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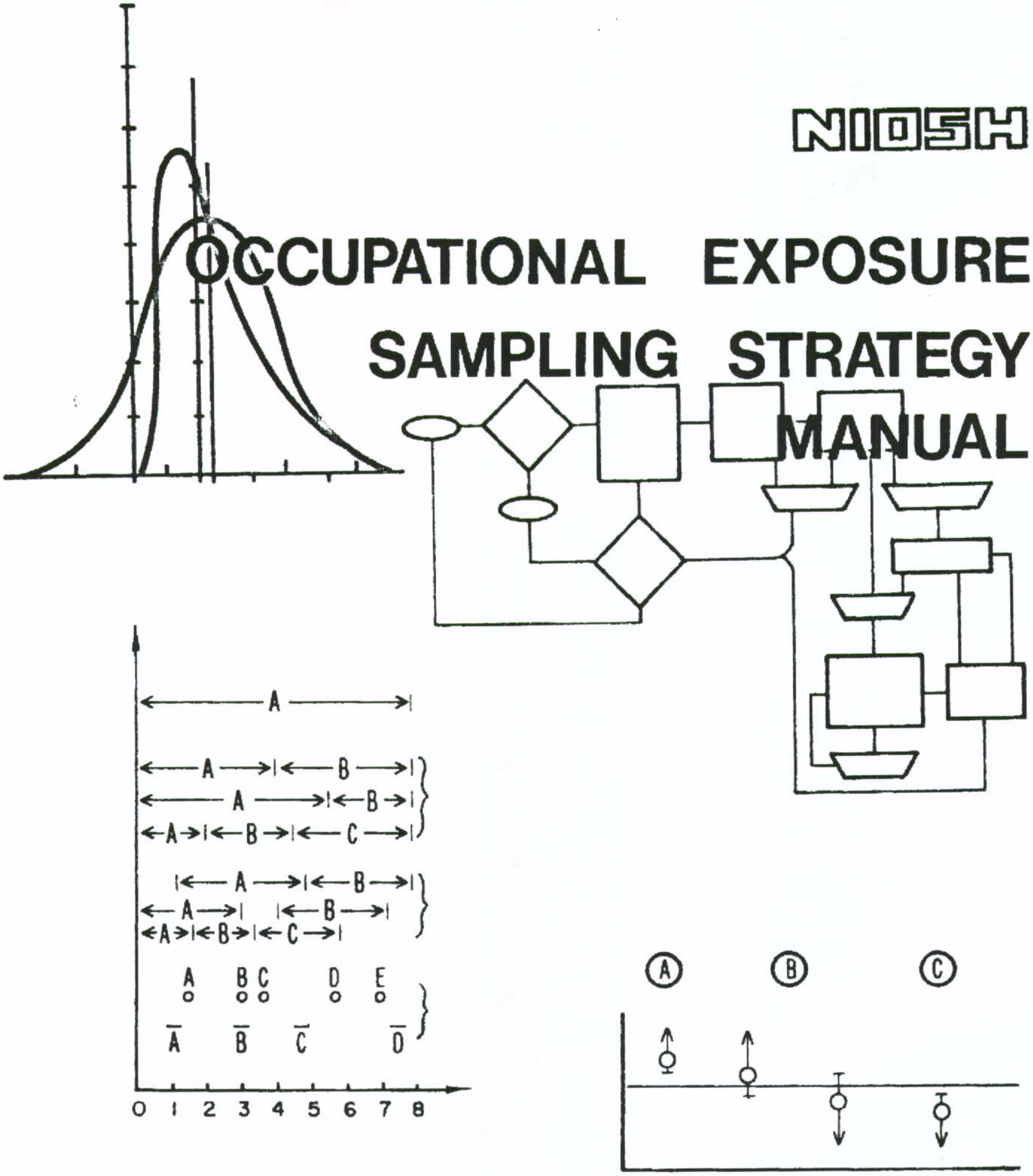
OCCUPATIONAL EXPOSURE SAMPLING STRATEGY MANUAL



U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Center for Disease Control
National Institute for Occupational Safety and Health

OCCUPATIONAL EXPOSURE SAMPLING STRATEGY MANUAL

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U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
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Center for Disease Control
National Institute for Occupational Safety and Health
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This manual is the fourth NIOSH report oriented toward use of predictive and analytical statistical methods in the field of industrial hygiene. The three previous works are:

Statistical Methods for the Determination of Noncompliance with Occupational Health Standards, NIOSH Report 75-159 (April 1975).

A handbook-type report treating noncompliance statistics and oriented toward the governmental compliance officer. The background material and conclusions are, however, also applicable to employers and industry industrial hygienists. Available for $1.30 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, as GPO #1733-00062.

Handbook for Statistical Tests for Evaluating Employee Exposure to Air Contaminants, NIOSH Report 75-147 (April 1975).

A research report containing a handbook and statistical theory for sampling time-varying industrial atmosphere contaminant levels. Sophisticated procedures are given for fitting trend curves to grab sample data. Available for $3.95 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, as GPO #1733-00058.

Exposure Measurement Action Level and Occupational Environmental Variability, NIOSH Report 76-131 (December 1975).

A research report explaining the necessity and technical basis for an exposure measurement action level of one-half an occupational health standard. Statistical theory is given for tolerance limits on TWA daily exposures. Employee risk curves presented show the varying probability (risk) that at least 5% of an employee's unmeasured daily 8-hour exposure averages will exceed the standard, given the fact that 1 day's measured 8-hour TWA exposure happened to fall below the standard by a specified amount. Available for $1.10 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, as GPO # 1733-00112-0.

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FOREWORD

One of the most important steps toward reducing the risk of impaired health resulting from inhalation of toxic chemicals is the measurement and evaluation of employee exposure to these chemicals. The Occupational Safety and Health Act of 1970 recognizes the critical importance of employee exposure measurements. Section 6(b)(7) of the Act requires that occupational safety and health standards promulgated by the Secretary of Labor provide for monitoring or measuring employee exposure at such locations and in such a manner as may be necessary for the protection of employees. Section 8(c)(3) of the Act directs regulations be issued requiring employers to maintain accurate records of employee exposure to those potentially toxic materials that are required to be monitored under Section 6.

To protect the health of employees, exposure measurements must be unbiased, representative samples of employee exposure. The proper measurement of employee exposures requires more than a token commitment of personnel, sampling equipment, and analytical resources. These resources are not limitless, however, and proper sampling strategy in monitoring programs can produce the best use of exposure measurement resources.

This manual contains the results of almost 5 years of statistical research by personnel and contractors of the National Institute for Occupational Safety and Health. The measurement of exposures and evaluation of the results require the use of statistical procedures that consider variations in exposure concentrations caused by sampling, analysis, and environment. Institute research has provided guidelines for efficient sampling strategies and evaluation of measurement data.

This manual is intended to help employers better understand the spirit and intent of existing and proposed Federal exposure monitoring regulations. It should provide guidance for establishing effective exposure measurement programs to protect the health of employees.

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PREFACE

In January 1974, we assisted in formulating the initial employee exposure monitoring requirements for draft occupational health standards being then written for the joint National Institute for Occupational Safety and Health (NIOSH)/Occupational Safety and Health Administration's (OSHA) Standards Completion Program (SCP). At that time we recognized an obligation to make available to employers and industrial hygienists an informative technical publication detailing the intent and purpose of the proposed employee exposure monitoring regulations. We also envisioned a handbook giving NIOSH recommendations concerning ways of meeting the requirements with minimum burden to the employer while providing adequate protection to the exposed employees. This handbook is aimed at both new and experienced industrial hygienists as well as safety professionals and compliance personnel. This material will assist them to meet the following professional responsibilities:

- — devise sampling plans to evaluate occupational exposures to airborne concentrations of chemical substances,
- — determine the need for exposure measurements,
- — evaluate exposure measurement data, and
- — make decisions concerning what action is required by Federal regulations such as 29 CFR 1910 Subpart Z.

A contract (NIOSH #CDC-99-74-75) was let to Systems Control, Inc. (SCI) to develop such a manual. The SCI Final Field Handbook (#SCI 5119-2) was delivered in May 1975. The present manual is an outgrowth of the SCI handbook and incorporates ideas and opinions received from outside reviewers concerning the SCI handbook.

This handbook also attempts to answer additional questions that the authors have received in the last year concerning points of technical intent and purpose of the proposed monitoring requirements. Please keep in mind that most elements of our statistical protocol in Chapter 4 were designed for use by nonstatisticians, and we were sometimes obliged to trade some statistical power or efficiency for simplicity. Also, the statistical procedures given are not regulatory in nature. They are technical recommendations from NIOSH to assist employers in developing efficient monitoring programs and in making better decisions regarding employee exposure measurement results.

The well-intentioned employer will want to use these procedures for the additional protection they will afford his employees. It is possible to develop alternative sampling strategies or decision procedures, or both, that provide equal or increased protection to employees. The authors would welcome additional research in this area.

It is hoped that this is only the first edition of this manual. Field trials of a draft manual would have been most desirable before this handbook was released, but we believe the interests of occupational health are best served by a timely release of this information. We request your comments and ideas concerning how this handbook can be improved, particularly in regard to making it a practical and useful guide for field personnel. Our goals have been simplicity, usefulness, and objectivity.

N.A.L., K.A.B., and J.R.L.

ABSTRACT

The intent and purpose of employee exposure monitoring requirements are explained for employers in this manual. These requirements were proposed in draft occupational health standards written for the joint Standards Completion Program of the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration. NIOSH technical recommendations are given concerning ways of meeting the requirements with minimum burden to the employer while providing adequate protection to the exposed employees. Statistical sampling strategies are given to assist employers in developing efficient programs to monitor occupational exposures to airborne concentrations of chemical substances.

Data analysis methods are given which assist in making better decisions regarding the relation of employee exposure measurement results to standards of safe exposure. Decision criteria are based on assumptions of normal and lognormal distribution models for sampling/analysis errors and for environmental fluctuations, respectively. The manual also discusses topics of industrial hygiene such as determination of the need for exposure measurements, recordkeeping, and the nature of effects and symptoms of toxic agents. Sampling strategies encompass selection of subjects as well as sampling times.

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GLOSSARY*

AL	Action level in a 29 CFR 1910 Subpart Z regulation.
CFR	Code of Federal Regulations.
CSTD	Ceiling standard for occupational health employee exposure such as in Federal Standards 29 CFR 1910 Subpart Z.
CV	Coefficient of variation, a measure of relative dispersion, also known as relative standard deviation (RSD). The sample CV is calculated by dividing the standard deviation by the sample average. Discussed in Technical Appendix D.
GM	Geometric mean, a measure of central tendency for a lognormal distribution. Used in section 4.4 and discussed in Technical Appendix M.
GSD	Geometric standard deviation, a measure of relative dispersion (variability) of a lognormal distribution. Used in section 4.4 and discussed in Technical Appendix M.
K	Number of unsampled intervals of expected high exposure. Used in section 4.3.2.
LCL	Lower confidence limit on a measured exposure average. Unless otherwise specified, LCL is at a 95% (one-sided) confidence level.
LCL (90%)	LCL at a 90% (one-sided) confidence level.
n	Sample size, e.g., number of samples or days being analyzed.
P_c	Probability of compliance with a CSTD for all K unsampled intervals. Used in section 4.3.2.
P_n	Long-term (multiday) estimate of probability of noncompliance for an employee. Calculated in section 4.4.
PEL	Permissible exposure limit in the 29 CFR 1910 Subpart Z Federal regulation.
s	Standard deviation of n values of y_i. A classification variable used in section 4.2.3.
S	Standard deviation of n values of Y_i. Calculated in sections 4.2.3; 4.3; and 4.4.
STD	Standard for TWA exposure, such as Federal Standards 29 CFR 1910.1000. Also known as "permissible exposure limit or level" (PEL).
TLV	Threshold limit value of ACGIH. Refer to section 1.3.
TWA	Time-weighted average exposure concentration. Refer to Technical Appendix H for details of calculation.
UCL	Upper confidence limit on a measured exposure average. Unless otherwise specified, UCL is at a 95% (one-sided) confidence level.

UCL (99%)	UCL at a 99% (one-sided) confidence level.
x	Standardized full period sample concentration calculated by dividing the value X by the STD or CSTD, i.e., $x = X/STD$ or $x = X/CSTD$.
x_i	Standardized sample concentration calculated by dividing the i^th^ sample concentration X_i by the STD or CSTD, i.e., $x_i = X_i/STD$ or $x_i = X_i/CSTD$.
X	Full period sample measurement (exposure average from one cumulative full period sample).
X_i	Exposure concentration calculated from the i^{th} sample within a group of n samples ($i = 1,n$).
$\overline{X}$*	Best estimate of average exposure concentration calculated from grab samples. Calculated in section 4.2.3.
$\overline{X}$*/STD	Best estimate of a standardized exposure average calculated from grab samples. Calculated in section 4.2.3.
y_i	Logarithm$_{10}$ of standardized sample concentration. Calculated in section 4.2.3, $y_i = \log_{10}(x_i)$.
$\overline{y}$	Arithmetic mean of n values of y_i. A classification variable used in section 4.2.3.
Y_i	Logarithm$_{10}$ of standardized measured daily exposure average. Calculated in section 4.4 $[Y_i = \log_{10}\ (x_i \text{ or } \overline{x}_i \text{ or } (\overline{X}^*/STD)_i]$.
$\overline{Y}$	Arithmetic mean of logarithmic values (Y_i). Calculated in section 4.4.
z	Standard normal variable used in Chapter 4 to obtain probabilities from Table 4.2.
β	Probability of noncompliance with a CSTD during any one unsampled interval. Used in section 4.3.2.
μ	True time-weighted average concentration.

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*When an entry is italicized in the text, it is representative of that entry as a variable in an equation.

INTRODUCTION

The American Industrial Hygiene Association (AIHA) has defined Industrial Hygiene as ". . . that science and art devoted to the recognition, evaluation, and control of those environmental factors or stresses, arising in or from the work place, which may cause sickness, impaired health and well being, or significant discomfort and inefficiency among workers or among citizens of the community." Two critical elements for protecting the health of employees in an occupational environment are the recognition and evaluation of employee exposures to toxic airborne chemicals. This Manual presents information that an employer or his representative can use in recognizing toxic substances occurring in the occupational environment and aids in the evaluation of employee exposures to these substances.

Proper evaluation of employee exposures necessitates taking valid quantitative exposure measurements, interpreting these measurements in the light of experience, and exercising professional judgment. The sampling strategy guidelines of Chapter 3 and statistical analysis procedures of Chapter 4 are tools to assist individuals responsible for protecting the health of workers in the design and implementation of occupational exposure monitoring programs. These procedures are a means to an end, not an end in themselves. IN ALL CASES, ONE MUST AVOID THE TRAP OF FALLING INTO A NUMBERS GAME AND KEEP IN PROPER PERSPECTIVE WHAT THE DATA REPRESENT IN RELATION TO WHAT THE WORKER IS EXPOSED TO. Later sections detail existing and proposed legal responsibilities of employers with regard to exposure monitoring of their employees. The purpose of this Manual is to aid the employer to meet his responsibility for providing a safe work environment by implementing a compliance exposure monitoring program. The proposed Occupational Safety and Health Administration (OSHA) employee exposure monitoring requirements detailed in Section 1.4 were developed from the dual principles of recognition and evaluation of hazardous employee exposures that industrial hygienists have followed for many years. Thus the organization of this Manual follows both the sequence of proposed OSHA requirements and the steps an industrial hygienist would follow in evaluating an occupational environment.

0.1 SCOPE OF MANUAL

The sampling strategies and statistical methods of this Manual specifically apply to occupational exposures to airborne concentrations of chemical substances (as dust, fumes, mists, gases, and vapors). The application of normal and lognormal distribution models to occupational exposure concentration measurements is detailed in earlier works by Leidel and Busch (0-1) and Leidel, Busch, and Crouse (0-2), and is discussed in Technical Appendix M. The applicability of these methods to exposure data for physical agents such as noise and heat is unknown at this time because of lack of knowledge concerning suitable distribution models for these types of data. However, if it is found that the normal or lognormal distributions are appropriate for the data in question, then the methods in this manual could be used as appropriate. For those interested in occupational exposures to radiation in mine environments, Misaqi (0-3) has provided an excellent manual on sampling and data analysis for this type of situation.

0.2 HOW TO USE THIS MANUAL

The following checklist is a general guide for the types of questions you should ask yourself when formulating a compliance monitoring program and the appropriate sections of this Manual to refer to. Also refer to the material in section 1.4, particularly the flowchart of Figure 1.1. Keep in mind that the recommended procedures, particularly the procedures of Chapter 4, go beyond existing and proposed legal minimum requirements.

REFERENCES

0-1. Leidel, N. A., and K. A. Busch: Statistical Methods for the Determination of Noncompliance with Occupational Health Standards. NIOSH Technical Information, HEW Pub. No. (NIOSH) 75-159, Cincinnati, Ohio 45226, April 1975.

0-2. Leidel, N. A., K. A. Busch, and W. E. Crouse: Exposure Measurement Action Level and Occupational Environmental Variability. NIOSH Technical Information, HEW Pub. No. (NIOSH) 76-131, Cincinnati, Ohio 45226, December 1975.

0-3. Misaqi, F. L.: Application of Statistics to Radiation Surveys in Mines. Mining Enforcement and Safety Administration Informational Report 1020, Washington, D.C. 20240, 1975.

Checklist for Employee Exposure Monitoring

Item		*Refer to*
1. Is there a toxic or hazardous material in the workplace that can be released into the workplace air?	Yes.... No....	Chap. 2
2. If "yes", have you made a written determination for each toxic material that states whether any employee may be exposed to airborne concentrations of each material?	Yes.... No....	Chap. 2
3. If "yes" to 2, does the written determination include at least the following:		Chap. 2
a. Any information, observations, or calculations that would indicate employee exposure?	Yes.... No....	
b. If employees are exposed to toxic material, statement that exposure is at or above the action level?	Yes.... No....	
c. Any employee complaints of symptoms attributable to exposures?	Yes.... No....	
d. Date of determination, work being performed, location within the worksite, names and social security numbers of employees possibly exposed?	Yes.... No....	
e. Any concentration measurements (area or personal) taken?	Yes.... No....	
f. Any comments from medical examinations that may point to possible exposures?	Yes.... No....	
4. Is there any reasonable possibility of any employee being exposed above the action level according to the written determination?	Yes.... No....	Chap. 2
5. If "yes", have you measured the exposure of the employee (s) most likely to have the greatest exposure (maximum risk employees)?	Yes.... No....	Chap. 3
6. If "no", have you repeated Step 2 and succeeding steps each time there has been a change in production, process, or control measures that could result in an increase in airborne concentrations of any material in Step 2?	Yes.... No....	Chap. 2
7. If any exposure measurement indicates exposure above the action level, have you:		Chap. 3
a. Identified all employees so exposed?	Yes.... No....	
b. Sampled those employees so identified?	Yes.... No....	
c. Classified all employees according to noncompliance exposure, possible overexposure, or compliance exposure?	Yes.... No....	Chap. 4

8. Have you taken the following actions, depending on employee classification:		
a. Resampled employees with noncompliance exposures within 1 month and decided whether controls are to be instituted?	Yes.... No....	Chap. 3
b. Resampled employees with possible overexposures within 2 months and reclassified them if appropriate?	Yes.... No....	
c. Resampled employees with compliance exposures every 2 months (or if changes occurred in the operation) and reclassified them if appropriate?	Yes.... No....	Chap. 4
9. Have employees with exposures exceeding Federal standards been informed?	Yes.... No....	
10. Have all employee exposure measurements been properly recorded and filed?	Yes.... No....	Section 3.6
11. Have you instituted appropriate controls for those exposed employees needing them?	Yes.... No....	(Technical Appendix N)

CHAPTER 1

BACKGROUND TO MONITORING EMPLOYEE EXPOSURE TO OCCUPATIONAL ATMOSPHERES

1.1 OCCUPATIONAL SAFETY AND HEALTH ACT OF 1970

Although the first recognized and recorded occupational disease occurred in the 4th century B.C., there was little concern for protecting the health of workers before the 19th Century. It was in 1833 that the Factory Acts of Great Britain were passed. Although these acts were directed more toward providing compensation for accidents than to preventing and controlling their causes, they are considered the first effective legislative acts in industry that required some concern for the working population.

It was not until 1908 that the United States passed a compensation act for certain civil employees. Then in 1911, the first state compensation laws were passed, and by 1948, all States had some form of workmens' compensation. However, it has been in the most recent decade that Federal legislation has had a dramatic impact on the occupational safety and health of the American worker. The Federal Coal Mine Health and Safety Act of 1969 (P.L. 91-173) was directed to the health, protection of life, and prevention of diseases in miners and persons who, although not miners, work with or around the products of coal mines.

The Occupational Safety and Health Act of 1970 (P.L. 91-596) is one of the most far-reaching federal laws ever enacted, in that it applies to all employees of an employer engaged in a business affecting commerce, except for government employees and employees and employers at employment sites being regulated under other federal laws. Quoting from the preamble to the Act, its purpose is:

> "To assure safe and healthful working conditions for working men and women; by authorizing enforcement of the standards developed under the Act; by assisting and encouraging the states in their efforts to assure safe and healthful working conditions; by providing for research, information, education, and training in the field of occupational safety and health; and for other purposes."

With respect to the above, the Act specifies the employer's obligations to furnish to each employee a place of employment free from the recognized hazards that are causing or likely to cause death or serious physical harm, and to comply with standards promulgated by OSHA. Court decisions defining the employer's duty have already been made, and there is little doubt that the final responsibility for compliance with the provisions of the Act rests with the employer. This responsibility includes the determination of whether a hazardous condition exists in a workplace, the evaluation of degree of the hazard, and where necessary, the control needed to prevent occupational illness.

But what are the employee's obligations under the Act? The employee also has to comply with the safety and health standards as they relate to his performance and actions on the job. Although no provisions exist in the law to issue citations to or to penalize an employee, good practice would dictate that he (a) notify the proper authority when certain conditions exist that may cause personal injury; and (b) observe all safety rules, make use of all prescribed personal protective equipment, and follow procedures established to maintain a safe and healthful work environment.

1.2 FEDERAL OCCUPATIONAL SAFETY AND HEALTH STANDARDS (29 CFR 1910, Subpart Z)

On April 28, 1971, the Occupational Safety and Health Act came into effect. The first compilation of health and safety standards promulgated by the Department of Labor's OSHA was derived from existing Federal standards and national consensus standards. Thus, many of the 1968 Threshold Limit Values (TLVs) established by the American Conference of Governmental Industrial Hygienists (ACGIH) became Federal standards because they had been included in an earlier Federal law. Also, certain workplace quality standards of the American National Standards Institute (ANSI) were incorporated as Federal health standards in 29 CFR 1910.1000 (Table Z-2) because they were considered national consensus standards.

The health regulations dealing with toxic and hazardous substances were originally codified under Subpart G, Occupational Health and Environmental Control, of 29 CFR Part 1910. The term "29 CFR 1910" refers to Title 29 (Labor) of the Code of Federal Regulations available from the Superintendent of Documents, U.S. Government Printing Office. The 1910 refers to Part 1910 of Title 29, which contains the Occupational Safety and Health Standards. The majority of the Federal toxic substances occupational exposure standards were contained in 29 CFR 1910.93, Air Contaminants, Tables G-1, G-2, and G-3. On May 28, 1975, OSHA announced recodification of the air contaminant standards into Subpart Z, Toxic and Hazardous Substances. The following two paragraphs are a modified version of that announcement.

On September 29, 1974, in 39 FR 33843, OSHA announced its intention to initiate rulemaking proceedings to issue more complete standards for each of the substances listed in Tables G-1, G-2, and G-3 of 29 CFR 1910.93. As a result, it is expected that approximately 400 additional standards dealing with toxic substances will be promulgated.

Regulations dealing with toxic substances are contained in Subpart G of Part 1910. This subpart contains only a few sections and additional serially numbered sections cannot be added without completely renumbering the subparts which follow. Therefore, new standards dealing with individual toxic substances have in the past been inserted following section 1910.93 by the addition of letter suffixes (e.g., section 1910.93a-Asbestos; section 1910.93b-Coal tar pitch volatiles).

Although such numbering is satisfactory for limited use, it is not suitable for a large group of new sections, because of the complex multiple-letter suffixes that result. Therefore, in view of the fact that OSHA contemplates promulgating a large number of standards dealing with toxic substances, this numbering system could not be continued. Consequently, the toxic substance standards contained in Subpart G of Part 1910 were recodified and placed in a new Subpart Z of Part 1910, beginning at section 1910.1000. This recodification will simplify the manner in which standards for toxic substances may be referenced and will eliminate unnecessary confusion.

The following table sets forth the recodification of Title 29 Part 1910, Sections 1910.1000 through 1910.1017, respectively.

Old Section No. (Subpart G)	*New Section No. (Subpart Z)*	
1910.93	1910.1000	Air contaminants
1910.93a	1910.1001	Asbestos
1910.93b	1910.1002	Interpretation of term coal tar pitch volatiles
1910.93c	1910.1003	4-Nitrobiphenyl
1910.93d	1910.1004	alpha-Naphthylamine
1910.93e	1910.1005	4,4′-Methylene bis (2-chloroaniline)
1910.93f	1910.1006	Methyl chloromethyl ether
1910.93g	1910.1007	3,3′-Dichlorobenzidine (and its salts)
1910.93h	1910.1008	bis-Chloromethyl ether
1910.93i	1910.1009	beta-Naphthylamine
1910.93j	1910.1010	Benzidine
1910.93k	1910.1011	4-Aminodiphenyl
1910.93l	1910.1012	Ethyleneimine
1910.93m	1910.1013	beta-Propiolactone
1910.93n	1910.1014	2-Acetylaminofluorene

1910.93o	1910.1015	4-Dimethylaminoazobenzene
1910.93p	1910.1016	N-Nitrosodimethylamine
1910.93q	1910.1017	Vinyl chloride

Tables G-1, G-2, and G-3 of section 1910.93 (new redesignated section 1910.1000) are redesignated as Tables Z-1, Z-2, and Z-3, respectively. All references in new section 1910.1000 to Tables G-1, G-2, and G-3 are revised to correspond with this redesignation.

A convenient paperback volume of the 29 CFR 1910 standards, available as OSHA publication 2206, contains information current to January 1, 1976.

1.3 ACGIH THRESHOLD LIMIT VALUES (TLVs)

In the field of industrial hygiene, control of the work environment is based on the assumption that, for each substance, there exists some safe or tolerable level of exposure below which no significantly adverse effect occurs. These levels are referred to in the generic sense as threshold limit values. However, the term threshold limit values also specifically refers to occupational exposure limits published by a committee of ACGIH that are reviewed and updated each year to assimilate new information and insights (1-1). They are commonly referred to as "TLVs," and the list (1-1) is known as the "TLV Booklet." The ACGIH periodically publishes a documention of TLVs in which it gives the data and information upon which the TLV for each substance is based (1-2). This documentation (1-2) can be used to provide the industrial hygienist with insight to aid professional judgment when applying the TLVs.

Several important points should be noted concerning TLVs. First, the term "TLV" is a copyrighted trademark of the ACGIH. It should not be used to refer to Federal or other standards. Since the TLVs are updated annually, the most current "TLV Booklet" should always be used. When referencing an ACGIH value, the year of publication should always preface the value as "The 1974 TLV for nitric oxide was 25 ppm." Second, TLVs are not mandatory Federal or State employee exposure standards. TLVs are updated annually and generally reflect the most current professional recommendations concerning employee exposures to specific substances. If a TLV happens to be lower than a Federal or State health standard, the employer should strive to limit employee exposure to the TLV even though his legal obligation is not to exceed the Federal or State standard.

The following informative material concerning TLVs is quoted from the preface of the 1976 TLV Booklet with the permission of the ACGIH:

> Threshold limit values refer to airborne concentrations of substances and represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect. Because of wide variation in individual susceptibility, however, a small percentage of workers may experience discomfort from some substances at concentrations at or below the threshold limit; a smaller percentage may be affected more seriously by aggravation of a pre-existing condition or by development of an occupational illness. . . .
>
> Time-weighted averages permit excursions above the limit provided they are compensated by equivalent excursions below the limit during the workday. In some instances it may be permissible to calculate the average concentration for a workweek rather than for a workday. The degree of permissible excursion is related to the magnitude of the threshold limit value of a particular substance as given in Appendix D. The relationship between threshold limit and permissible excursion is a rule of thumb and in certain cases may not apply. The amount by which threshold limits may be exceeded for short periods without injury to health depends upon a number of factors such as the nature of the contaminant, whether very high concentrations — even for short period — produce acute poisoning, whether the effects are cumulative, the frequency with which high concentrations occur, and the duration of such periods. All factors must be taken into consideration in arriving at a decision as to whether a hazardous condition exists.
>
> Threshold limits are based on the best available information from industrial ex-

perience, from experimental human and animal studies, and, when possible, from a combination of the three. The basis on which the values are established may differ from substance to substance; protection against impairment of health may be a guiding factor for some, whereas reasonable freedom from irritation, narcosis, nuisance or other forms of stress may form the basis for others.

The amount and nature of the information available for establishing a TLV varies from substance to substance; consequently, the precision of the estimated TLV is also subject to variation and the latest *DOCUMENTATION* should be consulted in order to assess the extent of the data available for a given substance.

The committee holds to the opinion that limits based on physical irritation should be considered no less binding than those based on physical impairment. There is increasing evidence that physical irritation may initiate, promote or accelerate physical impairment through interaction with other chemical or biologic agents. In spite of the fact that serious injury is not believed likely as a result of exposure to the threshold limit concentrations, the best practice is to maintain concentrations of all atmospheric contaminants as low as is practical.

These limits are intended for use in the practice of industrial hygiene and should be interpreted and applied only by a person trained in this discipline. They are not intended for use, or for modification for use, (1) as a relative index of hazard or toxicity, (2) in the evaluation or control of community air pollution nuisances, (3) in estimating the toxic potential of continuous, uninterrupted exposures or other extended work periods, (4) as proof or disproof of an existing disease or physical condition, or (5) for adoption by countries whose working conditions differ from those in the United States of America and where substances and processes differ. . . .

1.4 PROPOSED OSHA HEALTH STANDARDS

Since January 1974, the National Institute for Occupational Safety and Health (NIOSH) and OSHA have had underway a joint NIOSH/OSHA Standards Completion Program (SCP). Federal regulations 29 CFR 1910.1000, Tables Z-1, Z-2, and Z-3 (formerly 1910.93, Tables G-1, G-2, and G-3) establish permissible exposure limits for approximately 400 chemical substances. OSHA proposes to amend 29 CFR 1910 with health standards that, if adopted, will establish detailed requirements for each chemical substance regarding such areas as:

1. measurement of employee exposure,
2. medical surveillance,
3. methods of compliance,
4. handling and use of liquid substances,
5. employee training,
6. recordkeeping,
7. sanitation and housekeeping.

As of September 1976, toxic substance health standards had been published as proposed rules in the Federal Register for the following substances (in chronological order):

8 May 1975 - ketones (6), including 2-butanone, 2-pentanone, cyclohexanone, hexone, methyl n-amyl ketone, and ethyl butyl ketone
3 Oct. 1975 - lead
6 Oct. 1975 - toluene
8 Oct. 1975 - general (11), including alkyl benzenes (p-tert-butyltoluene, cumene, ethyl benzene, alphamethyl styrene, styrene, and vinyl toluene); cyclohexane; ketones (camphor, mesityl oxide, and 5-methyl-3-heptanone); and ozone
9 Oct. 1975 - asbestos
17 Oct. 1975 - beryllium
20 Oct. 1975 - trichloroethylene
24 Nov. 1975 - sulfur dioxide
25 Nov. 1975 - ammonia

As stated in the preface, one of the primary intents of this Occupational Exposure Sampling Strategy Manual is to detail the intent and purpose of the employee exposure monitoring requirements of the proposed health regulations. This Manual also contains recommendations concerning ways to comply with the proposed regulations. IT IS IMPORTANT TO NOTE THAT SOME PROCEDURES PRESENTED IN THIS MANUAL EXCEED MINIMUM REQUIREMENTS OF THE PROPOSED OSHA REGULATIONS. In particular, the proposed regulations do not require employers to maintain the upper confidence limit (UCL) on employee averages below the applicable permissible exposure limit. The only reference to statistics in the proposed regulations occurs where the method of measurement used must meet accuracy requirements at a confidence level of 95%. The method of measurement refers solely to the sampling device (as the pump used to draw air through a filter, sorbent tube, or impinger) and the chemical analysis procedure used to determine the amount of chemical substance.

However, it is believed that the well-intentioned employer will want to use the statistical procedures contained in Chapter 4. In Table 1.1 are the sections of this Manual that apply to specific portions of the proposed regulations for 2-pentanone as published on May 8, 1975, in the Federal Register. This section is almost identical in the majority of the toxic substance health standards.

Figure 1.1 provides a generalized flowchart of the proposed OSHA employee exposure determination and measurement strategy for the proposed regulatory requirements of Table 1.1.

1.5 STATISTICS AND OCCUPATIONAL EXPOSURE MEASUREMENTS

One of the most important objectives of any industrial hygiene program is to accurately assess employees' occupational exposures to airborne contaminants, where necessary, by exposure measurements. The use of statistics in this assessment process is necessary because all measurements of physical properties contain some unavoidable random measurement error. That is, because of the effect of random measurement errors, any exposure average for an employee calculated from exposure measurements is only an estimate of the true exposure average. This section will discuss several statistical concepts as they apply to occupational exposure sampling. Then the sources of measurement variation will be elaborated.

Before getting into the terminology of statistics, a basic question should be answered: "Why should industrial hygienists even bother with statistics?" Simply because of measurement errors? Won't statistical techniques take the professionalism out of the industrial hygiene profession? Absolutely not! First, realize that statistics deals with the entire field of techniques for collecting, analyzing, and most importantly making inferences (or drawing conclusions) from data. Snedecor and Cochran (1-3) have stated:

> "Statistics has no magic formula for doing this in all situations, for much remains to be learned about the problem of making sound inferences. But the basic ideas in statistics assist us in thinking clearly about the problem, provide some guidance about the conditions that must be satisfied if sound inferences are to be made, and enable us to detect many inferences that have no logical foundation."

Armitage (1-4) may be paraphrased regarding the rationale for the proper application of statistical techniques. The variation of occupational exposure measurements is an argument for statistical information, not against it. If the industrial hygienist finds on a single occasion that an exposure is less than a desired level, it does not follow that all exposures will be less than the target level. The industrial hygienist needs statistical information that the exposure levels are consistently low enough. The "professional experience" often referred to is likely to be, in part, essentially statistical comparisons derived from a lifetime of industrial practice. The argument, then, is whether such information should be stored in a rather informal way in the industrial hygienist's mind or whether it should be collected and reported in a systematic way. Very few industrial hygienists acquire, by personal experience, factual information over the whole range of occupational exposure situations, and it is partly by the collection, analysis, and reporting of occupational exposure statistical information that a common body of knowledge is built and solidified. Now to the discussion of terminology used in the statistical procedures.

A statistical population is an entire class of items about which conclusions are to be drawn. Usually it is impossible, or impractical, to take measurements on all items in the population.

TABLE 1.1. PROPOSED OSHA REGULATIONS AND RELATED SECTIONS OF THIS MANUAL

2-Pentanone.

(a) *Definitions.* (1) "Permissible exposure" means exposure of employees to airborne concentrations of 2-pentanone, not in excess of 200 parts per million (ppm) or 700 miligrams per cubic meter (mg/cu m) averaged over an eight-hour work shift (time weighted average), as stated in § 1910.93, Table G-1.

(2) "Action level" means one half (½) of the permissible exposure for 2-pentanone.

APPENDIX L

(b) *Exposure determination and measurement.* (1) Each employer who has a place of employment in which 2-pentanone is released into the workplace air shall determine if any employee may be exposed to airborne concentrations of 2-pentanone at or above the action level. The determination shall be made each time there is a change in production, process, or control measures which could result in an increase in airborne concentrations of 2-pentanone.

(2) A written record of the determination shall be made and shall contain at least the following information:

(i) Any information, observation, or calculations which may indicate employee exposure to 2-pentanone;

(ii) Any measurements of 2-pentanone taken;

(iii) Any employee complaints of symptoms which may be attributable to exposure to 2-pentanone; and

(iv) Date of determination, work being performed at the time, location within the work site, name, and social security number of each employee considered.

CHAPTER 2

(3) If the employer determines that any employee may be exposed to 2-pentanone at or above the action level, the exposure of the employee in each work operation who is believed to have the greatest exposure shall be measured. The exposure measurement shall be representative of the maximum eight-hour time weighted average exposure of the employee.

SECTION 3.1

(4) If the exposure measurement taken pursuant to paragraph (b)(3) of this section reveals employee exposure to 2-pentanone at or above the action level, the employer shall:

(i) Identify all employees who may be exposed at or above the action level; and

(ii) Measure the exposure of the employees so identified.

CHAPTER 3

(5) If an employee exposure measurement reveals that an employee is exposed to 2-pentanone at or above the action level, but not above the permissible exposure, the exposure of that employee shall be measured at least every two months.

(6) If an employee exposure measurement reveals an employee is exposed to 2-pentanone above the permissible exposure, the employer shall:

CHAPTER 4

(i) Measure the exposure of the employee so exposed monthly;

(ii) Institute control measures as required by paragraph (d) of this section; and

CHAPTER 3

(iii) Individually notify, in writing, within five days, every employee who is found to be exposed to 2-pentanone above the permissible exposure. The employee shall also be notified of the corrective action being taken to reduce the exposure to at or below the permissible exposure.

(7) If two consecutive employee exposure measurements taken at least one week apart reveal that the employee is exposed to 2-pentanone below the action level, the employer may terminate measurement for the employee.

(8) For purposes of this pargaraph employee exposure is that which would occur if the employee were not using a respirator.

(c) *Methods of measurement.* (1) An employee's exposure shall be obtained by any combination of long term or short term samples which represents the employee's actual exposure averaged over an eight-hour work shift (see Appendix B(IV) of this section for suggested measurement methods).

(2) The method of measurement shall have an accuracy, to a confidence level of 95 percent, of not less than that given in Table 1.

TABLE 1

Concentration:	*Required accuracy (percent)*
Above permissible exposure	±25
At or below the permissible exposure and above the action level	±35
At or below the action level	±50

APPENDIX D

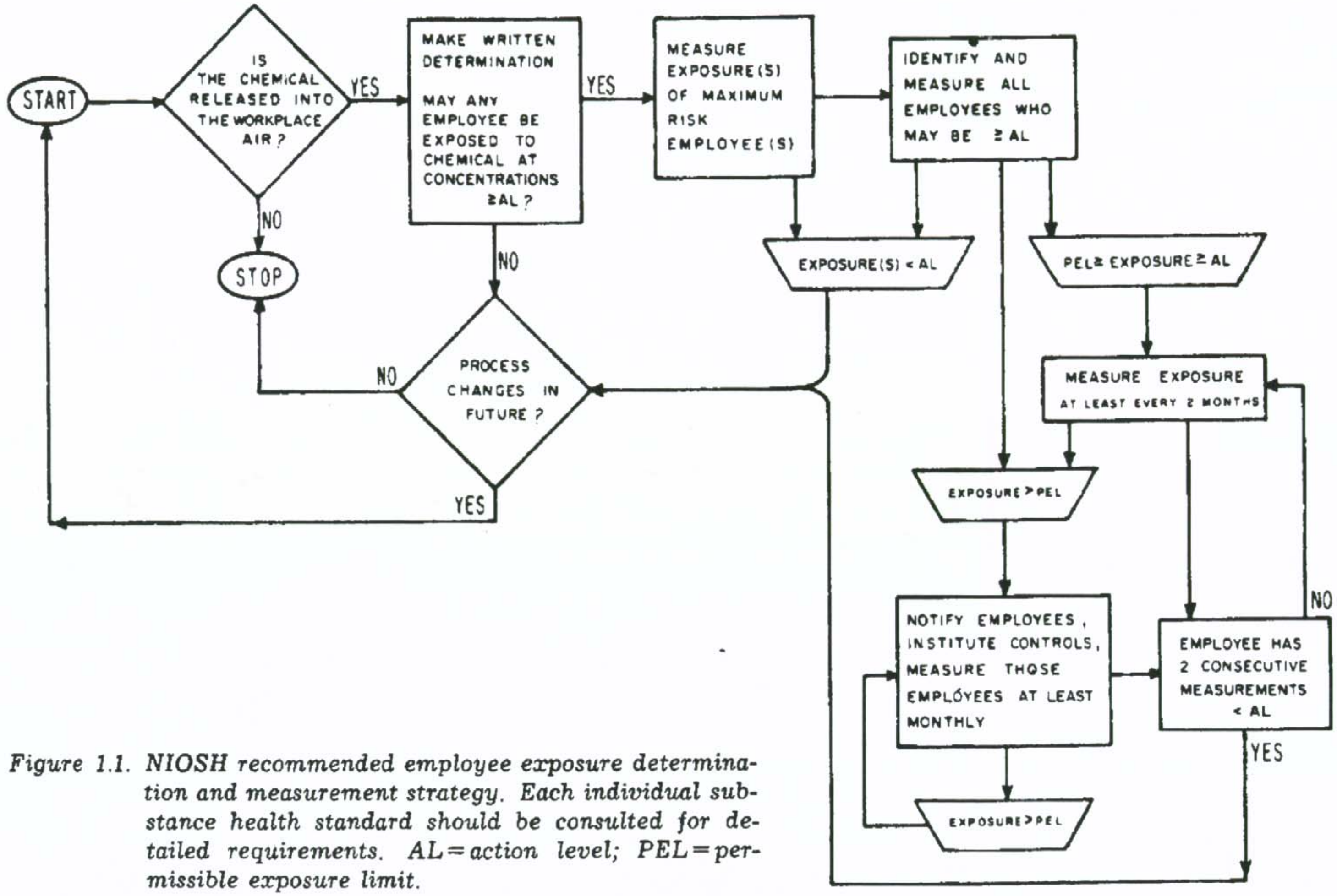

Figure 1.1. *NIOSH recommended employee exposure determination and measurement strategy. Each individual substance health standard should be consulted for detailed requirements. AL=action level; PEL=permissible exposure limit.*

Thus, we usually take measurements on several items comprising a *statistical sample* drawn from the population. The findings from the sample are generalized to obtain conclusions about the whole population. After taking measurements on items on the statistical sample, the measurements can be ranked in groups either in a table or graphically. One then recognizes that the measurements have some *distribution*.

The next step in data reduction is finding where the measurements are centered (or where the bulk of the measurements lie). There are several statistical *measures of central location* (or central tendency). The two used here are the arithmetic mean and geometric mean. The computations for these are demonstrated in Chapter 4. Lastly, how the measurements are distributed about the center value is determined. Several *measures of dispersion* give an idea of the scatter or variation of the measurements. The three used here are the geometric standard deviation, the normal standard deviation, and the coefficient of variation (or relative standard deviation). The methods of calculating these are given in Chapter 4.

The use of the word "sample" in this Manual might be a source of confusion. In the strict statistical sense, a sample consists of several items, each of which has some characteristic measured. In the industrial hygiene sense, however, a sample consists of an airborne contaminant(s) collected on a physical device (as a filter or charcoal tube). Industrial hygiene sampling is usually performed by drawing a measured volume of air through a filter, sorbent tube, impingement device, or other instrument to trap and collect the airborne contaminant. But in the sense of this Manual, an occupational exposure sampling strategy combines both the concept of a statistical sample and the physical sample that is chemically analyzed. In Table 1.2 are some examples of types of populations that may be encountered in occupational exposure sampling. Refer to Technical Appendix M, Normal and Lognormal Frequency Distributions, for a discussion on the application of these distributions.

TABLE 1.2. OCCUPATIONAL EXPOSURE SAMPLING POPULATIONS

Example population	Example of statistical sample used to estimate population parameters	Measure of central location of the distribution	Measure of dispersion	Best distribution model for fitting data
The airborne concentration values of a contaminant an employee is exposed to on one 8-hour workshift.	Grab sample measurements during the 8-hour workshift	(a) Arithmetic mean (8-hour TWA) (b) Geometric mean	Geometric standard deviation (intraday variability)	Lognormal
The daily (8-hour TWA) exposure averages of an employee obtained over many days.	Several measured daily exposure averages	(a) Long-term geometric mean (b) Long-term arithmetic mean	Geometric standard deviation (intraday variability)	Lognormal
The daily (8-hour TWA) exposure averages of all employees in an occupational group of similar expected exposure risk on a particular day.	Measured daily exposure averages for several employees in the group	(a) Group geometric mean (b) Group arithmetic mean	Geometric standard deviation (operator or intragroup variability)	Lognormal
Many replicate analyses performed on an industrial hygiene sample (as a filter or charcoal tube).	Several replicate analyses performed on the one IH sample	Arithmetic mean sample value	Coefficient of variation of analytical method	Normal
Many measurements of a calibrated contaminant test concentration obtained by a particular sampling and analytical procedure (as a low volume pump and charcoal tube with subsequent analysis by gas-liquid chromatography).	Several charcoal tubes exposed to the calibrated concentration	Arithmetic mean sample value	Coefficient of variation of sampling and analytical method	Normal

The following list details the primary sources of variation that affect estimates of occupational exposure averages:

1. Random sampling device errors (as random fluctuations in pump flowrate),
2. Random analytical method errors (as random fluctuations in a chemical laboratory procedure),
3. Random intraday (within day) environmental fluctuations in a contaminant's concentration,
4. Random interday (between days) environmental fluctuations in a contaminant's concentration,
5. Systematic errors in the measurement process (improper calibration, improper use of equipment, erroneous recording of data, etc.), and
6. Systematic changes in a contaminant's airborne concentration (as due to the employee moving to a different exposure concentration or shutting off an exhaust fan).

