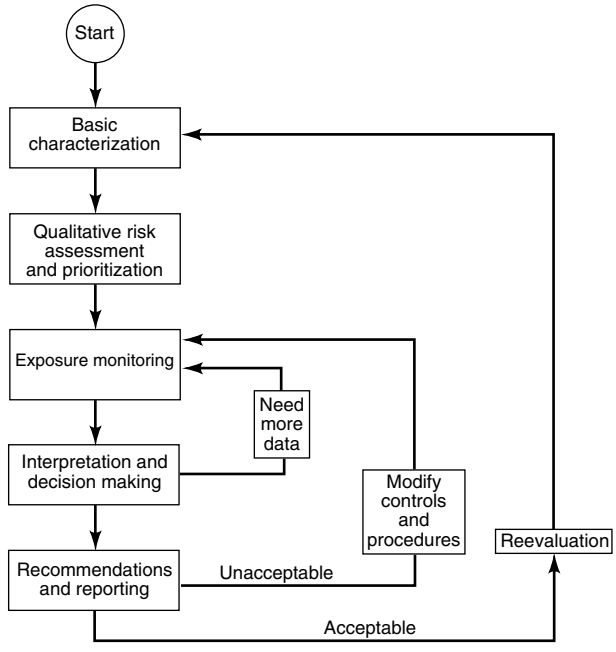

Fig. 2. Decision-making process.

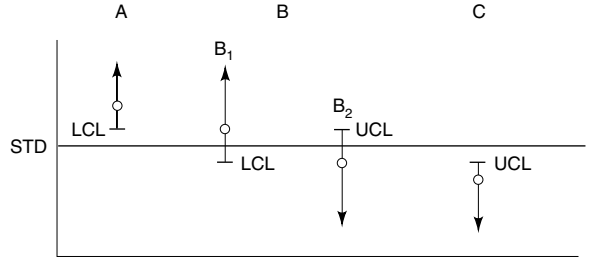

Fig. 3. Confidence limits for exposure levels. A, noncompliance; B, possible overexposure; C, compliance. STD is the standard value, LCL and UCL represent lower and upper confidence levels, between which it is 95% certain that the true exposure lies, and B_1 and B_2 correspond to two separate samples.

Table 1. **Exposure Sources in the Chemical Process Industry**

Parameter	Source type[a]	Worker activity	Relative importance	Control[b]
		Fugitive emissions or leaks		
pump seal	I or C	no	high	M
flange	C	no	low	M
agitator seal	I or C	no	medium	M
valve stem	C	no	high	M
		Process operations		
sampling	I, E	yes	medium	W, E
filter change	I, E	yes	low	W, P
gauging	I, E	maybe	low	E, W
venting and flaring	I or C	no	medium	E
extruding	I or C	yes	medium	E
		Material handling		
solid addition	I, E	yes	medium	
liquid transfer	I or C	no	high	E
bagging	C	yes	high	E
drumming	C	yes	high	E, W
bag dumping	I	yes	high	E, W
screening	C	no	medium	E
open mixing	I	no	medium	E, P
banbury mixing	I or C	yes	high	E, P
milling	I or C	no	medium	E, P
		Maintenance		
equipment opening	I, E	yes	high	W, P
instrument line draining	I, E	yes	medium	W, P
welding	I, E	yes	high	E, W, P
painting	I, E	yes	medium	W, P
sandblasting	I, E	yes	high	E, P
insulating	I, E	yes	high	W, P[c]
insulation removal[c]	I, E	yes	high	W, P
chemical cleaning	I, E	yes	medium	W, P
degreasing	I, E	yes	low	E
cutting and burning	I, E	yes	medium	W, P
catalyst handling	I, E	yes	high	W, P
		Waste handling		
baghouse cleaning	I, E	yes	high	P
drain and sewer venting	I or C	no	high	E
spill clean up	I, E	yes	medium	P
sweeping	I, E	yes	low	W
incineration	I or C	maybe	medium	E
wastewater treatment	C	no	medium	E
sludge handling	I, E	yes	medium	W, P

[a] C = continuous; I = intermittent, ie, over discrete intervals of time; E = episodic, ie, nonrandom, the result of an event.

[b] M = maintenance, ie, primarily the monitoring and repair of leaks by replacing pump seals, repacking valve glands, tightening flanges, sealing holes in duct work, etc; P = personal protection, ie, the use of an air purifying or supplied air respirator, usually for a short period of time, for a particular hazardous operation; W = work practices, ie, staying upwind of a release source, not spilling volatile liquids on the ground, keeping the work area clean to avoid redispersion of dusty materials; and E = engineering, ie, equipment or process modifications to prevent or contain release such as welded pipe joints, hermetic pumps, vent scrubbers, sealed drains, or local exhaust ventilation.

[c] Substitution of less toxic materials for asbestos (qv) is the most common control.

Table 2. **Catalyst Industrial Hygiene Concerns**

Catalyst	Molecular formula	Possible health effects
aluminum oxide	Al_2O_3	nuisance
aluminum chloride	$(AlCl_3)_x$	decomposes to HCl; irritation
aluminum alkyls		acute thermal burns from contact, lung damage
chromic oxide	CrO_3	Cr^{3+}, low toxicity; may convert to Cr^{6+}, toxic and carcinogenic
cobalt	Co	lung irritation
cobalt hydrocarbonyl	$CoH(CO)_4$	acute respiratory failure
ferric oxide	Fe_2O_3	siderosis; low toxicity
molybdenum compounds		pneumoconiosis
nickel compounds		carcinogenic; eg, nickel subsulfide, Ni_3S_2
platinum and compounds		low toxicity; dermatitis
thorium oxide	ThO_2	low toxicity; radioactive
uranium		kidney damage
vanadium		respiratory irritation

Table 3. **Comparison of Measurement System Attributes**

Attributes	Measurement system				
	Direct reading instruments[a]	Continuous monitors	Pumps–sorbent sampler	Detector tubes[b]	Passive badges
sample duration	short	long	short or long	short	long
sensitivity	poor	fair	good	poor	fair
time to result	short	short	long	short	long
intrusiveness	high	low	low	high	very low
breathing zone proximity	fair	poor	good	fair	good

[a] Not always specific.
[b] Long period tubes available.