Industrial Hygiene Engineering and the Process-Environment System

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A systems approach to industrial health would help integrate the concepts applied by engineers, industrial hygienists, toxicologists, and physicians, and organize them into a strategy for health maintenance that is compatible and measurable along common lines. The advantages of a systems approach to industrial health are viewed in terms of the application and refinement of industrial hygiene standards, participation of the engineering professions, communication among all members of the occupational health team, and transition we are enjoying with the increasing use of automation, process control and computer technology.

Introduction

IN HIS INTRODUCTION to *Industrial Hygiene Highlights*, Professor Theodore Hatch[1] reminds us that "it is the responsibility of industrial hygienists, toxicologists and physicians constantly to review the adequacy of the methods they employ to demonstrate health maintenance." This is a challenge to all of us who have sensed the broadening horizons of our profession. For if we are to apply the principles of industrial hygiene successfully in this time of rampant technological change, we must keep abreast of new developments in the basic disciplines that comprise our multidisciplinary profession.

Effective management of occupational health programs requires—more than ever—coordination and teamwork among those specialties that function within this broad field. We need to know and understand how each discipline that deals with occupational health can complement and interact with other members of the occupational health team.

One measure of the compatibility of an interdisciplinary approach to occupational health is the emphasis we place on the concepts and methods applied to industrial hygiene by several specialties—by engineers, industrial hygienists, toxicologists and physicians—concepts and methods which we have in common, and which can be reduced to quantities measurable along common lines.

One concept that relates to all the disciplines within the field of occupational health is that of an "acceptable exposure level" or an "industrial hygiene standard" for inhalation of materials in the work place.

We are familiar with threshold limit values (TLV's), maximum acceptable concentrations (MAC's), and, in more recent years, the multiple guidelines of the Z-37 Committee of the America National Standards Institute (ANSI). Much attention has been given to the development of these standards, but it appears that there has been less concern for the validation and refinement of those guidelines, and clearly, even less concern for the application of industrial hygiene standards in the work place.

Specifically, two aspects of the application of standards are glossed over to our disadvantage. First is the fact that TLV's and other hygienic standards are not easy to use properly. Second, many of the engineers in industry who could be, are not using the concept of an industrial hygiene standard in their decision making. Therefore, we do not benefit as fully as we could from the assistance the engineering profession could give us in the overall control of industrial health hazards. What can be done to improve this situation?

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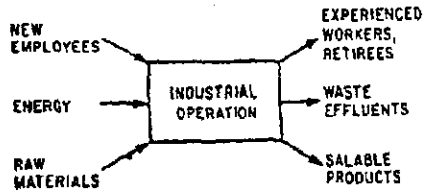

FIGURE 1. An industrial operation.

The Need for a Systems Approach

Clearly, the application of knowledge from engineering and medical research, industrial toxicology, and field experience in environmental control requires some communication system for the essential interplay to exist among the various parent disciplines within our field. If the communication is effective, that interaction can thrive.

On the other hand, if each discipline interested in occupational health attacks a particular problem independently, we likely will not meet the total need. Thus, we should adopt an integrated approach in organizing ourselves to deal with our common concerns.

In the integration of interdisciplinary interest which focuses on a complex problem, one promising technique is "systems analysis." Webster defines a system as a "regularly interacting or interdependent group of items forming a unified whole."[2] In simplest terms, a system consists of a set of components which, when combined, produce a useful result.

A "system" in terms of industrial health might be an organizational framework that defines the strategy for assuring the healthfulness of a worker population. To that end, the system might be composed of certain subsystems which could be examined and treated separately.

If we step back and look at an industrial operation and examine the various inputs and outputs from that industrial unit, we observe an interesting fact: From a larger viewpoint an industrial operation takes three inputs—new employees, raw materials, and energy—and converts them into three distinguishable products (see Figure 1). First, there are the salable products which are sold in the marketplace for profit. Second, there are waste effluents which take the form of solid, liquid, or gaseous materials—and in turn may contribute to the total environmental burden of air, water and soil pollution. Third, there is an output from the system which is of direct concern to those of us interested in occupational health—the exposed workers and retirees.

We have implied, then, that the work environment is only part of a larger system. Specifically, every work situation has three elements: a process (perhaps a limited operation or function task), a work environment, and a worker. Within an industrial unit the process, the work environment, and the worker are not totally independent entities. Each is affected, or could be affected, by the other two elements. In many cases, one cannot alter a process or even change a job procedure without changing the quality of the work environment. A worker often has enough latitude in his work procedure to create differences in the degree of exposure he will encounter on his job. All three of these items—the process, the work environment, and the worker—must receive attention in an occupational health program.

It is at this point that some of the functional differences within the occupational health team become important and necessary. Clearly, the physicians, the nurses, and the supportive role of toxicology must deal with the worker and his health; the industrial hygienists must deal primarily with the work environment; and the logical extension of this approach would have the engineers dealing with the process—which, after all, is causing the environmental stress in the first place.

The Need for Feedback

Control of health hazards in the work environment can be neither comprehensive nor complete unless we systematically use the information that such considerations yield. In a self-regulated system the key element for control is "feedback." This refers to a circularity of the flow among two or more parts of the system structure. Such an arrangement assures that the output of the system is maintained at a desired level. Typically, this requires constant monitoring of the system output, a comparison of the output with standards, evaluation of any discrepancies, and a flow of information concerning the abnormal deviations

back to other elements in the system structure so that the procedures may be changed if necessary. Figure 2 shows an example of a simple closed-loop system with feedback.

Likewise, in industrial health we have a critical need for feedback information. We must know the adequacy of specific environmental control techniques. We also must have feedback concerning our industrial hygiene standards. Useful standards should be continually verified or modified as our knowledge and experience grow.[3]

Figure 3 shows a system both for assuring environmental control—including feedback on the control techniques employed—and for validating industrial hygiene standards through systematic documentation of exposure together with systematic medical surveillance of the exposed worker. This combination industrial hygiene and medical survey is a simple application of a "systems analysis" because it integrates several functional specialties in our field into a unit that moves toward the same goal.

This particular approach centers upon the industrial hygiene standard that could be a basis but by no means the only basis for effective interaction among the parent disciplines represented in the overall system. Here then we have a strategy for harnessing the toxicological feedback that is available from the exposed worker in terms of the effect, if any, on his health at the levels of exposure measured in the work environment.

The engineering function is represented in that part of the overall system that deals with the Process and the Work Environment—as opposed to that part of the system which deals with the Worker.

If we separate out the Process-Environment portion of the overall system we notice a striking similarity with the typical engineering control network.

The Process–Environment System

Figure 4 depicts the Process–Environment System. This is represented as a closed-loop control network that stresses the engineering application of industrial hygiene standards. Most engineers are not primarily concerned with the requirements of industrial hygiene.