The random errors and fluctuations (1) through (4) are sometimes called statistical errors since they can be accounted for (but not prevented) by statistical analysis. Systematic errors under (5) include both instrumental errors and goofs or blunders of the fallible human using the equipment! Random errors under (1) and (2) are quantified and their effects minimized by the application of statistically based quality control programs. The quality control programs also enable one to get a good idea of the typical variation (coefficient of variation) of a sampling and analytical procedure. Refer to Technical Appendix D, Coefficients of Variation and Accuracy Requirements for Industrial Hygiene Sampling and Analytical Methods, for a further discussion of these types of errors.

Random intraday and interday environmental fluctuations in a contaminant's airborne concentration are most likely influenced primarily by the physical process that generates the contaminant and the work habits of the employee (spatial and temporal). There is no reason to believe the fluctuations are influenced by the chemical nature of a contaminant, but it is probable they are affected by its physical nature (dust, mist, gas).

It is important to note that the random environmental fluctuations of a contaminant in a plant may greatly exceed the random variation of most sampling and analytical procedures (often by factors of 10 to 20). Figure 1.2 shows actual environmental fluctuations for carbon monoxide. Figure 1.2 is a section of paper from a CO analyzer strip chart recorder. The vertical scale is zero to 100 ppm and the horizontal time scale contains a 15-minute period between any two vertical lines. A 1-inch distance represents 1 hour. The variability of the instrument is measured by a coefficient of variation of about 3%. Thus, the 95% confidence limits on a particular data point are approximately ± 6% of the measured concentration at any particular time. More about this in Chapter 4.

Systematic errors can either remain constant through a series of samples (because of improper calibration) or vary abruptly following some change in the process. Systematic errors cannot be accounted for statistically. If they are detected in the course of a measurement procedure, the data must first be corrected before the statistical analysis is performed. Many times, however, they go undetected and introduce much larger variation into the data than would be caused by the expected random errors and fluctuations. In the statistical sense, a systematic error (or change in the middle of a series of measurements) creates a second statistical population with a different average. If the systematic change goes undetected, the two "side by side" populations are analyzed as one, with a consequently much larger variation. The statistical procedures presented in this Manual will not detect and do not allow for the analysis of highly inaccurate results because of systematic errors or mistakes. Control of systematic errors is primarily a technical rather than a statistical problem.

Systematic changes in the contaminant exposure concentration for an employee can occur due to:

1. Employee moving to a different work area (as going from a solvent room to a warehouse),
2. Closing plant doors and windows (in cold seasons),
3. Decreases in efficiency or abrupt failure (or plugging) of engineering control equipment such as ventilation systems,

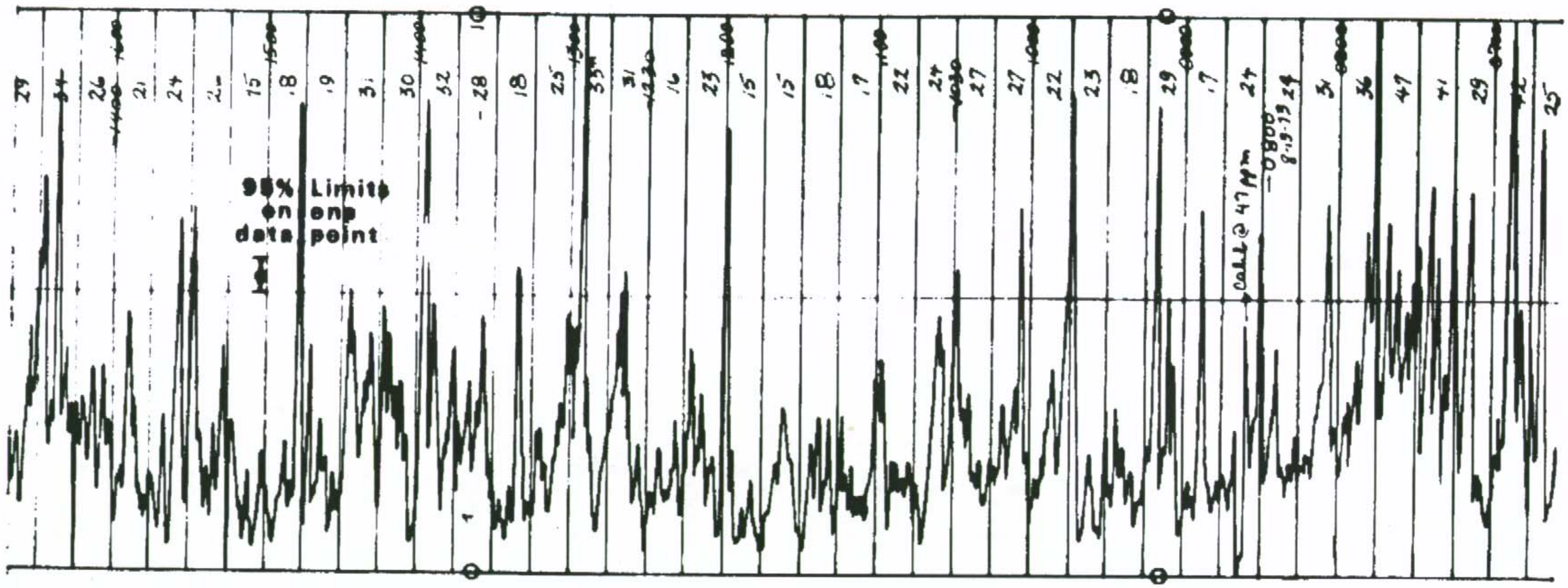

Figure 1.2. Actual industrial hygiene data showing intraday environmental fluctuations. Range of carbon monoxide data on chart is 0 to 100 ppm.

4. Changes in the production process or work habits of the employee.

One of the most important reasons for periodically measuring an employee's exposure every few months is to detect trends or systematic changes in the long-term exposure average. A secondary benefit is a better estimate of the variation of the exposures over extended periods, but this is not the primary purpose of periodic exposure measurement. Periodic measurements are one of the most informative ways to detect hazardous shifts in exposure levels or to indicate that hazardous levels are being approached.

1.6 STATISTICS AND COMPLIANCE ENFORCEMENT

Mandatory occupational exposure standards have been promulgated in the United States (29 CFR 1910, Subpart Z) with the intent of most adequately ensuring, to the extent feasible, that no employee will suffer material impairment of health or functional capacity. With these mandatory health standards has come the reality of necessary governmental enforcement. Duncan (1-5) has broadly defined enforcement as all those steps taken by a governmental agency to attain the desired level of quality. For OSHA, under the Occupational Safety and Health Act of 1970, these steps consist of proceedings, engineering judgment, court proceedings, and recommended voluntary compliance programs.

A simplistic legal approach toward the enforcement of these mandatory occupational health standards proceeds as follows. A sampling and analytical test method for the measurement of an employee's exposure to a particular hazardous substance is developed. The test method is used to measure a particular employee's exposure. If that measurement exceeds the standard, there has been a violation of the law. This simple point of view neglects the number and duration of samples that were taken from the random variation of the sampling and analytical method. Finally, there is no consideration of how many samples will be required of the enforcement agency or the employer to attain a specified level of effectiveness for the sampling program.

For example, if a compliance officer found an average air concentration of 105 ppm based on five samples taken over an entire workshift at a location in a plant and the standard was 100 ppm, then by the purely legal approach, he would be obligated to issue a citation. Suppose the citation was contested and the compliance officer was asked under cross examination whether he was certain his measurements have shown the standard has been exceeded. If he was aware of the statistics that underlies environmental sampling, he would have to answer legally, "Yes," but in actuality, "I don't know." It is essential that the sampling of the occupational environment should be performed utilizing appropriate statistically based sampling plans and statistical decision procedures so that the data can support the decision making processes regarding compliance or noncompliance with the mandatory health standards.

Tomlinson (1-6) in 1957 applied the concept of sequential testing to the problem of compliance monitoring, concerning a TWA standard, in British coal mines. Tomlinson recognized the large within-shift and shift-to-shift variation of the average airborne dust concentration. Roach (1-7, 1-8) introduced the concept of utilizing the upper confidence limit on the arithmetic mean of a group of short-term (grab) samples to determine the compliance status of an occupational environment. Roach, however, assumed a normal distribution for the samples, and later work has shown that it is better to assume the lognormal distribution for grab sample data. Roach made the very important point that any sampling procedure, no matter how carefully performed, can only estimate the true average concentration that existed in the occupational environment.

NIOSH first proposed the use of statistics for compliance monitoring in the carbon monoxide criteria document (1-9). Unfortunately, the procedure given for grab sample data was based on the assumption of normally distributed data and was inappropriate.

There is precedent in Federal regulations for including and referencing of statistical methods in mandatory product and health standards. Methods have been given both for governmental enforcement and private industry compliance monitoring programs. The Consumer Product Safety Commission (CPSC) has included very specific sampling and decision plans in several of its product standards. The FF 4-72 Flammability Standard for Mattresses (1-10) gives details for a manufacturer's compliance program and allows submission of alternate sampling plans by industry. The commission believed that these plans would protect the public against unreasonable risk and that they were reasonable, technologically practicable, and appropriate. These are goals that any sampling and decision plan must achieve. The Commission accepted the concept that the enforcement agency must assume the burden of demonstrating noncompliance by showing, with a high level of statistical confidence, that noncompliance did in fact exist. The CPSC included a sequential sampling plan in its test for Eye Irritants (16 CFR 1500.42) (1-11) and a table for lot size, sample size, and failure rate for testing clacker balls in 16 CFR 1500.86 (1-12).

The U.S. Public Health Service has issued a Drinking Water Standard (42 CFR 72, Subpart J) that specifies a minimum sampling frequency and sequential decision plan. The Food and Drug Administration's eyeglass impact standards (21 CFR 3.84) state that the manufacturer shall test a statistically significant number of lenses from each production batch.

In the field of industrial hygiene, NIOSH requires that manufacturers of certified gas detector tube units must maintain a quality control program similar in many respects to that described in MIL-Q-9858A "Quality Program Requirements," but adds the requirement to use sampling plans from MIL-STD-105D or MIL-STD-414. The Institute's certification procedures are based, in part, on the use of these sampling systems. The Institute has also proposed that similar quality control requirements would be extended to manufacturers of personal protective devices (42 CFR 83) and sound-level meters (42 CFR 82).

It appears that the Environmental Protection Agency (EPA) has never included or referenced statistical techniques for data analysis in air quality or water quality regulations. However, Larsen (1-13) of EPA has discussed the problem in an EPA technical report. Russell Train, EPA Administrator, expressed a desire to see standard statistical techniques for determining the validity of sample results become common to environmental standards (1-14). He believes that the methodology of statistical quality control charts has a place in environmental quality control.

An article in Electrical World (1-15) questioned the precision of Ringelmann chart smoke readings by a single observer. The conclusion was that poor precision led to poor reliability for enforcement purposes when regulatory controls were strict. A table of citation probabilities (%) was given for actual smoke density (RN — Ringelmann Number) versus maximum density allowed. More of this type of article based on statistics will probably appear in the literature as the statistical aspects of enforcing air concentration standards are more closely examined.

It is important to emphasize that the proposed OSHA health regulations (see section 1.4) DO NOT require the employer to use the statistical procedures in Chapter 4 of this Manual when making decisions regarding measured exposures of his employees. It is believed, however, that THE WELL-INTENTIONED EMPLOYER WILL WANT TO USE THESE PROCEDURES FOR THE ADDITIONAL PROTECTION THEY WILL AFFORD HIS EMPLOYEES. OSHA is considering adopting some statistical procedures for their noncompliance determinations.

Lastly, it is believed statistical procedures will appear more frequently in legal cases that involve sampling: an article by Katz (1-16) considered the practical aspects of statistics in the courtroom, and Corn (1-17) discussed applying statistics to determine noncompliance with the Federal coal dust exposure standard.

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1-16. Katz, L.: Presentation of a Confidence Interval Estimate As Evidence in a Legal Proceeding. American Statistician, 29(4):138-142, 1975.

1-17. Corn, M.: Remarks on Determination of Non-compliance with the Respirable Dust Standard, Federal Coal Mine Health and Safety Act of 1969. American Industrial Hygiene Association Journal, 36:404-407, 1975.

SUGGESTED READINGS FOR CHAPTER 1

Specific ANSI Standards as follows:
  Benzene (Z37.4-1969)
  Beryllium and beryllium compounds (Z37.5-1970)
  Cadmium dust (as Cd) (Z37.5-1970)
  Cadmium fume (as Cd) (Z37.5-1970)
  Carbon disulfide (Z37.3-1968)
  Carbon tetrachloride (Z37.17-1967)
  Ethylene dibromide (Z37.31-1970)
  Ethylene dichloride (Z37.21-1969)
  Formaldehyde (Z37.16-1967)
  Hydrogen fluoride (Z37.28-1969)
  Fluoride as dust (Z37.28-1968)
  Lead and its inorganic compounds (Z37.11-1969)
  Methyl chloride (Z37.18-1969)
  Methylene chloride (Z37.23-1969)
  Organo (alkyl) mercury (Z37.30-1969)
  Styrene (Z37.12-1969)
  Tetrachloroethylene (Z37.22-1967)
  Toluene (Z37.12-1967)
  Hydrogen sulfide (Z37.2-1966)
  Chromic acid and chromates (Z37.3-1971)
  Mercury (Z37.8-1971)
Source: American National Standards Institute, 1430 Broadway, New York, N. Y. 10018

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CHAPTER 2

DETERMINATION OF NEED FOR EXPOSURE MEASUREMENTS

The proposed OSHA health regulations discussed in section 1.4 require, for establishments where any of the regulated substances are released into the workplace air, that the employer make a written exposure determination. This determination is an estimate of whether any employee may be exposed to concentrations in excess of the action level. This written determination must be made even if the results are negative — that is, even if the employer determines that there is little chance that any employee may be exposed above the permissible exposure limit. This determination is the first step in an employee exposure monitoring program that minimizes employer sampling burden while providing adequate employee protection. Only if this exposure determination is positive (e.g., indicates that an employee may be exposed above the action level) is the employer required to measure (take airborne concentration samples of) employee exposures as detailed in Chapter 3. Refer to Technical Appendix L for a discussion of the action level.

The employer must consider relevant information from insurance companies, trade associations, and suppliers. In establishments having more than one work situation involving a regulated substance, a written determination must be made for each situation. For example, in a plant where a regulated substance is used in both dip tank and spray finishing operations, a written determination must be made for each operation.

Finally, a new written determination must be made each time there is a change in production, process, or control measures that could result in an increase in airborne concentrations of the regulated substance. However, this requirement applies only if the original written determination did not consider the changes. Therefore, the first written determination can specify production variables over ranges of anticipated operation for which the determination is negative or positive. Also, a "separate determination" does not necessarily imply (or require) a separate piece of paper. One sheet may consider several operations, several chemicals, and the associated operating condition ranges for which the determination applies. The following sections of this chapter give guidelines for considerations to be used in making the determination.

2.1 PHYSICAL STATES OF OCCUPATIONAL ENVIRONMENTAL CONTAMINANTS

Airborne contaminants can be present in the air as particulate matter in the form of liquids or solids; as gaseous material in the form of a true gas or vapor; or in combination of both gaseous and particulate matter. Most often airborne contaminants are classified according to physical state and physiological effect on the human body. Knowledge of these classifications is necessary for proper evaluation of the work environment, not only from the standpoint of how they affect the worker, but also so that correct exposure sampling methods can be employed. In addition, we must consider the route of entry and action of the contaminant.

2.1.1 Gases

Gases are defined as formless fluids that occupy a space or enclosure and that can be changed to the liquid or solid state only by the combined effect of increased pressure and decreased temperature. Examples: carbon monoxide, fluorine, hydrogen sulfide, and chlorine. Their size is molecular.

2.1.2 Vapors

Vapors are the gaseous form of substances that are normally in the solid or liquid state at normal temperatures and pressures. They can be condensed to these states only by either increasing the pressure or decreasing the temperature. Examples: trichloroethylene vapors, carbon tetrachloride vapors, and mercury vapors. Their size is molecular.

2.1.3 Dusts

Dust is a term used in industry to describe airborne solid particles that range in size from 0.1 to 25 micrometers (0.000004 to 0.001 inch) in diameter. Dusts are generated by physical processes, such as handling, crushing, or grinding of solid materials. Examples: silica, asbestos, and lead dusts.

2.1.4 Fumes

Fumes are solid particles that are generated by condensation of materials from the gaseous state, generally after volatilization from the molten state. The formation of fumes is often accompanied by chemical reaction, such as oxidation. Examples: lead oxide fume, iron oxide fume, and copper fume. Gases and vapors are not fumes, although they are often incorrectly called that, such as gasoline fumes, or carbon monoxide fumes. Fumes typically occur in the size range 0.01 to 5 micrometers (0.0000004 to 0.0002 inch).

2.1.5 Mists

Mists are suspended liquid droplets generated by condensation from the gaseous to the liquid state or by dispersing a liquid, by splashing, foaming, or atomizing. Examples: oil mists produced during cutting and grinding operations, acid mists from electroplating, and pesticide mists from spraying operations.

2.2 PHYSIOLOGICAL CLASSIFICATION OF TOXIC EFFECTS

2.2.1 Irritants

Irritants are corrosive in action. They inflame the moist mucous surfaces of the body. Airborne concentration is of far greater importance than length of time of exposure. Examples of irritant materials that exert their effects primarily on the upper respiratory tract are aldehydes, alkaline dusts and mists, acid mists, and ammonia. Materials that affect both the upper respiratory tract and lung tissues are chlorine, bromine, and ozone. Irritants that affect primarily the terminal respiratory passages are nitrogen dioxide and phosgene. There are also skin irritants.

2.2.2 Asphyxiants

Asphyxiants exert their effects on the body by interfering with the oxygenation of the tissues. They are generally divided into two classes: simple asphyxiants and chemical asphyxiants.

The *simple asphyxiants* are physiologically inert gases that dilute the available atmospheric oxygen below the level required to support life. Examples of simple asphyxiants: methane, ethane, hydrogen, and helium.

The *chemical asphyxiants* exert their action on the body by chemical action, by preventing either oxygen transport in blood or normal oxygenation of the tissues. Examples: carbon monoxide, hydrogen cyanide, and nitrobenzene.

2.2.3 Anesthetics and Narcotics

Anesthetics and narcotics exert their action on the body as simple anesthesia through a depressant action on the central nervous system. Examples: acetylene, ethylene, and ethyl ether.

2.2.4 Systemic Poisons

Systemic poisons are materials that cause injury to particular organs or body systems. The halogenated hydrocarbons (such as carbon tetrachloride) can cause injury to the liver and kidneys whereas benzene and phenol may cause damage to the blood-forming system. Examples of materials classified as nerve poisons: carbon disulfide, methyl alcohol, tetraethyl lead, and organic phosphorus insecticides. Lead, mercury, cadmium, and manganese are examples of metallic systemic poisons.

2.2.5 Chemical Carcinogens

Chemical carcinogens are chemicals that have been demonstrated to cause tumors in mammalian species. Carcinogens may induce a tumor type not usually observed, or induce an increased incidence of a tumor type normally seen, or induce such tumors at an earlier time than would otherwise be expected. In some instances, the worker's initial stages of exposure to the carcinogen and the tumor appearance are separated by a latent period of 20 to 30 years.

2.2.6 Lung Scarring Agents

Lung scarring agents are particulate matter other than systemic poisons that slowly produce damage to the lung. The damage occurs by lung scarring rather than by immediate irritant action. Chronic exposure to irritants can also produce these effects.

Fibrosis-producing dusts include crystalline silica and asbestos. Other dusts, such as coal dust, can produce pneumoconiosis, which has long been a concern in the mining industry.

2.2.7 Chemical Teratogens

Chemical teratogens are chemicals that produce malformation of developing cells, tissues, or organs of a fetus. These effects may result in growth retardation or in degenerative toxic effects similar to those seen in the postnatal human.

2.3 ROUTE OF ENTRY AND RATE OF EXPOSURE

Contaminants enter the body principally in three ways:

1. Skin absorption (through the skin),
2. Ingestion (through the digestive tract), and
3. Inhalation (through the respiratory tract).

The respiratory tract is by far the most common access for airborne contaminants to the body because of the continuous need to oxygenate the tissue cells and because of intimate contact with the body's circulatory system.

The effect of inhaled particulate material on the body depends strongly on the particle size. As can be seen in Figure 2.1, typical airborne contaminant particle sizes range from less than 0.01 micrometer to over 25 micrometers (0.0000004 to 0.001 inch). The diameter of particles of concern as a health hazard is generally considered to be below 10 micrometers. This is because the larger airborne particles, particularly those greater than 10 micrometers in diameter, have a much greater probability of being captured in the upper passages of the respiratory system. Particles down to about 0.5 micrometer (0.00002 inch) in size, such as smoke or fumes, penetrate deeper but are usually collected on the mucous lining of the airway ducts. Aerosol particles less than about 0.5 micrometer can reach the lung air exchange walls deep in the lungs. It is here that the lung is most vulnerable to damage.

The rate effect of exposure to toxic agents is usually generalized into acute and chronic.

Acute exposure is characterized by exposure to high concentration of the offending material over a short time span. The exposure occurs quickly and can result in immediate damage to the body. For example, inhaling high concentrations of carbon monoxide gas or carbon tetrachloride vapors will produce acute poisoning.

Chronic exposure occurs when there is continuous absorption of small amounts of contaminants over a long period of time. Each dose, taken independently, would have little toxic effect but the quantity accumulated over a long period (months to years) can result in serious damage. The toxicants can remain in the tissues causing steady damage. Chronic poisoning can also be produced by exposure to small amounts of harmful material that produce irreversible damage to tissues and organs so that the injury rather than the poison accumulates. An example of such a chronic effect of a toxicant is the disease known as silicosis, which is produced by inhaling crystalline silica dust over a period of years.

2.4 WORKPLACE MATERIAL SURVEY

The primary purpose of a survey of raw material is to determine if potentially harmful materials are being used in a work environment, and if so, the conditions under which these materials are being used.

The first step in the survey is to determine and tabulate all materials that may be used or produced in the work operations or manufacturing processes under investigation and that may be released into the workplace atmosphere or contaminate the skin. In many instances, this information may be obtained from purchasing records. Tabulating this information by process area or operation is useful. This could be done during the Workplace Observations of section 2.6, which is sometimes referred to as a "plant survey."

Many raw materials used in industrial operations will be identified by trade name rather than by chemical composition. In this case, the employer should obtain from the supplier (or the manufacturer) the composition of the raw materials so that each constituent may be identified and properly evaluated.

This information is conveniently recorded on a Material Safety Data Sheet. Two examples of useful formats are the OSHA form and the proposed NIOSH form. Note that the two-page OSHA Form 20, shown as Figure 2.2, is required

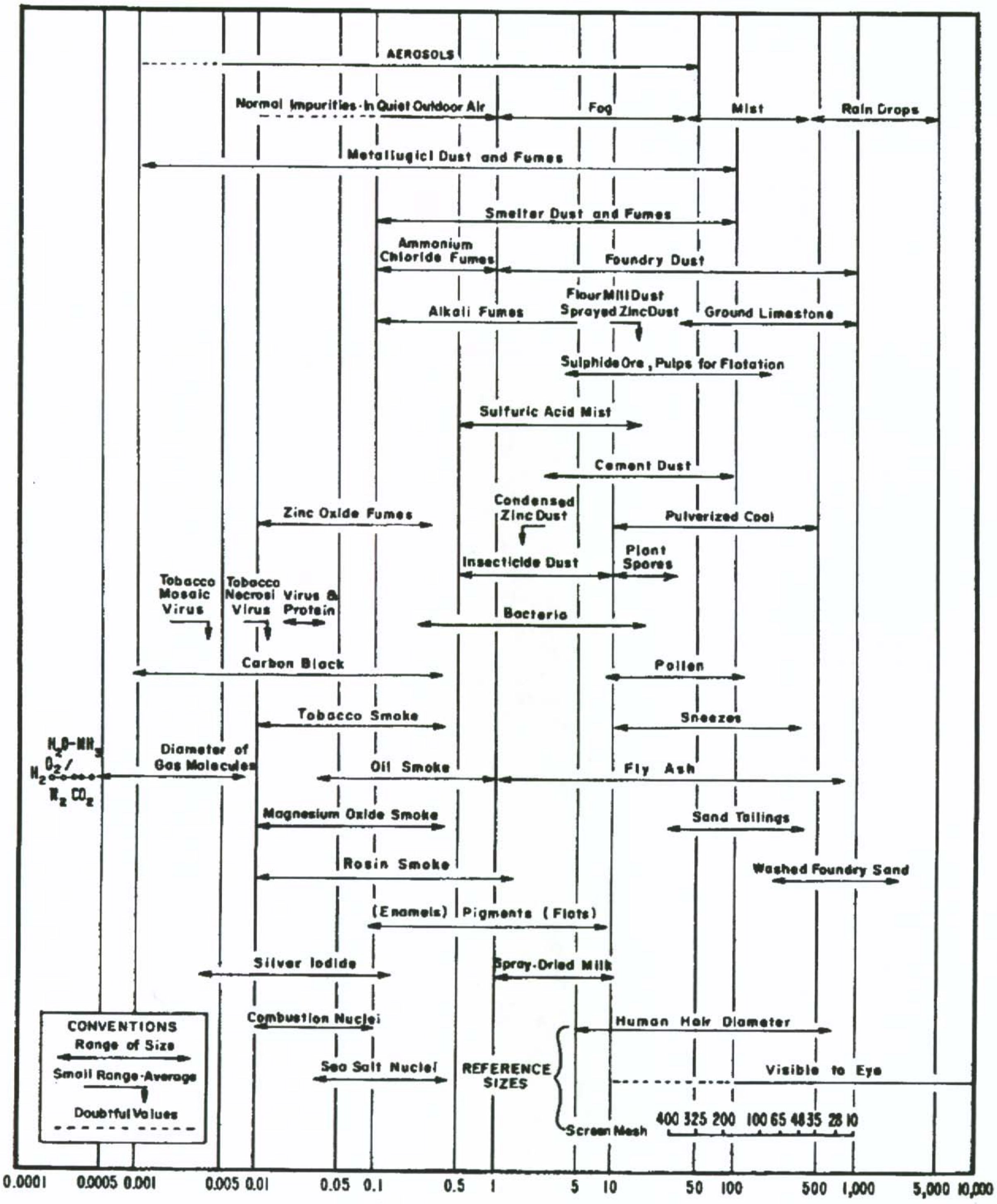
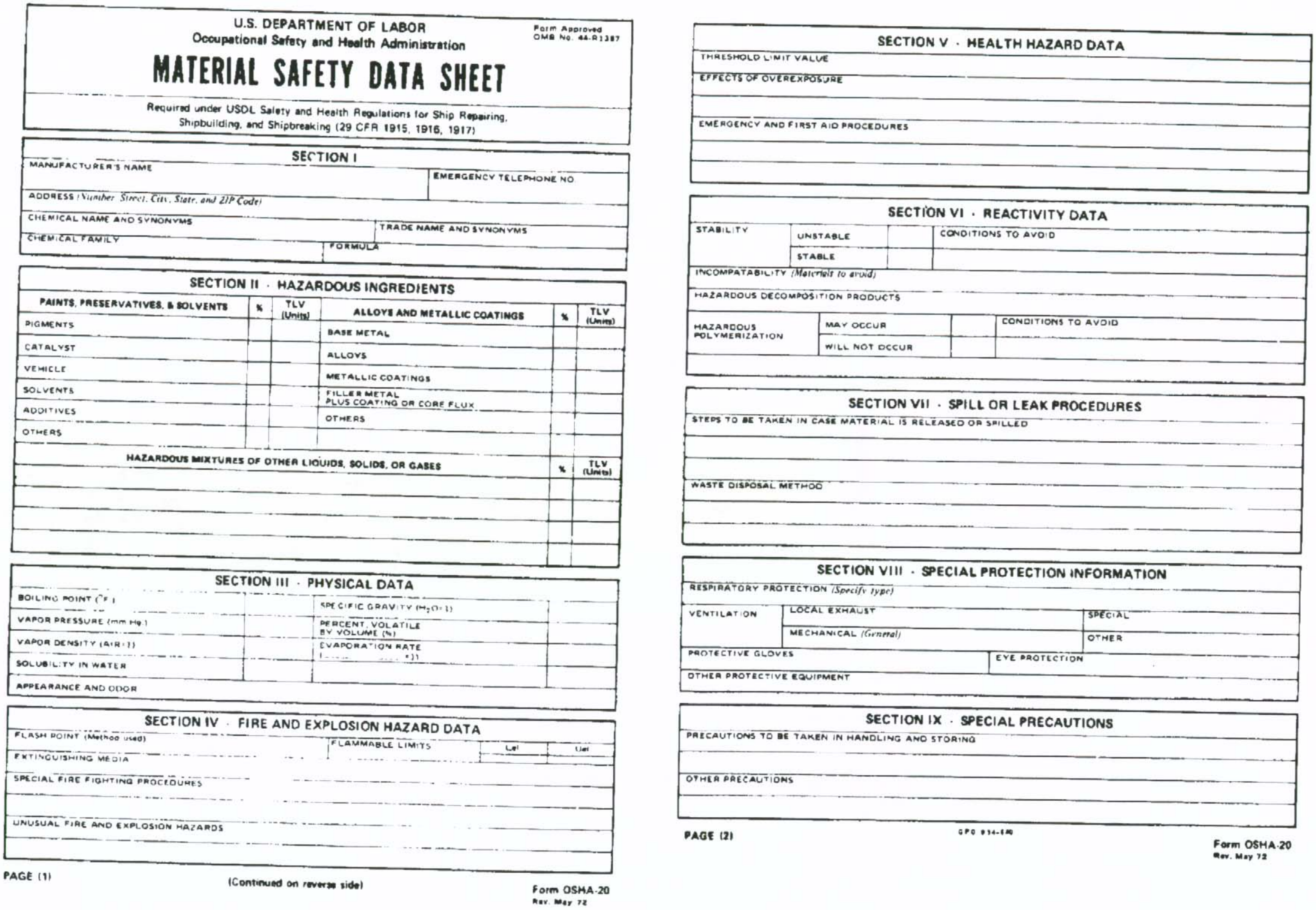


Figure 2.1. The size of airborne contaminants. (Chart reproduced by courtesy of the Mine Safety Appliances Company.)



U.S. DEPARTMENT OF LABOR
Occupational Safety and Health Administration

Form Approved
OMB No. 44-R1387

MATERIAL SAFETY DATA SHEET

Required under USDL Safety and Health Regulations for Ship Repairing,
Shipbuilding, and Shipbreaking (29 CFR 1915, 1916, 1917)

SECTION I

MANUFACTURER'S NAME	EMERGENCY TELEPHONE NO.
ADDRESS (*Number, Street, City, State, and ZIP Code*)	
CHEMICAL NAME AND SYNONYMS	TRADE NAME AND SYNONYMS
CHEMICAL FAMILY	FORMULA

SECTION II · HAZARDOUS INGREDIENTS

PAINTS, PRESERVATIVES, & SOLVENTS	%	TLV (Units)	ALLOYS AND METALLIC COATINGS	%	TLV (Units)
PIGMENTS			BASE METAL		
CATALYST			ALLOYS		
VEHICLE			METALLIC COATINGS		
SOLVENTS			FILLER METAL PLUS COATING OR CORE FLUX		
ADDITIVES			OTHERS		
OTHERS					

HAZARDOUS MIXTURES OF OTHER LIQUIDS, SOLIDS, OR GASES	%	TLV (Units)

SECTION III · PHYSICAL DATA

BOILING POINT (°F.)		SPECIFIC GRAVITY ($H_2O=1$)	
VAPOR PRESSURE (mm Hg.)		PERCENT, VOLATILE BY VOLUME (%)	
VAPOR DENSITY (AIR=1)		EVAPORATION RATE (______ =1)	
SOLUBILITY IN WATER			
APPEARANCE AND ODOR			

SECTION IV · FIRE AND EXPLOSION HAZARD DATA

FLASH POINT (Method used)	FLAMMABLE LIMITS	Lel	Uel
EXTINGUISHING MEDIA			
SPECIAL FIRE FIGHTING PROCEDURES			
UNUSUAL FIRE AND EXPLOSION HAZARDS			

PAGE (1)

(Continued on reverse side)

Form OSHA-20
Rev. May 72

SECTION V · HEALTH HAZARD DATA

THRESHOLD LIMIT VALUE

EFFECTS OF OVEREXPOSURE

EMERGENCY AND FIRST AID PROCEDURES

SECTION VI · REACTIVITY DATA

STABILITY	UNSTABLE		CONDITIONS TO AVOID
	STABLE		
INCOMPATABILITY (*Materials to avoid*)			
HAZARDOUS DECOMPOSITION PRODUCTS			
HAZARDOUS POLYMERIZATION	MAY OCCUR		CONDITIONS TO AVOID
	WILL NOT OCCUR		

SECTION VII · SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED

WASTE DISPOSAL METHOD

SECTION VIII · SPECIAL PROTECTION INFORMATION

RESPIRATORY PROTECTION (*Specify type*)		
VENTILATION	LOCAL EXHAUST	SPECIAL
	MECHANICAL (*General*)	OTHER
PROTECTIVE GLOVES	EYE PROTECTION	
OTHER PROTECTIVE EQUIPMENT		

SECTION IX · SPECIAL PRECAUTIONS

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORING

OTHER PRECAUTIONS

PAGE (2)

GPO 934-180

Form OSHA-20
Rev. May 72

Figure 2.2. Material Safety Data Sheet; Form OSHA-20.

only in the maritime industry for ship repairing, shipbuilding, and shipbreaking (29 CFR 1915, 1916, and 1917, respectively). Locations having this form of employment are the only locations for which a Material Safety Data Sheet has to be provided by law. Reference 2-1 gives instructions and an explanation of the terms used for preparing OSHA Form 20. The use of the proposed four-page NIOSH form, shown as Figure 2.3, is discussed in Reference 2-2. When using these forms, be sure to check if any of the material components are federally regulated under 29 CFR 1910. If so, there may be specific use regulations for these components, including informative appendices of the proposed OSHA regulations. The appendices are a convenient source of data for the specific properties of these substances.

When these forms are completed, they should be compared with the tables of substances published in the Occupational Safety and Health Standards, 29 CFR 1910. This procedure will allow employers to determine if they are subject to the provisions of Federal regulations by the use of, or the possession of, the substances listed in the published standards. Even if the toxic substances are not federally regulated, the same exposure monitoring, control procedures, etc., that apply to similar substances that are federally regulated should be instituted. Professional industrial hygiene consultation should be employed.

2.5 PROCESS OPERATIONS AS A SOURCE OF CONTAMINANTS

The processes and work operations using materials known to be toxic or hazardous must be investigated and understood. In this regard, there are many processes and work operations that should be suspect with respect to their potential for releasing toxic materials into the work environment and exposing employees to concentrations above the action level. The following are a few examples:

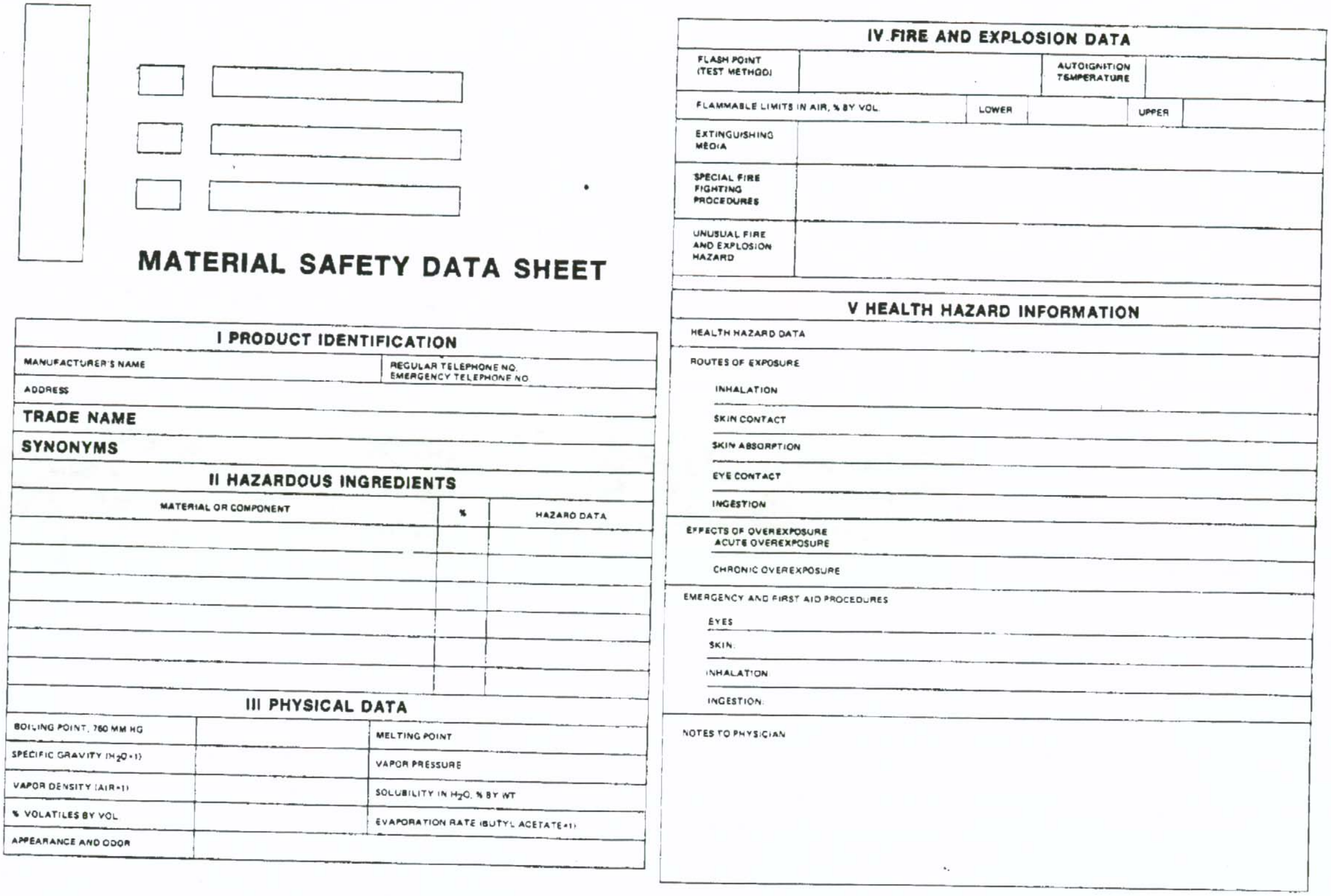
- Any process or operation that involves grinding, sanding, sawing, cutting, crushing, screening, sieving, or any manipulation of material that generates dust.
- Any process involving combustion.
- Processes that involve melting of metals that would release metal fumes and oxides.
- Any liquid or spray process involving the use of solvents or products that contain solvents, such as mixing wet materials, degreasing operations, spray painting, or drying operations. These may generate solvent vapors or mists.
- Processes that involve treatment of metal surfaces such as pickling, etching, acid dipping, and cleaning operations. These may release into the work environment acid or alkaline mists or various gases and vapors as a result of chemical reactions.

These processes and operations are only examples of the many that may be encountered in the wide variety of industries in our society. Some additional examples of potentially hazardous operations and air contaminant examples are given in Table 2.1.

2.6 WORKPLACE OBSERVATIONS

The previous sections generally indicate potential hazards that may be present in a workplace. They provide little or no insight into actual exposures to toxic materials. Their only intention is to provide an indicator as to the existence of potentially exposed employees. Thus, with information about the physical state and effects upon the human body of hazardous materials, the chemistry of products and byproducts, and a thorough knowledge of the process and operations involved, the survey is continued by a visit to the workplace to observe work operations. It is here that potential health hazards may be identified and a determination made as to whether an employee may be exposed to hazardous airborne concentrations of materials released into the work environment.

Some potentially hazardous conditions and sources of air contaminants can be visually identified, such as dusty operations. But the dusts or fumes that cannot be seen pose the greatest hazard to workers because they are in the size range that is most readily respirable. Respirable dust is considered that portion of the dust able to reach the nonciliated deep portions of the lungs such as the respiratory bronchioli, alveolar dusts, and alveolar sacs — dust with particle diameters less than about 10 micrometers. Refer to Reference 2-3 for a discussion of sampling devices used to estimate the health hazard due to inhalation of insoluble particulates.



MATERIAL SAFETY DATA SHEET

I PRODUCT IDENTIFICATION

MANUFACTURER'S NAME	REGULAR TELEPHONE NO. EMERGENCY TELEPHONE NO.
ADDRESS	
TRADE NAME	
SYNONYMS	

II HAZARDOUS INGREDIENTS

MATERIAL OR COMPONENT	%	HAZARD DATA

III PHYSICAL DATA

BOILING POINT, 760 MM HG		MELTING POINT	
SPECIFIC GRAVITY (H_2O=1)		VAPOR PRESSURE	
VAPOR DENSITY (AIR=1)		SOLUBILITY IN H_2O, % BY WT	
% VOLATILES BY VOL		EVAPORATION RATE (BUTYL ACETATE=1)	
APPEARANCE AND ODOR			

IV FIRE AND EXPLOSION DATA

FLASH POINT (TEST METHOD)		AUTOIGNITION TEMPERATURE			
FLAMMABLE LIMITS IN AIR, % BY VOL.	LOWER		UPPER		
EXTINGUISHING MEDIA					
SPECIAL FIRE FIGHTING PROCEDURES					
UNUSUAL FIRE AND EXPLOSION HAZARD					

V HEALTH HAZARD INFORMATION

HEALTH HAZARD DATA

ROUTES OF EXPOSURE

INHALATION

SKIN CONTACT

SKIN ABSORPTION

EYE CONTACT

INGESTION

EFFECTS OF OVEREXPOSURE
ACUTE OVEREXPOSURE

CHRONIC OVEREXPOSURE

EMERGENCY AND FIRST AID PROCEDURES

EYES

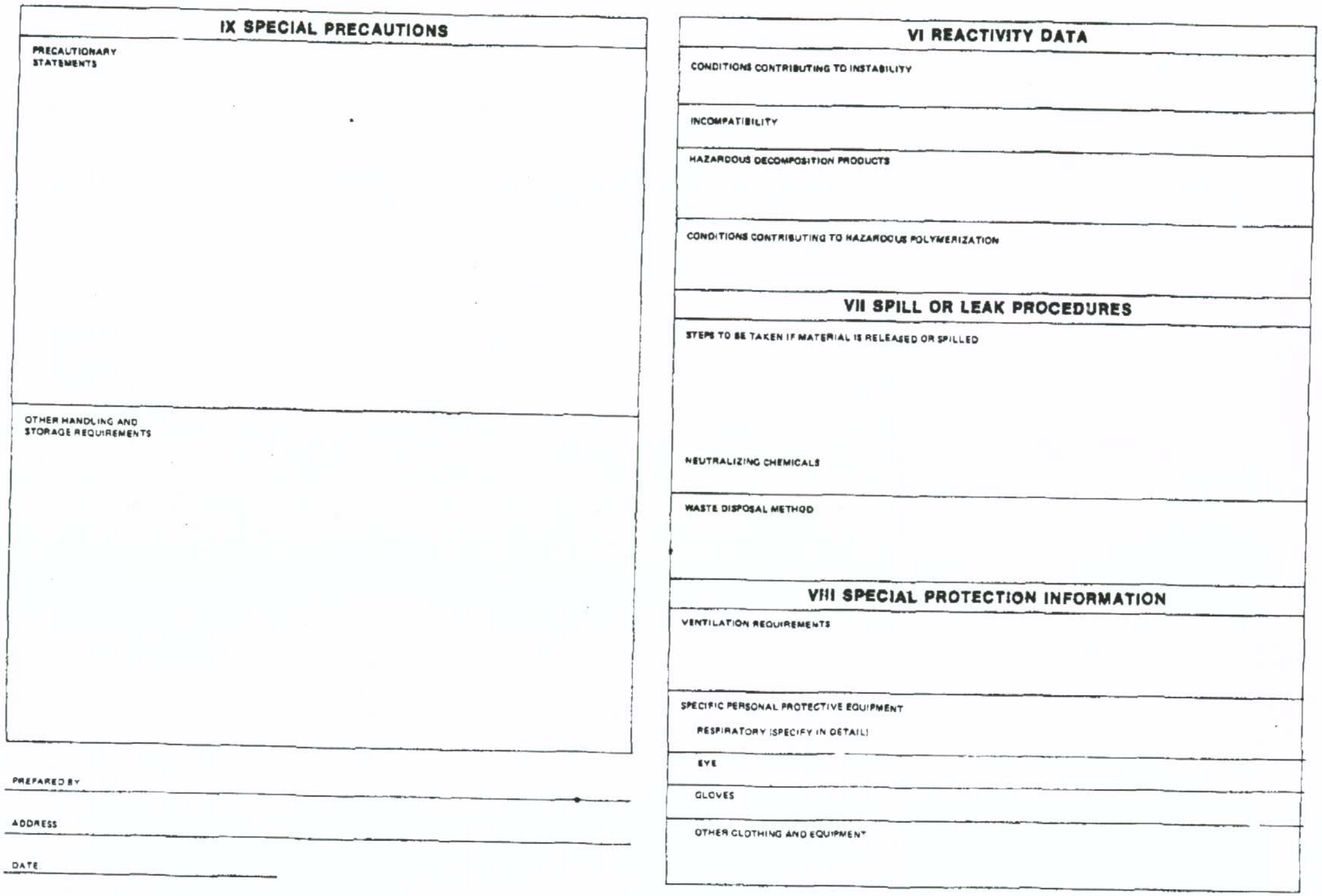
SKIN

INHALATION

INGESTION

NOTES TO PHYSICIAN

Figure 2.3. Proposed NIOSH form, Material Safety Data Sheet.