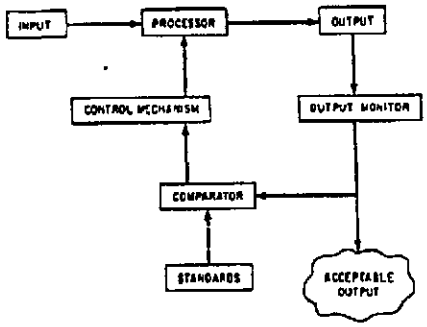

FIGURE 2. A typical control system with feedback.

Yet, effective communication on how engineering techniques can be utilized is an essential need and deserves more attention in practice.

The advantage we have in this respect is that engineers in general tend to deal with as large a system as they can handle from a computational standpoint. Therefore, the industrial hygiene standard could be used as an engineering standard in a larger system that includes the work environment.

Specifically, the *design* of a process should be directly related to the acceptable degree of environmental contamination by materials used or produced by the process. Environmental problems, unfortunately, are often created by poor engineering design. In other

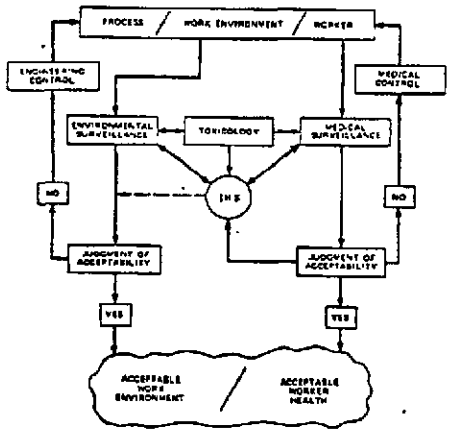

FIGURE 3. An overall system in occupational health.

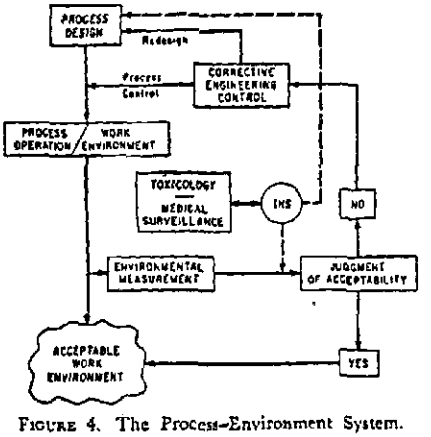

FIGURE 4. The Process–Environment System.

words, *environmental control must start on* the drawing board.

Second, the *operation* of the process can vary in a manner that will cause fluctuations in the level of contamination of the work environment. Again the acceptable exposure level serves as a guidepost toward which all future changes and improvements in the operation of the processes should be directed.

Third, the industrial hygiene standard directly affects the *measurement* of contamination in a particular work environment—such measurements to be used for judging acceptability of control, following comparison with the standard that applies in that particular case. With airborne chemical X, for example, there may be several ways to measure and monitor airborne concentrations of that contaminant in the work room air. The level of the threshold limit will often govern what type of instrument is used, and thereby the accuracy of the resulting information.

Fourth, we often think of a threshold limit value as the standard against which the estimate of the exposure is judged, but it is not *enough to take such judgment for granted, for* often the comparison of the measurement and the standard is made with inadequate information. Especially in the use of multiple guidelines, such as those of the Z-37 Committee of ANSI, we need a carefully planned *approach—both to gather the proper information* and then to use it meaningfully.

Finally, the measured deviation from the industrial hygiene standard frequently points the way to the type of *engineering control* or improvement that results when the measured concentration exceeds the standard. In other words, how far must we journey to arrive at the desired degree of contaminant control? If the deviation from the TLV is near zero, there is a different set of alternatives available than if the measured exposure exceeds the TLV by a gross amount.

Today's technological advances have brought us closer to the day when we can control the work environment just as we routinely control a manufacturing process. First we have seen the development of continuous monitoring, which can be an effective diagnostic tool for the identification of predominant sources of contamination in the work environment, the proper selection of contaminant control methods, and the documentation of occupational exposures.

The second development in this respect is the digital computer. When coupled to an environmental monitor the computer provides an effective means of reducing voluminous amounts of information into manageable form. These data, in turn, can be used to show both short-term and long-term trends of exposure. When correlated with day-to-day plant operation such information can result in even lower exposures.[4,5] In addition, such data can be used to describe the exposures of workmen in what is in effect a continuing industrial hygiene survey.

These two developments parallel the trend in the process industries where "on-stream *process analyzers*" and "*computer applications*" have mushroomed into prominence. Automatic regulation of product quality is commonplace—and the marriage of instrumentation and the computer has provided the engineering profession with some powerful new techniques.

This is important to our field because our allies in the engineering profession are increasingly well-versed in such techniques, and to the extent that engineers become engaged in environmental control, we can expect to take advantage of these and other technological advances in controlling the quality of the

work environment.

Advantages of Process–Environment System

Adequate Surveillance

A new process or facility should never be considered acceptable from our point of view until studies have proved the environmental control to be adequate. In view of the importance of process operation and its effect on the quality of the work environment, environmental surveillance often must be repeated regularly or, better yet, made a permanent feature of the Process–Environment System.

Frequency of environmental sampling is an important question, especially where we are confronted with variable concentrations or cyclic operations. A continuous monitor can be invaluable when we try to characterize the environment in such a way that our measurements are truly comparable with accepted hygienic standards. Also, the use of multiple guidelines in the control of the environment requires that a large number of regularly spaced samples be used to estimate the intensity of exposure.

Figure 5 shows a schematic representation of a multipoint continuous monitor that could be used to document exposures, and to aid in the control of air concentrations.[3] The several sampling probes extend into work areas where the worker spends his time during normal work activity. The concentrations at each of his work areas—or sampling locations—must be weighted according to the time spent there to estimate the time-weighted average concentration, the basis of most of the threshold limit values.

In addition, continuous monitors, if appropriately used, offer other important advantages. Among these are: (1) diagnostic air sampling, including time-dependent and location-dependent patterns, (2) efficient documentation, and (3) reduced material loss.

While controlling the air concentrations of a contaminant in the work room it is often possible to achieve an important savings from reduced material loss, especially if the contaminant is a raw material or product. Here is one area where it is very easy to enlist the help of the engineer. His prime concern with the economics of the operation of his process

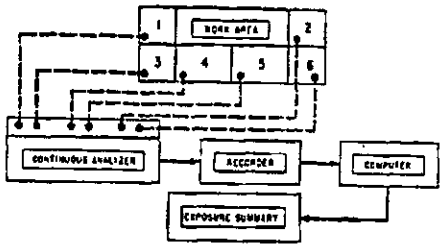

FIGURE 5. Schematic diagram of a continuous environmental monitoring system.

may help us to achieve our objective of limiting emissions into the work room. Sometimes it is possible to pay for a continuous monitoring system in a short time with the savings realized by its use.

Figure 5 indicates that the information from the schematic environmental monitor flows through a "computer." This again is indicative of the changing technology that bears on our field and at the same time opens new doors of opportunity for us to do a better job.

A continuous analyzer generates a great volume of information, and the full use of the data coming from such a device depends on how well we can reduce the output to meaningful terms. The digital computer offers us great help at this point because it can quickly translate a flood of concentration data into a comprehensive summary, including several parameters that may be of importance.

Proper Application of Standards

In a typical control system the error-detecting mechanism is critical. In the case of environmental surveillance, we are interested in comparing the estimated worker exposure with the appropriate industrial hygienic standards.

Whenever volatile substances are present in the work room, the concentrations will likely fluctuate so widely that it will be advantageous to monitor the environment continuously and test it repeatedly against the various standards that can be applied. In addition, the application of hygienic standards as they are defined virtually requires the use of continuous or semicontinuous sampling procedures, reduction of the measurements to the appropriate parameters, and then comparison with each of the appropriate guidelines.

For example, Table I shows the various in-

TABLE I
Industrial Hygiene Standard for Carbon Tetrachloride

TLV or "acceptable 8-hr TWA"	10 ppm
Acceptable ceiling concentration	25 ppm
Acceptable maximum concentration for peaks above acceptable ceiling	200 ppm
Acceptable number of peak concentrations of 5-minute duration for 8-hr period	2

dustrial hygiene standards that are available for carbon tetrachloride. To judge the acceptability of a particular work environment using these parameters, we would need a measurement in the worker's breathing zone at least every 5 minutes for 8 hours. This minimum of 96 samples would then have to be reduced to the various sampling statistics that could be compared with the standards.

Relatively little attention has been given to this problem of characterizing the work environment in a manner that will allow proper application of hygienic standards; it must receive more attention in the future. Table II shows one exposure summary that could be used to judge the intensity of exposure along several guidelines, both short-term and long-term. This exposure summary covers a 7-day period and reduces over 100,000 measurements to an informative, compact table. The information comes from a continuous environmental monitor linked directly to a digital computer.

Documentation and Feedback

The third advantage of the Process-Environment concept is that adequate environmental surveillance allows the use of feedback to provide a check on our environmental control efforts—to the extent that we correlate the environmental information with medical findings on the same worker population, we can use that feedback information to validate or refine our hygienic standards.

As the problems of concern in the work room from environmental stresses become more subtle and complex, the need for systematic studies on the relationship between *exposure and consequence increases, and we* need more than ever to complement the results from laboratory studies with planned systematic findings on groups of people exposed to the suspected agent under real conditions.[3,6,7]

Summary

Progress in our field—occupational health—will continue to depend on a "team approach." As Professor Hatch[1] pointed out, we must continually examine the methods we use to achieve results. Surely we must go beyond *that and be willing to apply* new techniques to our field whenever it can be demonstrated that such application will enable us to do a better job in conserving the health of the worker in the industrial environment. The development of our profession will depend on how well we integrate the common interests that each discipline brings to the field of occupational health. Our progress will also

TABLE II
Data Summary from a Continuous Environmental Monitor

Department—chemical plant
Material —methyl chloride
Date —2/17/69 to 2/23/69

	Sampling Location (raw data)						Job Classification (time-weighted)
	1	2	3	4	5	6	A
Mean concentration	14.3	29.5	38.8	42.8	61.3	79.3	26.8
Standard deviation	13.9	9.5	19.4	9.1	22.4	21.0	19.3
Frequency distribution							
25 ppm	8.5	49.4	60.5	100.0	100.0	100.0	39.6
50 ppm	1.9	9.1	20.4	16.4	31.4	100.0	13.5
100 ppm	0.5	0.2	3.4	0.2	6.7	14.5	1.4
200 ppm	0.2	0.0	0.4	0.0	1.1	0.3	0.1
300 ppm	0.1	0.0	0.3	0.0	0.1	0.0	0.0
Maximum concentration							
5 minutes	93.3	66.2	107.0	91.6	164.7	170.3	76.2
10 minutes	74.9	62.7	98.8	82.2	145.0	150.2	67.6
30 minutes	45.7	51.1	86.6	63.0	100.7	121.4	51.0
1 hour	30.7	43.0	73.7	54.9	94.9	102.9	41.5
4 hours	17.3	33.4	47.8	45.6	69.8	87.8	30.5

be measured by how well we find compatible, systematic methods of using the newest tools available to each basic discipline in our field.

A systems approach to industrial health would help us to take advantage of the transition we will enjoy with increasing use of automation, process control, and the digital computer. From a systems engineering point of view there is really little difference between controlling the process and controlling the work environment associated with it. A logical point of reference for the transition ahead would be the Process–Environment System.

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Gordon Research Conference

The 1970 Gordon Research Conference on Toxicology and Safety Evaluations will be held at Kimball Union Academy, Meriden, New Hampshire, July 27-31. This conference has been of considerable interest to industrial hygienists for a number of years because of the close relationship of problems encountered in industrial health work. This year the Chairman is J. Wesley Clayton, Jr. and Vice-Chairman is Edward D. Palmes. The program is as follows:

July 27. (R. A. Scala, discussion leader): H. H. Cornish, "Serum isozymes and organ damage"; J. L. Radomski, "The metabolism of 1- and 2-naphthylamine as related to carcinogenesis." (S. L. Friess, discussion leader): J. M. Barnes, "Toxic substances and the nervous system."

July 28. (S. Epstein, discussion leader): C. Jacobson, "Test systems for the reproductive evaluation of mutagens"; D. J. Kilian, "The role of cytogenics in evaluating the toxicity of chemical compounds." (H. V. Malling, Discussion leader): C. Valenti, "Effects of psychotropic drugs on mammalian chromosomes in vitro and in vivo observations."

July 29. (C. H. Hine, discussion leader): R. E. Hodges, "The role of human studies in evaluating potentially hazardous agents"; L. H. Schmidt, "What nonhuman primates have taught us relative to the action of chemicals on living systems." (Sidney Leskovitz, discussion leader): B. Pernis, "Immunological problems in toxicology."

July 30. (W. B. Ennis, discussion leader): D. O. King, "Rational Management of the environment"; K. C. Barrons, "Benefits of agricultural chemicals." (J. P. Frawley, discussion leader): L. Cole, "The chemical threat to our environment."

July 31. (E. D. Palmes, discussion leader): T. Foin, "Technology, population and the environment."

Attendance at the Conference is by application only. Application forms and full information regarding requirements for attendance may be obtained by writing to Dr. Alexander M. Cruickshank, Director Gordon Research Conference, Pastore Chemical Laboratory, University of Rhode Island, Kingston, Rhode Island 02881 (Telephone: 401-783-4011). Applications for this Conference should be submitted before June 1, 1970.