IX SPECIAL PRECAUTIONS

PRECAUTIONARY STATEMENTS

OTHER HANDLING AND STORAGE REQUIREMENTS

PREPARED BY

ADDRESS

DATE

VI REACTIVITY DATA

CONDITIONS CONTRIBUTING TO INSTABILITY

INCOMPATIBILITY

HAZARDOUS DECOMPOSITION PRODUCTS

CONDITIONS CONTRIBUTING TO HAZARDOUS POLYMERIZATION

VII SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED

NEUTRALIZING CHEMICALS

WASTE DISPOSAL METHOD

VIII SPECIAL PROTECTION INFORMATION

VENTILATION REQUIREMENTS

SPECIFIC PERSONAL PROTECTIVE EQUIPMENT

RESPIRATORY (SPECIFY IN DETAIL)

EYE

GLOVES

OTHER CLOTHING AND EQUIPMENT

Figure 2.3. Proposed NIOSH form, Material Safety Data Sheet (cont.).

TABLE 2.1 POTENTIALLY HAZARDOUS OPERATIONS AND AIR CONTAMINANTS

Process types	Contaminant type	Contaminant examples
Hot operations Welding Chemical reactions Soldering Melting Molding Burning	Gases (g) Particulates (p) (dust, fumes, mists)	Chromates (p) Zinc and compounds (p) Manganese and compounds (p) Metal oxides (p) Carbon monoxide (g) Ozone (g) Cadmium oxide (p) Fluorides (p) Lead (p) Vinyl chloride (g)
Liquid operations Painting Degreasing Dipping Spraying Brushing Coating Etching Cleaning Dry cleaning Pickling Plating Mixing Galvanizing Chemical reactions	Vapors (v) Gases (g) Mists (m)	Benzene (v) Trichloroethylene (v) Methylene chloride (v) 1,1,1-trichloroethylene (v) Hydrochloric acid (m) Sulfuric acid (m) Hydrogen chloride (g) Cyanide salts (m) Chromic acid (m) Hydrogen cyanide (g) TDI, MDI (v) Hydrogen sulfide (g) Sulfur dioxide (g) Carbon tetrachloride (v)
Solid operations Pouring Mixing Separations Extraction Crushing Conveying Loading Bagging	Dusts	Cement Quartz (free silica) Fibrous glass
Pressurized spraying Cleaning parts Applying pesticides Degreasing Sand blasting Painting	Vapors (v) Dusts (d) Mists (m)	Organic solvents (v) Chlordane (m) Parathion (m) Trichloroethylene (v) 1,1,1-trichloroethane (v) Methylene chloride (v) Quartz (free silica, d)
Shaping operations Cutting Grinding Filing Milling Molding Sawing Drilling	Dusts	Asbestos Beryllium Uranium Zinc Lead

Operations that generate fumes may sometimes be visually identified, since the melting of metals, such as in welding, may result in visible smoke emissions. In electroplating and other operations, where metallic surfaces are subjected to a variety of treatments by immersion in heated tanks of acids, alkalies, and degreasing agents, there are often visible mists in the form of steam.

Some sources of air contaminants in work operations can be determined by the sense of smell. Gases and vapors may often be detected by their distinct odors, tastes, or irritating effects, such as burning sensations in the nose, throat, and lungs. However, the ability to identify and detect their presence will vary widely with individuals. Caution is advised in this method of detection because of olfactory fatigue in some cases. Also, many gases and vapors have odor thresholds higher than the permissible exposure levels, so it would be possible for an overexposure to occur before the offending material could be detected by smell. Tables of odor threshold data are very hard to find in the literature and often contain conflicting data.

However, one can check each Federal health standard (29 CFR 1910) and examine the permitted Respiratory Protection Table for the substance. If OSHA specifically allows either a chemical cartridge or gas mask respirator for an organic vapor (without requiring an end-of-life indicator), it can be assumed that the organic vapor has some warning property (generally odor or irritation) at levels below that permissible exposure. One should then refer to Appendix A (Substance Safety Data) and Appendix B (Substance Technical Guidelines) of the particular substance standard for further information on what these warning properties may be. Finally, keep in mind that the senses such as sight, smell, and taste may help to detect contaminants, but they are not dependable in recognizing all health hazards.

Employee location in relation to a contaminant source is also an important factor in determining if an employee may be significantly exposed to a hazardous substance. It should be apparent that in most instances the closer a worker is to the source of an air contaminant, the higher the probability that a significant exposure will occur. In some instances, it may be necessary to investigate air flow patterns within a work establishment since many contaminants can be dispersed long distances from the source of evolution. Thus, it could be possible to significantly expose workers who are not in close proximity to the contaminant source.

The procedures or methods the worker uses to perform his job should also be analyzed. Exhaust ventilation equipment for degreasing tanks, which is designed to prevent or control the release of toxic materials into the worker's environment, may not perform its intended function if the worker bends directly over the tank to perform his job. In this same respect, a worker's habit of not using or improperly using control equipment may cause significant exposure to hazardous materials. Also, careless handling of toxic materials, whether intentional or unintentional, could cause situations in which significant exposures could occur.

Improper design, installation, or maintenance of control equipment can many times cause exposure situations. Far too often employers (or their contractors) ignorant of the principles of local exhaust ventilation will design and install ineffective control systems. The principles of design and measurements to determine system effectiveness contained in Reference 2-4 should be followed.

There are other characteristics of the workplace that should be considered in relation to how contaminant concentrations can be affected. Certainly high-temperature locations would give rise to higher evaporation rates of toxic solvents. The location of open doors and windows provides some natural ventilation that tends to disperse or dilute materials released in the workroom. Attention should also be directed toward general room ventilation that might provide some measure of control.

2.7 CALCULATION OF POTENTIAL EXPOSURE CONCENTRATIONS

By knowing the ventilation rate in a workplace and the quantity of material generated, calculations can often be made to determine if standards might be exceeded. For example, suppose 4 gallons of methyl ethyl ketone are used (evaporated) at a work station in 8 hours and the ventilation rate in the workplace is 600,000 cubic feet per hour dilution air. The dilution ventilation equations of Reference 2-4 can be modified to give:

Steady-state exposure concentration estimate

$$\text{(in ppm)} = \frac{(403)\ (a)\ (10^6)\ (b)\ (K)}{(c)\ (d)}$$

where:

a = specific gravity of solvents
b = pints solvent/hr
c = molecular weight of solvent
d = ventilation rate in cubic ft/hr

Molecular weights and specific gravities of many common solvents are contained in Reference 2-4. Also certain substances regulated in 29 CFR 1910 have an Appendix B (Substance Technical Guidelines) that contains molecular weight and specific gravity data.

K is a safety factor that must be included to take into account poor mixing of the material into the entire room, locations of fans in the workroom, proximity of employees to the work operation, etc. Reference 2-4 states that K values of 3 to 10 are usually chosen for dilution ventilation work. For our purposes, however, these may not be large enough. The factor K can be thought of as the approximate ratio of breathing zone concentration at the operation to the general room air concentration.

Gonzales, et al. (2-5) performed a study where DOP aerosol was released as a point source at one end of a 20- by 20- by 8-foot room. Ventilation conditions consisted of 6, 9, and 12 room air changes per hour with the entering air uniformly distributed across the entire wall with the outlet air plenum identically constructed. Under all conditions of ventilation, aerosol concentrations ranging up to 4% of the DOP generator concentration occurred within the probable breathing zone at distances 4 to 10 feet from the leak source. At the same time, close to and 2 feet above the leak, where the general concentration might be measured, concentrations ranged from 0.04 to 0.6% of source concentration. Ratios of 100 for breathing zone concentration near the source to fixed room samples concentration (and, thus, general air) were not uncommon.

Therefore, if the employee stays relatively close to the source (within a 10-foot radius), particularly if located downwind from the source, a K factor of 100 would be justifiably conservative. For other situations, $K = 10$ could be used. The preceding applies only if adequately designed and operated local exhaust ventilation is not used and mixing with room air is relied upon.

If $K = 10$ was used for the ketone example above, the equation would be:

$$\frac{(403)\ (0.81)\ (10^6)\ (4)\ (10)}{(72)\ (600{,}000)} = 300 \text{ ppm}$$

The TWA standard for methyl ethyl ketone (MEK) is 200 ppm. Definitely a maximum risk worker (typically the one closest to the source, such as a tank or solvent tray, of MEK) should be chosen for the measurement, and an exposure measurement representative of the maximum probable exposure should be obtained as detailed in Chapter 3. Judgments based on the previous equation should be very conservative since a value of $K = 1$ assumes (unattainable) perfect mixing in the room, and concentrations 10 to 100 times the average room concentration can easily occur near the solvent source.

If the room is "closed" or if the ventilation rate is unknown (or very low), a conservative assumption of one effective room change per hour can be made. Since the room air would probably be poorly mixed, it is best to assume $K = 50$. The previous equation becomes:

Steady-state exposure concentration estimate

$$\text{(in ppm)} = \frac{(403)\ (10^6)\ (\text{specific gravity of solvent})\ (\text{pints solvent/hr})\ (50)}{(\text{molecular weight of solvent})\ (\text{room volume in cubic ft})}$$

Suppose the MEK is used in a nonventilated room at the rate of 1 pint per 8-hour shift. The room is 20 feet long by 20 wide by 10 high, or 4000 cubic feet:

$$\frac{(403)\ (10^6)\ (0.81)\ (0.125)\ (50)}{(72)\ (4000)} = 7100 \text{ ppm}$$

Definitely in this case we should proceed with maximum-risk-employee exposure measurements as detailed in Chapter 3.

Hemeon (2-6) provides more sophisticated equations for conventional dilution at sources such as point, area, and strip sources. These equations are very useful for estimating concentrations that prevail in the breathing zone of workers if they are engaged in tasks that involve evaporation only a short distance (a few feet) from their breathing zone. In this case, the local breathing zone concentrations may be high whereas the average concentration in the room is low. Hemeon (2-6) has also provided estimates of typical solvent application rates where the solvent rate information is lacking. The following list of solvent application rates in certain typical individual operations is from Hemeon.

Operation	*Pints/minute/ worker*
Manual, small-brush cementing	0.02–0.03
Manual, large-brush applications	0.02
Manual, gross application, maximum use rate by hand (unusual)	¾–1½
Mechanical coating operations	⅓–2
Spray painting machinery	¼–½

The best information on solvent usage is, however, obtained from the employee or shop foreman.

2.8 EMPLOYEE COMPLAINTS OR SYMPTOMS

Employee complaints or symptoms that may be attributable to significant exposure to a chemical substance must always be considered in determining the need for exposure measurements. An employer can obtain information on the common symptoms of exposure to a substance from the Health Hazard Data section in Appendix A of a proposed substance standard (of the type discussed in Section 1.4) and the Signs and Symptoms section in Appendix C of the proposed standard. Any occupational health nurse or physician seeing the employees should be consulted in this aspect.

2.9 OCCUPATIONAL ENVIRONMENTAL DETERMINATION REPORT

The goal of the previous sections is to obtain a written report with a determination stating whether any employee may be exposed to airborne concentrations of a hazardous chemical substance. Refer to appropriate Federal regulations (29 CFR 1910 Subpart Z) to determine minimum required information for this report. The following guidelines provide recommendations concerning what a comprehensive report should contain. The report can be organized for convenience by either employee or work operation. It is compatible with proposed Federal health standard requirements.

1. Date of report.
2. Name and social security number of each employee considered at a work operation.
3. Work operations performed by the employee at the time of the report.
4. Location of work operations within the worksite.
5. Chemical substances to which the employee may be exposed at each work operation.
6. Any information, observations, and estimates that may indicate exposure of this employee to a chemical substance. List any exposure measurement data and calculations.
7. Federal permissible exposure limits and/or ACGIH TLV for each chemical.
8. Complaints or symptoms that may be attributable to chemical exposure.
9. Type and effectiveness of any control measures used. For mechanical ventilation controls, list measurements taken to demonstrate system effectiveness.
10. Operating condition ranges for production, process, and control measures for which the determination applies.
11. Determination summary including any further action required.

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CHAPTER 3

EXPOSURE MEASUREMENT SAMPLING STRATEGY

Once a determination is made that indicates the possibility of any significant employee exposure to airborne concentrations of a toxic substance, the employer is obligated to make measurements of the employee exposure to the substance. Several considerations are involved in formulating an employee exposure monitoring program.

- —Which employee or employees are to be sampled?
- —Where should the sampling device be located in relation to the employee sampled?
- —How many samples should be taken on each workday sampled to define an employee's exposure?
- —How long should the sampling interval be for a measurement sample?
- —What periods during the workday should the employee's exposure be sampled?
- —How many workdays during a year should be sampled, and when?

These considerations will be discussed in the following sections of this chapter.

Keep in mind that the phrase "employee exposure" is always meant to be that that would occur if the employee were not using a respirator.

3.1 SELECTION OF THE EMPLOYEE OR EMPLOYEES TO BE SAMPLED

The proposed OSHA health regulations require that once a positive determination is made that indicates the possibility of any employee exposures at or above the action level, then the employer is required to make an exposure measurement of the "employee believed to have the greatest exposure." The concept is known as sampling the "maximum risk employee." It is used to reasonably reduce the sampling burden on the employer, since the determination procedure in the previous chapter was intended only as a means of making an estimate with no actual measurements.

3.1.1. Selecting the Maximum Risk Employee(s)

Chapter 2 discussed the factors that must be considered to make a determination of whether employees may be exposed to toxic materials at concentrations above the action level.

If the determination is made that exposed employees may exist, then the next step is the selection of that employee ("maximum risk employee") or group of employees believed to have the greatest exposure so that their exposure may be measured. The same considerations that were used to make the written determination in the previous chapter must now be employed to select and categorize workers according to expected risk potential.

In making the first determination to assess potentially exposed employees, a judgment was made that employees were exposed to potentially toxic materials at or above a certain level. In the absence of definitive air sampling measurements, the judgment or selection of the maximum expected exposure risk employee (s) must be made by comparing the estimated exposure levels of the various exposed workers.

In an ideal situation, each potentially exposed worker should be individually sampled and appropriate decisions should be made regarding nonexposure, exposure, or overexposure. In most cases, however, we do not have an ideal situation, and the initial determination is a very rough one, generally with no actual air measurements. The most reasonable sampling strategy, for the most efficient use of sampling resources, is to sample the employee presumed to have the highest exposure risk. If there are a number of work operations as a result of different processes where there may be exposed employees, then a maximum risk employee should be selected for each work operation. This procedure will considerably reduce the burden on sampling resources since it is not necessary to initially sample employees who are expected to have lower exposure than those at maximum risk.

Again, it is not possible to set down blanket rules that would apply to every kind of process or operation for all industries. However, sufficient information can usually be obtained from the preliminary survey of a plant so that a competent, well-informed person can make a valid judgment as to the employees with highest exposure.

In general, the best procedure for determining the maximum risk employee is to observe and select the employee closest to the source of the hazardous material being generated. For example, in a grinding operation, the worker operating the grinder would most likely be the employee at maximum risk from exposure to toxic particulates. The farther a person is located from the source of generation (grinder), the lower the possibility of a significant exposure, because the material generated would probably be diluted by dispersion in the work area. Thus, in this type of operation, employees may be thought of as being within various zones of potential risk, based on estimated air concentrations for different distances from the contaminant source. Welding in an open room is another example where distance from the source could be the dominant factor in determining potential risk.

Distance from a source of generation of hazardous material is only one factor in determining risk potential. Employee mobility is another consideration. For example, consider an employee work station located adjacent to a drying oven releasing solvents into the atmosphere. If this employee is mobile in his various work tasks, he may not always be at the work station exactly when high concentrations of contaminants are present. Careful observation is required to get an accurate picture of the worker's movement within his work environment so that valid time-concentration exposures can be estimated.

Air movement patterns within a workroom should be analyzed to determine accurately the risk potential of employees. Especially in operations or processes involving heating or combustion, the natural air circulation could be such that the maximum risk employee might be located at considerable distance from the source of generation. The location of ventilation air exhausts and inlets, location of open doors and windows, and the size and shape of the work area would all be factors that could affect workroom air flow patterns and result in higher contaminant concentrations further away from the source.

Differences in work habits of individual workers can significantly affect levels of exposure. Even though several workers may be performing essentially the same jobs with the same materials, their individual methods of performing the task could produce varying exposure levels. For instance, in cleaning operations, metal parts in a basket are dipped into a large tank of solvent. When the basket is lifted from the tank, the correct procedure is to let the excess solvent drain from the parts back into the tank. If an employee does not take the time to let the solvent drain back into the tank, the solvent may splash onto the floor where it evaporates into the workroom air. This will increase the exposure levels over those where the worker properly lets the solvent drain back into the tank.

3.1.2. Random Sampling of a Homogeneous Risk Group of Workers

If a maximum risk worker cannot be selected for an operation with reasonable certainty, then it is necessary to resort to random sampling of the group of workers. The procedure is to randomly sample the group whose members have a similar expected exposure risk. The objective of the procedure is to select a subgroup of adequate size so that there is a high probability that the random sample will contain at least one worker with high exposure if one exists. (Note that this partial sampling procedure is not to be used once any employee exposure measurement reveals an employee exposure at or above the action level for reasons given in Technical Appendix B.) The following procedure should be used:

Step 1: Determine the number of employees to sample using Table 3.1.

Step 2: Randomly select the required number of employees using the random numbers given in Table 3.2, and measure their exposures.

Step 1: Determination of the Number of Employees to Sample

Table 3.1 gives the required sample size n of a random sample drawn from a group of size N ($N = 1$ to 50) which ensures with 90% confidence that at least one individual from the highest 10% exposure group is contained in the sample. Conversely, there is a 10% probability of missing all workers from the 10% highest exposure subgroup after sampling the required subgroup as specified in Table 3.1, which is taken from Table A.1 of Technical Appendix A.

TABLE 3.1. SIZE OF PARTIAL SAMPLE FOR TOP 10% AND CONFIDENCE 0.90

Size of group N*	Number of required samples†‡
8	7
9	8
10	9
11-12	10
13-14	11
15-17	12
18-20	13
21-24	14
25-29	15
30-37	16
38-49	17
50	18

*N = original equal risk group size.
†n = sample size or subgroup size.
‡$n = N$ if $N < 7$.

For example, suppose an equal expected exposure risk group of size $N = 26$ is considered. To be 90% confident that at least one of the three (i.e., 10% of 26) individuals with the highest of all exposures is included in a partial sample, see Table 3.1 for the required size of the partial subgroup, which is seen to be $n = 15$. That is, 15 workers should be randomly chosen from the total of 26. Thus, it is necessary to sample almost 60% of the group to ensure with 90% probability that at least one worker with an exposure in the highest 10% of all exposures in the group has been included.

Step 2: Random Sampling of Workers

After having selected the appropriate number of workers to sample, it is necessary to actually select the workers at random and measure their exposures. This section will describe how a random sampling procedure can be implemented with the use of a table of random numbers.

Table 3.2 contains the random numbers required for partial sampling. This table is used as follows:

1. Assign each individual in the risk group a number from 1 to N, where N is the number of people in the group.
2. Go to Table 3.2 and arbitrarily (ideally randomly) choose a starting position in the table. Read down, ignoring numbers greater than N as well as the number zero, and select the numbers less than or equal to N. Continue selecting numbers in this way until a partial sample of n numbers has been chosen. If necessary proceed to the next column, and, if at the bottom of column 25, proceed to the top of column 1.

For example, to select 15 individuals from 26 at random, the procedure of this section yields:

1. First number individuals in group from 1 to 26.
2. Arbitrarily choose the first number in column 10 of Table 3.2 as a starting position and read down, selecting the following numbers: 11, 20, 8, 1, 14, 13, 25, 23, 7, 22, 18, 19, 9, 10, 3.
3. Individuals who have been assigned these numbers will now be monitored for their exposure to contaminants.

If it is desired to use a confidence level other than 90% or to choose a percentage other than 10%, refer to Technical Appendix A, Calculation of Sample Size for a Maximum Risk Subgroup from a Homogeneous High Risk Group.

3.1.3. Selection of Employees for Periodic Exposure Monitoring Program

The proposed OSHA Health Regulations require that, if any of the exposure measurements taken on the maximum risk employee (or subgroup) shows exposures to toxic substance at or above the action level, the employer shall:

TABLE 3.2. TABLE OF RANDOM NUMBERS FOR PARTIAL SAMPLING*

ROW COLUMN	1				5					10					15					20					25
1	05	57	23	06	26	23	08	66	16	11	73	28	81	56	14	62	82	45	65	80	36	02	76	55	63
	37	78	16	06	57	12	46	22	90	97	78	67	39	06	63	60	51	02	07	16	75	12	90	41	16
	23	71	15	08	82	64	87	29	01	20	46	72	05	80	19	27	47	15	76	51	58	67	06	80	34
	42	67	98	41	67	44	28	71	43	08	19	47	76	30	26	72	33	69	92	51	95	23	26	85	76
	05	83	03	84	32	62	83	27	48	83	09	13	84	90	20	20	50	87	74	83	51	62	10	23	30
6	60	46	18	41	23	74	73	51	72	90	40	52	95	41	20	88	48	98	27	38	81	33	83	82	94
	32	80	64	75	81	98	09	40	64	89	29	99	46	35	69	91	50	73	75	92	90	56	82	93	24
	79	86	53	77	78	06	62	37	48	82	71	00	78	21	65	65	88	45	82	44	78	93	22	78	09
	45	13	23	32	01	09	46	36	43	66	37	15	35	04	88	79	83	53	19	13	91	59	81	81	87
	20	60	97	48	21	41	84	22	72	77	99	81	83	30	46	15	90	26	51	73	66	34	99	40	60
11	67	91	44	83	43	25	56	33	28	80	99	53	27	56	19	80	76	32	53	95	97	53	09	61	98
	86	50	76	93	86	35	68	45	37	83	47	44	52	57	66	59	64	16	48	39	26	94	54	66	40
	56	73	38	38	23	36	10	95	16	01	10	01	59	71	55	99	24	88	31	41	00	73	13	80	62
	55	11	50	29	17	73	97	04	20	39	20	22	71	11	43	00	15	10	12	35	09	11	00	89	05
	25	54	33	87	92	92	04	49	73	96	57	53	57	08	93	09	69	87	83	07	46	39	50	37	85
16	41	48	67	79	44	57	40	29	10	34	58	63	51	18	07	41	02	39	79	14	40	68	10	01	61
	03	97	71	72	43	27	36	24	59	88	82	87	26	31	11	44	28	58	99	47	83	21	35	22	88
	90	24	83	48	07	41	56	68	11	14	77	75	48	68	08	90	89	63	87	00	86	18	63	21	91
	98	98	97	42	27	11	80	51	13	13	03	42	91	14	51	22	15	48	67	52	09	40	34	60	85
	74	20	94	21	49	96	51	69	99	85	43	76	55	81	36	11	88	68	32	43	08	14	78	05	34
21	94	67	48	87	11	84	00	85	93	56	43	99	21	74	84	13	56	41	90	96	30	04	19	68	73
	58	18	84	82	71	23	66	33	19	25	65	17	90	84	24	91	75	36	14	83	86	22	70	86	89
	31	47	28	24	88	49	28	69	78	62	23	45	53	38	78	65	87	44	91	93	91	62	76	09	20
	45	62	31	06	70	92	73	27	83	57	15	64	40	57	56	54	42	35	40	93	55	82	08	78	87
	31	49	87	12	27	41	07	91	72	64	63	42	06	66	82	71	28	36	45	31	99	01	03	35	76
26	69	37	22	23	46	10	75	83	62	94	44	65	46	23	65	71	69	20	89	12	16	56	61	70	41
	93	67	21	56	98	42	52	53	14	86	24	70	25	18	23	23	56	24	03	86	11	06	46	10	23
	77	56	18	37	01	32	20	18	70	79	20	85	77	89	28	17	77	15	52	47	15	33	35	12	75
	37	07	47	79	60	75	24	15	31	63	25	93	27	66	19	53	52	49	98	45	12	12	06	09	32
	72	08	71	01	73	46	39	60	37	58	22	25	20	84	30	02	03	62	68	58	38	04	06	89	94
31	55	22	48	46	72	50	14	24	47	67	84	37	32	84	82	64	97	13	69	85	20	09	80	46	75
	69	24	98	90	78	29	34	25	33	23	12	69	90	50	38	93	84	32	28	96	03	65	70	90	12
	01	86	77	18	21	91	66	11	84	65	48	75	26	94	51	40	5	53	36	39	77	69	05	25	07
	5	43	94	06	80	61	34	28	46	28	11	48	48	94	60	65	06	63	71	06	19	35	05	32	56
	58	78	02	85	80	29	67	27	44	07	57	23	20	28	22	62	97	59	62	13	41	72	70	71	07
36	33	75	88	51	00	33	56	15	84	34	28	50	16	65	12	81	56	43	54	14	63	37	74	97	59
	58	60	37	45	62	09	95	93	16	59	35	22	91	78	04	97	98	80	20	04	38	97	13	92	30
	72	13	12	95	32	87	99	32	83	65	40	17	92	57	22	68	98	79	16	23	53	56	56	07	47
	22	21	3	16	10	52	57	71	40	49	95	25	55	36	95	57	25	25	77	05	38	05	62	57	77
	97	94	83	67	90	68	74	88	17	22	38	01	04	33	49	38	47	57	61	87	15	39	43	87	00
41	09	03	68	53	63	29	27	31	66	53	39	34	88	87	04	35	83	69	52	74	93	16	52	01	65
	29	95	61	42	65	05	72	27	28	18	09	85	24	59	46	03	91	55	38	62	51	71	47	37	38
	81	96	78	90	47	41	38	36	33	95	05	90	26	72	85	23	23	30	70	51	55	93	23	84	83
	44	52	20	81	21	57	57	85	00	47	26	10	87	22	45	72	03	5	75	23	38	38	56	77	97
	68	91	12	15	08	02	18	74	56	79	21	53	63	41	77	15	07	39	87	11	19	25	62	19	30
46	29	33	77	60	29	09	25	09	42	28	07	15	40	67	56	29	58	75	84	06	19	54	31	16	53
	54	13	39	19	29	64	97	73	71	61	78	03	24	02	93	86	69	76	74	28	08	98	84	38	23
	75	16	85	64	64	93	85	68	08	84	15	41	57	84	45	1	70	13	17	60	47	80	10	13	00
	36	47	17	08	78	03	92	85	18	42	95	48	27	37	99	98	81	94	44	72	05	95	42	31	17
	29	61	08	21	91	23	76	72	84	98	26	23	66	54	86	88	95	14	82	57	17	99	16	28	99

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*Reproduced from Table A-36 of Natrella (3.1), with permission of the Rand Corporation, "A Million Random Digits," The Free Press, 1955.

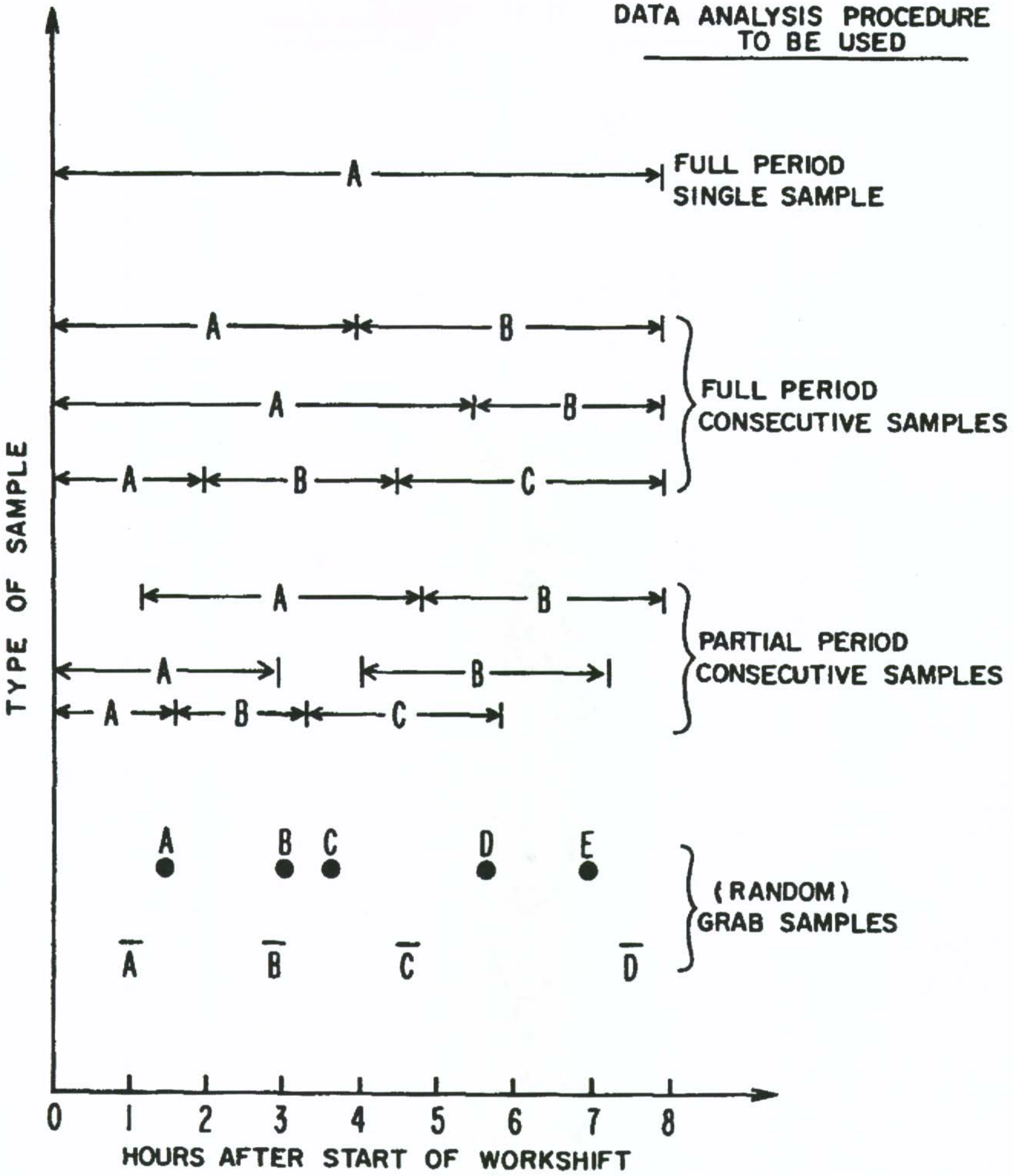

Figure 3.1. Reference chart of types of exposure measurements that could be taken for an 8-hour average exposure standard.

Example:

A personal sampling pump with a respirable dust sampling head is attached to an employee at the start of his shift at 8:00 a.m., turned off from 11:30 a.m. to 12:00 noon (lunch) and turned on again from 12:00 noon to 4:30 p.m. The sample collected constitutes a *full period sample* for the determination of respirable dust exposure because it covers the entire time period appropriate to the standard (8 hours).

3.3.2. Full Period Consecutive Samples Measurement

Several samples (equal or unequal time duration) are obtained during the entire period appropriate to the standard. The total time covered by the samples must be 8 hours for an 8-hour TWA standard and 15 minutes for a ceiling standard.

Example:

Personal samples are collected on an asbestos worker as follows:

Sample No.	*Time*
1	7:00 a.m. (start of shift) to 8:00 a.m.
2	8:00 a.m. to 9:30 a.m.
3	9:30 a.m. to 11:00 a.m.
4	11:00 a.m. to 1:00 p.m. (turned off and covered for 30 minutes during lunch)
5	1:00 p.m. to 3:30 p.m.

The measurement obtained is a *full period consecutive sample measurement* because it covers the entire time period appropriate to the standard (8 hours) and the samples are taken consecutively (or serially).

3.3.3. Partial Period Consecutive Samples Measurement

One or several samples (equal or unequal time duration) are obtained for only a portion of the period appropriate to the standard. For an 8-hour TWA standard this would mean that the sample or samples cover about 4 to less than 8 hours. Several samples totaling less than 4 hours (as eight 30-minute samples) would probably be best described as grab (short-term) samples for the purposes of analysis given in the next chapter.

Example:

Collection of a personal sample for lead exposure was started at 9:00 a.m. and continued until the end of the shift at 3:30 p.m. The 8-hour shift began at 7:00 a.m. with a half-hour lunch break from 11:30 a.m. till 12 noon. The measurement obtained is a *partial period sample measurement* since it covers only part (6 hours) of the period appropriate to the standard (8 hours).

3.3.4. Grab Samples Measurement

In some cases it is impossible, because of limitations in measurement methods as with direct reading meters or colorimetric detector tubes, to collect either a single sample or a series of consecutive samples whose total duration approximates the period for which the standard is defined. In this case, grab samples are taken over some number of short periods of time (less than 1 hour each; generally only minutes or seconds). Grab samples are taken at random intervals over the period of time for which the standard is defined.

Example:

It is necessary to obtain an exposure measurement for phosgene using detector tubes. Each detector tube sample takes 5 minutes to collect. It is intended to collect 10 samples out of the possible ninety-six 5-minute periods in the 8-hour period. These ten 5-minute duration samples constitute 10 *grab samples* of the worker's exposure on the given day. The estimate of the 8-hour TWA exposure obtained from averaging the readings of the 10 tubes would be a *grab sample measurement.*

3.4 EXPOSURE MEASUREMENTS FOR AN 8-HOUR TWA STANDARD

This section will discuss the factors that affect the choice of an exposure measurement strategy for a particular day's measurement. There is no such thing as one "best" strategy for all situations. However, some strategies are clearly better than others. Guidelines will be given for comparing alternative strategies. The following are broad considerations:

—Availability and cost of sampling equipment (pumps, filter, detector tubes, direct reading meters, etc.)

—Availability and cost of sample analytical facilities (for filters, charcoal tubes, etc.)

—Availability and cost of personnel to take samples

—Location of employees and work operations

—Occupational exposure variation (intraday and interday)

—Precision and accuracy of sampling and analytical methods

—Number of samples needed to attain the required accuracy of the exposure measurement.

The subject of intraday and interday occupational exposure variation has been discussed by Ayer and Burg (3-2) and Leidel et al. (3-3). The exposure variation of specific operations is practically impossible to predict. The only generalization that can be made is that intraday and interday variation, as measured by the geometric standard deviation (GSD), typically lie between 1.25 and 2.5, as shown by data in (3-2) and (3-3).

Precision and accuracy of sampling and analytical methods are discussed in Technical Appendix D, Coefficients of Variation and Accuracy Requirements for Industrial Hygiene Sampling and Analytical Methods. Again to generalize, most NIOSH sampling and analytical procedures have total coefficients of variation of 0.05 to 0.10 (5% to 10%). Also refer to Technical Appendix E, General Effect of Sample Size on Requirements for Demonstration of Compliance and Noncompliance.

After considering both exposure variation and the precision/accuracy of sampling/analytical methods, the following general guidelines can be given:

1. The Full Period Consecutive Samples Measurement is "best" in that it yields the narrowest confidence limits on the exposure estimate. There are statistical benefits to be gained from larger sample sizes (as eight 1-hour samples instead of four 2-hour samples), but with the disproportionately large additional costs incurred (especially analytical), the benefits are usually negligible. That is, the gains from additional (shorter) samples on the same work shift in "decision making power" are small compared with the significantly greater costs.

   Refer to Figures E-1 and E-3 of Technical Appendix E for the effect of increased sample size. Considering presently available sampling/analytical techniques, we can state that two consecutive full period samples (about 4 hours each for an 8-hour TWA standard) usually provide sufficient precision and are recommended as the "best" measurement to make.

2. The Full Period Single Sample Measurement (one 8-hour sample) is next to best if an appropriate sampling/analytical method is available. In this case, one 8-hour sample is essentially as good (all factors considered) as two 4-hour samples.

3. The Partial Period Consecutive Samples Measurement is the next choice. The major problem with this type of measurement is how to handle the unsampled portion of the period. Strictly speaking, the measurement results are valid only for the duration of the period that the measurements cover (as 6 out of 8 hours). However, professional judgment may allow inferences to be made concerning exposure concentrations during the unsampled portion of the period. Reliable knowledge concerning the operation is required to make this judgment. The sampled portion of the period should cover at least 70% to 80% of the full period.

   For exposure measurements made by the employer or his representative, it is probably sufficient to assign the exposure average for the partial period to the whole period. It is assumed that the unsampled period had the same exposure average as the sampled portion. However, the statistical decision tests in the next chapter are not fully valid in this situation. One can put confidence limits on a 6-hour exposure average, but it would not be proper to compare them with an 8-hour TWA standard since the work habits of the employee and the work operation must be identical during the sampled and unsampled portions of the work shift. This type of measurement should be avoided if possible.

For exposure measurements made by a governmental compliance officer, it is best to assume zero exposure for the unsampled period. Figure E-5 of Technical Appendix E shows the low "power" of the Partial Period Consecutive Samples Procedure. The effect of sample size and total time covered by all samples on requirements for demonstrating noncompliance is shown by the family of four curves. The bottom curve (8-hour total sample time) is the same curve as the CV = 0.10 curve of Figure E-3. The taking of partial period consecutive samples is a compromise between the preferred full period sample (s) and the least desirable grab samples. If a GSD of 2.5 is assumed on Figure E-4 (Technical Appendix E), a curve of about 5½ hours on Figure E-5 would have approximately the same *X/STD* ratios. Therefore, if it is not possible to sample for at least 70% of the time period appropriate to the standard (5½ hours for an 8-hour standard), it is better to go to a grab sampling strategy. Leidel and Busch (3-4) should be referred to for analysis of these types of data when zero exposure is assumed for the unsampled period.

4. A Grab Sample Measurement is the least desirable way of estimating an 8-hour TWA exposure. This is because the confidence limits on the exposure estimate are very wide and one has to have a low exposure average to statistically demonstrate compliance by the methods of the next chapter. Refer to Technical Appendix E, General Effect of Sample Size on Requirements for Demonstration of Compliance and Noncompliance, Figure E-2. Figure E-2 shows that the optimum number of grab samples to take for an exposure measurement is between 8 and 11. This only applies, however, to the 8-hour TWA exposure if the employee's operation and work exposure are relatively constant during the day. If the worker is at several work locations or operations during the 8-hour shift, then at least 8 to 11 grab samples should be taken during each period of expected differing exposure that significantly contributes to the 8-hour TWA exposure. If one is limited to taking fewer than 8 to 11 samples at each location (or operation), then choose the number of samples at each location in rough proportion to the time spent at each location. That is, *take more samples in areas where more time is spent.*

If grab samples are taken, their duration is important only in that enough samples must be collected for the analytical method. That is, any increase in sampling duration past the minimum time required to collect an adequate amount of material is unnecessary and unproductive. A 40-minute grab sample is little better than a 10-minute one. This is discussed by Leidel and Busch (3-4).

The last question to be answered concerns when to take the grab samples during the period of exposure. The accuracy of the probability level for the test depends upon implied assumptions of the lognormality and independence of the sample results that are averaged. These assumptions are not highly restrictive if precautions are taken to avoid bias when selecting the sampling times over the period for which the standard is defined. To this end, it is desirable to choose the sampling periods in a statistically random fashion.

For a standard defined as a time-weighted average concentration over a period longer than the sampling interval, an unbiased estimate of the true average can be ensured by taking samples at random intervals. It is valid to sample at equal intervals if the series is known to be stationary with contaminant levels varying randomly about a constant mean and fluctuations of short duration relative to length of the sampling interval. If means and their confidence limits were to be calculated from samples taken at equally spaced intervals, however, biased results could occur if cycles in the operation were in phase with the sampling periods. Results from random sampling are unbiased even when cycles and trends occur during the period of the standard.

The word random refers to the manner of selecting the sample. Any particular sample could be the outcome of a random sampling procedure. A practical way of defining random sampling is that any portion of the work shift has the same chance of being sampled as any other.

Technical Appendix F, Selection of Random Sampling Periods During an 8-Hour Workshift, gives the formal statistical method of choosing the random sampling periods.

3.5 EXPOSURE MEASUREMENTS FOR A CEILING STANDARD

Samples taken for determination of compliance with ceiling standards are treated in a manner similar to those taken for comparison with TWA standards. Two important differences should be noted.

The first is the samples taken for comparison with ceiling standards are best taken in a *nonrandom* fashion. That is, all available knowledge relating to the area, individual, and process being sampled should be utilized to obtain samples during periods of maximum expected concentrations of the substance.

The second point is that samples taken for comparison with ceiling standards are normally taken for a much shorter time period than those taken for calculating TWA's. There are four different ways in which the time period for a ceiling standard may be defined (29 CFR 1910.1000).

1. 29 CFR 1910.1000 (a) (1) for Table Z-1: No time period. "An employee's exposure . . . shall at no time exceed the ceiling value . . . ."
2. 29 CFR 1910.1000 (b) (2) for Table Z-2: No time period, but peak above the "ceiling" allowed. "An employee's exposure . . . shall not exceed at any time during an 8-hour shift the acceptable ceiling concentration limit . . . except for . . . a maximum peak value."
3. 29 CFR 1910.1000 (b) (2) for Table Z-2: Short time period (5 to 30 minutes) defined as "maximum duration" for "maximum peak." The ceiling standard directly above may be exceeded for short periods up to a concentration defined as "acceptable maximum peak above the acceptable ceiling concentration for an 8-hour shift."
4. Under the current joint NIOSH/OSHA Standards Completion Program, all ceiling standard substances in Table Z-1 of 29 CFR 1910.1000 will have the standard defined for 15-minute periods as: ". . . concentrations not in excess of . . . averaged over any 15-minute period during an 8-hour work shift."

Measurements taken for the purpose of determining employee exposure to ceiling standard substances should be taken during periods of maximum expected airborne concentrations of the substance. Each measurement should consist of a 15-minute sample (or series of consecutive samples totaling 15 minutes) taken in the employee's breathing zone. A minimum of three measurements should be taken on one work shift, and the highest of all measurements taken is a good estimate of the employee's upper exposure for that shift.

Taking at least three measurements on a shift makes it easier to spot gross errors or mistakes. In most cases, however, only the highest value would be statistically tested for compliance by the Full Period Single Sample Measurement Procedure in Chapter 4 (section 4.2.1). If the samples are taken for comparison to the "maximum peak" ceiling standard (29 CFR 1910.1000, Table Z-2), the sampling period should equal the "maximum duration" period for that particular standard. Thus, in the case of detector tubes, it might be necessary to take several consecutive samples and average the results. Then the Full Period Consecutive Samples Measurement Procedure (section 4.2.2) would be used to analyze the results. The classification of exposures for a ceiling standard is discussed in section 4.3 of Chapter 4.

Even though samples taken for comparison with ceiling standards are best taken in a nonrandom fashion, there may be situations where the process appears constant during the work shift. In this case, the number of time periods that should be sampled can be estimated so that representation (one or more) is assured from the desired exposures (top 15% or top 10%) by the techniques of section 3.1.2 and Technical Appendix A.

For instance, with a ceiling standard defined for a 15-minute period, there are 32 discrete nonoverlapping periods in an 8-hour work shift. Thus, with $N = 32$ and with the use of Technical Appendix A, the following appropriate sample sizes are determined:

15-Minute period

At least one period from:	Confidence level	Sample at least:
Top 20%	0.90	9 periods
Top 20%	0.95	11 periods
Top 10%	0.90	16 periods
Top 10%	0.95	19 periods

Where the ceiling standard is defined for a 10-minute period, there would be 48 periods and the following sample sizes are appropriate:

10-Minute period

At least one period from:	Confidence level	Sample at least:
Top 20%	0.90	9 periods
Top 20%	0.95	12 periods
Top 10%	0.90	17 periods
Top 10%	0.95	21 periods

Very short time samples may sometimes be taken, as with a 3-minute detector tube or spot readings with a direct-reading meter. Then the appropriate number of samples to take is given by equation 5 of Technical Appendix A, and the results are:

Less than a 5-minute period

At least one period from:	Confidence level	Sample at least:
Top 20%	0.90	10 periods
Top 20%	0.95	13 periods
Top 10%	0.90	22 periods
Top 10%	0.95	28 periods

Once the appropriate number of periods is chosen, the particular time periods to be sampled should be selected. This is done by the techniques of the Grab Sampling strategy in section 3.4.4 and Technical Appendix F. Another useful technique would be to plot the sample results on lognormal probability paper as given in Technical Appendix I. This will give a fair idea of the actual exposure distribution by percentages of time during the work shift.

3.6 RECORDING EXPOSURE MEASUREMENT SAMPLE RESULTS

Under the proposed OSHA health regulations, the employer is required to keep an accurate record of all measurements taken to determine employee exposure to a particular regulated substance. This record shall include, as a minimum:

—The date of the measurement;
—Operations involving exposure to the substance being monitored;
—Sampling and analytical methods used and evidence of their accuracy, including the method, results, and date of calibration of sampling equipment;
—Number, duration, and results of samples taken; and
—Name, social security number, and exposure of the employee monitored.

The record must be maintained until replaced by a more recent record, but in no event kept for less than 1 year. Some substances require longer than 1 year minimum retention periods.

The Employee Exposure Measurement Record (Figure 3.2) contains the type of information that should be recorded for each measurement. The average exposure calculations for the employee can be done on the back of the form for ready reference.

If the sampling device flowmeter (such as a pump rotameters or critical orifice) calibration location and sample location differ by more than several thousand feet in altitude, or more than 25 to 30 Fahrenheit degrees in temperature, then flowmeter correction factors should be used. This procedure is given in Technical Appendix G, Temperature and Pressure Corrections of Industrial Hygiene Sample Volumes and Calculation of Concentrations (ppm). The flowmeter correction procedure is not required for sampling devices with positive displacement pumps. Technical Appendix G also gives the procedure and a nomogram for converting mass concentrations (as milligrams per cubic meter) to part per million concentrations for comparison with the Federal standards. This latter procedure is required regardless of the sampler used.

The requirement for "evidence of accuracy" of the sampling and analytical methods might

EMPLOYEE EXPOSURE MEASUREMENT RECORD

Facility .... Area ....

Sampled by .... Date ....

Temperature .... Altitude ....

Sample #........... Employee name .... SS# ....

Operation(s) monitored ....

Type of sample: Personal .... Breathing zone .... Area ....

Operating conditions and control methods ....

....

Time on .... Time off ....

Elapsed time (min) .... Indicated flow rate (LPM) .... Volume (liters) ....

Calibration location .... By .... Date ....

Sampling/analytical method ....

Evidence of accuracy ....

....

Remarks, possible interferences, action taken, etc. ....

....

....

Results of sample analysis or instrument reading ....

....

Exposure of employee (indicate 8-hr average or 15 min) and sample numbers it is based on ....

....

....

Figure 3.2. Employee Exposure Measurement Record.

cause some concern. However, this need not be interpreted as requiring the employer to run his own accuracy tests of a laboratory's analytical method or tests of certified equipment. The following are examples of ways to meet this requirement:

1. Establish field calibration procedures for sampling equipment.
2. Have samples analyzed at a laboratory participating in an industrial hygiene quality control program such as the one conducted by AIHA.
3. Use NIOSH certified detector tubes (certified under 42 CFR Part 84), if available.
4. Refer to manufacturer's literature statements of accuracy.
5. Refer to analytical laboratories' statements that their analyses will meet the accuracy requirements of the regulations.

Refer to Technical Appendix D, Coefficients of Variation and Accuracy Requirements for Industrial Hygiene Sampling and Analytical Methods.

Remember that if any exposure measurement strategy other than the Full Period Single Sample Measurement is used, then the exposure average must be calculated by the TWA method. Refer to Technical Appendix H, Time-Weighted Average (TWA) Exposure Calculation for this procedure.

Finally, it can be very informative to graphically plot grab samples exposure measurement data (or exposure averages for employees in an occupational exposure group). The procedures with examples is given in Technical Appendix I, Lognormal Probability Plots of Exposure Measurement Data and Exposure Averages. Plotting exposure measurement results (or employee exposure averages) on lognormal probability paper provides a convenient representation of data percentiles (or exposure percentiles). The fitted lognormal distribution can be shown as a straight line on the same graph of Exposure Measurement Data and Exposure Averages.

Another way of presenting and analyzing an employee's daily exposures is to plot the averages versus time as on an industrial quality control chart. Leidel et al. (3-3) have discussed the similarities between employee exposure monitoring programs and quality control programs. For those interested in applying quality control chart techniques to exposure monitoring programs, the work of Morrison (3-5) is useful; work in this area is to be encouraged.

3.7 INTERVAL BETWEEN DAYS MONITORED

The proposed OSHA health regulations developed under the Standards Completion Program require the following:

1. The exposure of an employee whose exposure measurement is at or above the action level, but not above the permissible exposure, must be measured at least every 2 months.
2. For an employee whose exposure measurement exceeds the permissible exposure, the employer shall measure that employee's exposure at least every month until the exposure is reduced to below the standard by appropriate control measures.

The above are the proposed minimum legal requirements. More frequent measurements should be made based on professional judgment of the exposure situation.

3.8 TERMINATION OF EXPOSURE MONITORING

The proposed OSHA health regulations allow exposure monitoring on a particular employee to be terminated if two consecutive exposure measurements taken at least 1 week apart reveal that each of the employee's exposure measurements is less than the action level. That is, both measurements must be less than the action level.

3.9 SAMPLING STRATEGY FOR EMPLOYEES INFREQUENTLY WORKING WITH HAZARDOUS SUBSTANCES

Chapter 2 and the preceding sections of this chapter were developed with the knowledge that, where chemicals are used in industrial processes and released into the workplace air, most potential exposure situations for employees will be routine ones, such as daily. But there are types of industrial jobs where employees infrequently (nondaily, e.g., once per month) work with toxic chemicals. Laboratory and maintenance type operations are two examples. These infrequent operations often result in (or have the potential for) generation of contaminant levels higher than those experienced during normal operations.

The exposure determination phase of the proposed OSHA regulations (see Table 1.1 in section 1.4 and Chapter 2) is completely compatible with infrequent operations. If an employer considers all the factors required by the proposed regulations and determines with his best professional judgment that significant exposures are not likely to occur, then exposure measurements are not required. Refer to each specific hazardous substance regulation in 29 CFR 1910. 1000 series (Subpart Z) for detailed requirements. The physiological risk from the chemical (its toxic potential) should be a very important consideration in the determination of need to sample employees with infrequent exposures. Chemicals that may create acute toxic effects after high exposures lasting seconds to hours obviously have sampling priority. These chemicals need to be watched more closely in infrequent exposure situations. The informative appendices of the proposed OSHA regulations contain health hazard data and toxicology information that outlines the short- and long-term effects of each substance. Generally, those substances with ceiling standards should be looked at very carefully for overexposure risk in infrequent exposure situations.

Sections 3.1 through 3.6 are also directly applicable to infrequent operations. OSHA should be contacted for advice on complying with requirements for periodic monitoring of infrequent operations (section 3.7). The requirements for routine monitoring were primarily developed to detect hazardous shifts in routine exposure levels. Thus, the question of how often to monitor infrequent operations is best answered with professional judgment based on the considerations given above.

REFERENCES

3-1. Natrella, M. G.: Experimental Statistics. National Bureau of Standards Handbook 91. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, 1963.

3-2. Ayer, H. E., and J. Burg: Time-Weighted Averages vs. Maximum Personal Sample. Paper presented at the 1973 American Industrial Hygiene Conference in Boston, Mass.

3-3. Leidel, N. A., K. A. Busch, and W. E. Crouse: Exposure Measurement Action Level and Occupational Environmental Variability. NIOSH Technical Information, HEW Pub. No. (NIOSH) 76-131, Cincinnati, Ohio 45226, December 1975.

3-4. Leidel, N. A., and K. A. Busch: Statistical Methods for the Determination of Noncompliance with Occupational Health Standards. NIOSH Technical Information, HEW Pub. No. (NIOSH) 75-159, Cincinnati, Ohio 45226, April 1975.

3-5. Morrison, J.: The Lognormal Distribution in Quality Control. Applied Statistics, 7(3): 160-172, 1958.

SUGGESTED READINGS FOR CHAPTER 3

American Conference of Governmental Indusrial Hygienists: Air Sampling Instruments. American Conference of Governmental Industrial Hygienists, P. O. Box 1937, Cincinnati, Ohio 45201.

Linch, A. L.: Evaluation of Ambient Air Quality by Personnel Monitoring. CRC Press, Inc., 18901 Cranwood Parkway, Cleveland, Ohio 44128.

CHAPTER 4

STATISTICAL ANALYSIS OF EXPOSURE MEASUREMENT SAMPLE RESULTS

Chapter 3 discussed how the employee exposure measurement samples should be collected, chemically analyzed, and exposure measurement results recorded. This chapter details the application of standard statistical methods to these results for the purpose of answering such questions as:

- Was an employee exposure average in compliance with the health standard (either ceiling or 8-hour time weighted average [TWA]) on a particular day?
- What is an employee's long-term exposure estimate based on several exposure measurement daily averages?
- What is the percentage of days an employee can be expected to be exposed to above-standard levels, based on several exposure measurement daily averages?
- Should engineering controls be installed to reduce excessive exposures?

4.1 CONFIDENCE INTERVAL LIMITS

The decision making process based on statistical theory of hypothesis testing is closely linked to the concept of confidence interval limits (i.e., to the calculation of the confidence interval expected to contain the true average exposure). This subject is discussed in most introductory statistical texts. Leidel and Busch (4-1) have discussed the application of confidence limits to occupational health exposure measurements.

Briefly, when an employee is sampled and an average exposure calculated, this measured exposure average will rarely be exactly the same as the true average exposure. The discrepancy between the measured and true exposure averages results from random sampling errors and random occupational environmental fluctuations within a workshift. Thus, the result of the sampling is referred to as an *average exposure estimate* (or estimate of the true average exposure). Statistical methods allow us to calculate interval limits for each side of the average exposure estimate that will contain the true exposure average at a selected confidence level (as 95%). The numerically larger limit is known as the upper confidence limit (UCL), and the numerically smaller limit is known as the lower confidence limit (LCL). In the long run, nineteen of twenty 95% confidence intervals would include the true average exposure between the LCL and UCL.

We can compute either two-sided or one-sided confidence intervals. Two-sided intervals bracket, on both sides, the true exposure average at the stated confidence level. A one-sided confidence limit gives only the upper (or lower) bound on the true exposure average without considering the other side (or bound). All procedures of Leidel and Busch and this Handbook use *one-sided confidence limits* (either the UCL or LCL). These are chosen at the 95% confidence level. The LCL should be employed by a compliance officer to place the burden of proof of noncompliance upon the Government. However, the employer would more properly employ the UCL to ensure that safe employee exposure levels exist.

Figure 4.1 provides a graphic example of an LCL and UCL (each one-sided) for an average exposure estimate. The practical interpretation of a 95% one-sided LCL is that one can be 95% confident that the true average exposure is *greater* (larger) than the LCL (thus the arrow points up). Conversely, for a 95% one-sided UCL, one can be 95% confident that the true

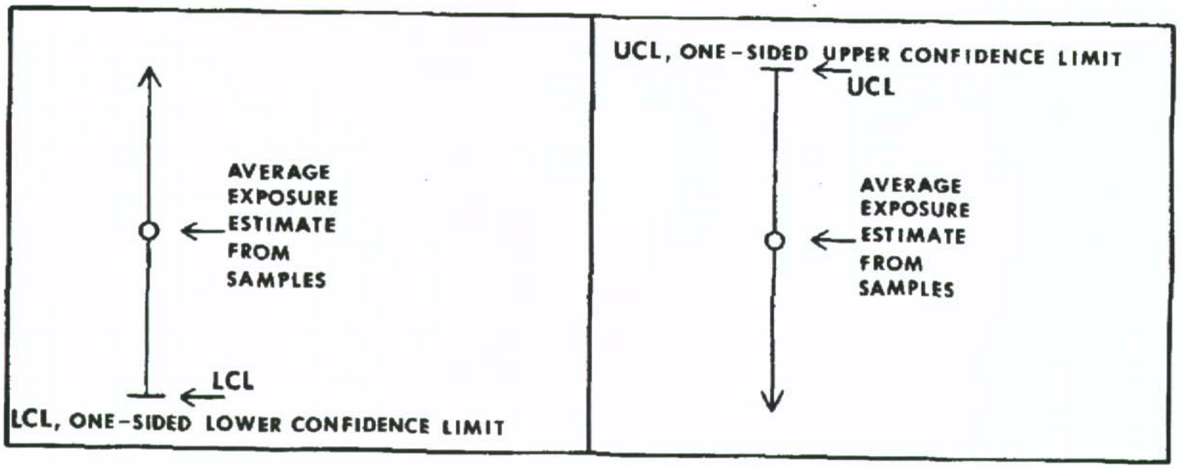

Figure 4.1. Example of one-sided LCL and UCL.

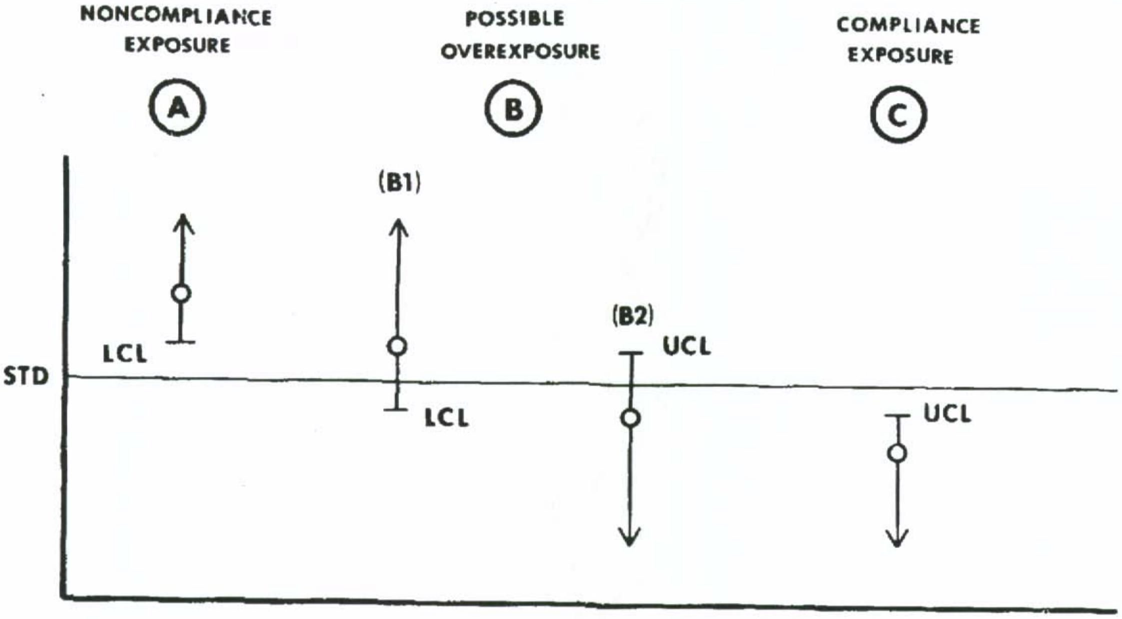

Figure 4.2. Classification according to one-sided confidence limits.

TABLE 4.1. CLASSIFICATION SYSTEM FOR EMPLOYEE EXPOSURE TO CONTAMINANTS

Classification	Definition	Statistical criterion
A. Noncompliance exposure	There is 95% confidence (based on measurements) that a worker's exposure is above the standard	LCL (at 95%) > STD
B. Possible over exposure	Any individual who cannot be classified in A or C	
C. Compliance exposure	There is a 95% confidence (based on measurements) that a worker's exposure is below the standard	UCL (at 95%) $\leqslant$ STD

average exposure is *less* (smaller) than the UCL (thus the arrow points down).

Technical Appendix J, Confidence Limits and Confidence Levels as They Affect Employee and Employer Risk, discusses choosing other confidence levels such as 90% or 99%.

A one-sided confidence limit (LCL or UCL) can be used to classify average exposures into one of the three possible exposure categories. The use of the LCL (by the compliance officer) would result in a decision of either Noncompliance Exposure or Possible Overexposure. The use of the UCL (by the employer) would result in a decision of either Compliance Exposure or Possible Overexposure. Figure 4.2 displays the three-way classification relative to the standard. (Figure 4.2 is a graphic presentation of the contents of Table 4.1.) The circle in each vertical line represents the average exposure estimate calculated from the measurement sample results.

The definition of an "exposed" employee deserves further explanation. Case B1 represents an employee whose average exposure estimate on a day was greater than the standard (overexposure in the conventional sense). But, the LCL did not exceed the standard, and a statistically definitive statement could not be made since there was a possibility that the true average exposure was under the standard in the region down to the LCL and, thus, not "overexposed." Conversely, Case B2 represents an employee whose average exposure estimate was less than the standard (safe exposure in conventional terms). But, the UCL was not lower than the standard, and a statistically definitive statement could not be made regarding compliance since there was a possibility that the true average exposure was in fact greater than the standard (up to the UCL).

The classification system for employee exposure is summarized in Table 4.1.

4.2 CLASSIFICATION OF EXPOSURE FOR AN 8-HOUR TWA STANDARD

The following procedures are concerned with an 8-hour TWA standard as defined in 29 CFR 1910, Subpart Z. The authors are not aware of any OSHA policy regarding workshifts of other than 8-hour duration. However, the employer may want to create his own lower exposure limits for workshifts exceeding 8 hours; Brief and Scala (4-2) have given guidance for longer than 8-hour workshifts.

4.2.1 Full Period Single Sample Measurement

Refer to sections 3.3.1 and 3.4 for the definition and application of this measurement strategy.

PROCEDURE	*EXAMPLE*
(1) Obtain the full-period sample value (X), the 8-hour TWA standard (STD), and the coefficient of variation (CV_T) for the sampling/analytical method, which is known from prior data. CV_T can be obtained from Technical Appendix D, from Coefficients of Variation and Accuracy Requirements for Industrial Hygiene Sampling, and from analytical procedures.	(1) A charcoal tube and personal pump were used to sample for alpha-chloroacetophenone. A flow rate of 100 cc/min was used for an 8-hour period. The analytical laboratory reported 0.04 ppm and gave a CV_T for the method of 0.09. The STD is 0.05 ppm. Thus, $X=0.04$ ppm.

(2) Divide X by the standard to determine x, the "standardized" concentration. That is:

$$x = \frac{X}{\text{STD}}$$

This division is performed to make the concentrations of contaminant independent of the standard (in concentration units) for the particular contaminant being investigated and to simplify later calculations. All values x are comparable to a single scale of compliance with a standard of unity. That is, the standard for the transformed variable x will always be unity.

(3) Compute LCL or UCL as follows:*

a) Compliance officer's test for noncompliance. Compute

$$\text{LCL}(95\%) = x - (1.645)\ (CV_T)$$

b) Employer's test for compliance. Compute

$$\text{UCL}(95\%) = x + (1.645)\ (CV_T)$$

(4) Classify the exposure average for the one sample according to the classification system.

a) Compliance officer's test for noncompliance.

- If LCL > 1, classify as Noncompliance Exposure.
- If $x > 1$ and LCL $\leqq 1$, classify as Possible Overexposure.
- If $x \leqq 1$, no statistical test for noncompliance would be made.

(2)

$$x = \frac{0.04 \text{ ppm}}{0.05 \text{ ppm}} = 0.8$$

(3)

a) $\text{LCL} = 0.8 - 1.645\,(0.09) = 0.65$

(Note: No LCL would be required since the value of x itself is below 1.0.)

b) $\text{UCL}\ (95\%) = 0.8 + (1.645)\ (0.09) = 0.95$

(4)

a) Since $x = 0.8$ is less than 1, the compliance officer would not need to make a statistical test for noncompliance.

---

*STATISTICAL NOTE: The use of the (CV_T) in the confidence limits formulae is equivalent to calculating the standard deviation of X (concentration) as (CV_T) (STD) instead of $(CV_T)\ (\mu)$. Thus, for $\mu >$ STD, the calculated LCL for μ/STD (the true relative concentration) is slightly higher than the correct LCL because of our having underestimated the standard deviation. Nevertheless, the use of LCL as computed in (3a) to make a noncompliance decision is correct since the decision rule selected is algebraically equivalent to a significance test of the null hypothesis of compliance. The rationale for the significance test is:

—Calculate an upper tolerance limit for full period concentration measurements (X) under the null hypothesis that the true TWA concentration is equal to the standard.

—Then, if the observed measurement exceeds the upper tolerance limit, reject the null hypothesis and decide for noncompliance.

Since the same allowance for measurement error would be added to STD to get the upper tolerance limit as would be subtracted from X to get the LCL for the true TWA concentration, the two decision rules are algebraically identical. The LCL format for the decision rule is preferred because it also provides a (conservative) quantitative lower limit on the actual exposure in the case of a noncompliance decision.

b) Employer's test for compliance.

- If UCL $\leqq$ 1, classify as Compliance Exposure.
- If UCL $>$ 1, classify as Possible Overexposure.
- If $x > 1$, no statistical test for compliance would be made.

b) Since 0.95 is less than 1, the employer could state that the exposure was a Compliance Exposure at the 95% confidence level.

4.2.2 Full Period Consecutive Samples Measurement and Partial Period Consecutive Samples Measurement

Refer to sections 3.3.2, 3.3.3, and 3.4 for definitions and applications of these measurement strategies.

For full period consecutive samples, section 4.2.2.1 assumes that all sampled periods have equal true average concentrations. If we expect the samples to have significantly different values because of different exposure situations during the workshift, then the conservative procedure in section 4.2.2.2 can be used. Where exposures are highly variable between the sampling periods in the day, the use of 4.2.2.1 would underestimate the random sampling error in the TWA, thus increasing the chance of deciding a Noncompliance Exposure (with the compliance officer's test) or deciding a Compliance Exposure (with the employer's test). The procedure in section 4.2.2.1 is exact ($\alpha = 0.05$) for the case of uniform exposure during the workshift. The procedure for nonuniform exposure given in section 4.2.2.2 is approximate and, typically, will have greater than 95% confidence levels. The probability α of making a type-I error using 4.2.2.2 would be less than 0.05 and the power of the test is also decreased as discussed in Technical Appendix J.

To summarize, for highly nonuniform exposure situations, the simpler section 4.2.2.1 procedure may underestimate the sampling error in the TWA. However, the approximate procedure in section 4.2.2.2 will usually overestimate the sampling error in the TWA. The LCL's from 4.2.2.2 will be lower than those from 4.2.2.1, and the UCL's from 4.2.2.2 will be higher than those from 4.2.2.1.

For partial period consecutive samples, the employer computes the UCL for the average exposure level during the sampled portion of the day using the procedure of section 4.2.2.1 or 4.2.2.2. He then compares the UCL to the 8-hour standard. This can be done if he assumes the same exposure existed during the unsampled portion of the workshift as existed during the measured portion. However, a more conservative procedure for use by the compliance officer would be to assume zero exposure for the unsampled portion of the workshift. See section 3.4 for a discussion of this point. The procedure in section 4.2.2.3 *is for the compliance officer only*.

4.2.2.1 Full Period Uniform Exposure

STANDARD PROCEDURE

(1) Obtain $X_1, X_2, \ldots, X_n$, the n consecutive sample values on one workshift and their durations $T_1, T_2, \ldots, T_n$. Also obtain CV_T, the sampling/analytical total coefficient of variation as in the preceding section 4.2.1 (step 1).

EXAMPLE

(1) A personal pump (50 cc/min) and three charcoal tubes were used consecutively to monitor an employee's uniform exposure to isoamyl alcohol. Appendix D gives a $CV_T = 0.08$ for this method. The 8-hour TWA *STD* is 100 ppm. The analytical lab reported the following results for the three tubes:

$X_1 = 90$ ppm, $X_2 = 140$ ppm, $X_3 = 110$ ppm
$T_1 = 150$ min, $T_2 = 100$ min, $T_3 = 230$ min

(2) Compute the *TWA* exposure as detailed in Technical Appendix H (Part A).

(2) $TWA = \frac{1}{480}\{(150 \text{ min})(90 \text{ ppm}) + (100 \text{ min})(140 \text{ ppm}) + (230 \text{ min})(110 \text{ ppm})\}$
$= 110. \text{ ppm}$

(3) Divide the *TWA* exposure by the standard to determine the standardized average (*TWA/STD*).

(3) $$(TWA/STD) = \frac{110. \text{ ppm}}{100 \text{ ppm}} = 1.10$$

(4) Compute the *LCL* or *UCL* as follows:

a) Compliance officer's test for noncompliance. Compute

$$LCL\ (95\%) = (TWA/STD) - \frac{1.645\,(CV_T)\sqrt{T_1^2 + T_2^2 + \ldots + T_n^2}}{T_1 + T_2 + \ldots + T_n}$$

(4)

a)

$$LCL\ (95\%) = 1.10 - \frac{(1.645)\,(0.08)\sqrt{(150)^2 + (100)^2 + (230)^2}}{150 + 100 + 230}$$

$$= 1.10 - 0.08 = 1.02$$

b) Employer's test for compliance. Compute

$$UCL\ (95\%) = (TWA/STD) + \frac{1.645\,(CV_T)\sqrt{T_1^2 + T_2^2 + \ldots + T_n^2}}{T_1 + T_2 + \ldots + T_n}$$

b) No employer's test is necessary since *TWA/STD* exceeds 1. For illustrative purposes, compute $UCL\ (95\%) = 1.10 + 0.08 = 1.18$

NOTE: If the sample durations are approximately equal, these short equations can be used:

a) $LCL\ (95\%) = (TWA/STD) - \frac{1.645\,(CV_T)}{\sqrt{n}}$

b) $UCL\ (95\%) = (TWA/STD) + \frac{1.645\,(CV_T)}{\sqrt{n}}$

(5) Classify the TWA exposure average for the n samples according to the classification system.	(5)
a) Compliance officer's test for noncompliance. • If $LCL > 1$, classify as Noncompliance Exposure. • If $(TWA/STD) > 1$ and $LCL \leqq 1$, classify as Possible Overexposure. • If $(TWA/STD) \leqq 1$, no statistical test for noncompliance would be made.	a) Since 1.02 exceeds 1, this TWA exposure is classified as a Noncompliance Exposure at the 95% confidence level using an analytical method with a $CV_T = 0.08$. The sample results indicate a fairly uniform exposure.
b) Employer's test for compliance. • If $UCL \leqq 1$, classify as Compliance Exposure. • If $UCL > 1$, classify as Possible Overexposure. • If $(TWA/STD) > 1$, no statistical test for compliance would be made.	

4.2.2.2 Full Period Nonuniform Exposure Procedure

PROCEDURE	*EXAMPLE*
(1) Obtain $X_1, X_2, \ldots, X_n$, the n consecutive sample values on one workshift and their durations $T_1, T_2, \ldots, T_n$. Also obtain CV_T, the sampling/analytical total coefficient of variation as in section 4.2.1 (step 1).	(1) A personal pump (50 cc/min) and two charcoal tubes were used to monitor an employee's nonuniform exposure to isoamyl alcohol. Appendix D gives a $CV_T = 0.08$ for this method. The 8-hour TWA STD is 100 ppm. These results were reported back from the lab. $X_1 = 30$ ppm and $X_2 = 140$ ppm $T_1 = 300$ min and $T_2 = 180$ min
(2) Compute the TWA exposure as detailed in Technical Appendix H (Part A).	(2) $TWA = \dfrac{(300\text{ min})\ (30\text{ ppm}) + (180\text{ min})\ (140\text{ ppm})}{(300+180)\text{ min}}$ $= 71.$ ppm
(3) Divide the TWA exposure by the standard to find the standardized average (TWA/STD).	(3) $(TWA/STD) = \dfrac{71.\text{ ppm}}{100\text{ ppm}} = 0.71$

(4) Compute the *LCL* or *UCL* as follows:

a) Compliance officer's test for noncompliance. Compute

$$LCL\ (\geqq 95\%) = (TWA/STD) - \frac{1.645\,(CV_T)\sqrt{T_1^2X_1^2+\dots+T_n^2X_n^2}}{(STD)\,(T_1+\dots+T_n)\sqrt{1+CV_T^2}}$$

b) Employer's test for compliance. Compute

$$UCL\ (\geqq 95\%) = (TWA/STD) + \frac{1.645\,(CV_T)\sqrt{T_1^2X_1^2+\dots+T_n^2X_n^2}}{(STD)\,(T_1+\dots+T_n)\sqrt{1+CV_T^2}}$$

(4)

a) Since $(TWA/STD) < 1$, no test for noncompliance would be needed.

b) $$UCL\ (\geqq 95\%) = 0.71 + \frac{(1.645)\,(0.08)\sqrt{(300)^2(30)^2+(180)^2(140)^2}}{(100)\,(300+180)\sqrt{1+(0.08)^2}}$$

$$= 0.71 + 0.07 = 0.78$$

NOTE: If the sample durations are approximately equal, these short equations can be used:

a) $$LCL\ (\geqq 95\%) = (TWA/STD) - \frac{1.645\ (CV_T)\sqrt{X_1^2+\dots+X_n^2}}{(n)\,(STD)\sqrt{1+CV_T^2}}$$

b) $$UCL\ (\geqq 95\%) = (TWA/STD) + \frac{1.645\ (CV_T)\sqrt{X_1^2+\dots+X_n^2}}{(n)\,(STD)\sqrt{1+CV_T^2}}$$

(5) Classify the *TWA* exposure average for the *n* nonuniform samples according to the classification system.

a) Compliance officer's test for noncompliance.

- If $LCL > 1$, classify as Noncompliance Exposure.
- If $(TWA/STD) > 1$ and $LCL \leqq 1$, classify as Possible Overexposure.
- If $(TWA/STD) \leqq 1$, no statistical test for noncompliance would be made.

(5)

a) Since $0.71 < 1$, the compliance officer would not make a statistical test for noncompliance.

b) Employer's test for compliance.

- If $UCL \leq 1$, classify as Compliance Exposure.
- If $UCL > 1$, classify as Possible Overexposure.
- If $(TWA/STD) > 1$, no statistical test for compliance would be made.

4.2.2.3 Partial Period Consecutive Samples Procedure (compliance officer only)

To calculate the LCL, follow the full period procedures of section 4.2.2.1 (uniform exposure) or 4.2.2.2 (nonuniform exposure) and examples through part (4) of either section. For example, suppose the three samples of section 4.2.2.1 had covered only 6.4 hours and the *LCL* (95%) was still 1.02. Then a *Partial Period Limit* (*PPL*) would be calculated as follows:

$$PPL = \left[\frac{\text{period of } STD = 8 \text{ hours}}{\text{total time of samples}} \right] = (8 \text{ hr}) \;/\; (6.4 \text{ hr}) = 1.25$$

Then classify the *TWA* exposure for the n samples with the following test for noncompliance.

- If $LCL > PPL$, classify as Noncompliance Exposure.
- If $(TWA/STD) > PPL$ and $LCL \leq PPL$, classify as Possible Overexposure.
- If $(TWA/STD) \leq PPL$, no statistical test for noncompliance would be used.

Since 1.10 is less than 1.25, no statistical test for noncompliance would be used because there is no possibility of statistically demonstrating noncompliance under the previous assumptions.

4.2.3 Grab Samples Measurement, Small Sample Size (less than 30 samples during period appropriate to standard)

Refer to sections 3.3.4 and 3.4 for the definition and application of this measurement strategy. The statistical theory for the material in this section is contained in Bar-Shalom et al. (4-3).

b) Since 0.78 is less than 1, the employer would classify this *TWA* exposure as Compliance Exposure at the 95% or greater confidence level.

PROCEDURE

(1) Collect data.

The available contaminant data consist of less than 30 exposure grab samples $X_1, \ldots, X_n$ (sample concentrations for the short sampling periods).

Technical Remark: One should not attempt to decide the 8-hour average contaminant level based upon short samples from only a small portion (e.g., last 2 hours) of the 8-hour work day. The sampled periods should have been chosen as a random and unbiased sample from the entire period of the standard as detailed in section 3.4.4.

NOTE: THIS PROCEDURE CANNOT HANDLE ZERO DATA VALUES. Refer to Technical Appendix I, Lognormal Probability Plots of Exposure Measurement Data and Exposure Averages, for a discussion of this problem.

(2) Standardize the sample concentrations and compute the logarithm of each standardized value.

a) Calculate the standardized concentrations using the applicable Federal standard (29 CFR Part 1910 Subpart Z).

Let the Federal standard for the contaminant being investigated be denoted by STD. Compute the following quantities:

$$x_1 = \frac{X_1}{\text{STD}},\ x_2 = \frac{X_2}{\text{STD}},\ \ldots,\ x_n = \frac{X_n}{\text{STD}}$$

That is, divide each of the sample concentrations by the standard. The new $x_1, x_2, \ldots, x_n$ are called the standardized concentrations.

b) Compute the common (base 10) logarithms for each standardized concentration. The logarithms of the standardized concentrations are denoted by $y_1, y_2, \ldots, y_n$. Therefore:

$$y_1 = \log x_1,\ y_2 = \log x_2, \ldots, y_n = \log x_n.$$

EXAMPLE

(1) A personal pump (25 cc/min) and 8 charcoal tubes were used to monitor an employee's exposure to ethyl alcohol. Each tube was exposed for 20 minutes. The 8-hour TWA *STD* is 1000 ppm. Appendix D gives a CV_T of 0.06 for this method. The following results were reported.

$X_1 = 1225$ ppm
$X_2 = 800$ ppm
$X_3 = 1120$ ppm
$X_4 = 1460$ ppm
$X_5 = 975$ ppm
$X_6 = 980$ ppm
$X_7 = 525$ ppm
$X_8 = 1290$ ppm

(2)

Data (ppm) X_i	*Standardized concentrations* x_i	$y_i = \log_{10}(x_i)$
1225	1.225	0.0881
800	0.800	−0.0969
1120	1.120	0.0492
1460	1.460	0.1644
975	0.975	−0.0110
980	0.980	−0.0088
525	0.525	−0.2798
1290	1.290	0.1106

(3) Compute the Classification Variables ($\bar{y}$, s, n).

Obtain the arithmetic mean of logarithm values, denoted by $\bar{y}$, and the standard deviation of the logarithms, denoted by s. Then $\bar{y}$, s, and n are the classification variables. These variables will be used in classifying the exposure average.

These can be conveniently computed using a preprogrammed calculator, or the following equations can be used. The formula for $\bar{y}$ is

$$\bar{y}=\frac{1}{n}(y_1+y_2+\ldots+y_n)$$

The formula for s is

$$s=\sqrt{\frac{1}{n\text{-}1}([y_1-\bar{y}]^2+[y_2-\bar{y}]^2+\ldots+[y_n-\bar{y}]^2)}$$

Or, in a simpler form, s is

$$s=\sqrt{\frac{1}{n\text{-}1}(y_1^2+y_2^2+\ldots+y_n^2-n\bar{y}^2)}$$

(3) $\bar{y}=0.002$
$s=0.140$
$n=8$

(4) Plot a point whose coordinates are $\bar{y}$ and s on the classification chart.

a) The $\bar{y}$ classification variable appears on the vertical axis.

b) The s classification variable appears on the horizontal axis.

c) A set of curves form the boundaries of the classification regions. Each of these boundaries is a function of the number of observations denoted by n. Values of n from 3 to 25 are provided.

(4) To use the classification chart, proceed as follows:

- Plot a point defined by the classification variables $\bar{y}$ and s on Figure 4.3.
- If the classification point lies on or above the upper curve corresponding to the number of measurements n, then classify as Noncompliance Exposure.
- If the classification point lies below the lower curve corresponding to the number of measurements n, then classify as Compliance Exposure.
- If the classification point is between two curves, then classify as Possible Overexposure.
- If the value of s is greater than 0.5, one or more of the concentration measurements is relatively distant from the main body of the sample distribution. Additional exposure measurements should be obtained for this employee.

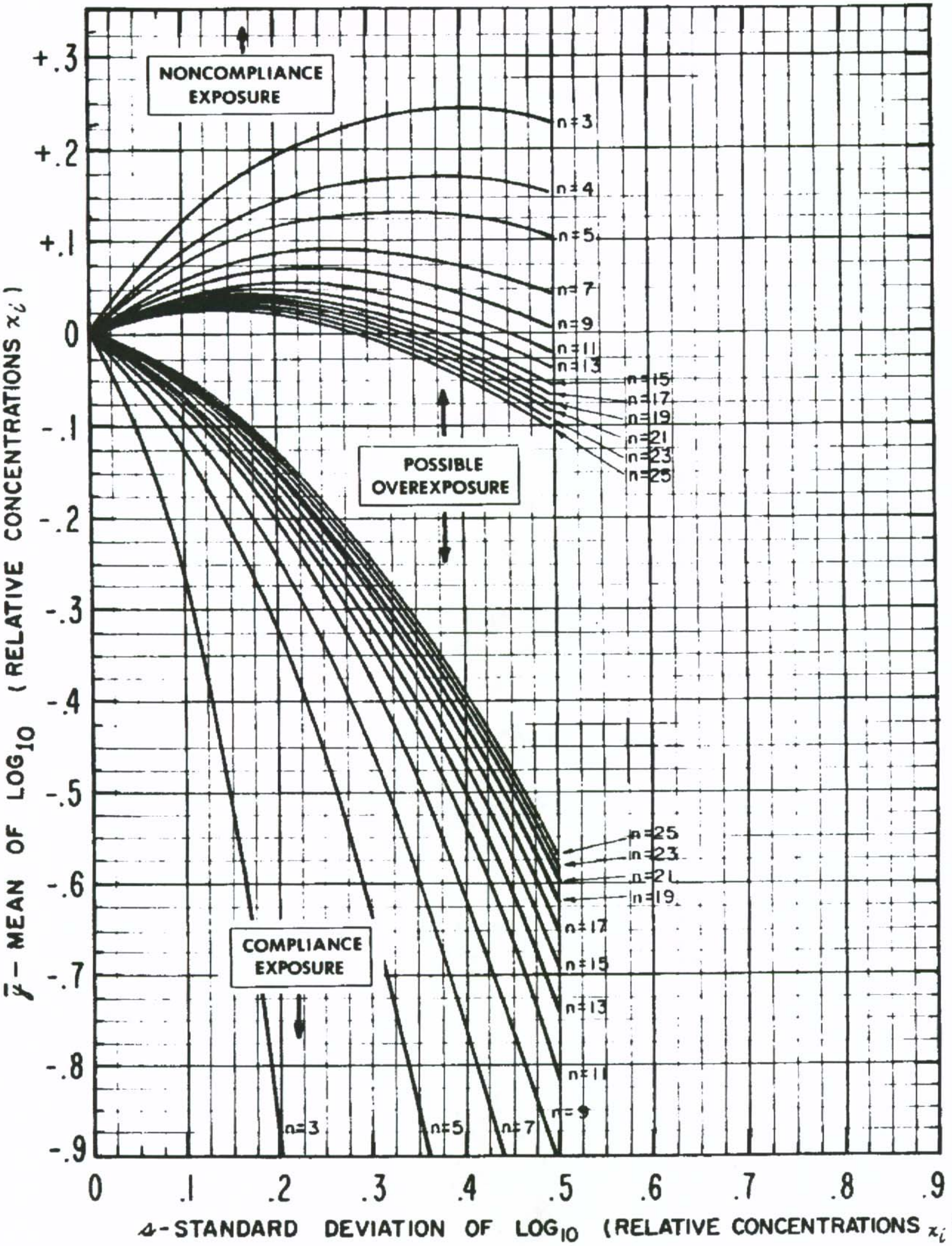

Figure 4.3. Grab sample measurement average classification chart.

In this case, the plotted point is shown on Figure 4.4 between the $n=8$ curve in the upper family and the $n=8$ curve in the lower family. Thus, the exposure is classified as Possible Overexposure.

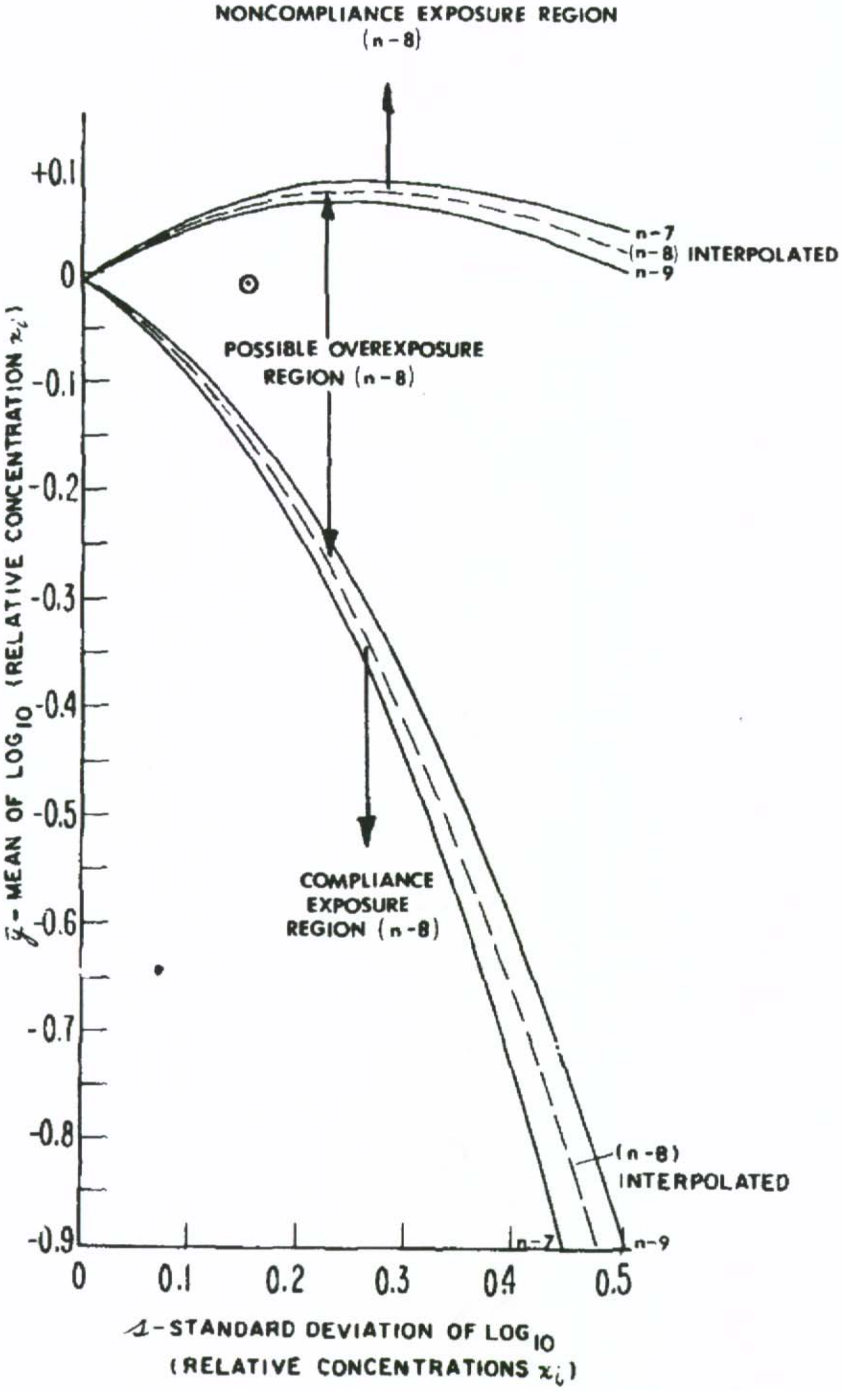

Figure 4.4. Grab sample classification chart for example of section 4.2.3.

(5) Compute the best estimate of the average exposure ($\overline{X}^*$).

The classification variables $\bar{y}$ and s are also used to obtain the best estimate of the average exposure ($\overline{X}^*$). The best estimate of the average exposure is obtained using the estimation graph presented in Figure 4.5. This estimation graph contains the following:

a) a vertical axis for the $\bar{y}$ classification variable,
b) a horizontal axis for the s classification variable, and

c) a set of curves for reading the best estimate of the standardized average exposure (exposure divided by the standard) denoted by $\overline{X}^*/\mathrm{STD}$.

If the values of $\bar{y}$ or s are outside the range of the measurements, the formula

$$\frac{\overline{X}^*}{\mathrm{STD}} = \frac{1}{n}(x_1 + x_2 + \dots + x_n)$$

is to be used to estimate the standardized average exposure.

(5) The procedure for using Figure 4.5 is as follows:

- Plot the variables $\bar{y}$ and s, with $\bar{y}$ on the vertical axis and s on the horizontal axis.
- Follow the graph curve nearest to the plotted point to the $\overline{X}^*/\mathrm{STD}$ axis on the right-hand side of the graph.
- Interpolate between two values of $\overline{X}^*/\mathrm{STD}$ to obtain the appropriate $\overline{X}^*/\mathrm{STD}$. If the value of $\overline{X}^*/\mathrm{STD}$ is multiplied by STD, then the best estimate of the average exposure ($\overline{X}^*$) will be obtained.