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Monitoring Exposures to Vinyl Chloride Vapor: Breath Analysis and Continuous Air Sampling

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An environmental survey was conducted to determine the time-weighted average exposure (TWA) of a group of chemical plant workers to vinyl chloride (VCl) vapor. This survey featured continuous multipoint air sampling and analysis using an infrared spectrophotometer. The inhalation exposure data were digitized and recorded on paper tape for subsequent computer analysis and derivation of daily TWA values for each worker. A breath sampling program was conducted concurrently with the environmental survey, and a series of breath decay curves relating postexposure breath concentration to vapor exposure were derived from the data. To validate the breath curves derived from on-the-job data, postexposure breath curves were also constructed from breath data obtained following experimental human exposures to carefully controlled concentrations of VCl vapor. The close agreement between postexposure breath concentrations at the corresponding TWA's obtained by each of the methods suggests that either continuous air monitoring or breath analysis is valid for estimating the worker's individual daily exposure to VCl, and provides further evidence that breath analysis is a useful industrial hygiene technique for evaluating vapor exposure.

Introduction

THE QUESTION THAT MAY ARISE following an environmental survey is whether the chemical vapor concentrations measured are truly representative of the exposure being experienced by the workmen. Evaluation of the ranges of atmospheric concentrations and estimates of time-weighted average concentration (TWA) are all too often based on a few spot samples obtained under conditions which are not representative of all phases of a given operation. A more exact measurement of vapor exposure would have to be based on continuous monitoring of air in the workman's breathing zone during his entire work shift. Obviously this task is made difficult and often impossible by the large number and variety of tasks performed by today's modern chemical plant worker.

Recent improvements in automatic monitoring and data processing equipment have provided a means for a more satisfactory solution. Sequential samplers and automatic analyzers and recorders can now be used to continuously monitor several locations or operations to provide more valid data on which to base estimates of chemical exposure. Computers can be utilized to manage the large volume of data generated by continuous monitoring.[1]

Meanwhile a technique has been under development which more precisely defines the level of individual exposure. The realization that the total body burden of a volatile chemical is directly related to its concentration in expired air led to the development of techniques for collecting and analyzing breath samples useful in estimating the more indi-

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vidualized exposure experience of each workman. Studies by Stewart *et al.*[3-6] have shown that the excretion or "decay" of vapor in the breath can be used to characterize the exposure. Breath decay curves constructed for several chemical solvents have proved clinically useful as an index to chemical exposure.

These breath decay curves, for the most part, were constructed from postexposure breath data obtained from experimental human exposures to carefully controlled and relatively constant vapor concentrations. However, breath decay curves have recently been constructed from breath data collected from workers whose work environment was being continuously monitored.[7]

In this study of human exposure to vinyl chloride (VCl) vapor, breath decay curves constructed from data obtained during experimental exposures to the relatively uniform concentration within an exposure chamber were compared with those derived at the theoretically equal, but broadly fluctuating, concentrations encountered in a chemical plant atmosphere. A measure of the validity of continuous monitoring data and the usefulness of breath analysis in assessing time-weighted average exposure was reflected by a close similarity between the two sets of breath decay curves.

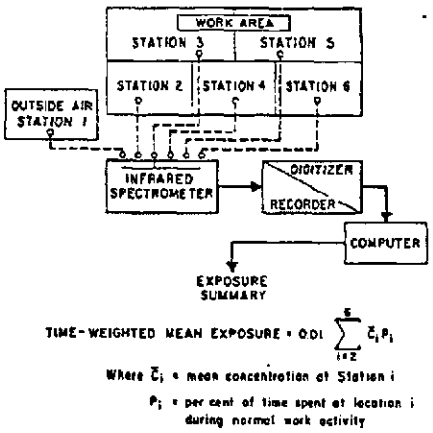

FIGURE 1. Schematic diagram of the infrared continuous monitoring system.

Procedures

Monitoring the Plant Atmosphere

The chemical installation surveyed was a closed structure housing several separate chemical processing operations. First, a job survey was conducted for each of four job classifications to determine the work areas frequented by the workmen and the time they spent in each area. For each job classification, five sampling probes were strategically placed in the work area. A sixth probe was placed outside the building, and charcoal and silica gel filters were placed in the sampling line to assure a clean air reference. The sample probes were 5/16-inch I.D. Saran tubing through which air samples were drawn by a vacuum pump at a rate of 17.5 liters/min to a centrally located infrared spectrophotometer. The spectrophotometer was equipped with a 10-meter path-length gas cell sensitive to 5 ppm of VCl at a wavelength of 10.63 microns. The VCl concentration was linearly related to absorbance up to approximately 1000 ppm.

A schematic diagram of the sampling system is shown in Figure 1. Sampling was executed sequentially with a set of six two-way solenoid valves controlled by a timer which advanced the sampling location every 5 minutes. A visual account of transmittance was recorded on a strip chart recorder. Meanwhile the data were recorded in digital form on paper tape by a tape punch and digitizer-programmed to record three equally spaced transmittances during the last half of each 5-minute sampling period.

The transmittance data furnished by the spectrophotometer was converted to absorbance and reduced to concentration according to Beer's law:

$$A = \mathrm{Log}_{10}\frac{(X_1 - X^{\infty})}{(X_i - X^{\infty})}$$

where

A	=	absorbance
X_1	=	base-line response
X^{∞}	=	response at total absorption.
X_i	=	response at location i.
i	=	2, 3, 4, 5, 6.

Finally,

$$C = KA$$

where

K = a proportionality constant,
C = concentration

The taped data were processed by a Burroughs 5500 computer at The Dow Chemical Company Computation Research Laboratory. The computer was used to calculate the mean and standard deviation of concentrations at each location for each 8-hour work shift. Finally, time-weighted average concentrations were calculated for each job classification using the time–location data obtained from the job surveys. As described elsewhere,[1] the weighted percentage of time during which concentrations exceeded several prechosen levels was also computed for use in establishing exposure profiles.

Figure 2 describes the exposure profiles (frequency distributions) for the four job classifications studied during this survey. These profiles show the percentage of time that concentrations exceeded the levels shown. They summarize several tens of thousands of individually measured concentrations and reduce them to single curves. Figure 3 shows the corrective trend brought about by actions undertaken to reduce the atmospheric concentration of VCl over the 7-month period during which the study was conducted. Only two job classifications warranted extensive study, but men in all four classifications were asked to participate in the breath sampling program.

On-the-Job Breath Sampling

Three separate breath sampling programs were conducted concurrently with the environmental plant survey, designated by the boxed portions in Figure 3. Each worker collected three breath samples daily—the first on his arrival home from work, the second 5 to 10 hours later, and a final sample before returning to work the following day. The samples were collected in pipets constructed from short lengths of 20-mm soft glass tubing to which had been welded at each end the threaded portion of a 2-dram (8-ml) screw-cap glass vial (Figure 4). The overall length of the pipet was about 9 inches, so it could be conveniently and inconspicuously transported to and from work in a lunch bucket.