In this example, the plotted point (shown on graph) indicates

$$\overline{X}^*/STD = 1.05$$
$$\overline{X}^* = (1.05)\,(1000\text{ ppm}) = 1050\text{ ppm}$$

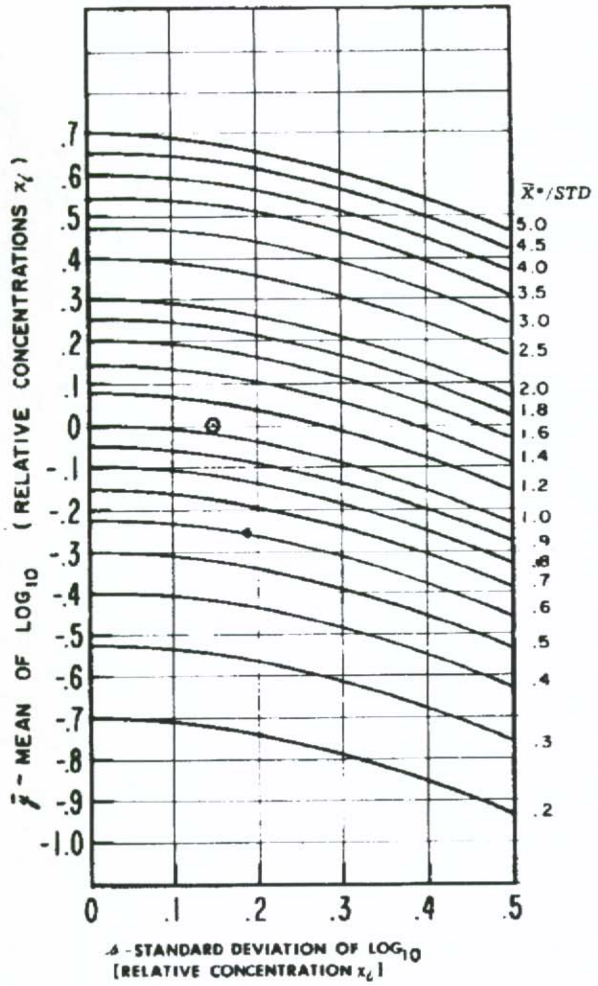

Figure 4.5. Estimation graph for $\overline{X}^*/STD$.

4.2.4 Grab Samples Measurement, Large Sample Size (greater than 30 samples during the period appropriate to standard)

Refer to sections 3.3.4 and 3.4 for the definition and application of this measurement strategy. Usually one collects far fewer than 30 samples during an 8-hour (TWA standard) or 15-minute (ceiling standard) period because of the cost of each sample (as with colorimetric detector tubes) and limited availability of personnel to take the samples. However, if one has a direct reading instrument available (especially with an attached strip chart recorder) for the contaminant of interest, then it is very feasible to obtain more than 30 samples during the period appropriate to the standard. This is preferable to the small sample size (less than 30) analysis of the previous section (4.2.3) since for larger sample sizes the confidence limits about the exposure average are tighter than for small sample sizes. Additionally, for sample sizes larger than about 30, the distribution of the measured exposure average is better described by the normal distribution. Thus, one does not have to calculate the logarithms of the sample values (as in section 4.2.3) and the tests for compliance and noncompliance are simplified. However, most direct reading instruments are not suitable for personal samples and can be used only for general air samples. Refer to Technical Appendix C, The Inadequacy of General Air (Area) Monitoring for Measuring Employee Exposures.

PROCEDURE

(1) Collect data.

The available contaminant data consist of more than 30 exposure grab samples $X_1, \ldots, X_n$ (sample concentrations for each short sampling period randomly selected over the total period appropriate to the standard). NOTE: This procedure is able to handle zero data values.

(2) Standardize the sample values as shown in part 2(a) of the previous section (4.2.3). These are denoted by $x_1, \ldots, x_n$.

(3) Compute the arithmetic mean and standard deviation of the standardized sample values. Use either a preprogrammed calculator (with $\bar{x}$ and s buttons) or use the computational formulas of part 3 of the previous section (4.2.3).

EXAMPLE

(1) A direct reading ozone meter with strip chart recorder was used to monitor a stationary employee's exposure to ozone. The 8-hour TWA *STD* is 0.1 ppm. The following 35 values were read off the strip chart record of an 8-hour period for 35 randomly selected times during the period (all values in ppm).

0.084	0.062	0.127	0.057	0.101	0.072	0.077
0.145	0.084	0.101	0.105	0.125	0.076	0.043
0.079	0.078	0.067	0.073	0.069	0.084	0.061
0.066	0.085	0.080	0.071	0.103	0.075	0.070
0.048	0.092	0.066	0.109	0.110	0.057	0.107

(2)

0.84	0.62	1.27	0.57	1.01	0.72	0.77
1.45	0.84	1.01	1.05	1.25	0.76	0.43
0.79	0.78	0.67	0.73	0.69	0.84	0.61
0.66	0.85	0.80	0.71	1.03	0.75	0.70
0.48	0.92	0.66	1.09	1.10	0.57	1.07

(3) mean $= 0.831 = \bar{x}$
standard deviation $= 0.230$
$n = 35$

(4) Compute the LCL or UCL as follows:

a) Compliance officer's test for noncompliance. Compute

$$\text{LCL}\,(95\%) = \bar{x} - \frac{(1.645)\,(s)}{\sqrt{n}}$$

b) Employer's test for compliance. Compute

$$\text{UCL}\,(95\%) = \bar{x} + \frac{(1.645)\,(s)}{\sqrt{n}}$$

where
1.645 = critical standard normal deviate for 95% confidence (one-sided)

(4)

b) $\text{UCL}\ (95\%) = 0.831 + \dfrac{(1.645)\ (0.230)}{\sqrt{35}}$

$= 0.89$

(5) Classify the standardized TWA exposure average according to the classification system.

a) Compliance officer's test for noncompliance:

- If LCL $>$ 1, classify as Noncompliance Exposure.
- If $\bar{x} > 1$ and LCL $\leq$ 1, classify as Possible Overexposure.
- If $\bar{x} \leq 1$, no statistical test for noncompliance would be made.

b) Employer's test for compliance:

- If UCL $\leq$ 1, classify as Compliance Exposure.
- If UCL $>$ 1, classify as Possible Overexposure.
- If $\bar{x} > 1$, no statistical test for compliance would be made.

(5)

b) Since 0.89 is less than 1, this exposure is classified as a Compliance Exposure at the 95% confidence level.

4.3 CLASSIFICATION OF EXPOSURE FOR A CEILING STANDARD

Refer to section 3.5 for guidelines on sampling for a ceiling standard. This section (4.3) is divided into two parts:

—Classification of exposure based on measurement samples taken during periods of expected high concentration (4.3.1).

—Classification of exposure based on unsampled periods of potentially high concentrations (4.3.2).

4.3.1 Classification Based on Measurement Samples

PROCEDURE	*EXAMPLE*
(1) a) Obtain the ceiling measurements (each measurement may consist of one or more samples): $X_1, X_2, \ldots, X_n$ Obtain CV_T, the sampling/analytical coefficient of variation, as in section 4.2.1 (step 1).	(1) a) An employee is exposed to hydrogen sulfide for about 16 short periods each workshift. The ceiling standard is 20 ppm. NIOSH method S4 specifies a reagent in midget impinger sample procedure. Each sample was taken for 10 minutes at 0.2 liter per minute. Appendix D gives a CV of 0.12 for this method. Five impingers were used, and 5 samples were taken from 5 periods randomly chosen from the 16 possible. The laboratory reported: $X_1 = 12$ ppm, $X_2 = 14$ ppm, $X_3 = 13$ ppm, $X_4 = 16$ ppm, $X_5 = 15$ ppm
b) Select the largest measurement and refer to it as X.	b) $X = 16$ ppm
c) Calculate the maximum relative ceiling value $x = X/\text{CSTD}$ where CSTD is the ceiling standard.	c) $x = (16 \text{ ppm}) / (20 \text{ ppm}) = 0.80$
(2) Classify using either section 4.2.1 or 4.2.2. Use section 4.2.1 if a single 15-minute sample is the highest measurement. Use section 4.2.2 if the average of several consecutive samples (as detector tubes) comprised the highest measurement.	(2) $\text{UCL}(95\%) = 0.80 + (1.645)(0.12) = 0.997$ and since 0.997 is less than 1, classify the highest measurement as a Compliance Exposure.
(3) If the classification is Compliance Exposure, go to section 4.3.2. Otherwise, this terminates the ceiling classification procedure.	(3) Go to section 4.3.2 below.

4.3.2 Classification Based on Unsampled Periods

This optional classification procedure is used where there are unsampled periods of potentially high (ceiling) exposure. It is used to make a conservative statistical inference (from the standpoint of employee protection) regarding the unsampled periods. Refer to Technical Appendix K, Statistical Decision Theory for Ceiling Exposure Measurements, for the derivation, assumptions, and statistical methods used in this section.

PROCEDURE

(1) a) Calculate the relative ceiling measurements and their $\log s_{10}$:

$x_1 = X_1/\text{CSTD}, x_2 = X_2/\text{CSTD}, \ldots,$
$x_n = X_n/\text{CSTD}$

$y_1 = \log_{10}(x_1), \quad y_2 = \log_{10}(x_2), \ldots, y_n = \log_{10}(x_n)$

b) Then calculate the mean $\bar{y}$ of the log values $(\bar{y}_i)$ and their standard deviation (s). This is best done using a calculator. The following equations can be used if a calculator is not available.

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i = \frac{1}{n}(y_1 + y_2 + \ldots + y_n)$$

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y})^2}$$

(2) Compute probability β (β is the probability that, during an arbitrary unobserved interval, the exposure is above the standard) as follows:

Form $z = \frac{|\bar{y}|}{s}$ where $|\bar{y}|$ is the absolute value of y.

EXAMPLE

(1) a) (CSTD = 20 ppm)

X_i *Data*	x_i	$y_i = \log_{10}(x_i)$
12	0.600	−0.2218
14	0.700	−0.1549
13	0.650	−0.1871
16	0.800	−0.0969
15	0.750	−0.1249

b) $\bar{y} = -0.1571$
$s = 0.0494$
$n = 5$

(2) $z = \frac{|-0.1571|}{0.0494} = 3.18$

since $\bar{y} < 0$, $\beta = 1 - (0.9993) = 0.0007$

This means there is a 0.07% probability that any particular one of the unsampled periods will exceed the CSTD.

Use Table 4.2 and z to evaluate the value of β as follows:

If $\bar{y} < 0$, compute $\beta = 1 -$ (value in Table 4.2), but if $\bar{y} \geq 0$, then $\beta =$ value in Table 4.2.

(3) Classify the employee's exposure for the remaining unsampled intervals.

From Step 2, β is the probability that the exposure during any one unsampled interval is above the standard. Another way of stating the above is that β is the probability of "violation" of the standard. Thus $(1-\beta)$ is the probability of "compliance" with the standard for any particular unsampled period.

The probability of compliance for all of the K unsampled intervals of expected high exposures is computed from:

$$P_c = (1-\beta)^K$$

Again this is best done on a calculator, but P_c can be computed from a table of logarithms as follows:

$$\log_{10} P_c = K \log_{10}(1-\beta)$$
$$P_c = \text{antilog}_{10}(\log P_c)$$

Perhaps the number of the remaining intervals in the workshift that may be of expected high exposure is unknown. In that case, a conservative approach is to assume K equals the number of remaining intervals. For example, if five 15-minute measurements were taken during an 8-hour workshift (32 possible 15-minute intervals), it is assumed that K equals 27 $(32-5)$.

(3) $(1-\beta) = 1 - 0.0007 = 0.9993$
$K = 16 - 5 = 11$
$P_c = (0.9993)^{11} = 0.992$

Thus there is 99.2% probability that all of the 11 unsampled periods are in compliance.

The classification is performed as follows:

- If $P_c > 0.9$, classify as Compliance Exposure.
- If $P_c < 0.1$, classify as Noncompliance Exposure.
- If $0.1 \leq P_c \leq 0.9$, classify as Possible Overexposure.

Thus, this case is classified as a Compliance Exposure.

4.4 CALCULATION OF GEOMETRIC MEAN OF LONG-TERM EXPOSURE AND THE USE OF THE PROBABILITY OF NONCOMPLIANCE WHEN DECIDING WHETHER TO INSTALL ENGINEERING CONTROLS

Proposed OSHA exposure regulations require that control measures be instituted if "an employee exposure measurement reveals an employee is exposed to (substance name) above the permissible exposure." The type of controls permitted and conditions of use required are specified in each substance standard. These should always be consulted before any control is planned or implemented. There are two broad categories of controls: work practice and engineering. In the sense of this section, engineering controls are meant to be local exhaust ventilation systems or permanent engineering modifications to the operation that reduce employee exposures.

TABLE 4.2. TABLE FOR COMPUTING PERCENTAGE OF AREA IN THE TAIL OF A CUMULATIVE NORMAL DISTRIBUTION*

	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998

*Reproduced from Table A-1 of Natrella (4.4).

Since engineering controls do involve potentially large capital outlays, the employer would like to assure himself that the present employee protection is truly inadequate. That is, does the one day's exposure measurement(s) truly reflect the long-term exposure? Or was the high exposure average on the one day due to an unusual problem that occurred on that day and can the employee be protected in another way (such as through plant operating guidelines or stricter supervision of plant procedures)?

The employer should attempt to limit the probability of employee overexposure (daily exposures exceeding the permissible exposure limit) to 5%. That is, no more than 5% of an employee's true daily exposure averages should exceed the standard. The procedures of this section will calculate the long-term probability of noncompliance (P_n) for an employee based on any number of appropriate daily exposure averages. This P_n can be interpreted as an estimate of the proportion of days an employee will be overexposed if the situation at the time of the daily measurements holds constant. This condition is referred to as a stationary long-term exposure mean.

Other assumptions of this section include a model where the true daily exposure averages are lognormally distributed. The long-term geometric mean (GM) of this distribution is estimated from the measured daily exposure averages. The day-to-day variation of the true daily exposure averages is estimated by the geometric standard deviation (GSD). This model is discussed in Leidel, Busch, and Crouse (4-5). Random sampling and analytical errors that contribute to uncertainty in the calculation of any one daily exposure average contribute relatively little to the uncertainty of a long-term exposure average. That is, the dispersion of the distribution of true daily exposure averages is dominated by day-to-day environmental fluctuations. Thus, a very good estimate of the variation of the true daily exposure averages is given by the GSD of the measured daily exposure averages. (The GSD includes negligible contributions from sampling/analysis errors that are believed to be normally distributed.)

Also note that confidence levels are not involved in this section because we are not placing confidence limits on the calculated probability P_n. Neither are we testing the hypothesis that a 5% probability of overexposure was exceeded by the measured daily averages. This section is intended only as a recommended guide to assist in making a decision about installation of engineering controls; simplicity was the primary goal. Given the previous assumptions, there is approximately a 50 percent chance that the true long-term probability of noncompliance is greater than or less than the calculated P_n.

PROCEDURE

(1) Select all appropriate daily exposure averages to be used in calculating P_n. Professional judgment and knowledge of the employee exposure situation must be heavily relied upon here. Only those data representative of the current "stable" exposure situation should be used. One way of doing this is to plot the employee's measured daily exposure averages against time (days or months scale). If the averages are trending upward (or downward) then this section *should not be used* because an erroneous P_n would be calculated. Only if the long-term exposure average appears "level" should one proceed further.

EXAMPLE

(1) An employee is exposed to dioxane in a work environment. The 8-hour TWA *STD* is 100 ppm. Charcoal tubes were used to measure the employee's exposure on 10 different days over a 6-month period. The following ten 8-hour TWA exposures were obtained:

67, 51, 33, 72, 122,
75, 110, 93, 61, 190.

All daily exposure averages should then be standardized; that is, divided by the appropriate health standard. This was covered in section 4.2 and the following is a reference of the nomenclature used for each sampling strategy.

Sampling strategy	*Section*	*Daily exposure average (concentration)*	*Daily standardized exposure average*
Full period single sample	4.2.1	X	x
Full period consecutive sample	4.2.2	TWA	TWA/STD
Grab samples	4.2.3	$\overline{X}^*$	$\overline{X}^*/STD$

(2) Compute the common (base 10) logarithm for each standardized exposure average. The logarithms of the standardized exposure averages are denoted by $Y_1, Y_2, \ldots, Y_n$. The subscripts indicate a particular day in the data series.

$$Y_i = \log_{10}\ [x_i \text{ or } (TWA/STD)_i \text{ or } (\overline{X}^*/STD)_i]$$

Standardized exposure averages from different sampling strategies can be mixed.

This procedure cannot handle zero data values. Refer to Technical Appendix I, Lognormal Probability Plots of Exposure Measurement Data and Exposure Averages, for a discussion of this problem.

(2)

TWA data	*TWA/STD*	*Y_i, log values*
67	0.67	−0.1739
51	0.51	−0.2924
33	0.33	−0.4815
72	0.72	−0.1427
122	1.22	0.0864
75	0.75	−0.1249
110	1.10	0.0414
93	0.93	−0.0315
61	0.61	−0.2147
190	1.90	0.2788

(3) Compute the arithmetic mean of the logarithm values ($\overline{Y}_i$), denoted by $\overline{Y}$, and the standard deviation of the logarithms, denoted by S. These are best computed on a calculator, but the computational equations of section 4.2.3 (step 3) can be used.

(3) $\overline{Y} = -0.1055$
$S = 0.212$
$n = 10$

(4) The long-term exposure GM is given by:

$$GM = [\text{antilog}_{10}\ (\overline{Y})]\ (STD)$$

and the day-to-day variation of the daily exposure average is given by the GSD:

$$GSD = \text{antilog}_{10}\,(S)$$

(4) GM = (0.7843) (100) = 78.4 ppm
GSD = 1.63

(5) The probability of noncompliance (P_n) is calculated from $\overline{Y}$ and S as follows:

Compute $z = \frac{|\overline{Y}|}{S}$ where $|\overline{Y}|$ is the absolute value of $\overline{Y}$.

Then use Table 4.2 to evaluate P_n by:
if $\overline{Y} < 0$, compute $P_n = 1 -$ (value in Table 4.2),

if $\overline{Y} \geqq 0$, then $P_n =$ value in Table 4.2
This is done the same as is step 2 in section 4.3.2.

(6) If P_n exceeds 0.05, a strong indication exists that engineering controls should be installed.

(5) $z = \frac{|-0.1055|}{0.212} = 0.498$

since $\overline{Y} < 0$, $P_n = 1 - (0.691) = 0.309$.

This can be interpreted as a 30.9% probability of noncompliance for this employee over the 6-month period. Also we can say that we could expect about 31% of the daily TWA's to be in noncompliance during this period.

(6) Controls should be implemented to lower this exposure situation.

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TECHNICAL APPENDIX A*

CALCULATION OF SAMPLE SIZE FOR A MAXIMUM RISK SUBGROUP FROM A HOMOGENEOUS HIGH RISK GROUP

In some cases it may not be possible to select the *maximum risk worker* from a group of workers with a similar exposure risk. That is, the industrial hygiene considerations of Chapter 2 fail to yield an individual whose exposure is likely to be higher than other employees. This could occur where many employees are involved in work operations with identical exposure potential or the air in the workroom is well mixed, or both. The material in this Appendix was developed to provide guidelines for an adequate sample size for this homogeneous high risk group. This Appendix describes a sampling procedure that can be used by an employer in order to minimize the sampling burden while obtaining a high probability of sampling a *high risk employee*. The number of workers in such a homogeneous risk group is denoted by N, and a random sample of a subgroup $n < N$ is to be taken.

The criterion will be that a high probability will exist that at least one worker from a subgroup with highest exposures should be in this sample. If *highest exposures* is defined as the *top 10%* of all exposures in the parent group, then the sample will have to include (with high probability $[1-\alpha]$) one worker out of a given subgroup of size $N_0 = \tau N$ where τ is the proportion of the group included as the *high exposures*, $0 < \tau < 1$. In the *top 10%* case, $\tau = 0.1$. The allowed probability of missing all N_0 workers with highest exposure in the sample of n out of N is α.

The expression of the probability of missing all workers from a subgroup of size N_0 from a group of N when sampling n is

$$P_0 = \frac{(N - N_0)!}{(N - N_0 - n)!} \; \frac{(N - n)!}{N!} \qquad \text{(A-1)}$$

This expression follows from calculations found in the theory of sampling without replacement treated in reference A-1. Note that

$$P_0 = P_0\ (N, \tau, n) \qquad \text{(A-2)}$$

and, to obtain the sample size, the following equation has to be solved

$$P_0\ (N, \tau, n) = \alpha \qquad \text{(A-3)}$$

for the sample size n, given N (the size of the parent group under consideration), τ (the desired high exposure subgroup percentage), and α (the allowed probability of missing all of the workers in the top exposure group).

The solution, rounded off to the nearest integer, is presented in Tables A-1–A-4, for the following ranges of values:

—Group size $N = 1, \ldots, 50$
—Top 10% and 20% fractions, i.e.,
$\tau = 0.1, 0.2$
—Confidence levels of 90% and 95%, i.e.,
$\alpha = 0.1$ and 0.05.

(When $n << N$, the above exact solution is approached by the solution for sampling with replacement.) The procedure in this case is to guarantee with confidence $1 - \alpha$ that, in n trials, the event whose probability of occurring in one trial is τ will not occur. The probability of such an event not occurring in n trials is

$$(1 - \tau)^n = \alpha \qquad \text{(A-4)}$$

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*The material in this Appendix was developed by Systems Control, Inc., and originally appeared in SCI Report #5119-1, pp. 7-12 (May 1975) produced under NIOSH Contract #CDC-99-74-75.

and

$$n = \frac{\log \alpha}{\log (1 - \tau)} \qquad \text{(A-5)}$$

For example,

$$n(\tau = 0.1, \alpha = 0.1 = \frac{\log 0.1}{\log 0.9} = \frac{-1.0}{-0.0458} = 21.9 \text{ or } 22$$

and this is the limit towards which n tends in Table A-1 as $N \longrightarrow \infty$.

Note that even for $N=50$, the value of n from Table A-1 is still far from the above limit and, thus, it is advantageous to use the sampling without replacement approach as in equation (A-3).

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TABLE A-1. SAMPLE SIZE FOR TOP 10% ($\tau=0.1$) AND CONFIDENCE 0.90 ($\alpha=0.1$) (USE n=N if N ≦ 7)

Size of group (N)	8	9	10	11-12	13-14	15-17	18-20	21-24	25-29	30-37	38-49	50	∞
Required No. of measured employees (n)	7	8	9	10	11	12	13	14	15	16	17	18	22

TABLE A-2. SAMPLE SIZE FOR TOP 10% ($\tau=0.1$) AND CONFIDENCE 0.95 ($\alpha=0.05$) (USE n=N if N ≦ 11)

Size of group (N)	12	13-14	15-16	17-18	19-21	22-24	25-27	28-31	32-35	36-41	42-50	∞
Required No. of measured employees (n)	11	12	13	14	15	16	17	18	19	20	21	29

TABLE A-3. SAMPLE SIZE FOR TOP 20% ($\tau=0.2$) AND CONFIDENCE 0.90 ($\alpha=0.1$) (USE n=N if N ≦ 5)

Size of group (N)	6	7-9	10-14	15-26	27-50	51-∞
Required No. of measured employees (n)	5	6	7	8	9	11

TABLE A-4. SAMPLE SIZE FOR TOP 20% ($\tau=0.2$) AND CONFIDENCE 0.95 ($\alpha=0.05$) (USE n=N if N ≦ 6)

Size of group (N)	7-8	9-11	12-14	15-18	19-26	27-43	44-50	51-∞
Required No. of measured employees (n)	6	7	8	9	10	11	12	14

TECHNICAL APPENDIX B

EXPOSURE VARIATION IN OCCUPATIONAL GROUPS OF SIMILAR EXPECTED EXPOSURE RISK

In the past it has been accepted industrial hygiene practice to estimate the exposures of a group of workers with similar exposure risk by sampling only a few workers in the group. The measured exposures would be averaged, and this average group exposure was assumed for all employees in the exposure risk group. However, this procedure was an undesirable compromise because there were limited numbers of industrial hygienists and few resources available to measure the exposure of each employee. Also, it was assumed that the variation of exposure averages within a group of similar expected exposure risk would be small, with only small differences between the group average and the low and high exposures in the group.

Ayer and Burg (B-1) made a valuable contribution to industrial hygiene by demonstrating the inaccuracies introduced by the above procedure. Their paper discussed the difference between the maximum 8-hour personal sample that might be obtained on an individual worker and the time-weighted average exposure for a group of workers. Unfortunately, their paper went largely unnoticed. Their work was important because of a requirement established by the Occupational Safety and Health Act of 1970 (B-2). Section 6 (b) 7 of the Act requires the Department of Labor to promulgate standards that ". . . shall provide for monitoring or measuring employee exposure at such locations and intervals and in such manner as may be necessary for the protection of employees."

Ayer and Burg (B-1) recognized that the distribution of sample results from a given operation is generally lognormal. This distribution and its application to occupational exposure measurements has also been discussed by Leidel and Busch (B-3) and Leidel, Busch, and Crouse (B-4). Recognizing the lognormal distribution of individual exposure averages in a group has important implications. The exposure averages (for groups with typical geometric standard deviations [*GSD*]) cover a wide range of values, often an order of magnitude. The ratio of a high exposure, such as that of the 95th-percentile employee (that employee whose exposure average exceeds 95% of all others in the group) to the group arithmetic average exposure can typically be 2 or 3 to 1. That is, the 95th-percentile employee exposure can easily be 200% to 300% of the group average.

In Figure B-1, the distribution of employee exposures within a group for different amounts of exposure variation is graphically shown. The relation between the true arithmetic average exposure μ and the *GSD* is given by

$$\mu = GM \exp\left[\tfrac{1}{2}\,(\ln GSD)^2\right]$$

where

μ = true arithmetic average exposure of the group

GM = true geometric mean exposure of group (= 50th percentile employee exposure)

GSD = true geometric standard deviation of group exposure distribution

This relation was used to prepare Figure B-1 and Table B-1. In all cases, the true group arithmetic exposure average is fixed at 100 ppm.

Ayer and Burg (B-1) and Leidel et al. (B-4) present tables showing that group *GSD*'s commonly occur in the range 1.5 to 2.5. Table B-1 shows that if the group exposure average was assigned to all employees in the group, the exposure of at least 5% of the employees would be recorded at 56% to 34% (or less) of their true values (for *GSD*'s of 1.5 to 2.5).

TABLE B-1. HIGHER LEVEL EXPOSURES IN A LOGNORMAL DISTRIBUTION

GSD	GM, ppm	90th percentile exposure, ppm	95th percentile exposure, ppm	Ratio 95th/group average	Group avg. as % of 95th percentile
1.1	99.5	112	116	1.16	86%
1.3	97	135	149	1.49	67%
1.5	92	155	179	1.79	56%
1.75	86	175	215	2.15	47%
2.0	79	191	246	2.46	41%
2.5	66	213	297	2.97	34%

Under most situations, it is incorrect to assign the group average exposure to all employees because the group average can significantly underestimate high exposures. Only when the group *GSD* is very low (about 1.15 or less) could the group average be assigned to all employees with less than about 20% error introduced. However, it takes large sample sizes to determine the group *GSD*, and in the vast majority of occupational groups, the *GSD* would exceed 1.15 anyway.

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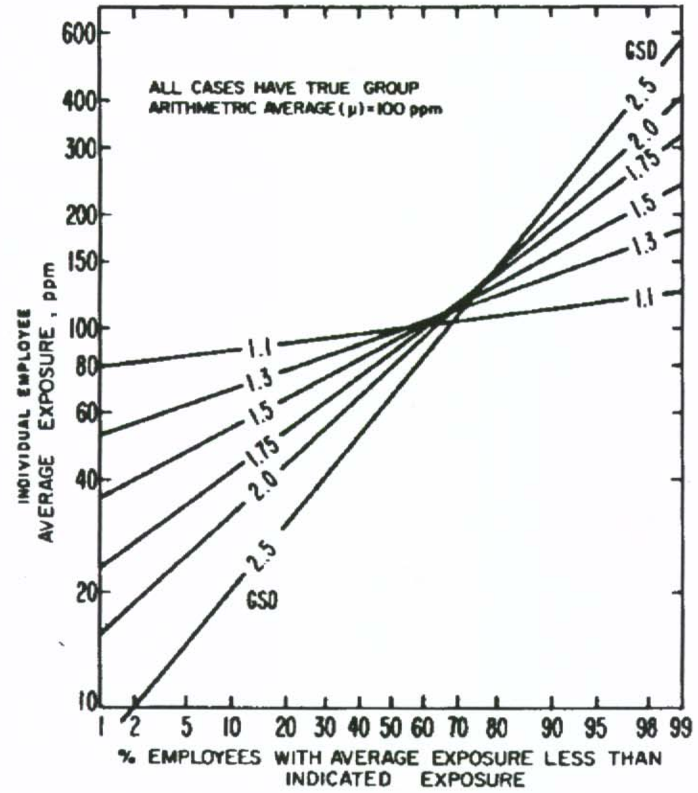

Figure B-1. Lognormal exposure distribution for an occupational group of similar expected exposure. Lines are for differing geometric standard deviations.

TECHNICAL APPENDIX C

THE INADEQUACY OF GENERAL AIR (AREA) MONITORING FOR MEASURING EMPLOYEE EXPOSURES

There are three basic types of occupational environment sample collection techniques:

- Personal — The sampling device is directly attached to the employee and worn continuously during all work and rest operations.
- Breathing Zone — The sampling device is held by a second individual who attempts to sample the air in the "breathing zone" of the employee. The "breathing zone" is that air that would most nearly represent the air inhaled by the employee.
- General Air — The sampler is placed in a fixed location in the work area (this is also referred to as environmental monitoring, area monitoring, static sampling, fixed sampling, and fixed-station monitoring).

Breslin et al. (C-1) is often quoted as "proof" that general air samples yield highly accurate measurements of average daily employee exposure. Breslin, however, shows that the average daily exposures were calculated from a combination of breathing zone and general air samples combined with time-and-motion studies. In addition he states, "The foregoing measurements of average exposure represent the very best accuracy the study team could achieve and were based on far more samples than are collected on a routine survey." Finally, the authors showed (Figure 4 of the article) the approximately 40-fold range the calculated exposure values covered.

Other authors have discussed the problems of general air or static samplers. Sherwood (C-2) concluded that "static samplers may grossly misrepresent the exposure of individual workers who are likely to be exposed to airborne activity of their own making." Sherwood (C-3) has also shown the very wide variation (typically 100-fold) of air concentrations employees are exposed to at particular work operations. These data contradict the assumption that air concentrations can be expected to be the same everywhere at the work operation. Ayer and Burg (C-4) also present data showing the extreme variation in sampling data. Shulte (C-5) observed a median ratio of four to one (C-4) between personal samplers and fixed (general air) samplers in a uranium graphite processing operation.

Tebbens (C-6) has pointed out that the Act declares as congressional policy the intent "to assure so far as possible every working man and woman in the nation safe and healthful working conditions," and thus the attention in exposure sampling is refocused from groups to individual workers. This concern for individuals appears in the Federal Coal Mine Health and Safety Act of 1969 (C-7) and the MESA Dust Sampling Requirements (C-8). Compliance with dust standards is determined almost exclusively by personal monitoring. Tebbens (C-6) also states, "It is the recognition of the probability of large temporal and spatial measurement errors which had led slowly to the concept of personal sampling or dosimetry, attaching the sensing element of a sampler to the worker himself — he carries it about continuously, often during an entire workday."

Linch and co-workers have compared fixed-station (area) monitors to personal samplers in sampling for tetraalkyl lead (C-9) and carbon monoxide (C-10). In neither case did they find correlation between the area and personal monitors. Regarding the tetraalkyl lead exposures, Linch et al. (C-9) wrote:

> ". . . [the conclusion] that the fixed-station monitors may not disclose the true inhaled

> air concentrations of lead in a highly variable ambient work atmosphere appeared to be sufficiently valid to justify the establishment of an extensive personnel monitoring survey."
>
> ". . . fixed-station air monitoring does not provide valid results required for organic lead exposure control based on air analysis."
>
> ". . . in those cases where air analysis is required for exposure control, personnel monitoring is the preferred procedure for the collection of the sample."

For the carbon monoxide study of exposure in a large warehouse, in which gasoline-powered trucks were operated, Linch and Pfaff (C-10) concluded that "only by personal monitoring could a true exposure be determined."

A study by Baretta et al. (C-11) concluded that continuous air sampling at fixed locations is valid for estimating an employee's individual daily exposure to vinyl chloride. The study featured multipoint air sampling, analysis using an IR spectrophotometer, and data subsequently analyzed by computer. As was stated in the Breslin et al. article (C-1), this study demonstrated that area samplers provide an inadequate estimate of an employee's exposure. First, a comprehensive job study was required for each of four job classifications to determine the work areas frequented by the workmen and the time they spent in each area. No data were given regarding the variation for individual workers for these time and motion studies or confidence intervals for percent of time spent at each work location. Second, a computer was required for analysis of the vast amount of data and calculation of exposure estimates. Third, no confidence estimates were given for the TWA exposures calculated from the continuous monitoring combined with the comprehensive job study. Fourth, the authors state:

> "Continuous monitoring, however, is extremely costly both in time and in the equipment required. The scope of data acquired is limited by the number of sampling probes, and these probes are not alway accurately measuring the individual's daily exposure experiences, especially should these involve unusual incidences such as chemical spills or exposures outside the monitored area."

Lastly, a recent NIOSH report (C-12) gives the results of a statistical analysis of a 1973 study in the beryllium industry. The study compared the airborne beryllium exposure estimates obtained with three different sampling techniques: the Atomic Energy Commission (AEC) sampling method, personal total dust, and personal respirable dust. The AEC method uses the results of general area samples (15 to 60 minutes duration) and breathing zone samples (2 to 10 minutes duration) along with a time and motion study of the worker's job to calculate his daily weighted average for a 3-month period. The personal sampling methods differed from the AEC method in that the sampler used was worn by the workers during the work shift. The NIOSH report (C-12) states that no reliable conversion was found to exist between results obtained from the three methods on a single sample basis. However, it appeared that for large numbers of samples taken under the same sampling conditions, when the concentration is 2 μgBe/m^3 by the AEC method, the value by the personal total sample will be about 3 μgBe/m^3. Thus, the personal sample yielded a value about 50% higher than the general air AEC method on the average.

Therefore, the intent of NIOSH recommendations concerning the proposed OSHA health regulations is that measurements of employee exposure should normally only be based on sampling by the personal or breathing zone methods. It should be necessary to demonstrate that samples taken by the general air method measure employee exposure as accurately as those obtained by the personal or breathing zone methods.

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TECHNICAL APPENDIX D

COEFFICIENTS OF VARIATION AND ACCURACY REQUIREMENTS FOR INDUSTRIAL HYGIENE SAMPLING AND ANALYTICAL METHODS

The relative variation of a normal distribution (such as the randomly distributed errors occurring in industrial hygiene sampling and analytical procedures) is commonly described by the *coefficient of variation* (*CV*). The *CV* is also known as the *relative standard deviation* (*RSD*). The *CV* is a useful index of dispersion in that limits computed from the true mean of a set of data plus or minus twice the *CV* will contain about 95% of the data measurements. Thus, if an analytical procedure with a *CV* of 10% is used to repeatedly measure some constant physical property (such as the concentration of a chemical in a beaker of solution), then about 95% of the measurements will fall within plus or minus 20% (2 times the *CV*) of the true concentration.

The accuracy required of airborne concentration measurements in the proposed OSHA health standards takes into account (1) random variations in the sampling device (repeatability of the sampling device), (2) random variations in the analytical procedure (repeatability of the replicate analyses of a given sample), (3) systematic errors in the sampling method (determinate errors or bias in the collection technique), and (4) systematic errors in the analytical procedure (determinate error or bias in the analysis).

The term *accuracy* in the proposed OSHA health standards and in this Manual refers to the difference between a measured concentration and the true concentration of the sample. Thus, it includes both the random variation of the method about its own mean (commonly referred to as precision) and the difference between the average result from the method and the true value (commonly referred to as the bias of the method). The term accuracy does not refer to the difference between a measured concentration and the true employee exposure. There are additional considerations that affect the difference between a measured airborne concentration and the true employee exposure. These include sampler location in relation to the breathing zone of the employee and sampling strategy of exposure measurement — both numbers of samples and duration. (Refer to Chapter 3.)

The proposed OSHA health standards state that the accuracy of a method shall have a *confidence level of 95%*. This means that 95% of the measurements must be as accurate as the standard requires. If one assumes the method is unbiased and errors are normally distributed, the *CV* (or relative standard deviation) can be used to judge if the method has the required accuracy. The *CV* in percentage units is defined as the standard deviation of the method, times 100, divided by the true value. The required *total coefficient of variation* (CV_T) of the sampling and analytical method is obtained by dividing the required accuracy by 1.96 (statistical standard normal deviate for 95% two-sided confidence limits, also referred to as *z*-value). Typical required CV_T's would be:

Concentration	*Required accuracy (plus or minus)*	*Required CV_T*
Above permissible exposure	25%	$< 12.8\%$
At or below the permissible exposure and above the action level	35%	$< 17.9\%$
At or below the action level	50%	$< 25.5\%$

The statistical decision techniques in Chapter 4 utilize CV_T. Table D-1 lists some CV_T's for specific NIOSH sampling and analytical procedures. If a specific method is not listed for

TABLE D-1. TOTAL COEFFICIENTS OF VARIATION FOR SOME SPECIFIC NIOSH SAMPLING/ANALYTICAL PROCEDURES

Air contaminant	CV_T	NIOSH method number
Acetic anhydride	0.06	S170
Acetone	0.08	S1
Acetonitrile	0.07	S165
Acetylene tetrabromide	0.10	S117
Acrylonitrile	0.07	S156
Allyl alcohol	0.11	S52
Allyl chloride	0.07	S116
Alpha-methyl styrene	0.05	S26
n-Amyl acetate	0.05	S51
sec-Amyl acetate	0.07	S31
Antimony and compounds (as Sb)	0.09	S2
Arsenic and compounds (as As)	0.06	S309
Arsine	0.06	S229
Asbestos	0.24-0.38	P&CAM239
Barium, soluble compounds	0.05	S198
Benzyl chloride	0.10	S115
Beryllium and beryllium compounds (as Be)	0.06	S339
Butadiene	0.06	S91
2-Butanone	0.07	S3
2-Butoxyethanol	0.06	S76
Butyl acetate	0.07	S47
sec-Butyl acetate	0.05	S46
tert-Butyl acetate	0.09	S32
Butyl alcohol	0.07	S66
sec-Butyl alcohol	0.07	S53
tert-Butyl alcohol	0.08	S63
n-Butyl glycidyl ether	0.07	S81
p-tert-Butyltoluene	0.07	S22
Calcium oxide	0.06	S205
Camphor	0.07	S10
Carbaryl (Sevin)	0.06	S273
Carbon tetrachloride	0.09	S314
Chlorinated camphene	0.08	S67
Chlorobenzene	0.06	S133
Chlorobromomethane	0.06	S113
Chlorodiphenyl (54% chlorine)	0.06	S121
Chloroform	0.06	S351
Chromic acid and chromates	0.08	S317
Chromium, metal, and insoluble compounds	0.08	S352
Chromium, soluble chromic, and chromous salts (as Cr)	0.08	S323
Copper dusts and mists	0.05	S186
Cresol (all isomers)	0.07	S167
Cumene	0.06	S23
Cyanide (as Cn)	0.10	S250
Cyclohexane	0.07	S28
Cyclohexanol	0.08	S54
Cyclohexanone	0.06	S19
Cyclohexene	0.07	S82
Diacetone alcohol	0.10	S55
Diazomethane	0.08	S137
Dibutyl phthalate	0.05	S33
o-Dichlorobenzene	0.07	S135
p-Dichlorobenzene	0.05	S281
1, 1-Dichloroethane	0.06	S123
1, 2-Dichloroethylene	0.05	S110
1, 1-Dichloro-1-nitroethane	0.05	S213
Diethylamine	0.07	S139
Di-2-ethylhexylphthalate	0.06	S40
Difluorodibromomethane	0.09	S107
Diisobutyl ketone	0.07	S358
Dimethyl acetamide	0.07	S254
Dimethylamine	0.06	S142
Dimethylaniline	0.05	S164
Dimethyl formamide	0.06	S255
Dioxane	0.05	S360
Dipropylene glycol methyl ether	0.06	S69
di-sec-Octyl phthalate (see di-2-ethylhexylphthalate)		
Epichlorohydrin	0.06	S118
2-Ethoxyethylacetate	0.06	S41
Ethyl acetate	0.06	S49
Ethyl acrylate	0.05	S35
Ethyl alcohol	0.06	S56
Ethyl benzene	0.04	S29
Ethyl bromide	0.05	S106
Ethyl butyl ketone	0.09	S16
Ethyl ether	0.05	S80
Ethyl formate	0.08	S36
Ethyl sec-amyl ketone (see 5-methyl-3-heptanone)		
Ethyl silicate	0.06	S264
Ethylamine	0.11	S144
Ethylene chlorohydrin	0.08	S103
Ethylene dichloride (1, 2-dichloroethane)	0.08	S122
Ethylene glycol dinitrate and/or nitroglycerin	0.10	S216
Ethylene oxide	0.10	S286
N-ethylmorpholine	0.10	S146
Glycidol	0.08	S70
Heptane	0.06	S89
Hexachloronaphthalene	0.06	S100
Hexane	0.06	S90
2-Hexanone	0.05	S178
Hexone (methyl isobutyl ketone)	0.06	S18
Hydrazine	0.09	S237
Hydrogen bromide	0.07	S175
Hydrogen chloride	0.06	S246
Hydrogen fluoride (HF)	0.06	S176
Hydrogen sulfide (aqueous)	0.12	S4
Isoamyl acetate	0.06	S45
Isoamyl alcohol	0.08	S58
Isobutyl acetate	0.07	S44
Isobutyl alcohol	0.07	S64
Isophorone	0.06	S367
Isopropyl acetate	0.07	S50
Isopropyl alcohol	0.06	S65
Isopropylamine	0.07	S147
Isopropyl glycidyl ether	0.07	S77
Ketene	0.06	S92
Lead and inorganic lead compounds	0.07	S341
LPG (liquefied petroleum gas)	0.05	S93
Magnesium oxide fume	0.06	S369
Manganese and compounds (as Mn)	0.06	S5
Mesityl oxide	0.07	S12
Methyl acetate	0.06	S42
Methyl acrylate	0.07	S38
Methyl alcohol	0.06	S59
Methyl (n-amyl) ketone	0.07	S1
Methyl "Cellosolve"	0.07	S79
Methyl "Cellosolve" acetate	0.07	S39
Methyl chloroform (1, 1, 1-trichloroethane)	0.05	S328
Methyl cyclohexane	0.05	S94
5-Methyl-3-heptanone	0.10	S13

TABLE D-1. TOTAL COEFFICIENTS OF VARIATION FOR SOME SPECIFIC NIOSH SAMPLING/ANALYTICAL PROCEDURES (cont.)

Air contaminant	CV_T	NIOSH method number
Methyl iodide	0.07	S98
Methyl isoamyl acetate	0.06	S37
Methyl isobutyl carbinol	0.08	S60
Methyl isobutyl ketone (see Hexone)		
Methyl methacrylate	0.13	S43
Methylal (dimethoxymethane)	0.06	S71
alpha-Methylstyrene	0.05	S26
Molybdenum, soluble compounds	0.09	S193
Monomethyl aniline (N-methylaniline)	0.09	S153
Morpholine	0.06	S150
Naphtha, coal tar	0.05	S86
Naphthalene	0.05	S292
Nickel, metal and soluble compounds (as Ni)	0.06	S206
Nicotine	0.07	S293
Nitrobenzene	0.06	S217
p-Nitrochlorobenzene	0.10	S218
Nitrotoluene	0.06	S223
Octachloronaphthalene	0.07	S97
Octane	0.06	S378
Ozone (alkaline MI)	0.08	S8
Parathion	0.08	S295
Pentane	0.05	S379
2-Pentanone	0.06	S20
Petroleum distillate (naptha)	0.05	S380
2-Pentyl acetate (see sec-amyl acetate)		
Phenol	0.07	S330
Phenyl ether	0.07	S72
Phenyl ether-biphenyl mixture	0.09	S73
Phenylglycidyl ether	0.06	S74
Phenylhydrazine	0.06	S160
Phosphoric acid	0.06	S333
Phthalic anhydride	0.09	S179
Platinum, soluble salts	0.06	S191
Propane	0.05	S87
n-Propyl acetate	0.06	S48
Propyl alcohol	0.08	S62
Propylene dichloride	0.06	S95
Propylene oxide	0.08	S75
n-Propyl nitrate	0.05	S227
Pyridine	0.06	S161
Rhodium, metal fume and dust	0.08	S188
Rhodium, soluble salts	0.07	S189
Selenium compounds	0.09	S190
Stoddard solvent	0.05	S382
Styrene	0.06	S30
Sulfuric acid	0.08	S174
Tellurium	0.06	S204
Tellurium hexafluoride	0.05	S187
Terphenyls	0.10	S27
1, 1, 1, 2-Tetrachloro-2, 2-difluoroethane	0.07	S131
1, 1, 2, 2-Tetrachloro-1, 2-difluoroethane	0.05	S132
1, 1, 2, 2-Tetrachloroethane	0.06	S124
Tetrahydrofuran	0.06	S78
Tetranitromethane	0.08	S224
Tetryl	0.06	S225
Thallium, soluble compounds (as Tl)	0.06	S306
Tin, inorganic compounds except oxides	0.06	S185
Titanium dioxide dust	0.11	S385
o-Toluidine	0.06	S168
Tributyl Phosphate	0.08	S208
1, 1, 2-Trichloroethane	0.06	S134
Trichloroethylene	0.08	S336
1, 2, 3-Trichloropropane	0.07	S126
1, 1, 2-Trichloro-1, 2, 2-trifluoroethane	0.07	S129
Trifluoromonobromethane	0.06	S125
Triorthocresyl phosphate	0.07	S209
Triphenyl phosphate	0.07	S210
Turpentine	0.05	S88
Vinyl chloride	0.08	—
Vinyl toluene	0.06	S25
Xylidine	0.06	S162
Yttrium	0.05	S200
Zirconium compounds (as Zr)	0.05	S185

a chemical, then the general coefficients of variation in Table D-2 may be used with care. Tables D-1 and D-2 apply only to laboratories with adequate maintenance and calibration facilities for sampling equipment (such as pumps) and a quality control program for the analytical laboratory.

The CV_T's in Table D-1 were reported by the NIOSH Measurement Research Branch and obtained from NIOSH Contract CDC-99-74-45, Laboratory Validation of Air Sampling Methods Used to Determine Environmental Concentrations in Work Places, June 26, 1974 to July 30, 1976. Additional work in this area was performed by Reckner and Sachdev (D-1) under NIOSH Contract HSM 99-72-98.

TABLE D-2. GENERAL COEFFICIENTS OF VARIATION FOR SOME SAMPLING/ANALYTICAL PROCEDURES

Sampling/analytical procedure	CV	Data sources*
Colorimetric detector tubes	0.14	A
Rotameter on personal pumps (sampling only)	0.05	B
Charcoal tubes (sampling/analytical)	0.10	C
Asbestos (sampling/counting)	0.24-0.38	D
Respirable dust, except coal mine dust (sampling/weighing)	0.09	E
Gross dust (sampling/analytical)	0.05	E

*Data source references

A. Leidel, N. A., and K. A. Busch: Statistical Methods for the Determination of Noncompliance with Occupational Health Standards, NIOSH Technical Information, HEW Pub. No. (NIOSH) 75-159, Cincinnati, Ohio 45226, 1975.

B. NIOSH Engineering Branch estimate of typical calibrated pumps capable of the range 1.5 to 3.0 lpm.

C. Conservative estimate by the authors. Recent work under NIOSH Contract CDC-99-74-45 have shown typical CV_T's (precision only) of 0.05 to 0.09 for charcoal tubes.

D. Leidel, N. A., S. G. Bayer, R. D. Zumwalde, and K. A. Busch: USPHS/NIOSH Membrane Filter Method for Evaluating Airborne Asbestos Fibers, NIOSH Technical Information Report, Cincinnati, Ohio 45226 (to be published, 1977).

E. NIOSH Engineering Branch estimate based on the use of pumps in the flow range 1.5 to 3.0 lpm and a collected mass of at least 1.0 milligram.

If an analytical coefficient of variation different from that given in Tables D-1 and D-2 is available from a laboratory, it is better to use a computed total coefficient of variation. It is important to realize that CV's are not directly additive, but that the CV_T increases as the square root of the sum of the squares of component CV's. In general there are only two component CV's: the CV_P for the sampling pump and the CV_A for the analytical method. Thus, the CV_T would be calculated from

$$CV_T = \sqrt{(CV_P)^2 + (CV_A)^2}$$

where

CV_P = pump CV, generally taken as 0.05
CV_A = analytical CV

Example:

Charcoal tubes were used to sample for acetone and were taken to a local laboratory for analysis. The laboratory reported that its CV_A for acetone on charcoal tubes was 0.09. The CV_T is calculated as

$$CV_T = \sqrt{(0.05)^2 + (0.09)^2} = 0.10$$

Another example dealing with coal mine dust samples was given by Leidel and Busch (D-2).

REFERENCES

D-1. Reckner, L. R., and J. Sachdev: Collaborative Testing of Activated Charcoal Sampling Tubes for Seven Organic Solvents. NIOSH Technical Information, HEW Pub. No. (NIOSH) 75-184, Cincinnati, Ohio 45226, 1975.

D-2. Leidel, N. A., and K. A. Busch: Comments — Statistical Methods for Determination of Noncompliance. American Industrial Hygiene Association Journal, 36: 839-840, 1975.

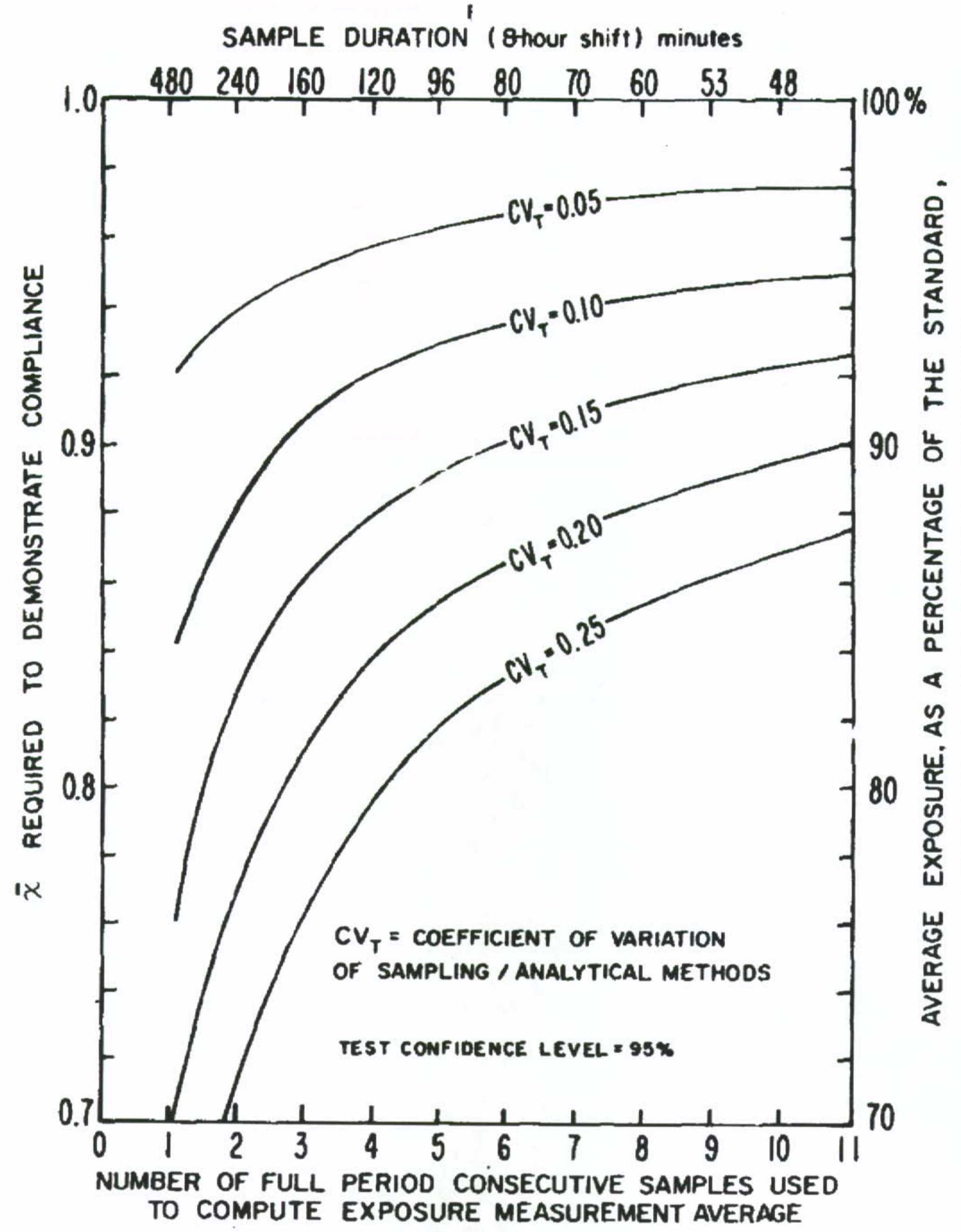

Figure E-1. Effect of full period consecutive sample size on compliance demonstration when test power is 50%.

when an 8-hour average standard is sampled for.

If one had a sampling/analytical technique with a CV_T of 10%, Figure E-3 shows that the standardized exposure average $\bar{x}$ required to demonstrate noncompliance decreases from about 1.12 for two samples to about 1.06 for seven samples. Or, for two samples, we can demonstrate noncompliance when the mean of the two samples is 12% above the standard. But with seven samples, we can demonstrate noncompliance when the mean of the seven samples is 6% above the standard. The uncertainty of the TWA measurement can be further reduced by taking more than seven samples; however, the additional sampling effort is not usually justified.

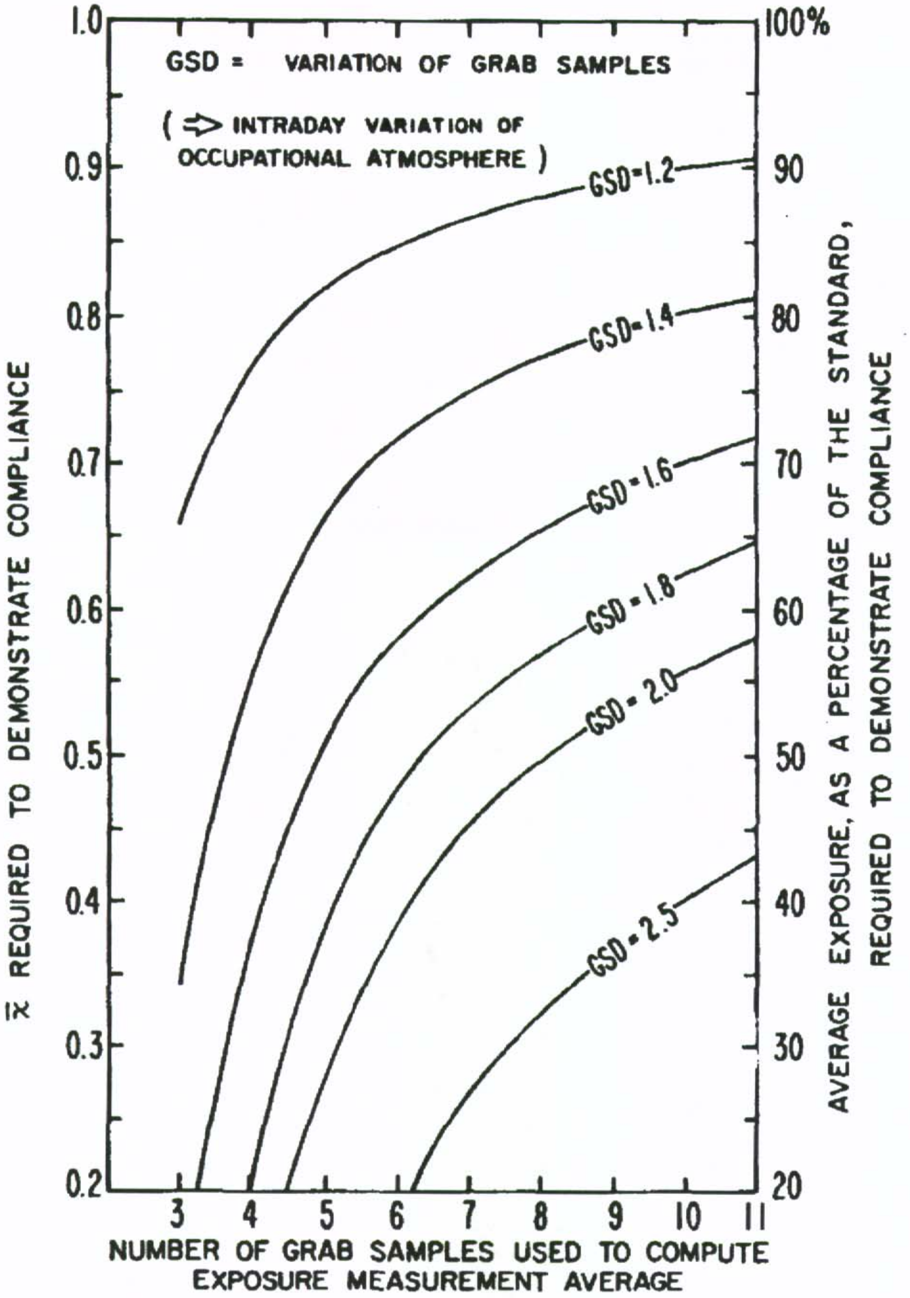

Figure E-2. Effect of grab sample size on compliance demonstration.

There are theoretical benefits with larger sample sizes, but in relation to the large additional costs involved (especially from extra analyses), the benefits are usually negligible. Thus, we can conclude that two consecutive full period samples (about 4 hours each for an 8-hour TWA standard) is usually the "best" number to use, as discussed in section 3.4.

Grab Samples Measurement

For grab samples, fewer than four samples requires unreasonably large values of $\bar{x}$ to demonstrate noncompliance. As with consecutive full period samples, Figure E-4 shows there is a point of diminishing returns in attempting to reduce uncertainty in the measured mean by

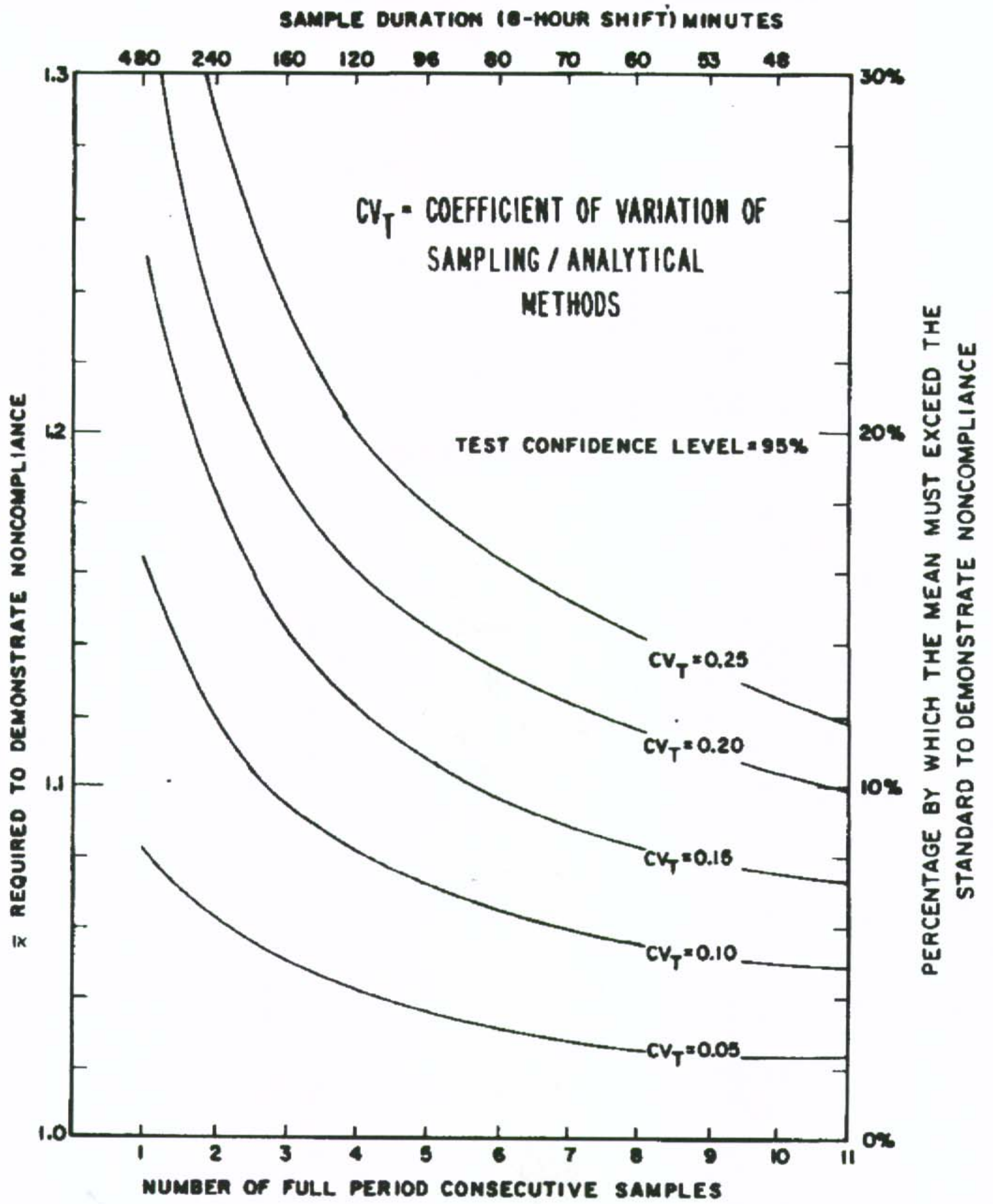

Figure E-3. Effect of full period consecutive sample size on noncompliance demonstration when test power is 50%.

taking more than about seven grab samples. However, since the random variation in a grab sample average is usually much greater than for the same number of full period samples, one might have to take many times more than seven grab samples to approach the low variation of four or fewer full period consecutive samples. Thus, we have a statistical criterion that can lead to a reduced sampling effort, but with a predictable level of confidence. For noncompliance, the best number of grab samples to take over the specified time period is between four and seven. Note that this is less than the recommended 8 to 11 grab samples for compliance demonstration.

Partial Period Consecutive Samples Measurement

Figure E-5 demonstrates the effect of sample size on the Partial Period Consecutive Samples Procedure, when demonstrating compliance.

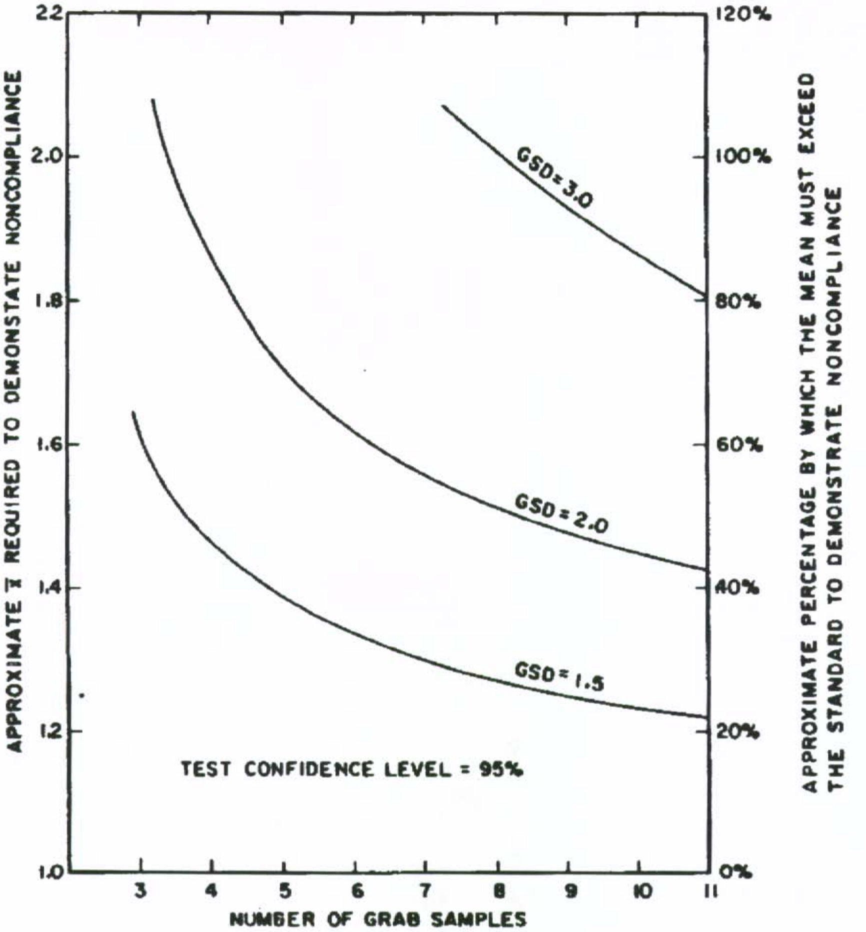

Figure E-4. Effect of grab sample size on noncompliance demonstration. Three different data geometric standard deviations (GSD) are shown that reflect the amount of intraday variation in the environment.

(Note: This procedure is not applicable when demonstrating compliance, as discussed in section 3.4(3).) A typical sampling/analytical CV_T of 0.10 is used for all curves. The bottom curve (for 8-hour total sample time) is the same curve as the $CV_T=0.10$ curve of Figure E-3. Partial period consecutive samples are a compromise between the preferred full period sample(s) and grab samples, which are least desirable. Note that a *GSD* curve of 2.5 on Figure E-4 is roughly equivalent to a 5.5-hour curve on Figure E-5. Therefore, if one cannot sample for at least 70% of the time period required by the standard (such as 5.5 hours for an 8-hour standard), it is better to use grab sampling for demonstrating noncompliance.

REFERENCES

E-1. Leidel, N. A., and K. A. Busch: Statistical Methods for the Determination of Noncompliance with Occupational Health Standards. NIOSH Technical Information, HEW Pub. No. (NIOSH) 75-159, Cincinnati, Ohio 45226, April 1975.

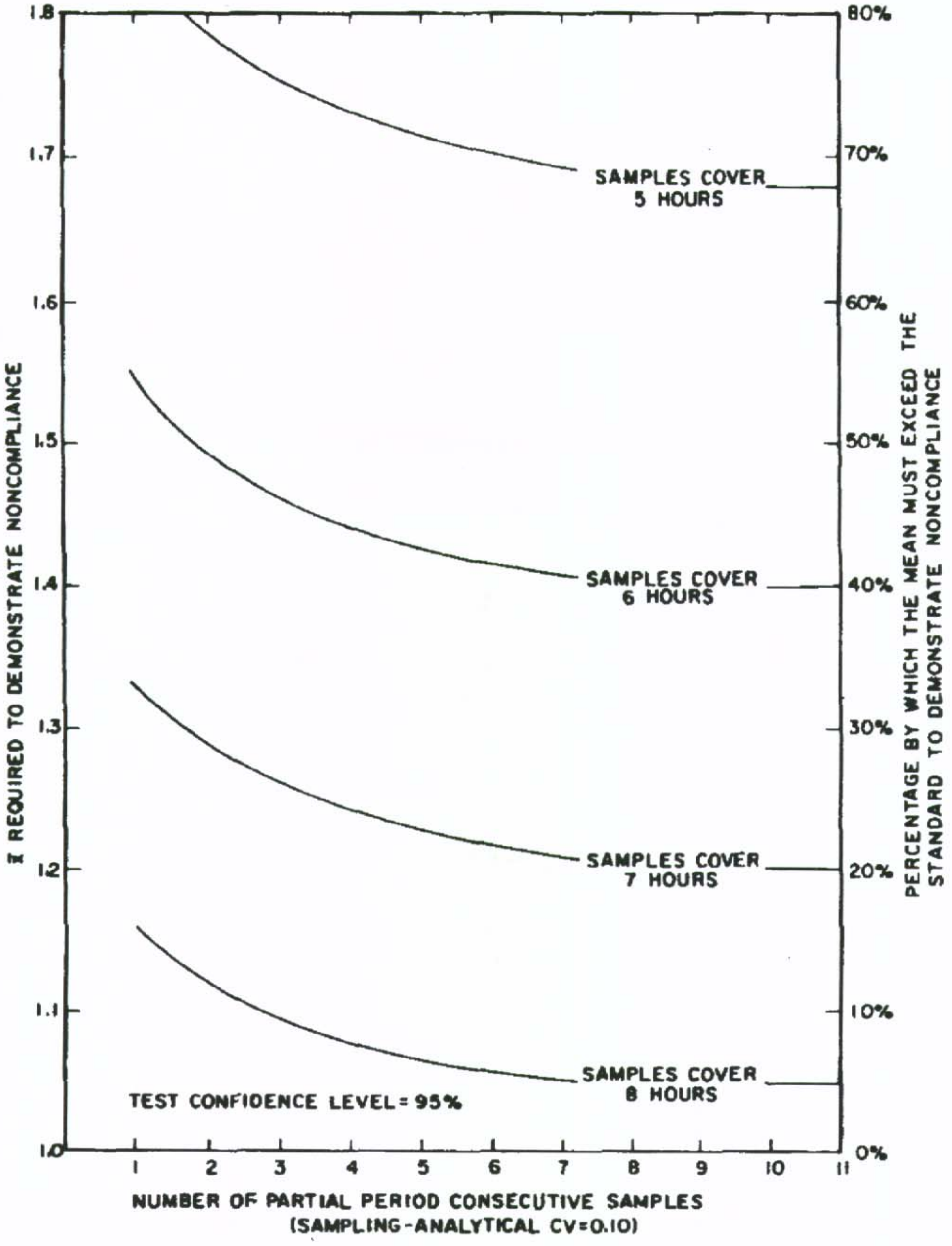

Figure E-5. Effect of partial period consecutive sample size and total time covered by all samples on noncompliance demonstration when test power is 50%.

TECHNICAL APPENDIX F*

SELECTION OF RANDOM SAMPLING PERIODS DURING AN 8-HOUR WORKSHIFT

To select a random sample, proceed as follows:

1. Divide the total period over which the standard is defined into n mutually exclusive (non-overlapping) intervals whose collective lengths equal the period for the standard. The number n is equal to P/s, where P is the period of the standard and s is the length of sampling intervals.

   For example, if 15-minute samples are taken and the standard is a time-weighted average (TWA) over an 8-hour period, there would be $n = 32$ possible sampling intervals from which a random sample could be selected.

2. Number the possible sampling intervals consecutively: 1, 2, 3, . . ., n. For example, for an 8-hour standard over a workday from 8:00 a.m. to 4:30 p.m. with 12:00 noon to 12:30 p.m. spent outside the work area for lunch, we would assign the following code numbers for 15-minute sampling intervals.

Code #	*Interval*
1	8:00 - 8:15 a.m.
2	8:15 - 8:30 a.m.
3	8:30 - 8:45 a.m.
•	
•	
•	
15	11:30 - 11:45 a.m.
16	11:45 - 12:00 noon
17	12:30 - 12:45 p.m.
18	12:45 - 1:00 p.m.
•	
•	
•	
31	4:00 - 4:15 p.m.
32	4:15 - 4:30 p.m.

3. If n random samples are to be taken, use a table of random numbers such as Table F-1. Select an arbitrary starting point, and from there, list the first n different integers between 1 and n.

   For example, suppose five random 15-minute sampling periods from 32 possible periods are to be selected. Arbitrarily choose the first column and the eleventh row (where the integer 67 appears) from the first page of Natrella's Table A-36 as our starting point (Table F-1, Reference F-2). By moving vertically downward in the table, the five periods would be 24, 6, 29, 16, and 4 since all integers greater than 32 would be ignored. We would then sample during the time periods given below.

Period	*Interval*
4	8:45 - 9:00 a.m.
6	9:15 - 9:30 a.m.
16	11:45 - 12:00 noon
24	2:15 - 2:30 p.m.
29	3:30 - 3:45 p.m.

Small deviations in the starting times shown of up to 10 minutes (either earlier or later) would probably not significantly affect their randomness. Juda and Budzinski (F-3) give a similar procedure.

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*This material originally appeared in Leidel and Busch (F-1).

↓																								
46	96	85	77	27	92	86	26	45	21	89	91	71	42	64	64	53	22	75	81	74	91	48	46	18
44	19	15	32	63	55	87	77	33	29	45	00	31	34	84	05	72	90	44	27	78	22	07	62	17
34	39	80	62	24	33	81	67	28	11	34	79	26	35	34	23	09	94	00	80	55	31	63	27	91
74	97	80	30	65	07	71	30	01	84	47	45	89	70	74	13	04	90	51	27	61	34	63	87	44
22	14	61	60	86	38	33	71	13	33	72	08	16	13	50	56	48	51	29	48	30	93	45	66	29
40	03	96	40	03	47	24	60	09	21	21	18	00	05	86	52	65	40	73	73	57	68	36	33	91
52	33	76	44	56	15	47	75	78	73	78	19	87	06	98	47	48	02	62	03	42	05	32	55	02
37	59	20	40	93	17	82	24	19	90	80	87	32	74	59	84	24	49	79	17	23	75	83	42	00
11	02	55	57	48	84	74	36	22	67	19	20	15	92	53	37	13	75	54	89	56	73	23	39	07
10	33	79	26	34	54	71	33	89	74	68	48	23	17	49	18	81	05	52	85	70	05	73	11	17
→ 67	59	28	25	47	89	11	65	65	20	42	23	96	41	64	20	30	89	87	64	37	93	36	96	35
93	50	75	20	09	18	54	34	68	02	54	87	23	05	43	36	98	29	97	93	87	08	30	92	98
(24)	43	23	72	80	64	34	27	23	46	15	36	10	63	21	59	69	76	02	62	31	62	47	60	34
39	91	63	18	38	27	10	78	88	84	42	32	00	97	92	00	04	94	50	05	75	82	70	80	35
74	62	19	67	54	18	28	92	33	69	98	96	74	35	72	11	68	25	08	95	31	79	11	79	54
91	03	35	60	81	16	61	97	25	14	78	21	22	05	25	47	26	37	80	39	19	06	41	02	00
42	57	66	76	72	91	03	63	48	46	44	01	33	53	62	28	80	59	55	05	02	16	13	17	54
(06)	36	63	06	15	03	72	38	01	58	25	37	66	48	56	19	56	41	29	28	76	49	74	39	50
92	70	96	70	89	80	87	14	25	49	25	94	62	78	26	15	41	39	48	75	64	69	61	06	38
91	08	88	53	52	13	04	82	23	00	26	36	47	44	04	08	84	80	07	44	76	51	52	41	59
68	85	97	74	47	53	90	05	90	84	87	48	25	01	11	05	45	11	43	15	60	40	31	84	59
59	54	13	09	13	80	42	29	63	03	24	64	12	43	28	10	61	65	62	07	79	83	05	59	61
39	18	32	69	33	46	58	19	34	03	59	28	97	31	02	65	47	47	70	39	74	17	30	22	65
67	43	31	09	12	60	19	57	63	75	11	80	10	97	15	70	04	89	61	78	54	84	87	83	42
61	75	37	19	56	90	75	39	03	56	49	92	72	95	27	52	57	47	12	52	54	62	43	23	13
78	10	91	11	00	63	19	63	74	58	69	03	51	38	60	36	53	56	77	06	69	08	89	91	24
93	23	71	58	09	78	08	03	07	71	79	32	25	19	61	04	40	33	12	06	78	91	97	88	95
37	55	48	82	63	89	92	59	14	72	19	17	22	51	90	20	03	64	96	60	48	01	95	44	84
62	13	11	71	17	23	29	25	13	85	33	35	07	69	25	68	57	92	57	11	84	44	01	33	66
(29)	89	97	47	03	13	20	86	22	45	59	98	64	53	69	64	94	51	55	87	73	81	58	46	42
(16)	94	85	82	89	07	17	30	29	89	89	80	98	36	25	36	53	02	49	14	34	03	52	09	20
(04)	93	10	59	75	12	98	84	60	93	68	16	87	60	11	50	46	56	58	45	88	72	50	46	11
95	71	43	68	97	18	85	17	13	08	00	50	77	50	46	92	45	26	97	21	48	22	23	08	32
86	05	39	14	35	48	68	18	36	57	09	62	40	28	87	08	74	79	91	08	27	12	43	32	03
59	30	60	10	41	31	00	69	63	77	01	89	94	60	19	02	70	38	72	33	38	88	20	60	86
05	45	35	40	54	03	98	96	76	27	77	84	80	08	64	60	44	34	54	24	85	20	85	77	32
71	85	17	74	66	27	85	19	55	56	51	36	48	92	32	44	40	47	10	38	22	52	42	29	96
80	20	32	80	98	00	40	92	57	51	52	83	14	55	31	99	73	23	40	07	64	54	44	99	21
13	50	78	02	73	39	66	82	01	28	67	51	75	66	33	97	47	58	42	44	88	09	28	58	06
67	92	65	41	45	36	77	96	46	21	14	39	56	36	70	15	74	43	62	69	82	30	77	28	77
72	56	73	44	26	04	62	81	15	35	79	26	99	57	28	22	25	94	80	62	95	48	98	23	86
28	86	85	64	94	11	58	78	45	36	34	45	91	38	51	10	68	36	87	81	16	77	30	19	36
69	57	40	80	44	94	60	82	94	93	98	01	48	50	57	69	60	77	69	60	74	22	05	77	17
71	20	03	30	79	25	74	17	78	34	54	45	04	77	42	59	75	75	64	99	37	03	18	03	36
89	98	55	98	22	45	12	49	82	71	57	33	28	69	50	59	15	09	25	79	39	42	84	15	70
58	74	82	81	14	02	01	05	77	94	65	57	70	39	42	48	56	84	31	59	15	70	41	74	60
50	54	73	81	91	07	81	26	25	45	49	61	22	88	41	20	00	15	59	93	51	60	65	65	63
49	33	72	90	10	20	65	28	44	63	95	86	75	78	69	21	41	65	56	10	34	10	32	00	93
11	85	01	43	65	02	85	69	56	88	34	29	64	35	45	15	70	11	77	83	01	34	82	91	04
34	22	46	41	84	74	27	02	57	77	47	93	72	02	95	63	75	74	69	69	61	34	31	92	13

TABLE F-1. USE OF A RANDOM NUMBER TABLE FOR SELECTION OF RANDOM SAMPLING PERIODS*

*Reproduced from Table A-36 of Natrella (F-2), with permission of the Rand Corporation, "A Million Random Digits," The Free Press, 1955.

REFERENCES

F-1. Leidel, N. A., and K. A. Busch: Statistical Methods for the Determination of Noncompliance with Occupational Health Standards. NIOSH Technical Information, HEW Pub. No. (NIOSH) 75-159, Cincinnati, Ohio 45226, 1975.

F-2. Natrella, M. G.: Experimental Statistics. National Bureau of Standards Handbook 91. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, 1963.

F-3. Juda, J., and K. Budzinski: Determining the Tolerance Range of the Mean Value of Dust Concentration, Staub, 27: 12-16, (English translation), April 1967.

TECHNICAL APPENDIX G*

TEMPERATURE AND PRESSURE CORRECTIONS OF INDUSTRIAL HYGIENE SAMPLE VOLUMES AND CALCULATION OF CONCENTRATIONS (ppm)

The objective of industrial hygiene sampling is to obtain the best estimate of the true concentration the employee is exposed to at the sampling site. This is because Federal health standards such as 29 CFR 1910, Subpart Z, are exposure standards. Analytical laboratories generally report the mass of contaminant found on a filter, charcoal tube, or in an impinger sample. To calculate the original airborne concentration at the time of sampling, the true volume of air that passed through the sampling device must be calculated. Suppose a pump rotameter is calibrated for a specific flow rate (such as 2.0 lpm) at Cincinnati, OH (elevation, 575 feet; temperature, 75°F) and this pump is then used at a higher altitude (such as 5000 feet) or another temperature. If, at the time of sampling the pump rotameter float is set to the 2.0 lpm calibration mark (indicated flow rate), the actual flow through the pump will not be 2.0 lpm.

The indicated flow rate at the time of sampling must be corrected to determine the actual flow rate at the time of sampling. This correction is a function of the basic flow equation for the particular flow meter used (rotameter, limiting orifice, or critical orifice) and IS NOT A SIMPLE GAS LAW CORRECTION.

TEMPERATURE AND PRESSURE CORRECTIONS

These procedures are not necessary for positive displacement pumps. For these devices, see "Calculation of Concentration," below.

Flow Meter Corrections for Linear Scale Rotameters and Limiting Orifices

$$Q_{\text{actual}} = Q_{\text{indicated}} \sqrt{\frac{P_{\text{cal}} \quad T_{\text{actual}}}{P_{\text{actual}} \quad T_{\text{cal}}}}$$

with

actual = true sample conditions
cal = true calibration conditions
indicated = indicated calibration flow rate on rotameter

and both pressure P and temperature T are in absolute units (as psia, absolute inches Hg, degrees Kelvin or Rankine)
where

psia = psig + 14.7 (psig is gauge pressure)
deg Rankine = deg Fahrenheit + 460
deg Kelvin = deg Celsius + 273

Note that local barometric changes due to weather conditions do not have a significant effect on the average absolute atmospheric pressure at a location. Generally, we know the altitude at both the calibration and sampling locations. Table G-1 can be used to obtain adequate estimates of the average absolute atmospheric pressure at the calibration location (P_{cal}) and at the time of sampling (P_{actual}).

Example:

The rotameter on a battery-operated pump was calibrated and marked for 2.0 lpm in Cincinnati, OH (elevation, 575 feet; temperature, 75°F). The pump was then used to obtain a sample at an elevation of 6000 feet with a temperature of 50°F; with the rotameter ball set at the 2.0 lpm calibration mark.

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*These corrections are based on material prepared by Roper (G-1), and the derivations were prepared by Heitbrink (G-2).

TABLE G-1. AVERAGE ABSOLUTE ATMOSPHERIC PRESSURE

Altitude, feet	Absolute pressure, psia	Absolute pressure, inches Hg
sea level	14.7	29.92
Cincinnati, OH (575′)	14.4	29.31
1000	14.2	28.87
2000	13.7	27.82
3000	13.2	26.81
4000	12.7	25.85
5000	12.2	24.90
6000	11.7	23.98
7000	11.3	23.10
8000	10.8	22.22
9000	10.5	21.39
10000	10.1	20.58

To obtain the actual flow rate through the pump at time of sampling use

$$Q_{\text{actual}} = 2.0 \text{ lpm} \sqrt{\frac{(14.4 \text{ psia})}{(11.7 \text{ psia})} \cdot \frac{(460+50)\ {}^\circ\text{R}}{(460+75)\ {}^\circ\text{R}}}$$

$$= (2.0 \text{ lpm})\ (1.083) = 2.17 \text{ lpm}$$

An error of about −8% would have resulted if the correction had not been made.

Critical Orifices

We are assured of critical orifice conditions if the orifice is operated with at least 15 inches Hg downstream suction. Generally, it is best to operate the downstream vacuum pump at about 20 inches suction pressure. The correction for a critical orifice is

$$Q_{\text{actual}} = Q_{\text{indicated}} \sqrt{T_{\text{actual}} / T_{\text{cal}}}$$

where temperature T is in absolute units.

Example:

A 9 lpm (nominal) critical orifice was calibrated at 9.1 lpm in Cincinnati, OH (temperature, 75°F). This critical orifice was then used in a sampling train to collect an area silica sample at 35°F. To obtain the actual flow rate through the critical orifice, use

$$Q_{\text{actual}} = 9.1 \text{ lpm} \sqrt{(460+35) / (460+75)}$$

$$= (9.1 \text{ lpm})\ (0.962) = 8.75 \text{ lpm}$$

An error of about +4% would have resulted if the correction had not been made.

CALCULATION OF CONCENTRATION

When calculating the mass concentration (mg/m^3) of a contaminant, the actual air volume sampled (as determined by the flow meter correction factors discussed above) must be used for the calculation.

All gas or vapor concentrations must be converted to *ppm* (parts per million) before they are analyzed for noncompliance. Only the *ppm* values of the Federal health standards (29 CFR 1910, Subpart Z) should be used because the mass concentration values of the standards are only approximate and some contain significant round-off errors.

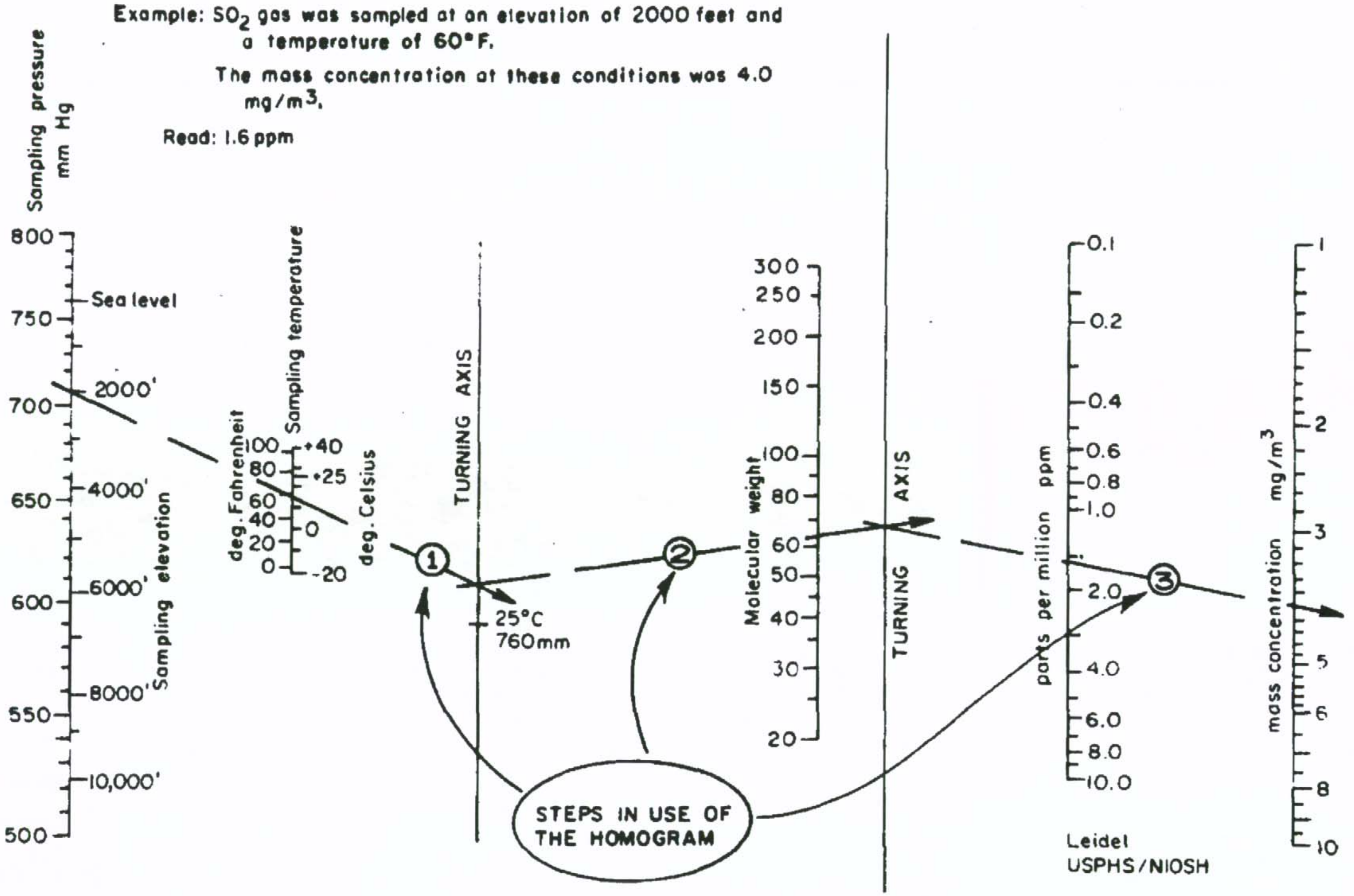
Most equations for converting to *ppm* use the factor 24.45. This is the number of liters a gram-mole (gmole) of gas occupies at OSHA/ACGIH standard temperature and pressure (STP: 25°C and 760 mm Hg), which is also known as the STP gram-molecular volume. What the conversion equation actually does is calculate the gram-molecular volume at the sampled temperature and pressure. However, the equation can also be interpreted as calculating the volume occupied at STP by the amount of gas in the actual sampled volume. The equation is

$$ppm = \frac{(C)\ (24.45)\ (T+460)\ (14.7)}{(MW)\ (537)\ (P)}$$

where

C = concentration in mg/m^3 at the sampled T and P
MW = contaminant molecular weight (g/gmole)
T = actual sampling temperature (degrees Fahrenheit)
P = actual sampling pressure (psia)

Or the nomogram given as Figure G-1 can be used for a quick approximate conversion. It is important to realize that, in effect, it is the actual sampled volume that is being converted to an STP volume in the above equation. One does not correct *ppm* to STP. Once a *ppm* concentration is calculated, it remains the same regardless of temperature and pressure.


Example: SO_2 gas was sampled at an elevation of 2000 feet and a temperature of 60°F.

The mass concentration at these conditions was 4.0 mg/m^3.

Read: 1.6 ppm

Figure G-1. Nomogram relating mg/m^3 to ppm.

SUMMARY OF PROCEDURE

1. The altitude, temperature, calibration location, and indicated flow rate should be recorded when a sample is taken.
2. Using the flow meter altitude/temperature correction factors, the actual volume sampled should be calculated. This is necessary only for rotameter, limiting orifices, or critical orifices.
3. When calculating mass concentration (mg/m^3), the actual sample volume should be used. The mass concentration should be reported at the actual temperature and pressure (or altitude) conditions at the time of sampling.
4. The *ppm* concentration must be calculated before the exposure data are examined for noncompliance with the Federal *ppm* standards (29 CFR 1910, Subpart Z).

DERIVATION OF CORRECTION FACTORS

Source of Correction Factor for Flow Rate Indicated by a Calibrated Rotameter

In Perry's Chemical Engineers' Handbook (G-3), the ratio of the flow rates for two different fluids in the same rotameter is given by equation 5-24 on page 5-13:

$$\frac{W_a}{W_b} = \frac{K_A}{K_B}\sqrt{\frac{(\rho_f - \rho_a)\,\rho_a}{(\rho_f - \rho_b)\,\rho_b}} \qquad \text{(G-1)}$$

where

W = mass flow rate
ρ_f = density of float
K = flow parameter
ρ = gas density
a,b = subscript for different gases or gas at two conditions

Because we are only concerned with air under two different conditions, two assumptions can be made:

$$K_a = K_b$$
$$\rho_f - \rho_a = \rho_f - \rho_b$$

As a result, equation G-1 can be expressed as

$$\frac{W_a}{W_b} = \sqrt{\rho_a / \rho_b}$$

But, $W = \rho q$ where q = volumetric flow rate. Applying this relation, we have

$$\frac{q_a}{q_b} \sqrt{= \rho_b / \rho_a}$$

From the ideal gas law,

$$\rho = MP/RT$$

where
M = molecular weight
P = ambient pressure
R = gas law constant
T = temperature

Now equation G-1 can be expressed as

$$\frac{q_a}{q_b} = \sqrt{\frac{P_b}{T_b} \cdot \frac{T_a}{P_a}}$$

The subscript a now refers to ambient conditions during sampling, and b refers to conditions at the time of calibration.