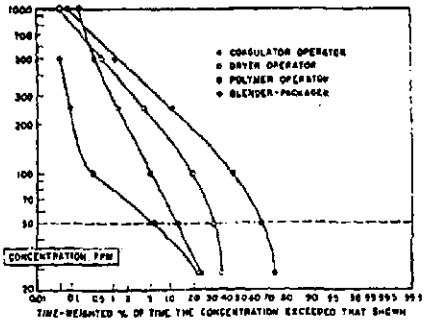

FIGURE 2. Exposure profiles expressed as VCl vapor concentration versus the exposure frequency distribution for the four job classifications.

The plastic caps were lined with six layers of Saran film identical to that used for the construction of Saran air sampling bags. A 3/32-inch hole predrilled through one of the caps provided an access for withdrawing samples. The Saran liners provided an effective gas barrier so that vapor losses were held to less than 10% for a holding period of 3 days.

When collecting a sample the subject was asked to remove the caps, place the pipet to his lips, and breathe normally in through his nose and exhale through the pipet three

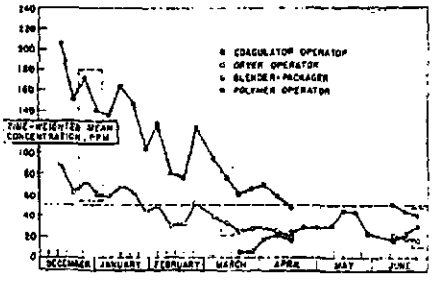

FIGURE 3. Weekly mean vapor exposure concentrations measured during the survey. Periods during which breath sampling was conducted are represented by the boxed-in areas.

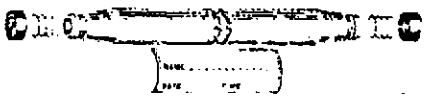

FIGURE 4. Glass pipet (50 ml) used for collecting breath samples. One cap has a predrilled hole for gas sampling. Both caps have Saran liners which seal the pipet chamber.

times. After expelling the fourth breath he quickly caps the tube, trapping a portion of alveolar air. The importance of writing the name, date, exact time of sampling, and the workshift most recently completed, on the label attached to each pipet, was stressed.

Aliquots were drawn from the pipets with a 1-ml Hamilton gas-tight syringe and analyzed in an Aerograph A-600B gas chromatograph using N_2 carrier gas and a hydrogen flame detector. Separations were made with a 6-foot, ⅛-inch I.D. stainless-steel column packed with Carbowax 20M alkaline on Chromosorb W 60/80 mesh acid-washed.

Exposure Chamber Operation

Three experimental human exposures to VCl were conducted at nominal vapor concentrations of 50, 250, and 500 ppm. The exposure chamber was a room measuring 41 feet by 6 feet wide by 7.5 feet high. The room had a continuous positive air supply and exhaust system capable of maintaining a slight negative pressure within the chamber. Continuous distribution of the chamber air was achieved by recirculating the air with a squirrel cage fan through a series of inlet and outlet ducts spanning the length of the chamber. The VCl was metered into the duct carrying air exhausted by the squirrel cage fan and entered the room atmosphere via the recirculation system at a rate sufficient to maintain the desired atmospheric concentration. The vapors were introduced from a pressurized storage cylinder through 6 feet of ⅛-inch I.D. stainless-steel tubing into a rotometer prior to entering the circulating air duct. A heating tape wrapped around the stainless-steel tubing prevented condensation of the VCl and stabilized the flow of the vapor.

The concentration of VCl in the chamber was constantly monitored with a Perkin-Elmer infrared spectrophotometer equipped with a 10-meter path-length gas cell. A sampling probe, consisting of 5/16-inch I.D. Saran tubing, was centrally located during the exposure to represent the breathing zone of all subjects within the chamber. The probe was moved about prior to each exposure to detect imbalance of vapor concentrations within the chamber so that necessary corrections in the recirculating system could be made. Air samples collected periodically within the chamber throughout the exposure day were analyzed by gas chromatography for added assurance of analytical accuracy. Both the infrared spectrophotometer and the gas chromatograph were calibrated before each experiment and at intervals throughout the exposure day.

Each 7.5-hour exposure day included a 0.5-hour lunch period in an uncontaminated area outside the exposure chamber. The TWA concentration was calculated on the basis of 7.5 hours of exposure.

Clinical and Laboratory Procedures

Each subject had been under careful medical surveillance by the medical department for a number of years, and each was given a complete medical examination a few days prior to the VCl exposures. Included were a complete urinalysis and 24-hour urine for urobilinogen, complete blood count with sedimentation rate, reticulocyte count, SGOT, SGPT, LDH, alkaline phosphatase, BUN, creatinine, and bilirubin.

Each subject received a repeat physical examination 1 hour before entering the exposure chamber. This examination included measurement of temperature, blood pressure, and pulse rate, a neurological examination, and collection of blood and breath samples. A questionnaire noting the presence of any symptoms of illness (for example, headache, nausea, dry throat) completed the preexposure medical evaluation.

After the subject entered the chamber, total expired breath samples were collected every hour by having him breathe out through a Saran tube leading to a Saran plastic collection bag located outside the chamber. Tidal volume and total expiratory capacity

were measured in the morning and again late in the afternoon exposure periods.

Subjective and neurological responses were measured before the subject entered the chamber, 15 minutes after entrance, and at 1-hour intervals thereafter. Flannagan Coordination and Crawford Manual Dexterity Tests were conducted at midmorning and again in the afternoon. Breath sampling began immediately after the subject left the exposure chamber. A 24-hour postexposure urine sample was collected and a blood sample was drawn the following morning for SGPT, LDH, alkaline phosphatase, BUN, creatinine, and bilirubin determinations.

Analysis of Breath Data

The decay curves for the breath vinyl chloride concentrations were constructed by stepwise multiple regression using a digital computer. An empirical relationship of the form Concentration = f (TWA, time) was selected from a choice of several terms, each based on TWA and/or time. The resulting regression equation best represents the ordered relationship between breath vinyl chloride concentration, time-weighted average exposures, and postexposure time.

Each breath decay curve has an associated standard error of regression which can be used to compute the confidence band for any chosen level of significance. The 95% confidence band for the mean of a group of observations was chosen in this case to describe the statistical error associated with the breath data and the regression technique.

Results

Experimental Breath Curves

A total of 13 men participated in the three experimental chamber exposures at nominal concentrations of 50, 250, and 500 ppm producing a total of 160 valid breath data points. Five of the six subjects exposed to 50 ppm were re-exposed at 500 ppm 2 days later. There was no measurable residual vinyl chloride detected on the breaths of the subjects prior to the second exposure. Serial breath sampling was initiated immediately after the subjects left the exposure chamber and continued up to 20 hours following the exposures.