Source of Correction for Flow Rate of a Calibrated Critical Orifice

On Page 5-9 of Perry's Handbook (G-3), the equation for the flow rate of air through a critical orifice is given as

$$W_x = \frac{0.533\,(C)\,(A)\,(P)}{\sqrt{T}}$$

where

W_x = mass flow rate
C = coefficient of discharge
A = cross sectional area of orifice
P = upstream pressure
T = upstream temperature

When the same orifice is used under different conditions of temperature and pressure, different mass flow rates result. The ratio of these flow rates is

$$\frac{W_a}{W_b} = \frac{P_a / \sqrt{T_a}}{P_b / \sqrt{T_b}} \qquad \text{(G-2)}$$

where a and b refer to different conditions of fluid temperature and pressure. Mass flow rate can be converted to volumetric flow rate by using this expression:

$$W = q\rho \qquad \text{(G-3)}$$

where

q = volumetric rate (liters/minute)
ρ = gas density

The air's density can be computed from

$$\rho = (M)\,(P)\ /\ (R)\,(T) \qquad \text{(G-4)}$$

where

M = molecular weight
P = pressure
R = gas law constant
T = temperature

After applying equations G-3 and G-4 to equation G-2, the correction equation is obtained:

$$q_a / q_b = \sqrt{T_a / T_b}$$

The subscript a now refers to ambient conditions during sampling, and b refers to conditions at the time of calibration.

REFERENCES

G-1. Roper, P.: Calibration of Orifices. NIOSH in-house report, Cincinnati, Ohio 45226, 1972.

G-2. Heitbrink, W. A.: NIOSH memorandum. Measurement Research Branch, Division of Physical Sciences and Engineering, Cincinnati, Ohio 45226, September 14, 1976.

G-3. Perry, J. H., ed.: Chemical Engineers' Handbook, 4th ed. McGraw-Hill Book Company, New York, N.Y. 1963.

$$TWA = \frac{(75\text{ min})\ (320\text{ ppm}) + (70\text{ min})\ (250\text{ ppm}) + (140\text{ min})\ (350\text{ ppm})}{(285\text{ min})}$$

$$= 318\text{ ppm for the 4.75-hour period.}$$

Refer to section 4.2.1 for analysis of these data. Note this example *does not* meet the recommendations of section 3.4 (3) that the sampled portion of the period cover at least 70% to 80% of the total 8-hour period.

GRAB SAMPLE MEASUREMENT

If the employee's operation and work exposure can be assumed relatively constant during the workshift, then all samples can be directly averaged. If the duration of each sample is relatively short compared with the period of the standard (such as each sample is less than 5% of that period), then the times can be omitted in the *TWA* calculation.

Sample	*Time period*	*Sample results*
A	0830 - 0835	20 ppm
B	0940 - 0945	45
C	1105 - 1110	10
D	1250 - 1255	15
E	1430 - 1435	30
F	1550 - 1555	25

The *TWA* for the 8-hour workday would be

$$TWA = \frac{(20+45+10+15+30+25)}{6} = 24\text{ ppm}$$

Refer to section 4.2.3 for analysis of these data.

However, if the employee was at several work locations or operations during the 8-hour shift and several grab samples were taken during each of the operations with different expected exposures (see section 3.4 (4)), then the results are analyzed as follows:

Operation	*Duration*	*Sample*	*Results (of each 5-min sample)*
Solvent room	0800-1030	A	110 ppm
		B	180
		C	90
		D	120
		E	150
Printer feed	1030-1630	F	50
		G	35
		H	60
		I	40

The solvent room average exposure is

$$\bar{x}_1 = \frac{(110+180+90+120+150)}{5} = 130\text{ ppm}$$

The printer feed average exposure is

$$\bar{x}_2 = \frac{(50+35+60+40)}{4} = 46\text{ ppm}$$

Then the *TWA* exposure for the 8-hour shift (excluding 30 minutes for lunch) is

$$TWA = \frac{(2.5\text{ hr})\ \ (130\text{ ppm}) + (5.5\text{ hr})\ \ (46\text{ ppm})}{8\text{ hr}}$$

$$= 72\text{ ppm}$$

Note that data analysis and decision procedures are not presented in Chapter 4 for this sampling strategy. They would be too complex for a manual at this level. The preferred approach would be to use the Full Period Consecutive Samples procedure.

TECHNICAL APPENDIX I

LOGNORMAL PROBABILITY PLOTS OF EXPOSURE MEASUREMENT DATA AND EXPOSURE AVERAGES

The utility and convenience of lognormal probability paper for plotting industrial hygiene exposure measurement data have been discussed previously by Hounam (I-1), Gale (I-2, I-3), Coenen (I-4), Jones and Brief (I-5), and Sherwood (I-6). This appendix will address the practical aspects of using lognormal probability paper. First, the "how to" of using this paper will be given. Then, two examples using exposure measurement data and exposure averages of individual employees in an occupational group will be shown.

Figures I-1 and I-2 show examples of commercially available lognormal probability paper (2-cycle and 3-cycle, respectively). Generally, these papers will cover the usual range of exposure measurement. If additional cycles are required, the "cut and paste" method for creating 4- or 5-cycle paper can be used.

The first step in plotting data is to rank the data by increasing exposure measurement value. The smallest measurement becomes ordinal value 1, and the largest value becomes ordinal value n where there are n measurements or exposure averages to be plotted. The ranked values are then assigned plotting positions on the probability scale. No universal agreement exists among statisticians as to the correct way of plotting sample data on probability paper. Santner (I-7) has provided a table of plotting positions that has wide acceptance. Santner's table is given as Table I-1. The table covers sample sizes of $n=2$ to 50 and an equation is given for larger sample sizes.

After the data have been plotted and subjectively decided to be linear, the regression line of best fit is drawn. It is very important to realize that the common analytic technique of minimizing the squared deviations from the fitted line (least squares regression line) *cannot* be used with lognormal probability paper. Kottler (I-8) has pointed out the reasons for this.

If the line is fitted visually to the plotted data points, one must resist the tendency to give equal weight to all data points. The data points in the central region of the plot should have greater influence on the fitted line. Any deviation in percentage probability occurring at low and high probabilities (such as below 5% and above 95%) will appear much exaggerated on the lognormal probability paper, particularly when compared with a deviation of the same absolute magnitude in percentage in the central region of the paper (approximately the 20% and 80% probability region). For example, compared with the 50% plot position, the deviation is exaggerated 15 times at the 99% plot position and 28 times at the 99.5% position. It is impossible to even approximate the size of the deviations by mere inspection because the lognormal probability paper distorts. An example of a similar distortion occurs in cartography. Mercator's projection of the Earth onto a plane tends to exaggerate the distances along the vertical lines, especially near the poles.

Lognormal probability paper should only be used to plot data and make preliminary judgments about the suitability of a lognormal model. It is also useful for providing quick estimates of the geometric mean (*GM*) and the geometric standard deviation (*GSD*) of a fitted lognormal model. But lognormal probability paper cannot be used to make statistically definitive judgments about the goodness-of-fit to a straight line representing the fitted lognormal model. In fitting a straight line to the data points observe the following:

- disregard all data outside the bounds of 1% and 99% probability;

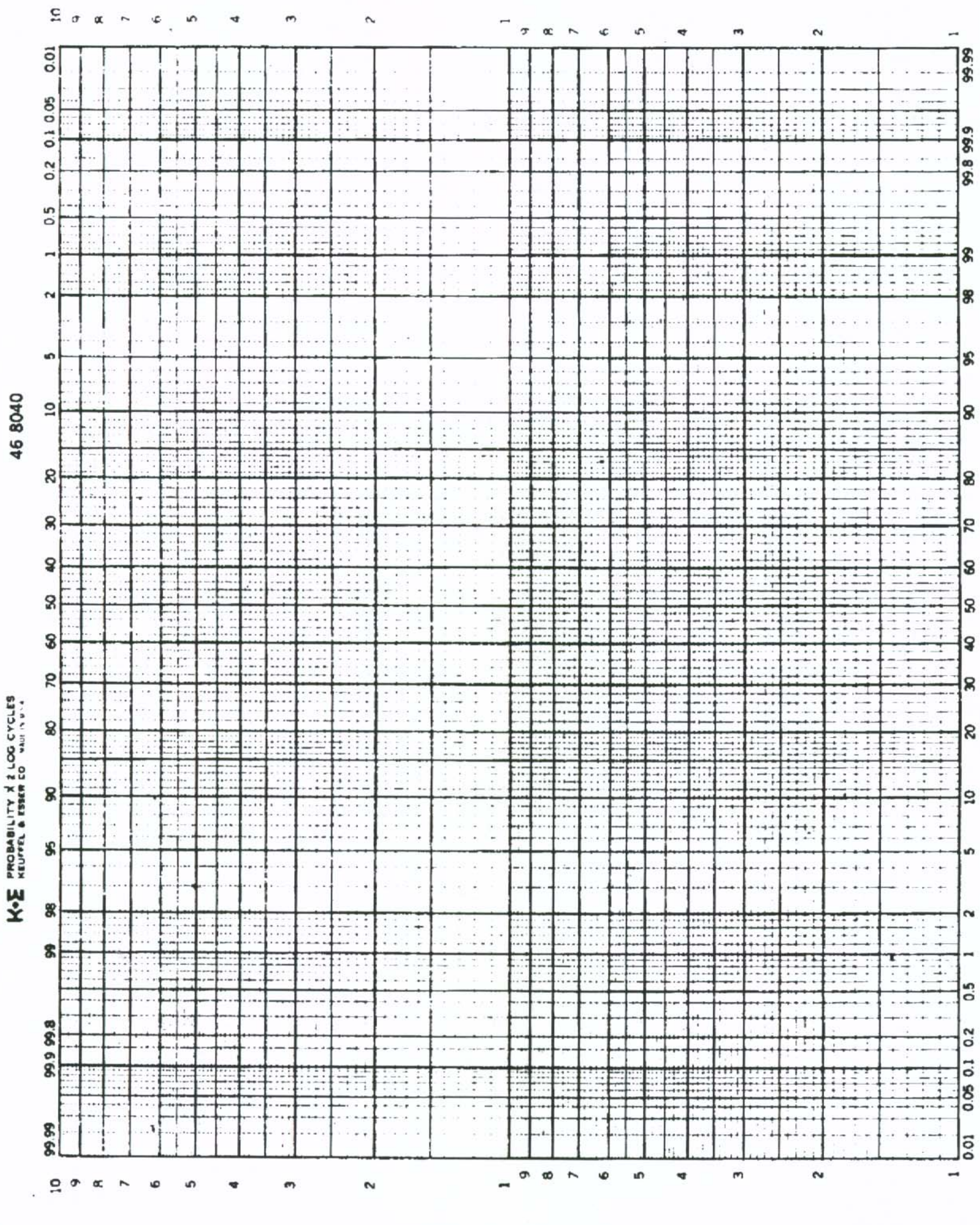


Figure I-1. Lognormal probability paper — 2 cycle.

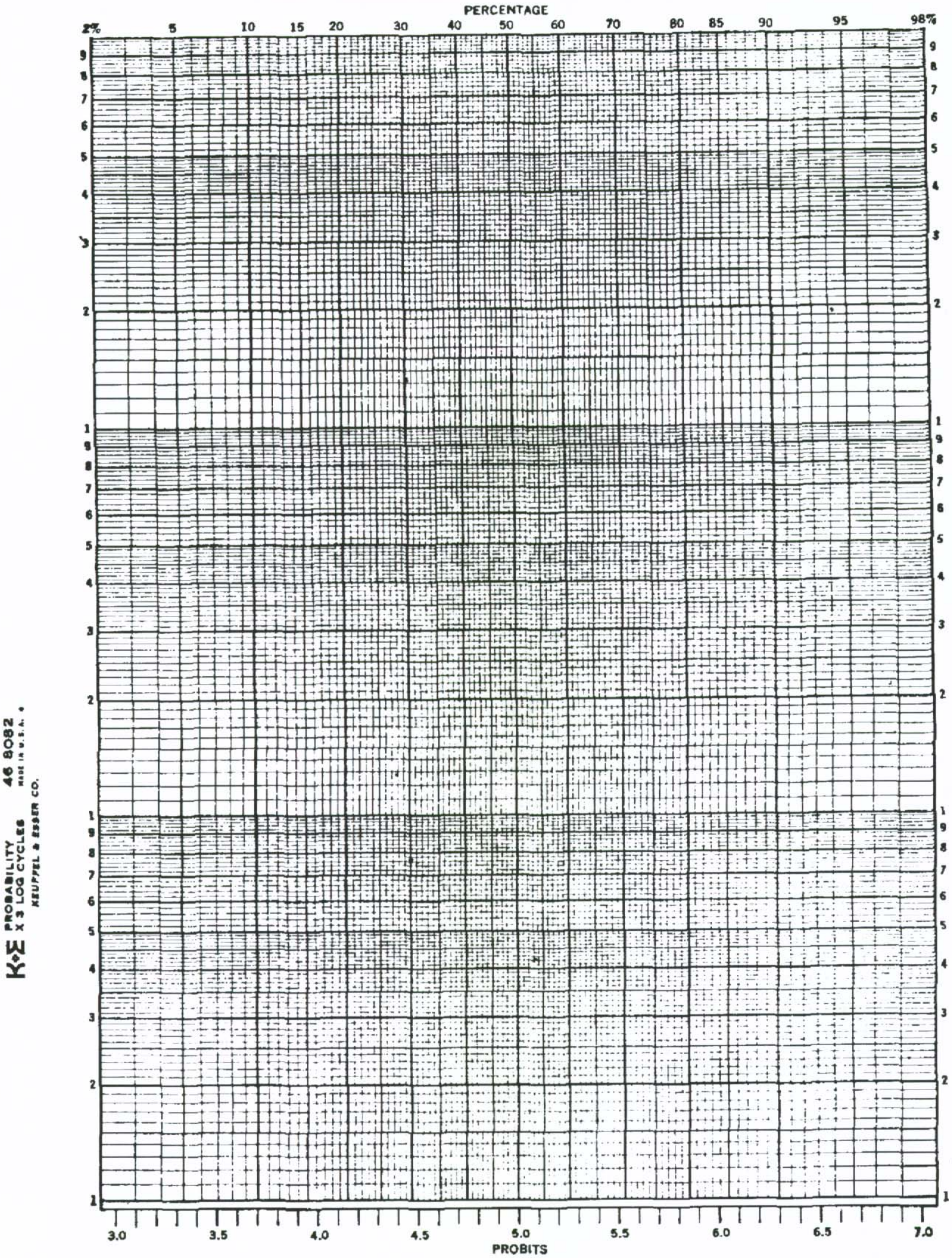


Figure I-2. Lognormal probability paper — 3 cycle.

TABLE I-1. PLOTTING POSITIONS FOR NORMAL PROBABILITY PAPER

Ordinal No.	Sample Size																														Ordinal No.
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
1	28.6	19.9	15.2	12.2	10.3	8.8	7.7	6.9	6.2	5.6	5.2	4.8	4.4	4.1	3.9	3.6	3.4	3.3	3.1	2.9	2.8	2.7	2.6	2.4	2.4	2.3	2.2	2.1	2.1	2.0	1
2	71.4	50.0	38.3	31.0	26.0	22.5	19.7	17.6	15.8	14.4	13.2	12.2	11.4	10.6	9.9	9.4	8.9	8.4	8.0	7.7	7.2	6.8	6.7	6.4	6.2	5.9	5.7	5.5	5.3	5.2	2
3		80.1	61.7	50.0	42.0	36.2	31.8	28.4	25.6	23.3	21.4	19.8	18.4	17.2	16.1	15.2	14.3	13.6	12.9	12.3	11.7	11.3	10.7	10.4	9.9	9.5	9.2	8.9	8.7	8.4	3
4			84.8	69.0	58.0	50.0	43.9	39.2	35.3	32.2	29.6	27.3	25.4	23.7	22.3	21.0	19.8	18.8	17.9	17.1	16.4	15.6	14.9	14.2	13.8	13.3	12.7	12.3	11.9	11.5	4
5				87.8	74.0	63.8	56.1	50.0	45.1	41.1	37.8	34.9	32.4	30.3	28.4	26.8	25.3	24.0	22.8	21.8	20.6	19.8	18.9	18.1	17.6	16.9	16.4	15.9	15.2	14.7	5
6					89.7	77.5	68.2	60.8	54.9	50.0	45.9	42.5	39.5	36.5	34.6	32.6	30.8	29.2	27.8	26.4	25.1	24.2	23.3	22.4	21.5	20.6	19.8	19.2	18.7	17.9	6
7						91.2	80.3	71.6	64.7	58.9	54.1	50.0	46.5	43.4	40.7	38.4	36.3	34.4	32.7	31.2	29.8	28.4	27.4	26.1	25.1	24.2	23.3	22.7	21.8	21.2	7
8							92.3	82.4	74.4	67.8	62.2	57.5	53.5	50.0	46.9	44.2	41.8	39.6	37.6	35.9	34.1	32.6	31.6	30.2	29.1	28.1	27.1	26.1	25.1	24.6	8
9								93.1	84.2	76.7	70.4	65.1	60.5	56.6	53.1	50.0	47.2	44.8	42.6	40.5	38.6	37.1	35.6	34.1	33.0	31.6	30.5	29.5	28.4	27.4	9
10									93.8	85.6	78.6	72.7	67.6	63.1	59.3	55.8	52.8	50.0	47.5	45.2	43.3	41.3	39.7	38.2	36.7	35.2	34.1	33.0	31.9	30.9	10
11										94.4	86.8	80.2	74.6	69.7	65.4	61.6	58.2	55.2	52.5	50.0	47.6	45.6	43.6	42.1	40.5	39.0	37.4	36.3	35.2	34.1	11
12											94.8	87.8	81.6	76.3	71.6	67.4	63.7	60.4	57.4	54.8	52.4	50.0	48.0	46.0	44.4	42.5	41.3	39.7	38.6	37.1	12
13												95.2	88.6	82.8	77.7	73.2	69.2	65.6	62.4	59.5	56.7	54.4	52.0	50.0	48.0	46.4	44.8	43.3	41.7	40.5	13
14													95.6	89.4	83.9	79.0	74.7	70.8	67.3	64.1	61.4	58.7	56.4	54.0	52.0	50.0	48.4	46.4	45.2	43.6	14
15														95.9	90.1	84.8	80.2	76.0	72.2	68.8	65.9	62.9	60.3	57.9	55.6	53.6	51.6	50.0	48.4	46.8	15
16															96.1	90.6	85.7	81.2	77.2	73.6	70.2	67.4	64.4	61.8	59.5	57.5	55.2	53.6	51.6	50.0	16
17																96.4	91.1	86.4	82.1	78.2	74.9	71.6	68.4	65.9	63.3	61.0	58.7	56.7	54.8	53.2	17
18																	96.6	91.6	87.1	82.9	79.4	75.8	72.6	69.8	67.0	64.8	62.6	60.3	58.3	56.4	18
19																		96.7	92.0	87.7	83.6	80.2	76.7	73.9	70.9	68.4	65.9	63.7	61.4	59.5	19
20																			96.9	92.3	88.3	84.4	81.1	77.6	74.9	71.9	69.5	67.0	64.8	62.9	20
21																				97.1	92.8	88.7	85.1	81.9	78.5	75.8	72.9	70.5	68.1	65.9	21
22																					97.2	93.2	89.3	85.8	82.4	79.4	76.7	73.9	71.6	69.1	22
23																						97.3	93.3	89.6	86.2	83.1	80.2	77.3	74.9	72.6	23
24																							97.4	93.6	90.1	86.7	83.6	80.8	78.2	75.4	24
25																								97.6	93.8	90.5	87.3	84.1	81.3	78.8	25
26																									97.6	94.1	90.8	87.7	84.8	82.1	26
27																										97.7	94.3	91.1	88.1	85.3	27
28																											97.8	94.5	91.3	88.5	28
29																												97.9	94.7	91.6	29
30																													97.9	94.8	30
31																														98.0	31

References:

(1) Statistical Tables for Biological Agricultural and Medical Research, by Fisher and Yates, Hafner Pub. Co., '63, Table XX, 94-95
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(3) Pearson, E. and Hartley, H., Biometrika Tables for Statisticians Volume I, Cambridge University Press, '54, Table 28, 175, Table 1, 104-110
(4) Harter, H. Leon, Expected Values of Normal Order Statistics, ARL Technical Report 60-292, Wright-Patterson Air Force Base, July '60

TABLE I-1. PLOTTING POSITIONS FOR NORMAL PROBABILITY PAPER (cont.)

Ordinal No.	Sample Size 32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	Ordinal No.
1	1.92	1.88	1.83	1.74	1.70	1.66	1.62	1.58	1.54	1.50	1.46	1.43	1.39	1.36	1.32	1.32	1.29	1.25	1.22	1
2	4.9	4.8	4.6	4.6	4.5	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.4	3.3	3.2	3.2	2
3	8.1	7.8	7.6	7.4	7.2	6.9	6.8	6.7	6.4	6.3	6.2	6.1	5.8	5.7	5.6	5.5	5.4	5.3	5.2	3
4	11.1	10.9	10.6	10.2	10.0	9.7	9.4	9.2	9.0	8.7	8.5	8.4	8.1	7.9	7.8	7.6	7.5	7.4	7.2	4
5	14.2	13.8	13.3	13.1	12.7	12.3	12.1	11.7	11.5	11.1	10.9	10.6	10.4	10.2	10.0	9.7	9.5	9.3	9.2	5
6	17.4	16.9	16.4	15.9	15.4	15.2	14.7	14.2	14.0	13.6	13.3	12.9	12.7	12.3	12.1	11.9	11.7	11.3	11.1	6
7	20.6	19.8	19.2	18.7	18.1	17.9	17.4	16.9	16.4	16.1	15.6	15.4	14.9	14.7	14.2	14.0	13.8	13.3	13.1	7
8	23.6	23.0	22.4	21.5	20.9	20.3	19.8	19.5	18.9	18.4	18.1	17.6	17.1	16.9	16.4	16.1	15.9	15.4	15.2	8
9	26.8	25.8	25.1	24.5	23.6	23.3	22.7	22.1	21.5	20.9	20.3	20.0	19.5	18.9	18.7	18.1	17.9	17.4	17.1	9
10	29.8	28.8	28.1	27.4	26.4	25.8	25.1	24.5	23.9	23.3	22.7	22.4	21.8	21.2	20.9	20.3	20.0	19.5	19.2	10
11	33.0	31.9	30.9	30.2	29.5	28.4	27.8	27.1	26.4	25.8	25.1	24.5	23.9	23.6	23.0	22.4	22.1	21.5	21.2	11
12	35.9	34.8	34.1	33.0	31.9	31.2	30.5	29.5	28.8	28.1	27.4	26.8	26.1	25.8	25.1	24.5	24.2	23.6	23.0	12
13	39.0	37.8	36.7	35.9	34.8	33.7	33.0	32.3	31.2	30.5	29.8	29.1	28.4	27.8	27.4	26.7	26.1	25.5	25.1	13
14	42.1	40.9	39.7	38.6	37.4	36.7	35.6	34.8	33.7	33.0	32.3	31.6	30.9	30.2	29.5	28.8	28.1	27.8	27.1	14
15	45.2	44.0	42.9	41.3	40.5	39.4	38.2	37.1	36.3	35.6	34.5	33.7	33.0	32.3	31.6	30.9	30.2	29.8	29.1	15
16	48.4	46.8	45.6	44.4	43.3	42.1	40.9	39.7	39.0	37.8	37.1	35.9	35.2	34.5	33.7	33.0	32.3	31.6	31.2	16
17	51.6	50.0	48.4	47.2	46.0	44.4	43.6	42.5	41.3	40.1	39.4	38.6	37.4	36.7	35.9	35.2	34.5	33.7	33.0	17
18	54.8	53.2	51.6	50.0	48.8	47.2	46.0	44.8	43.6	42.9	41.7	40.9	39.7	39.0	38.2	37.4	36.7	35.9	35.2	18
19	57.9	56.0	54.4	52.8	51.2	50.0	48.8	47.6	46.4	45.2	44.0	43.3	42.1	41.3	40.1	39.4	38.6	37.8	37.1	19
20	61.0	59.1	57.1	55.6	54.0	52.8	51.2	50.0	48.8	47.6	46.4	45.2	44.4	43.3	42.5	41.7	40.5	34.7	39.0	20
21	64.1	62.2	60.3	58.7	56.7	55.6	54.0	52.4	51.2	50.0	48.8	47.6	46.4	45.6	44.4	43.6	42.9	41.7	40.9	21
22	67.0	65.2	63.3	61.4	59.5	57.9	56.4	55.2	53.6	52.4	51.2	50.0	48.8	47.6	46.8	45.6	44.8	44.0	42.9	22
23	70.2	68.1	65.9	64.1	62.6	60.6	59.1	57.5	56.4	54.8	53.6	52.4	51.2	50.0	48.8	48.0	46.8	46.0	44.8	23
24	73.2	71.2	69.1	67.0	65.2	63.3	61.8	60.3	58.7	57.1	56.0	54.8	53.6	52.4	51.2	50.0	48.8	48.0	46.8	24
25	76.4	74.2	71.9	69.8	68.1	66.3	64.4	62.9	61.0	59.9	58.3	56.7	55.6	54.4	53.2	52.0	51.2	50.0	48.8	25
26	79.4	77.0	74.9	72.6	70.5	68.8	67.0	65.2	63.7	62.2	60.6	59.1	57.9	56.7	55.6	54.4	53.2	52.0	51.2	26
27	82.6	80.2	77.6	75.5	73.6	71.6	69.5	67.7	66.3	64.4	62.9	61.4	60.3	58.7	57.5	56.4	55.2	54.0	53.2	27
28	85.8	83.1	80.8	78.5	76.4	74.2	72.2	70.5	68.8	67.0	65.5	64.1	62.6	61.0	59.9	58.3	57.1	56.0	55.2	28
29	88.9	86.2	83.6	81.3	79.1	76.7	74.9	72.9	71.2	69.5	67.7	66.3	64.8	63.3	61.8	60.6	59.5	58.3	57.1	29
30	91.9	89.1	86.7	84.1	81.9	79.7	77.3	75.5	73.6	71.9	70.2	68.4	67.0	65.5	64.1	62.6	61.4	60.3	59.1	30
31	95.1	92.2	89.4	86.9	84.6	82.1	80.2	77.9	76.1	74.2	72.6	70.9	69.1	67.7	66.3	64.8	63.3	62.2	61.0	31
32	98.08	95.2	92.4	89.8	87.3	84.8	82.6	80.5	78.5	76.7	74.9	73.2	71.6	69.8	68.4	67.0	65.5	64.1	62.9	32
33		98.12	95.4	92.6	90.0	87.7	85.3	83.1	81.1	79.1	77.3	75.5	73.9	72.2	70.5	69.1	67.7	66.3	64.8	33
34			98.17	95.4	92.8	90.3	87.9	85.8	83.6	81.6	79.7	77.6	76.1	74.2	72.6	71.2	69.8	68.4	67.0	34
35				98.26	95.5	93.1	90.6	88.3	86.0	83.9	81.9	80.0	78.2	76.4	74.9	73.2	71.9	70.2	68.8	35
36					98.30	95.7	93.2	90.8	88.5	86.4	84.4	82.4	80.5	78.8	77.0	75.5	73.9	72.2	70.9	36
37						98.34	95.8	93.3	91.0	88.9	86.7	84.6	82.9	81.1	79.1	77.6	75.8	74.5	72.9	37
38							98.38	95.9	93.6	91.3	89.1	87.1	85.1	83.1	81.3	79.7	77.9	76.4	74.9	38
39								98.42	96.0	93.7	91.5	89.4	87.3	85.3	83.6	81.9	80.0	78.5	77.0	39
40									98.46	96.1	93.8	91.6	89.6	87.7	85.8	83.9	82.1	80.5	78.8	40
41										98.50	96.2	93.9	91.9	89.8	87.9	86.0	84.1	82.6	80.8	41
42											98.54	96.3	94.2	92.1	90.0	88.1	86.2	84.6	82.9	42
43												98.57	96.4	94.3	92.2	90.3	88.3	86.7	84.8	43
44													98.61	96.5	94.4	92.4	90.5	88.7	86.9	44
45														98.64	96.6	94.5	92.5	90.7	88.9	45
46															98.68	96.6	94.6	92.6	90.8	46
47																98.68	96.7	94.7	92.8	47
48																	98.71	96.8	94.8	48
49																		98.75	96.8	49
50																			98.78	50

For sample sizes larger than 50 plotting position is estimated as:

$$\frac{100\ (\text{ordinal number} - 0.5)}{\text{sample size}}$$

EXAMPLE:

Sample Size 51	Ordinal number
$0.98 = \dfrac{100(1-0.5)}{51}$	1
$2.94 = \dfrac{100(2-0.5)}{51}$	2
$\vdots$	$\vdots$
$99.02 = \dfrac{100(51-0.5)}{51}$	51

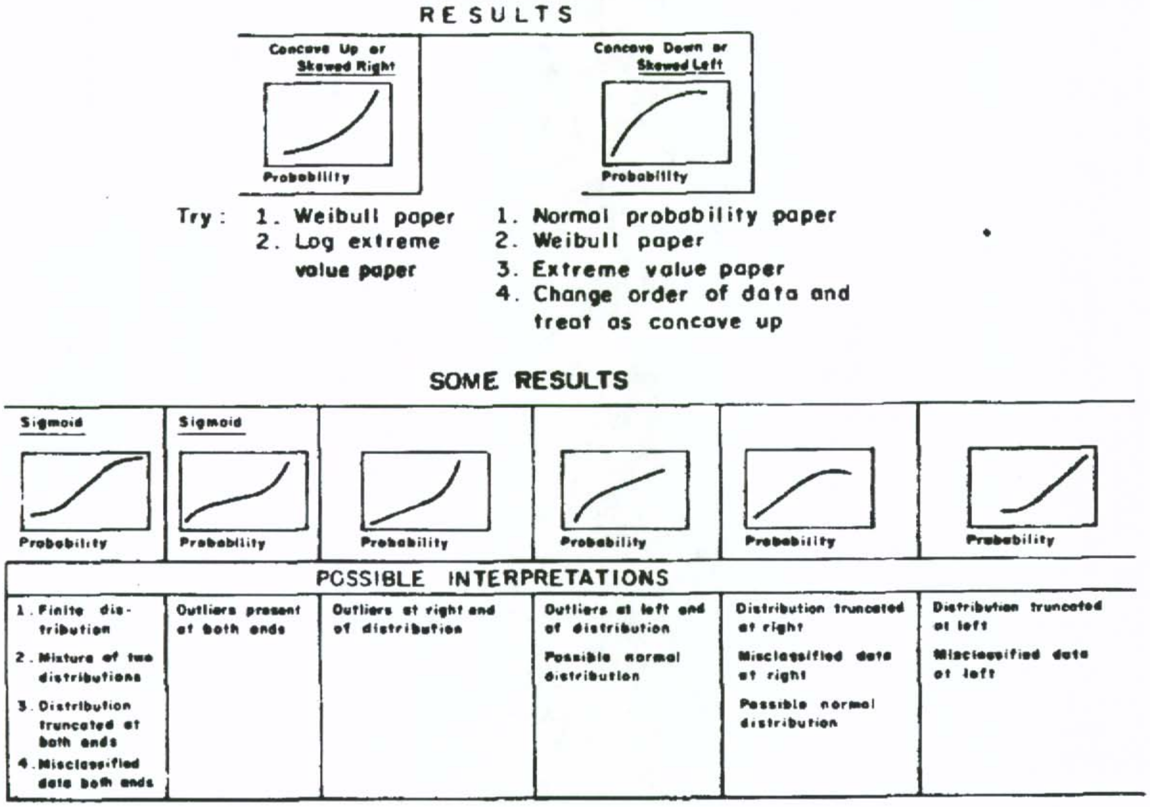
- of the remaining data, give preference to those nearest the central 50% position, that is, in the 20% to 80% region.

Santner (I-7) has provided the guidelines (Figure I-3) to aid in the interpretation of data plotted on lognormal probability paper. Other models for linearizing the data plot are considered and suitable plotting paper is suggested.

A useful reference dealing with plotting on probability paper is Hahn and Shapiro (I-9). In their Chapter 8, "Probability Plotting and Testing of Distributional Assumptions," many probability plots are provided. They include plots comparing typical deviations from linearity on normal probability paper, using $n=20$ and $n=50$ samples from two distributions with varying deviations from normality. For samples from a normal distribution (especially $n=20$ samples), the plots can show considerable deviation from linearity due to random variations.

Daniel and Wood (I-10) also show common deviations from linearity due to random sampling variations. In their Appendix 3A probability distribution plots of random normal deviates with sample sizes $n=8$, 16, 32, 64, and 384 are given. They observe that samples of 8 tell us almost nothing about normality. Sets of 16 from a true normal distribution can still show large deviations from linearity. Sets of 32 and 64 behave much better, but can still bend away from the fitted straight line in the tails of the distribution (less than 10% and greater than 90% probability).

Once the best-fit line has been drawn through the data points, using the guidelines above, the two parameters of the distribution may be estimated. A true lognormal distribution is completely determined by the *GM* and the *GSD*. The *GM* value is the 50% probability value and may be read directly from the plot where the fitted line intersects the 50% probability line. The *GSD* is a measure of the variation or dis-



Try:

1. Weibull paper
2. Log extreme value paper

1. Normal probability paper
2. Weibull paper
3. Extreme value paper
4. Change order of data and treat as concave up

1. Finite distribution 2. Mixture of two distributions 3. Distribution truncated at both ends 4. Misclassified data both ends	Outliers present at both ends	Outliers at right end of distribution	Outliers at left end of distribution Possible normal distribution	Distribution truncated at right Misclassified data at right Possible normal distribution	Distribution truncated at left Misclassified data at left

Figure I-3. Interpretation of data plotted on lognormal probability paper. (Adapted from Santner [I-7].)

persion of the data. It can be calculated from the ratio

$$GSD = \frac{84\% \text{ value}}{50\% \text{ value}} = \frac{50\% \text{ value}}{16\% \text{ value}}$$

Finally, there is the problem of how to handle "zero" data values. In industrial hygiene work, "zero" values are generally undetectable values. If large numbers of these occur, another type of data analysis may be required. Berry and Day (I-11) have discussed the use of the gamma distribution. Before the data are manipulated, consider two other possibilities. First, if exposure measurement data for an employee on one workshift is being analyzed, look for a grouping or run of "zero" (undetectable) values during some portion of the workshift. The employee might have changed operations or left the exposure area. These low values are then from another distribution and should not be included in the exposure measurement analysis of the significant values. This elimination of data should be done with great care and knowledge of the employee's movements Second, the low values may occur in a series of exposure averages for employees in an occupational group of similar exposure risk. Often groups of similar exposure risk are created for survey purposes by using only the employee's job title. Employees may be misclassified by this procedure. One should have actual knowledge of an employee's exposure risk situation before including the employee in the group data analysis.

Undetectable levels do occur, however, and there is no single accepted way to handle them. One method is to obtain the "least detectable amount" of contaminant for the analytical method from the analytical laboratory and use this value to determine the least detectable concentration in the amount of air the pump sampled. The least detectable concentration value is then substituted for all the "zero" values. Another method is to eliminate the zeros by adding a small arbitrary constant to all the data values before they are plotted. Unfortunately, this sometimes must be done by trial and error. Hald (I-12) discusses additions to data that aid in this transformation. Keep in mind that the constant chosen must be small if the location parameter of the distribution is not to be affected. Start with a constant that is about 5% of the geometric mean of the data.

Example — Exposure Measurement Data:

Hydrogen fluoride (HF) concentrations were sampled with a sequential sampler at a fixed location (near control panel) in an HF production building. The following results were reported:

Collected data		*Ranked data*	
Start time	*ppm*	*Ranked data*	*Plot position*
1525	0.91	0.11	5.2%
1625	1.3	0.11	13.2
1725	10.0	0.12	21.4
1825	0.8	0.14	29.6
1925	2.6	0.14	37.8
2025	0.12	0.21	45.9
2125	0.14	0.33	54.1
2225	0.11	0.8	62.2
2325	0.14	0.91	70.4
0025	0.11	1.3	78.6
0125	0.33	2.6	86.8
0225	0.21	10.0	94.8

The plot positions for the $n=12$ values were obtained from Table I-1. The plotted results are shown in Figure I-4. The data seem to show a lack of lognormality in the left tail. Such a distribution would result if there were lognormal random additive variations in addition to a fixed background level. The data plot can be linearized by going to a 3-parameter lognormal model where a constant is subtracted from each concentration value before plotting. An appropriate constant can be estimated from the initial plot by noting the concentration the data approach asymptotically. For Figure I-4, the data appear to converge to a value of about 0.1 ppm. Thus, 0.1 ppm was subtracted from each concentration before it was replotted on Figure I-4. The resulting geometric mean is read as 0.16, which corresponds to a concentration of $(0.16+0.1)$ or 0.26 ppm. The *GSD* of the transformed variable (concentration -0.1) is calculated as

$$GSD = \frac{84\% \text{ value}}{50\% \text{ value}} = \frac{2.05 \text{ ppm}}{0.16 \text{ ppm}} = 12.8.$$

By direct calculation (see section 4.2.3), the mean of $\log_{10}$ (concentration -0.10) is -0.739 and the corresponding concentration is 0.28. The calculated *GSD* of (concentration −0.10) is 9.8. Thus, the graphic determinations are close to the calculated values. Although the latter are preferred for objectivity and accuracy, the graphic estimates would be good enough for most practical purposes. The distribution corresponding to the calculated *GM* and *GSD* of (concentration −0.10) is shown as a dotted line in Figure I-4.

Example — Exposure averages of individual employees in an occupational exposure group:

The following exposure averages were obtained for 24 employees in the job category "mix men" at a facility using methyl methacrylate (MMA) in ppm:

26, 53, 8.8, 37, 19, 31, 45, 56, 15,
49, 16, 44, 96, 39, 63, 90, 23, 16,
31, 24, 30, 24, 116, 49

The plotted data are shown in Figure I-5. Following the previous procedures, the *GM* is 34 ppm and the *GSD* is

$$GSD = \frac{65\text{ ppm}}{34\text{ ppm}} = 1.9$$

For this set of data, calculated values were almost the same as graphic values: $GM = 34.5$ ppm and $GSD = 1.89$.

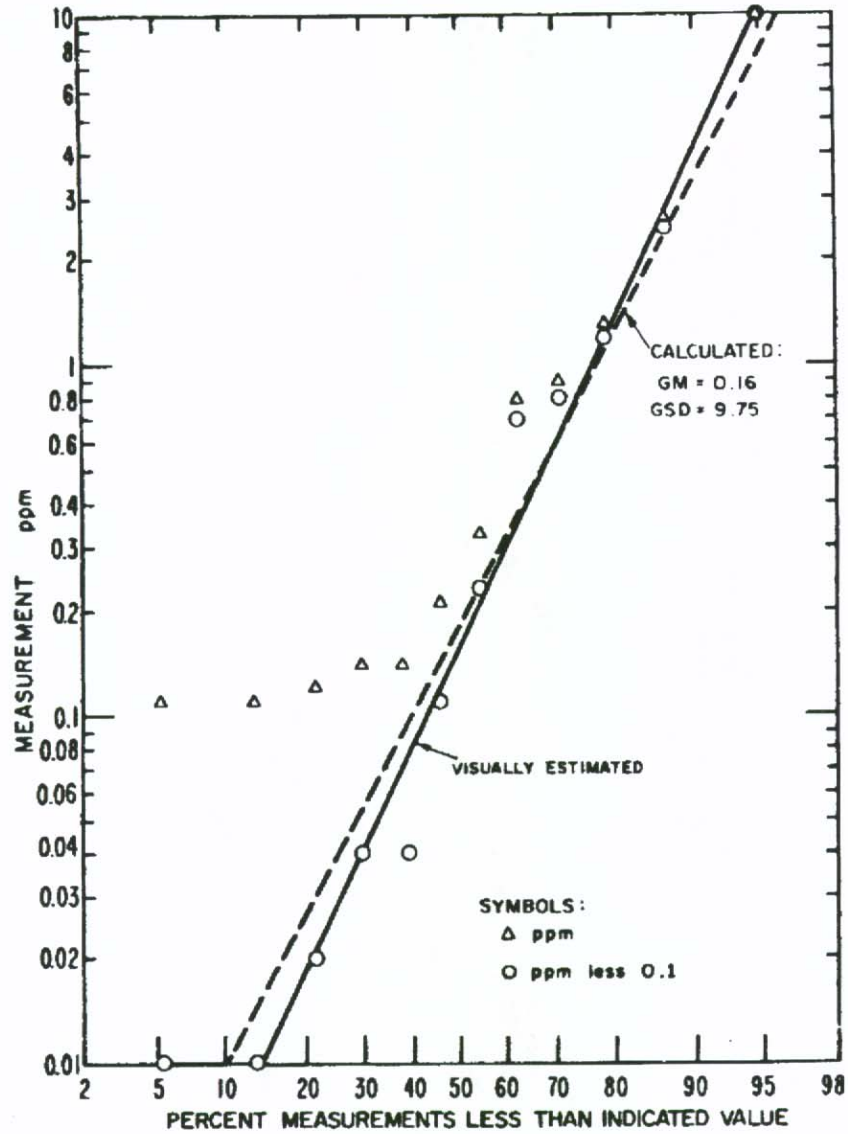


Figure I-4. Hydrogen fluoride measurement distribution.

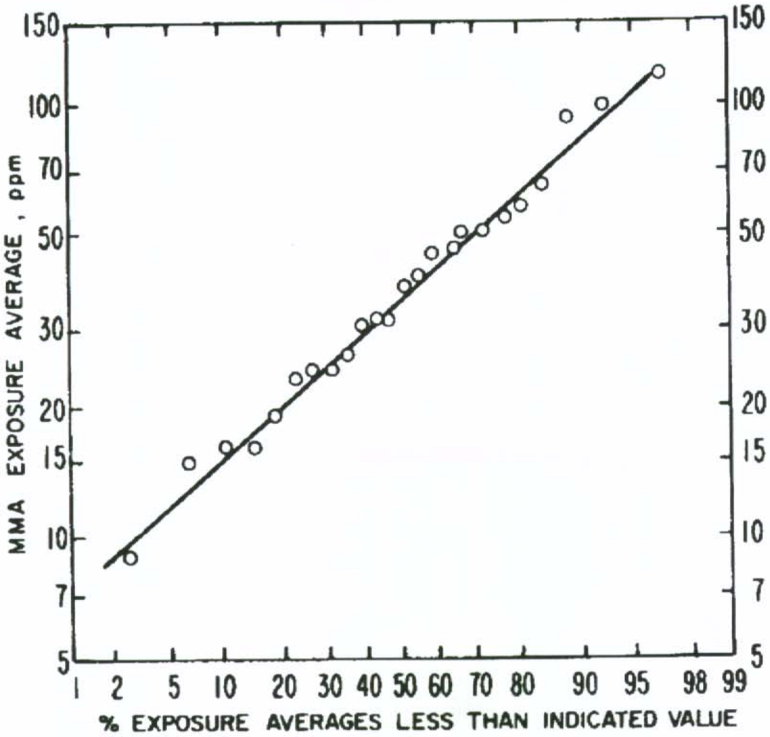


Figure I-5. MMA exposure average distribution in mix men classification.

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TECHNICAL APPENDIX J

CONFIDENCE LIMITS AND CONFIDENCE LEVELS AS THEY AFFECT EMPLOYEE AND EMPLOYER RISK

In section 1.5 it was stated that because of the effect of random measurement errors, any exposure average for an employee calculated from exposure measurements is only an estimate of the unknown true exposure average. The procedures of Chapter 4 take into account the random differences between the measured exposure average and the true exposure average. Decision statements can be made regarding the value of the true exposure average relative to an occupational health standard. These decision statements have a predetermined risk level or confidence level associated with them. This Appendix will discuss the effect of choosing different risk levels on the probabilities of declaring compliance or noncompliance. The concepts of confidence interval limits, hypothesis testing, type I and II errors, and power function curves will first be discussed to build a background for comparing risk levels.

CONFIDENCE INTERVAL LIMITS

The procedures of Chapter 4, particularly sections 4.2.1 and 4.2.2, are statistical hypothesis testing in the framework of confidence limits. Section 4.1 discussed the relation of the one-sided lower confidence limit (LCL) and one-sided upper confidence limit (UCL) to decision statements of compliance exposure, possible overexposure, and noncompliance exposure. It is useful to elaborate here on the purpose and utility of confidence interval limits when making decisions regarding the true exposure average.

Suppose an employee had a true exposure average of 80 ppm on a particular day. A sampling and analytical procedure having a total coefficient of variation (CV_T) of 10% was used to measure the 8-hour TWA exposure with one 8-hour full period sample measurement. If it were possible to obtain many simultaneous 8-hour samples on the same day for the same employee, the sample results would be distributed as shown in Figure J-1. Of course, one would usually only take a single measurement on a day to estimate the employee's exposure average. We would like to make a quantitative statement concerning the value of the unknown true average based on our one actual measurement.