TABLE I
Experimental Human Exposure to Vinyl Chloride

Chamber Concentration (ppm) $\bar{X}$	S.D.	Range (ppm)	TWA* (ppm)	Number of Subjects
59	2	65–53	48	6
261	8	289–243	248	4
493	7	518–471	459	4
491	5	525–475	491[b]	7

*Time-weighted average concentration based on 7.5 hours including a 0.5-hour lunch period in an uncontaminated area.
[b]Continuous exposure for 3.5 hours.

Table I shows the analyzed concentration to which the subjects were exposed. Calculations of the mean and standard deviation of exposure concentration are based on chart readings from the infrared spectrophotometer taken at 5-minute intervals over the two 3.5-hour exposure periods. The TWA is based on the total 7.5 hours which included a 0.5-hour lunch period in an uncontaminated area.

The final breath decay curves intended for use as an index to VCl exposures were adjusted to TWA concentrations of 50, 250,

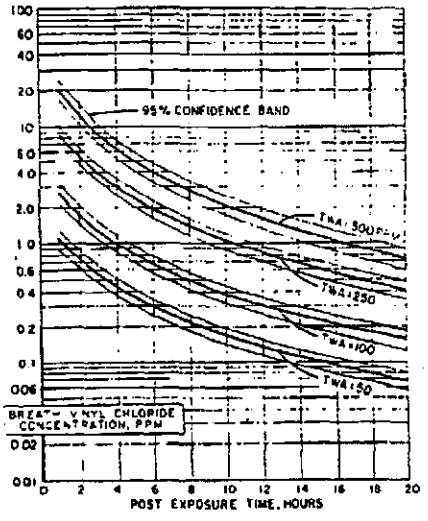

FIGURE 5. Breath decay curves based on experimental human exposures to 50, 250, and 500 ppm of VCl (7.5-hour TWA).

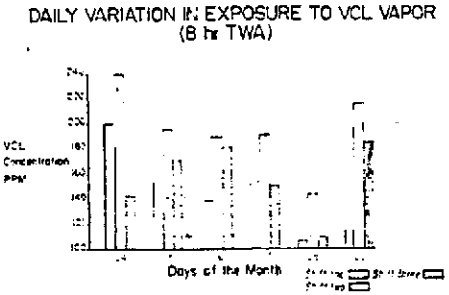

FIGURE 6. Variation in VCl vapor exposure for three shifts.

and 500 ppm (Figure 5). A 100-ppm decay curve was interpolated from the available data using regression analysis. These curves are presented with the calculated 95% confidence bands for the mean of a group of observations.

On-the-Job Breath Curves

Ten workmen participated in the on-the-job breath sampling program, producing a total of 91 usable sets of data. Ten percent of the breath samples collected were discarded because of pipet leakage or poor sampling techniques.

Absolute breath levels ranged from about 20 ppm in one sample taken less than 1 hour after an 8-hour TWA of 250 ppm, to barely detectable levels (<0.05 ppm) in samples taken after exposures at TWA's below 50 ppm.

The extremely broad variation in the TWA's experienced by workmen during one of the periods in which breath sampling was being conducted is demonstrated for three shifts of men bearing the job classification "coagulator operator" (Figure 6). Minute, hourly, and daily fluctuations in the concentration of a contaminant are most descriptively revealed by continuous monitoring. This method of sampling quickly points out the fallacy of judging TWA and peak exposure concentrations on the basis of spot sampling or periodic surveys of brief duration.

The remarkable correlation between breath concentration and corresponding TWA values made it possible to construct the series of breath decay curves shown in Figure 7, with confidence bands only slightly wider than those from controlled human experiments. The close similarity between these curves and those constructed from controlled exposure data are further illustrated in Figure 8.

Human Responses

From a subjective standpoint no significant untoward affects were noted at any of the exposure concentrations. The only complaints were those of two subjects who reported mild headache and some dryness of their eyes and nose during the 500-ppm exposure experiments.

No odor was detected by anyone entering the exposure chamber at 50 ppm. At 250 ppm all four subjects entering the chamber initially reported that they could detect a very slight odor of the chemical. Five of the seven subjects entering the exposure chamber at 500 ppm were able to detect the odor of VCl, but after 5 minutes of exposure those five were unable to detect it even with forced inspiration. Three of the four subjects re-entering the chamber after lunch were able

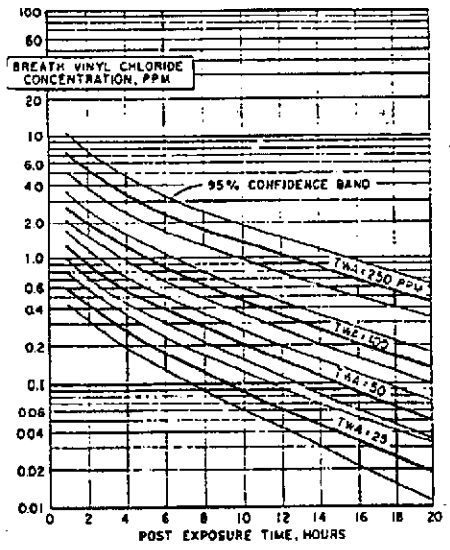

FIGURE 7. Breath decay curves derived from breath data collected from workers following on-the-job exposures to VCl vapor (8-hour TWA).

to detect a faint odor of VCl. One subject could detect a faint odor on deep inspiration for approximately 15 minutes after entering the exposure chamber.

The exposure had no noticeable effect on neurological responses, nor did it produce significant changes in the results of mental, coordination, or manual dexterity tests conducted during the exposure period. All clinical laboratory studies performed in the post-exposure period were normal and not significantly different from pre-exposure values.

Discussion

The object of the environmental health survey is to identify the atmospheric contaminant, determine the exposure level, and relate this to the health hazard it presents. If one is to judge hazard by ambient concentration measurements, then those measurements must accurately describe the exposure on a continuing individual basis. A carefully conducted survey combining continuous analysis of the work room atmosphere with a comprehensive job study will provide data valid for estimating time-weighted average exposure.

On the other hand, breath decay curves constructed from breath data collected during continuous plant monitoring are in close agreement with those obtained from exposure chamber experiments with VCl. These curves should therefore be useful as a second method for assessing exposure to VCl vapor.

The choice of whether one or both methods should be used depends on prevailing circumstances and on the thoroughness desired. For example, data useful in describing peak exposures are obtained from continuous monitoring. Concurrently, exposure trends and concentration gradients may help identify plant operational inefficiencies and equipment malfunctions by revealing specific sources of emission. Correcting these problems not only restores a healthful work environment but often results in bonus savings by reducing losses of raw material and product.

Continuous monitoring, however, is extremely costly both in time and in the equipment required. The scope of data acquired is

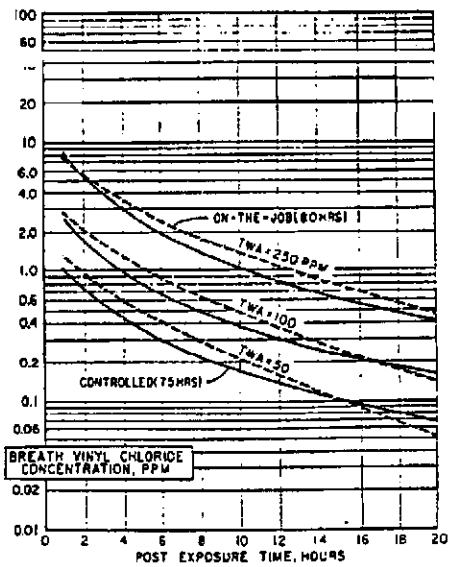

FIGURE 8. Comparison of breath decay curves derived from the on-the-job data and the experimental human exposure data.

limited by the number of sampling probes, and these probes are not always capable of accurately measuring the individual's daily exposure experiences, especially should these involve unusual incidences such as chemical spills or exposures outside the monitored area.

Breath analysis has the advantage of individualizing each worker's integrated daily exposure. Breath decay curves, as an index of exposure, offer a means of estimating the average daily individual exposure on the basis of a few breath samples taken serially in the postexposure period. Consequently breath analysis can be used to diagnose as well as quantitate an exposure which has already occurred. It is a relatively inexpensive and simple method which can be put into operation without extensive and costly preliminary preparations.

However, postexposure breath analysis does not provide information on the daily fluctuations of exposure, and the peak exposure concentrations are not made evident by breath data. Finally, breath analysis is not applica-

ble to all chemicals, and breath decay curves established for one chemical are not useful as an index of exposure to any other chemical.

The decay curves presented here are intended to serve as an index of exposure to vinyl chloride vapor and are based on an exposure duration of 7.5 hours for the experimental exposures, and 8 hours for the on-the-job study. The close agreement between the two sets of curves and the narrow confidence bands obtained in each case demonstrate the usefulness and accuracy of both methods for estimating TWA exposures and indicate the importance of breath analysis and the need for expanding its use in evaluating exposures to other widely used volatile organic chemicals.

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The Application of Computer Science to Industrial Hygiene

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Automatic sampling and analysis of environmental atmospheres can result in voluminous amounts of data describing exposures to chemicals. The use of a digital computer to process such data and the advantages and disadvantages of the technique are presented.

Introduction

AUTOMATIC AIR monitoring equipment is expensive. Nevertheless, if it is used to signal the need for action by operating personnel to eliminate leaks and to effect needed repairs of equipment, its cost can easily be justified in terms of reduced exposures, reduced hazards, and reduced loss of process material. Furthermore, if sample locations are properly chosen, it provides data on the concentrations of air contaminants to which men are exposed. That information, handled properly, can be used to show long-term trends of exposure which, correlated with plant operations, can result in still lower exposures. In addition, such data can be used to determine the exposures of workmen in what is, in effect, a continuing industrial hygiene survey. These data, in turn, could be correlated with medical information on effects of the exposures to confirm or deny present standards or to suggest new ones.

At The Dow Chemical Company, automatic air sampling and analysis were first used in 1950 to monitor air concentrations of carbon tetrachloride in a production plant. At that time no method was available for handling the mass of data generated by the air monitoring equipment. Even though the instrument was successfully employed by plant supervision to control exposures, full use of the data to estimate the average concentration to which men were exposed was not feasible. To illustrate: The instrument recorded air concentrations at the rate of one every six seconds; this is 432,000 times per month.

Because the first continuous air monitor was a success at day-to-day control, others were installed in several plants during the 1950's. As each monitor was put into use, even more information on workmen's exposures was "going to waste" simply because there was too much of it. The advent of digital computers suggested a solution. Taking advantage of the fact that the Computations Research Laboratory had a Burroughs B220 computer, the Environmental Research Laboratory in 1961 acquired a machine for translating air concentration data from the recorder to punched paper tape. Continuous air concentration data could then be combined with computer analysis to yield a much more complete description of inhalation exposures than had heretofore been possible.

This paper recounts some of the problems involved, from the installation of air monitoring equipment to the interpretation of the data as summarized by the computer. Actual data are used, but only for illustrative purposes, so plant, process, and even the air contaminant are immaterial. This is not a report of an environmental survey; it is a primer on the application of computer science to industrial hygiene.

Presented at the Annual Meeting of the American Conference of Governmental Industrial Hygienists, Houston, Texas, May 1965.

Obtaining Air Samples

n automatic air monitoring system must be sensitive enough to detect concentrations of *significance to health. Sensitivity must* r ge from concentrations that may be im- r diately hazardous to those that have little or no significance even for prolonged, re- p ated exposures. The instrument should be s ective; it must respond only to the mate- ial(s) of interest. It must be stable; it should be unaffected by minor (or even · jor) variations of temperature, humidity, ration, and line voltage. The instrument must be capable of operating unattended for relatively long periods of time. Daily atten- n by the operator, minor service weekly by instrument man, and occasional performance testing should be adequate to keep it in eration. Finally, because a permanent rec- d of air concentrations can be important, concentration data must be automatically recorded. Any continuous analyzer that satisfies ese specifications can be used. So far we ave used only combustion-conductivity instruments and long-path gas cell infrared pectrometers; both types produce data suitble for computer analysis.

Single-point monitoring in a production plant is seldom economical. Usually the analyzer is positioned at a central location in he plant, and air samples are brought continuously to it through probes of some sort. Tubing used for these probes must not react with, or sorb, the air contaminant of interest.

Preparing Data for Analysis

There is no method presently available for reading results automatically from multiple-point chart paper into a computer. This means that a device must be used to "digitize" the data as they are obtained. At the minimum, the digitizer must translate the analog data (usually the position of a wiper on the slide wire of a potentiometer) to digital form (for example, numbers) that can be handled by the computer.

Because data on the time of exposure can minimize programing difficulties, the digitizer includes a digital clock with an output of the day number, hour, and minute. A switch selects a "type of data" digit (from 0 to 9) which is incorporated into the digitizer output. An extra "type of data" (for example, from an infrared spectrometer or from a combustion-conductivity analyzer) digit can allow the computer to reject data that obviously do not belong with that being processed. To minimize costs, punched paper tape is used to transfer data from the digitizer to the computer.

For each datum the digitizer punches two "words" on the tape. The first "word" contains the day number, hour, and minute, as well as the "type of data" identification number. The second "word" contains the probe number and the actual datum which, in this case, is a number from 0 to 999, proportional to the concentration of the air contaminant. This information is obtained at a rate that may vary from two times a minute to once in 2.5 minutes. Because collecting each datum generated is not always necessary, the digitizer can be programed to skip the collection of some data. In every case, once data from probe No. 1 are punched onto the tape, data from the other probes are obtained in serial order, but the digitizer can ignore all but every second, fifth, or tenth sets of analyses.

Programing the Computer

We decided that the minimum time in the data summary should be an eight-hour shift. For this period the Dow Computations Research Laboratory programed the computer to calculate the mean concentration at each location, the standard deviation of these data, the percentage of time that the concentration was above several preselected levels, and the appropriate time-weighted averages.

Computers are versatile. For instance, if one probe is located to sample air outside the building, the computer can be programed to correct automatically for deviations in the "background." It can take into account peculiarities in the calibration curve of the instrument used for air analysis and can recognize several kinds of errors in the data and use only "good" data for calculations.

Computer Output

The basic computer output consists of the mean concentration, standard deviation, number of analyses recorded, and percentage of time the concentration was above preselected levels, all at each location for each shift during the survey. Shift or daily averages can also be obtained over any selected time interval such as a week or a month. These data, further identified as to department, air contaminant, etc., are permanently stored on magnetic tape.

The computer has been programed to reject poor data such as that caused by a sticking punch or by a faulty encoder. If poor data are being obtained, this fact is often signaled first by an unexplained decrease in the number of analyses used by the computer to obtain the shift averages. This has become the normal signal for nonroutine maintenance of the digitizing equipment.

In addition to the basic output, the computer calculates time-weighted averages of two kinds. The first kind is the "usual" time-weighted average concentration to which men are exposed. It is obtained by combining the air analysis data with "job analysis" information on the percentage of time spent by men in the vicinity of specific analyzer probes. Job analysis information is also combined with the data on the percentage of time during which concentrations exceed the preselected levels. This results in a second kind of average which is the "time-weighted percentage of time" exposures exceeded the preselected levels.

An example of how the time-weighted percentage of time is calculated is given below. Assume that the following information is true for an operator in a plant:

Data Location Number	Percentage of Time Spent at That Location
1	12.5
7	31.3
4	18.8
12	25.0
Unexposed	12.4
	100.0

Furthermore, assume that, over the time period of interest, concentrations at these data locations behaved in this manner:

% of Time Concentration Exceeds Selected Values at Specified Locations

Concentration greater than	Data Location Number 1	7	4	12
25 ppm	26.63%	28.68%	93.44%	31.55%
50	16.39	22.13	20.08	23.77
100	6.55	10.65	17.62	11.47
250	1.63	2.04	16.39	3.68
500	0.00	0.00	0.00	0.00

The time-weighted percentage of time spent by operators in concentrations above 25 ppm will then be:

$$\frac{(12.5)\,(26.63) + (31.3)\,(28.68) + (18.8)\,(93.44) + (25.0)\,(31.55) + (12.4)\,(0)}{100} = 38.92$$

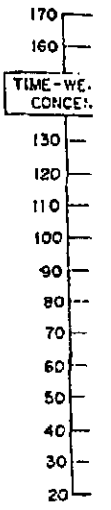
This means that *on the average,* during the time period of interest, men in the operators classification encountered concentrations above 25 ppm 38.92% of the time.

Similar calculations show that these men encountered concentrations above 50 ppm 28.24% of the time; above 100 ppm 10.95% of the time; above 250 ppm 4.00% of the time; and above 500 ppm 0.00% of the time.

Data Analysis

Automatic air monitoring reveals that in an industrial situation the variation of concentration with time can be large despite the use of a rather large time base. Figure 1 is a plot of daily time-weighted average concentrations to which operators were exposed on each shift over one week. Each point on the graph is the mean of several hundred determinations spaced equally over an eight-hour period. These are actual plant data.

On the second shift there was little variation during the first four days, but over the last three days of this period the shift average varied by a factor of almost four. If the threshold limit value (TLV) for this material were 50 ppm, an industrial hygienist taking air samples during the first three days on the second shift would probably have declared that the hazard to health was low or nonexistent. On the other hand, if he had



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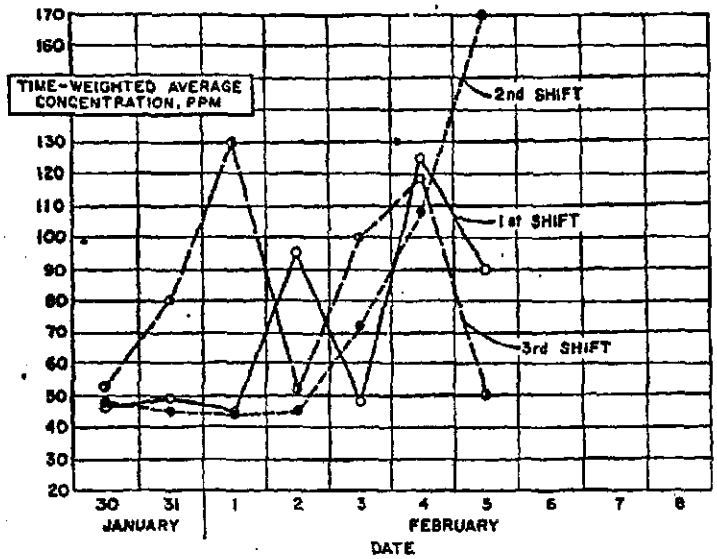

FIGURE 1. Daily time-weighted average exposures for each shift from January 30 to February 5. Time-weighted average for the week (all shifts) was 82.32 ppm.

sampled on the last day of this period (on the second shift) he could have experienced a strong inclination to "push the panic button."

Variation of concentration between shifts can also be striking, as illustrated by a comparison of the third shift with the first or second shifts during the first three days.

Figure 2 places Figure 1 in a broader context. Data for Figure 2 are also time-weighted average concentrations to which operators were exposed. The rather extreme variation shown in Figure 1 for a time basis of one shift can be repeated for a time basis of one week. The information contained in Figure 2 is based upon hundreds of thousands of individual air samples.

Average concentrations and time-weighted average concentrations are not the only data summaries provided by the computer; average concentrations are accompanied by the standard deviation of the data. Having the standard deviation and using it quantitatively are two different things, however. We do not yet know how to use such information efficiently.

On the other hand, the spread or variability of the data is indicated in a more meaningful manner by the percentage of time the concentration exceeded certain levels. Figure 3 is a plot of the time-weighted percentage of time above these levels on log-probability paper. The interval during which data were gathered and the operational classification are identical to those in Figure 2. This graph shows that the median concentration to which men on all shifts in this classification were exposed was 40 ppm and that they were exposed to 500 ppm or higher 2% of the time.

The conventional plot (Figure 2) shows a maximum concentration of about 135 ppm, but it is one of seven-day averages, whereas Figure 3 is a summation of instantaneous values. Both kinds of graph have advantages. A conventional plot illustrates better how exposures vary with time, and any trends become readily apparent. With this kind of graph, however, the only usable index of exposure is the time-weighted average, a number of limited utility because it cannot reflect