The sampling distribution of Figure J-1 shows the relative frequency of the many possible values we might find with our one measurement. Several points are worth noting. About 68% of the possible sample values lie within the region centered about the true average exposure, from 72 ppm ($\mu-\sigma$) to 88 ppm ($\mu+\sigma$). Thus, there is a 68% probability that our one sample will fall within ± 10% (± 8 ppm or $\pm\sigma$) of the true average exposure. But, about one-third of the time it could fall, by chance, outside this narrow central region. A larger region from 64.3 ppm ($\mu-1.96\sigma$) to 95.7 ppm ($\mu+1.96\sigma$) contains 95% of all possible measurement values. As noted in Appendix D, this sampling and analytical method would be said to have a 95% confidence level accuracy of about 20% ($1.96 \times CV_T$) since single 8-hour measurements would lie within ± 20% of the true average exposure 95% of the time.

The true exposure is always unknown. But we do know the sampling/analytical method's CV_T, the sample size (one, in this example), and we assume normally distributed errors (as shown in Figure J-1). From this information, we can calculate confidence limits, which bound a two-sided interval around the measured exposure, that will *probably* contain the true mean. The high probability that the computed interval

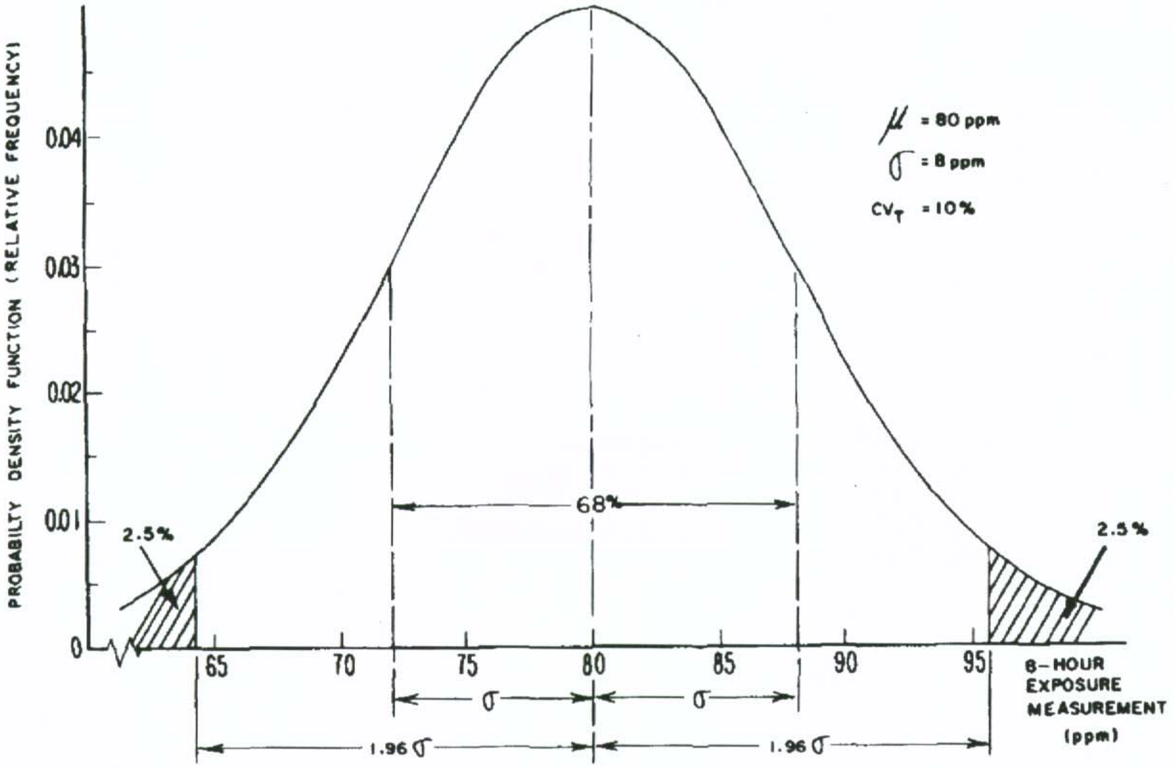

Figure J-1. Predicted sampling distribution of simultaneous single 8-hour samples from an employee with a true exposure average (μ) of 80 ppm. Samples obtained with a $CV_T=0.10$ sampling/analytical method (about ± 20% accuracy at 95% confidence level).

will contain the true exposure average is called the confidence level. Natrella (J-1) has several illustrations (Natrella's Figures 1-8 through 1-10) demonstrating this point. Generally, we choose the 95% confidence level (i.e., confidence coefficient of 0.95) in computing the limits. The word *probability*, as used here in connection with confidence level, refers to the relative frequency (i.e., proportion of cases) of confidence limits that would, in fact, contain the true value as stated. Thus, in the long run 95% of the confidence intervals computed by the appropriate statistical procedure at a confidence level of 95% would be expected to contain the respective true exposure averages. Therefore, since we only take one measurement of a given employee's exposure, there is a 5% risk (i.e., probability) that the calculated two-sided 95% confidence limits *do not* include the true average on that occasion.

Sometimes we are only interested in an upper bound that has a high probability of exceeding the true average or in a lower bound that has a high probability of being below the true average. As an example of the use of an upper bound, we might want to ensure that the true average is less than a threshold limit value (TLV) or Occupational Safety and Health Administration (OSHA) standard, apart from a 1 in 20 chance. To pass the test, the 95% one-sided UCL must be less than the standard. This concept is elaborated on in section 4.1.

To summarize the concept of confidence limits, we see that we don't have to be content with only reporting that the true exposure average has a value somewhere near the measured average. We make use of the sampling distribution (based on the known accuracy of the sampling/analytical method) to construct either a two-sided confidence interval around the measured average or a one-sided confidence interval (i.e., upper bound or lower bound) on one side of the measured average. Then we can state (at a desired confidence level) that the two-sided interval (or either one-sided interval) contains the true average. The chance that we might be unlucky enough to get a measurement so far from the true mean that the confidence interval does not contain the true average is the risk level of the confidence interval statement. The term *risk level* is used here to mean the complement of the confidence level; e.g., a 95% confidence interval would have a 5% risk level (100% − 95% = 5% probability of *not* including the true average exposure).

TESTS OF SIGNIFICANCE OR HYPOTHESIS TESTING

The decision tests of Chapter 4 based on confidence intervals are algebraically equivalent to appropriate statistical tests of significance. It is useful to discuss the concepts and terminology of significance and hypothesis testing and compare them with decisions based on confidence intervals.

The industrial hygienist is interested in testing a hypothesis concerning the value of the true exposure average relative to a TLV or standard. In this context, a hypothesis is an assumption about the state of the true exposure average μ. Statistical significance tests involve two hypotheses. Before the exposure measurement is made, a tentative assumption about the value of the total exposure average relative to the standard is made. This tentative assumption is then accepted unless it is *proven wrong* by the statistical test. By *proven wrong*, we mean that the sampling measurements actually obtained would have had low probability (e.g., less than 0.05) of occurring before the samples were taken if the tentative assumption were true. This tentative negative hypothesis is called the *null hypothesis*. Correspondingly, an alternative assumption, referred to as the *alternative hypothesis*, is made. This alternative hypothesis must be accepted whenever the null hypothesis is rejected. These hypotheses are based on the philosophy of the industrial hygienist. The philosophies of an employer and a governmental compliance officer would differ and the appropriate points of view are discussed below.

HYPOTHESES FOR THE EMPLOYER

Each employer is required to furnish to each of his employees a place of employment free from recognized hazards that are likely to cause death or serious injury. To do this, the employer must keep true employee exposures at levels below the appropriate TLV's or standards. Thus, the employer must make decisions regarding his exposure measurements in such a manner that he is confident that there is no employee whose average exposure exceeds the average exposure standards and that no employee will at any time be exposed to levels above the ceiling exposure standards. In statistical terms, the employer must formulate the null hypothesis that the true exposure exceeds the standard and put the "burden of proof" on the data, which must indicate compliance after allowing for random measurement variability. For the Employer's Test for Compliance:

Null hypothesis is $H_o: \mu >$ standard, i.e., noncompliance

Alternative hypothesis is $H_A: \mu \leq$ standard, i.e., compliance

HYPOTHESES FOR COMPLIANCE OFFICER

The governmental agency has to meet the substantial evidence test and has the burden of proving that a health standard has been exceeded on a particular day. This is because the OSHA health standards are either average exposure standards defined for an 8-hour averaging period or ceiling exposure standards that at no time shall be exceeded (29 CFR 1910. 1000). Therefore, the compliance officer should state the null and alternative hypotheses such that the data must indicate noncompliance after allowing for random measurement variability. For the Compliance Officer's Test for Noncompliance:

Null hypothesis is $H_o: \mu \leq$ standard, i.e., compliance

Alternative hypothesis $H_A: \mu >$ standard, i.e., noncompliance

ERRORS IN HYPOTHESIS TESTING

When we used the confidence interval as test criterion for the measured exposure average $(\overline{X^*})$, we realized there was a risk that the confidence interval did not include the true exposure average. Hypothesis testing uses the terms *type I* and *type II errors* to describe the two types of wrong decisions we might make based on the results of our tests. If we reject the null hypothesis (accept the alternative hypothesis) when the null hypothesis is really true, we commit a type I error. On the other hand, if we fail to reject the null hypothesis when it is truly false, then we commit a type II error.

In the context of the compliance officer's and employer's tests:

COMPLIANCE OFFICER'S TEST FOR NONCOMPLIANCE

Test result	True state: Compliance with standard	True state: Noncompliance with standard
Decide compliance	No Error	Type II error
Decide noncompliance	Type I error	No Error

EMPLOYER'S TEST FOR COMPLIANCE

Test result	True state: Compliance with standard	True state: Noncompliance with standard
Decide compliance	No Error	Type I error
Decide noncompliance	Type II error	No Error

To clarify the interpretation of the statistical decision procedure, we will discuss the decision table used by compliance officers. In Chapter 4, we formulated a decision criterion for use by compliance officers:

Reject H_0: $\mu \leq$ standard and
Accept H_A: $\mu >$ standard whenever a confidence interval for the true mean at the $100(1-\alpha)\%$ confidence level does not contain the standard.

The risk (probability) of making a *type I error* is designated α. The *maximum* value of α is the test's level of significance. Note that the confidence level $(1-\alpha)$ is the complement of the probability α of a type I error. This is true because our decision rule is based on a confidence interval but was formulated to be algebraically equivalent to an α-level significance test of the null hypothesis H_0. Thus, a decision rule based on a 95% confidence interval is the same as a significance test with a 5% maximum risk of committing a type I error.

The risk of making a type II error is designated by β. The value of β varies with magnitude of the real difference between the standard and the true exposure average. The relation between these two types of risks can be summarized on either an operating characteristic (OC) curve for the test or the power function (PF) curve discussed below. The *power* of the test is the probability of accepting the alternative hypothesis when the alternative hypothesis is true. The *power* is designated by $(1-\beta)$, the complement of the probability of a type II error.

RELATION OF CONFIDENCE LIMITS TO TESTS OF SIGNIFICANCE

The equivalence of the Chapter 4 tests to appropriate tests of significance has been indicated above and will not be demonstrated in this Technical Appendix. Suffice it to say, our decision rules are equivalent to significance tests of the null hypotheses given above. Chapter 21 of Natrella (J-1) has an excellent discussion comparing the two approaches. We prefer the LCL and UCL approach since the magnitude of the difference between the LCL (or UCL) and the standard gives an idea of how firm our decision is. Other texts such as Bowker and Lieberman (J-2), Crow et al. (J-3), and Snedecor and Cochran (J-4) can be consulted for further information on these topics.

POWER FUNCTION CURVES

Earlier the term *95% confidence level* was introduced in reference to statistical hypothesis testing. The term arose from the choice of a *5% risk level* for the equivalent statistical significance test to be used. The clear advantage of using statistical tests for the decision process regarding exposure standards is that the maximum desired risk levels can be selected in advance and power function probability curves can be calculated. The PF curve gives the power $(1-\beta)$ of the test as a function of the true mean μ. Bartlett and Provost (J-5) have shown how standards, tolerances, and risk levels can be interpreted in up to five different ways. Employers, government inspectors, and employees can all interpret a standard in different ways. The interpretations involve sample size, chosen confidence (risk) levels, and acceptance/rejection criteria.

A way of illustrating the various interpretations is through the PF curves for each test. The PF is the complement of the OC function. Operating characteristic curves for many of the conventional statistical tests are given in Natrella (J-1) and Bowker and Lieberman (J-2). We will calculate similar power functions for the tests of sections 4.2.1 and 4.2.2. In these tests, the CV_T is assumed to be known without error when testing the null hypothesis that the true mean equals the OSHA standard. Therefore, the quantity 1.645 $CV_T\ \sqrt{n}$ constitutes an allowance for sampling and analytical error in the sample mean of standardized concentrations. More specifically, in this formula, the factor 1.645 is the 95th percentile of the standardized normal distribution. The error allowance given by the above formula is added to the sample mean to compute a one-tailed upper (or subtracted from the sample mean to compute a one-tailed lower) 95% *confidence limit* for the true mean standardized concentration, according to sections 4.2.1 and 4.2.2. (For a discussion of the sense in which the term *confidence limit* is used, see "Statistical Note" in section 4.2.1.) A more exact 95% limit of error could be calculated by taking into account, that there is an error of estimate in CV_T as well as $\bar{x}$. (The CV_T values given in Technical Appendix D for the NIOSH sampling/analytical methods were obtained from six samples at each of three contaminant concentrations.) If this were done, it would be necessary for most methods to increase the multiplier 1.645 by about 10% to account for the uncertainty in the experimental estimate of CV_T. However, the exact multipliers to replace 1.645 cannot yet be calculated because our CV_T values were estimated from samples collected using a carefully controlled flow rate through a critical orifice. The CV for additional field error accountable to the personal sampling pump (denoted by CV_P) had to be "added in" using a conservative to obtain the CV_T values of Technical Appendix D.

We have treated the CV_T as a known quantity* and used the normal distribution (not the Student-t) as a basis for the test statistic and for the corresponding power functions given further below. We believe that when the corrections are made, using an experimental estimate of CV_p in place of 0.05, the net effect of the refinements will be negligible because the two corrections are expected to be in opposite directions. The factor 1.645 will increase slightly, but the CV_P estimate (a component of CV_T) is expected to be lower than 0.05. To summarize, we believe that the test statistics given in sections 4.2.1 and 4.2.2, as well as the power function curves given in this section, are sufficiently accurate. However, to be conservative (until a good experimental estimate of pump error becomes available), half-widths of confidence intervals could be increased by about 10% (i.e., use 1.81 in place of 1.645).

The following discussion concerns calculating the power curves. Figure J-2 is for the Employer's Test to ensure compliance; the test statistic (section 4.2.2.1) is

$$UCL\ (95\%) = \bar{x} + \frac{1.645\ (CV_T)}{\sqrt{n}}$$

where 1.645 is the 95% point (one-sided) of the normal distribution.

The test rejects the null hypothesis H_o of noncompliance and chooses the alternative hypothesis H_A of compliance exposure if $UCL < 1$. An equivalent decision rule is

$$[\bar{x}] < \left[\ 1 - \frac{1.645\ (CV_T)}{\sqrt{n}}\ \right]$$

for compliance exposure.

Example:

For one 8-hour full period sample ($n=1$) and for $CV_T = 0.10$,

$$[\bar{x}] < 0.8355$$

for compliance exposure.

For the PF curve, we must consider all the possible standardized sample values ($\bar{x}$) that could arise and which of them would lead to rejection of the null hypothesis. Suppose the true standardized exposure average μ/STD was 0.9, i.e., the employer is in compliance by a margin of 10%. When he tests the null hypothesis of noncompliance, the power of the test is the probability that the test data will yield a decision of compliance, i.e., reject the null hypothesis. The probability of rejecting H_o is:

$$\text{Prob}\ [\bar{x} < 0.8355]$$

We compute the standard normal variable:

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*When a good experimental CV_p estimate becomes available, NIOSH will publish a new table giving revised CV_T estimates, along with refined (i.e., slightly increased) multipliers to replace 1.645.

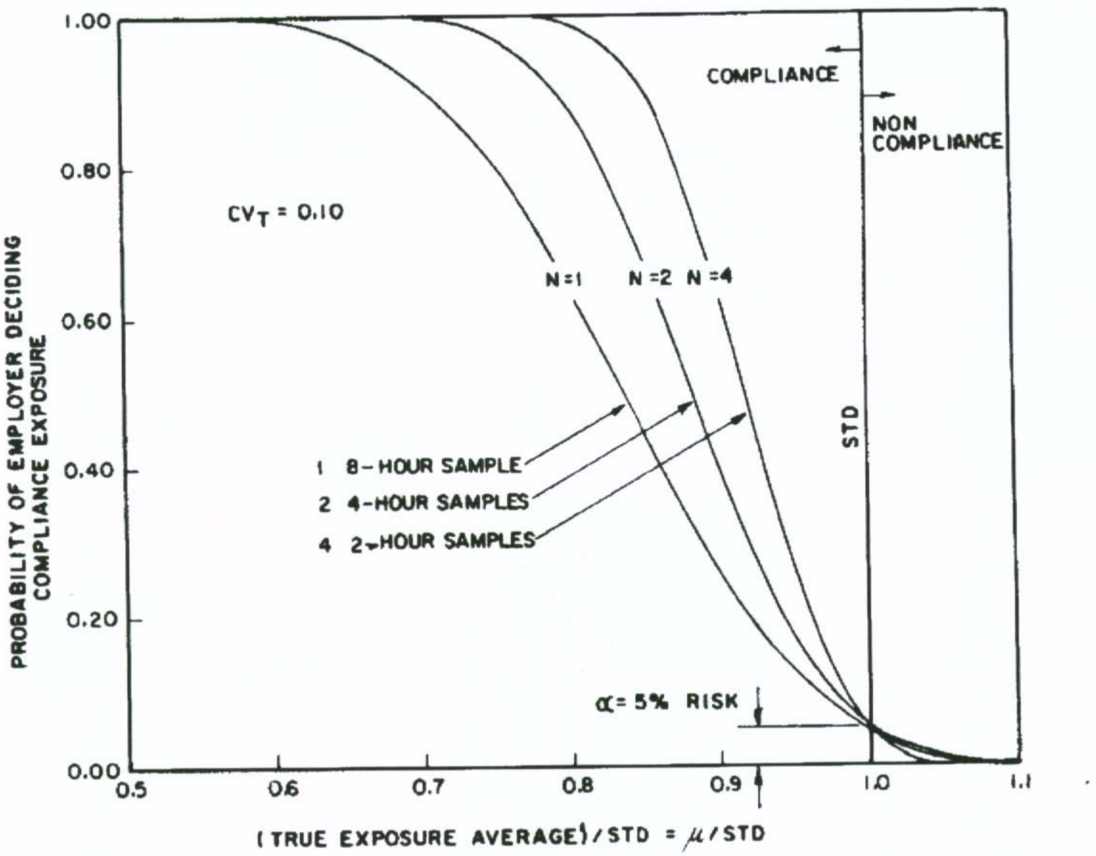

Figure J-2. Power function (PF) curve for one-sided Employer's Test (5% risk level) to ensure compliance as given in sections 4.2.1 and 4.2.2. Calculated for sampling/analytical method with CV_T= 0.10 (about ± 20% accuracy at 95% confidence level).

$$z=\frac{(0.8355-0.9)}{CV_T/\sqrt{n}} = \frac{-0.0645}{0.10/\sqrt{1}} = -0.645$$

The probability of rejecting H_o is the probability of obtaining a value less than (-0.645) from a standard normal distribution (mean 0, variance 1).

$$\text{Prob}\ [z < (-0.645)] \simeq 0.26$$

In this way, the standard normal distribution was used to compute the curves of Figures J-2 through J-6. The calculations were performed on a Wang 2200 calculator using program PS.01-2200.01A-00F1-16-0 to compute integrals of the normal curve.

COMPARISON OF POWER FUNCTIONS FOR COMPLIANCE OFFICER'S TESTS WITH 1% AND 5% SIGNIFICANCE LEVELS

For the compliance officer, the PF curve gives the power (probability) that the test data will yield a decision for noncompliance when noncompliance of a specified amount truly exists. Figure J-3 gives the PF curve for the Compliance Officer's Test at a 5% risk (significance) level. The criterion is that a citation should not be issued unless the 95% LCL for the employee exposure exceeds the standard. Since the probability of a type I error is 5%, can the employer state he will be incorrectly cited 5% of the time? Certainly not. Only if the true average employee exposure of the measured employee is just at or slightly below the standard is there a 5% chance of an incorrect citation and this probability rapidly drops to essentially zero for true average employee exposures under the standard. The term 5% *risk level* refers to the *maximum risk* of declaring noncompliance when the true average employee exposure is exactly equal to the standard. The term has no meaning elsewhere on the PF curve.

An example demonstrating the use of Figure J-3 would be a compliance officer obtaining two

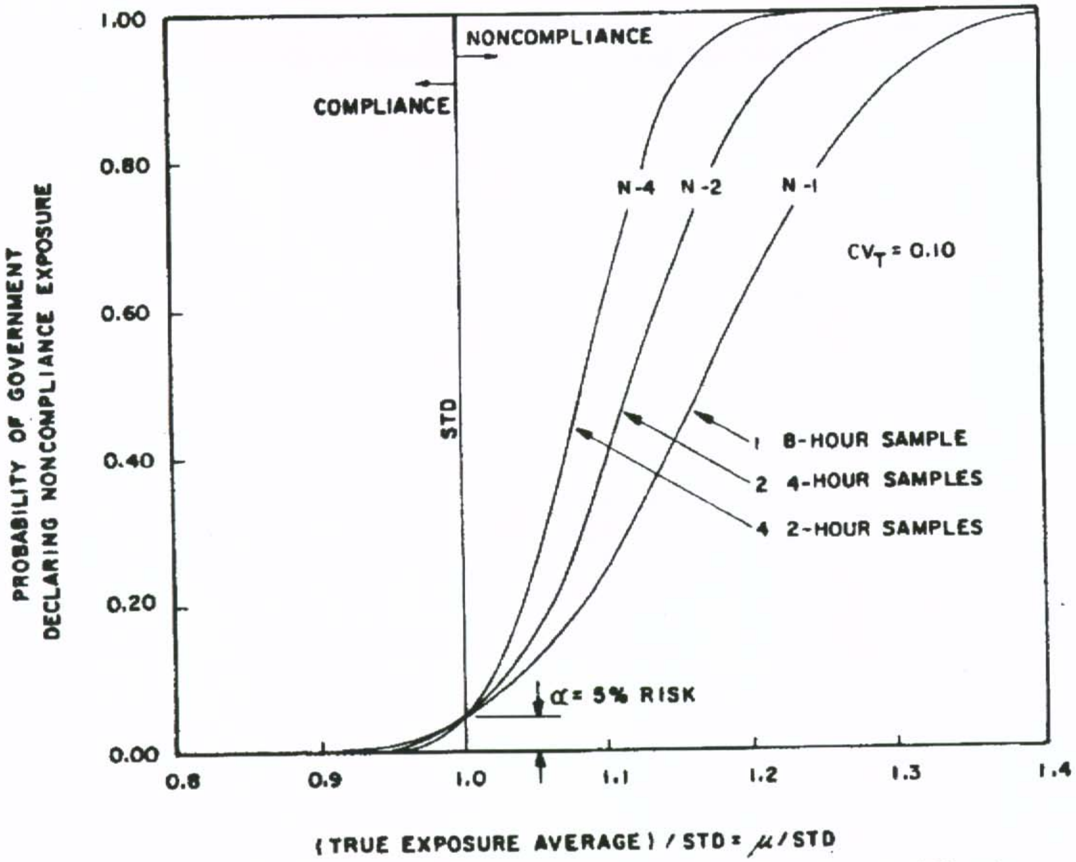

Figure J-3. Power function (PF) curve for one-sided Compliance Officer's Test (5% risk level) to detect noncompliance as given in sections 4.2.1 and 4.2.2. Calculated for sampling/analytical method with $CV_T = 0.10$ (about ± 20% accuracy at 95% confidence level).

consecutive 4-hour samples using a NIOSH method with $CV_T = 10\%$. By the procedure of section 4.2.2, noncompliance should not be declared unless the standardized exposure measurement $\overline{x}$ exceeded 1.116, or 11.6% above the standard. If the true standardized exposure average happened to be at 1.116, Figure J-3 shows there would be only a 50% chance of alleging noncompliance. This is because only half of the possible measurement values would exceed the true average and result in a declaration of noncompliance. The employee might believe this provides him with an adequate level of protection.

However, the employer could possibly argue that the choice by the government of a 5% risk level test would not provide him sufficient protection against an incorrect citation if the true average employee exposure (for one employee on one day) were at or slightly below the standard. The employer could propose that the government use a *1% risk level test,* and Figure J-4 illustrates the effect of this proposal on the PF curve. The probability of a citation for a true case of noncompliance (where the true exposure average exceeds the standard) decreases markedly. For the previous example with a true standardized exposure average of 1.116, the probability of the compliance officer alleging noncompliance drops to 27% (from 50%) using the 1% risk level test. The true exposure average has to be 1.164 (16.4% above the standard) before there is a 50% chance of alleging noncompliance. Thus, when the *employer's risk* is decreased, the protection afforded the employee is markedly decreased.

The effect of sampling/analytical method accuracy on the PF curves is shown for the Compliance Officer's Test (5% risk level) by Figure J-3 ($CV_T = 10\%$) and Figure J-6 (CV_T

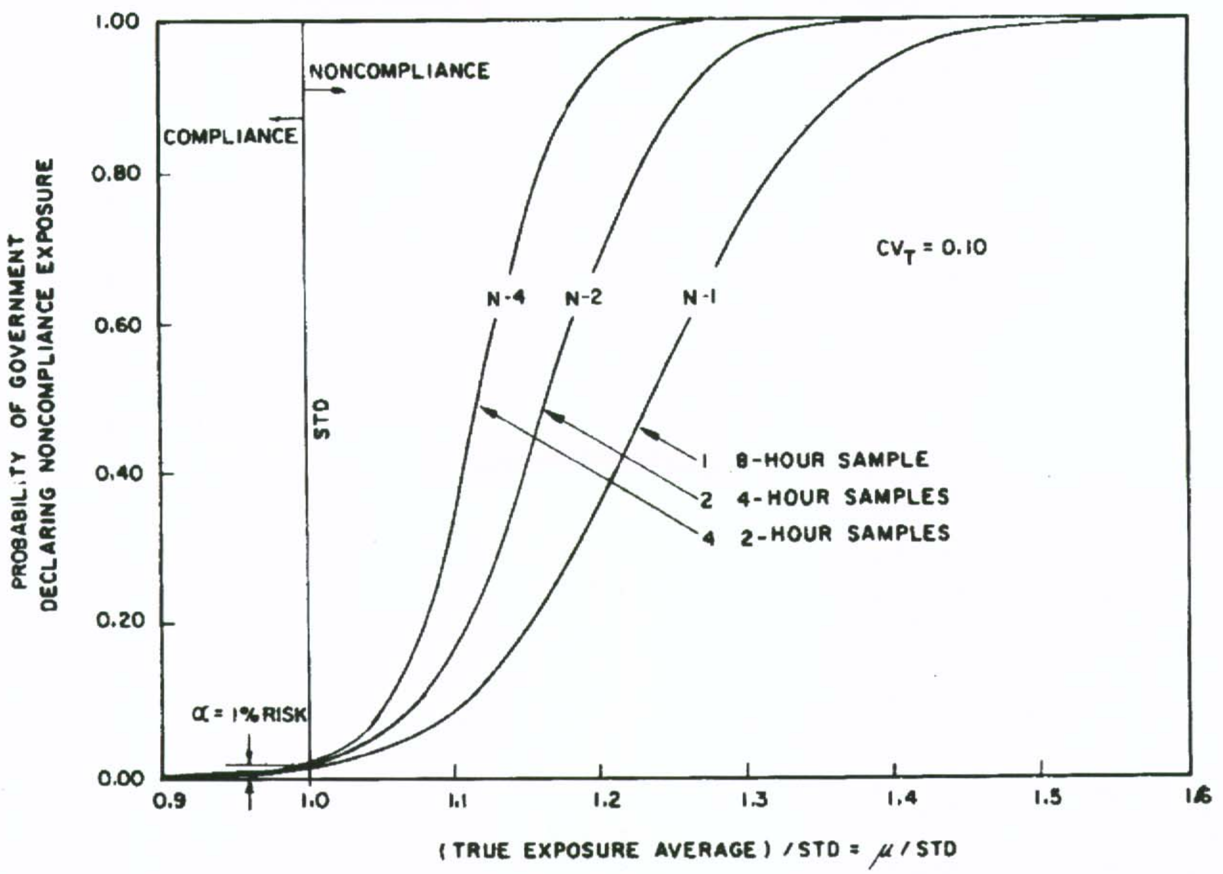

Figure J-4. Power function (PF) curve for one-sided Compliance Officer's Test (1% risk level) to detect noncompliance as given in sections 4.2.1 and 4.2.2. Calculated for sampling/analytical method with $CV_T=0.10$ (about ± 20% accuracy at 95% confidence level).

=5%). The effect on the Employer's Test (5% risk level) is shown by Figure J-2 ($CV_T=10\%$) and Figure J-5 ($CV_T=5\%$).

In conclusion, we have seen the necessity for using statistical sampling plans and decision theory both in the monitoring of employee exposures and as part of the decision making processes regarding compliance or noncompliance with mandatory health exposure standards. The use of statistical tests means that maximum desired risk levels can be selected in advance and the burden of the sampling program minimized. The selection of a 5% risk level for both compliance and noncompliance tests is appropriate in that it protects both the employer and employee aganst unreasonable risk.

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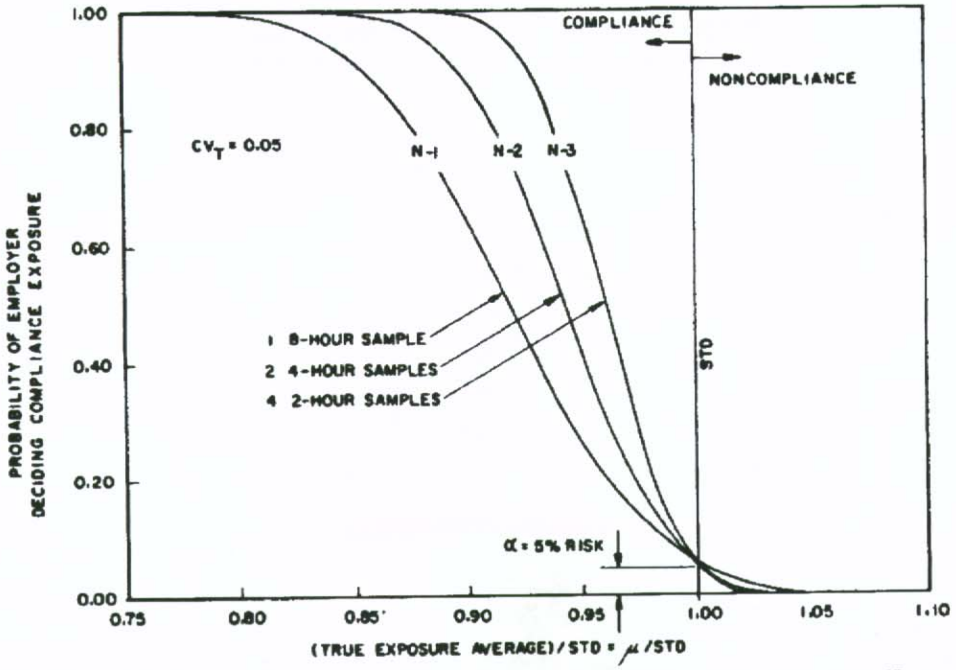

Figure J-5. Power function (PF) curve for one-sided Employer's Test (5% risk level) to ensure compliance as given in sections 4.2.1 and 4.2.2. Calculated for sampling/analytical method with $CV_T = 0.05$ (about ± 10% accuracy at 95% confidence level).

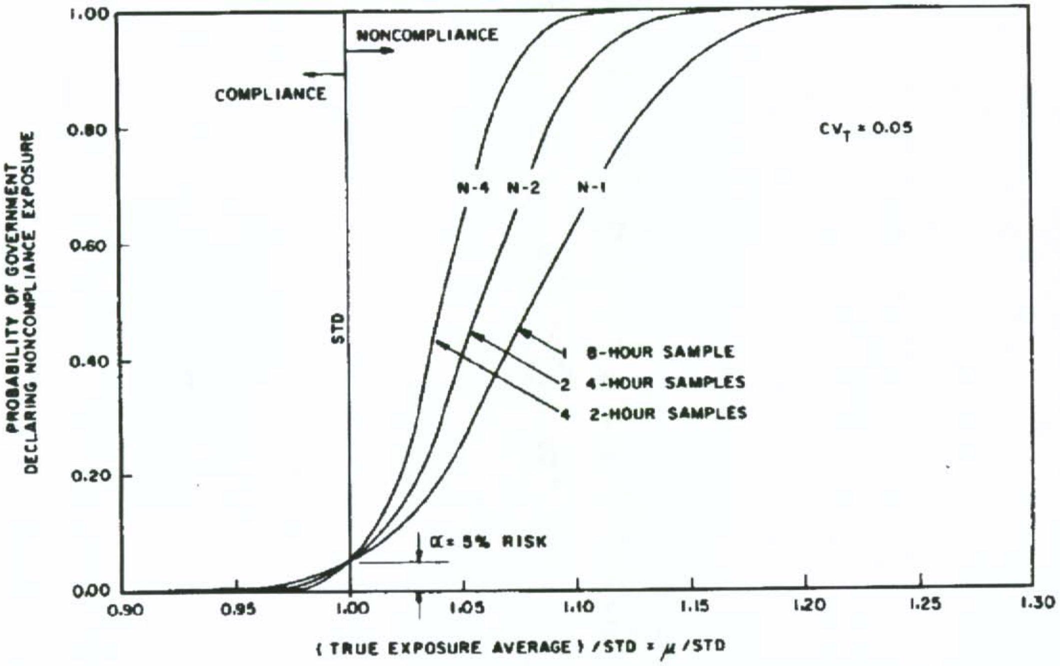

Figure J-6. Power function (PF) curve for one-sided Compliance Officer's Test (5% risk level) to detect noncompliance as given in sections 4.2.1 and 4.2.2. Calculated for sampling/analytical method with $CV_T = 0.05$ (about ± 10% accuracy at 95% confidence level).

TECHNICAL APPENDIX K*

STATISTICAL DECISION THEORY FOR CEILING EXPOSURE MEASUREMENTS

The problem in the ceiling decision procedure (section 4.3) is that given a set of samples of short (generally 15-minute) ceiling exposure measurements on any one day, an inference has to be made about the exposure during the sampled intervals and the exposure during the remaining unsampled intervals of that day.

DECISION ON THE EXPOSURE DURING THE SAMPLED INTERVALS

The decision about the exposure for the sampled intervals is made by using the one-sided confidence region for the highest observed exposure measurement. This confidence region is determined assuming that the random measurement errors are normally distributed with known standard deviation. This standard deviation is based on the coefficient of variation of the samping/analytical procedure. If all the available samples indicate (with high confidence) that the exposure during the observed intervals is below the ceiling standard (*CSTD*), use the following procedure to make a statistical inference for the remaining unsampled intervals (potential measurements).

DECISION ON THE EXPOSURE DURING THE REMAINING INTERVALS

The problem can be stated as a test of the null hypothesis:

H_0: The whole population of potential samples is below the ceiling standard (*CSTD*)

versus the alternative hypothesis:

H_1: At least one of the potential samples could exceed the *CSTD*.

Assume the following set of ceiling measurements from a given day is available, each with a duration equal to the period for which the ceiling standard has been defined: X_j, $j=1, \ldots, n$. Let

$$x_j = \frac{X_j}{CSTD}$$

be the standardized (with respect to the ceiling standard, *CSTD*) measurements.

These are short-term samples, and if they are not contiguous, it is assumed that they are independent, identically distributed, lognormal random variables. Furthermore, since only temporal variations are being considered, the random measurement error due to the sampling and analytical procedure will be neglected in this case.

The statistical model will be formulated in terms of the logarithms (base 10) of the standardized data. Therefore, let

$$y_j = \log x_j,\ j=1, \ldots, n \qquad \text{(K-1)}$$

To make a decision concerning an employee's ceiling level exposure, the following hypotheses must be tested with given maximum probabilities of error of type I and II.

$$H_0\colon y_i \leqq 0 \text{ for all } i=n+1, \ldots, \mathrm{N} \qquad \text{(K-2)}$$

versus

$$H_1\colon y_j > 0 \text{ for at least one } i,\ n+1 \leqq i \leqq N \qquad \text{(K-3)}$$

where N is the size of the sample space. If the ceiling level standard is defined for 15-minute sampling intervals, then $N=32$ for an 8-hour day. H_0 is the *compliance exposure* decision,

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*The material in this appendix was developed by Systems Control, Incorporated and originally appeared in SCI Report #5119-1, pp. 17-20 (May 1975) produced under NIOSH Contract #CDC-99-74-75.

and H_1 is the *noncompliance exposure* decision. If neither decision can be asserted with sufficiently high confidence, then a *possible overexposure* classification is made.

The above hypothesis testing problem can be formulated in terms of a probability statement. Given the set of samples $y^n \triangleq \{y_1, \ldots, y_n\}$, compute the probability of compliance.

$$P_c \triangleq \{y_{n+1} \leqq 0, \ldots, y_N \leqq 0 | y^n\} \quad \text{(K-4)}$$

The probability density of one of the potential samples can be written as

$$p(y_k|y^n) = \quad p(y_k \mu, \sigma | y^n)\, d\mu d\sigma, \; k = n+1, \ldots, N \quad \text{(K-5)}$$

where μ and σ are the (unknown) mean and standard deviation of y_j, $j = 1, \ldots, N$, and $p(y_k, \mu, \sigma|y^n)$ is the joint a posteriori density of y_k, μ, and σ given the observations y^n.

Using the fiducial distribution of μ (see reference K-1),

$$\mu \sim \mathcal{N}(\overline{y}, \frac{\sigma^2}{n}) \quad \text{(K-6)}$$

where $\mathcal{N}(a,b)$ is the normal density with mean a and variance b and

$$\overline{y} = \frac{1}{n} \left[\sum_{i=1}^{n} y_i \right] \quad \text{(K-7)}$$

Assuming for the present σ as known, one obtains from equation K-5

$$p(y_k|y^n) = \mathcal{N}[\overline{y}, \sigma^2(1+\frac{1}{n})] \quad \text{(K-8)}$$

Then,

$$P\{y_k > 0 | y^n\} = {}_0^{\infty} \mathcal{N}[y_k; \overline{y}, \sigma^2(1+\frac{1}{n})]\, dy_k \triangleq \beta \quad \text{(K-9)}$$

$$k = n+1, \ldots, N$$

The probability of compliance (equation K-4) is now given by

$$P_c = \prod_{k=n+1}^{N} P\{y_k \leqq 0\} \quad \text{(K-10)}$$

$$= \prod_{k=n+1}^{N} [1 - P\{y_k > 0\}]$$

Using the notation introduced in equation K-9 one has

$$P_c = (1-\beta)^{N-n} \quad \text{(K-11)}$$

If $(N-n)\, \beta < < 1$, then a good approximation for the above is

$$P_c = 1 - (N-n)\, \beta \quad \text{(K-12)}$$

The assumption of known σ is not totally justified. An approach that would account for this additional uncertainty could be developed along the lines of (K-2) using Bayesian arguments with diffuse priors. However, the complexity of the resulting procedure would prevent it from being implemented. The sample variance

$$s^2 = \frac{1}{n-1} \sum_{j=1}^{n} (y_j - \overline{y})^2 \quad \text{(K-13)}$$

is recommended for equation K-9 in place of σ^2.

Equation K-11 indicates that if $N-n$ (number of unobserved intervals) is large, the probability of compliance P_c becomes small. There are more "chances" for at least one sample to exceed the standard. Therefore, the direct application of equation K-11 might be overly pessimistic.

This leads to the concept of expected number of peaks during a day. Suppose that a "biased" ceiling sample procedure was used to obtain a few random samples from expected "critical" intervals. From knowledge of the industrial process, suppose the number of remaining peaks during the day is available and equal to n'. Then the number of unsampled intervals in equation K-9 is taken as n', rather than $N-n$. If all the n' peak intervals were sampled, there would be no need to go to the inference procedure for the unsampled intervals and the only test to be done would be the one described in the section on "Decision on the Exposure During the Sampled Intervals," above. Recall that the motivation for developing the inference procedures based upon samples from only a part of the workday stems from the basic objective of minimizing the employer's burden. Thus, if the available samples have been taken from known peaks and there are in addition n' unsampled expected peaks during the day, then the decision (exposure classification) is made based upon

$$P_c = (1-\beta)\, n' \qquad \text{(K-14)}$$

if the available samples do not indicate overexposure or exposure. If the probability of compliance P_c exceeds a present threshold — say 0.9 — the worker is classified as unexposed. On the other hand, if P_c is below another threshold — say 0.1 — then the worker can be classified as overexposed. Otherwise, the classification is "exposed."

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TECHNICAL APPENDIX L

THE NEED FOR AN OCCUPATIONAL EXPOSURE MEASUREMENT ACTION LEVEL*

Some of the proposed OSHA standards define the *action level* as one-half the value of the *permissible exposure limit* currently found in Tables Z-1, Z-2, and Z-3 of 29 CFR 1910.1000. The *action level* is the point at which certain provisions of the proposed standards must be initiated, such as periodic employee exposure measurements, training of employees, and medical surveillance (if appropriate for the particular substance). These provisions are initiated if *single day exposure measurements* on an employee exceed the *action level*.

Section 6(b)(7) of the Occupational Safety and Health Act directs that, where appropriate, occupational health standards shall provide for monitoring or measuring employee exposure at such locations and intervals in such a manner as may be necessary for the protection of employees. NIOSH and OSHA recognized the need to designate an exposure measurement level at which these procedures become appropriate. The function of the action level is to designate this exposure measurement level.

The objective of this presentation is to explain the necessity for an employee exposure measurement action level and its relation to variations in the occupational environment.

Employee exposure monitoring programs are analogous to quality control and assurance programs used widely in industry. The daily average of concentrations that an employee is exposed to during his employment is very similar to a product off an assembly line. The assembly line product and, by analogy, daily exposure average are subject to

- random fluctuations in the process such as between employees or machines performing the same task;
- gradual trends toward an out-of-tolerance state of the process such as might be caused by machine tool wear; and
- sudden occurrence of defective parts due to drastic changes in the process.

There are also similarities in purpose between employee exposure monitoring programs and quality control programs (Table L-1).

Each of the factors in Table L-1 has been considered in the proposed OSHA standards. Two factors in particular (numbers 1 and 6) have special relevance to the action level concept: the *variations* in employees' daily exposures and *limiting the risk* (to a low probability) that an employee will be overexposed due to failure to detect days of high exposure.

The action level was set with the view that the employer should minimize the probability that even a very low percentage of actual daily employee exposure averages (8-hour time-weighted averages [TWA]) will exceed the standard. That is, the employer should monitor employees in such a fashion that he has a high degree of confidence that a very high percentage of actual daily exposures are below the standard. In statistical terms, the employer should try to attain 95% confidence that no more than 5% of employee days are over the standard.

It is important to realize that the employee's exposure concentration is not a fixed phenomenon. In statistical terms, the exposure concentrations fluctuate in a lognormal manner. First, the exposure concentrations are fluctu-

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*This material was originally presented by Nelson A. Leidel at the OSHA Informal Public Hearing on Proposed Ketone Standards, Washington, D.C., September 4, 1975. The full NIOSH Technical Report is available as Reference L-2.

TABLE L-1. COMPARISON OF QUALITY CONTROL AND EMPLOYEE EXPOSURE MONITORING PROGRAMS

Quality control programs	Employee exposure monitoring programs
1. Identify variation in product quality due to —differences among machines; —difference among workers; —differences in raw materials or component parts; —differences in each of these factors over time.	1. Identify variation in measurements of employees' daily exposures due to —differences in work techniques of individual employees (even in the same job category); —differences in the exposure concentrations during a day (reflected in grab samples); —differences in the average daily exposure concentrations between days; —differences due to random variations in sampling and analysis.
2. Detect if a product is out of tolerance or a process is yielding unsatisfactory products.	2. Detect if any employee exposures exceed a permissible limit.
3. Institute sampling plans that furnish a maximum amount of protection against sampling errors with a minimum amount of inspection.	3. Institute a monitoring program that needs a minimum amount of sampling for a maximum amount of protection against exposure measurement errors.
4. Institute methods that indicate quickly when something is wrong or about to go wrong with the process before defective products are made.	4. Institute exposure measurement plans that indicate when the occupational exposures are hazardous or approaching hazardous levels before overexposures occur.
5. Periodically sample from a production process.	5. Periodically measure an employee's daily exposure.
6. Limit to a low probability that a bad lot (one containing defectives) will be accepted on the "luck of the draw" inherent in the sampling process.	6. When not all exposure days are measured, limit, to a low degree, an employee's probability of overexposure caused by failure to detect high exposure days.
7. Detect and attempt to correct sources of process variation that lead to defects.	7. Detect and try to eliminate sources of high employee exposures.

ating over the 8-hour period of the TWA exposure measurement. Breathing zone grab samples (samples of less than about 30 minutes' duration — typically, only a few minutes) tend to reflect the environmental variation within a day so that grab sample results have relatively high variability. However, this variation in the sample results can be eliminated by using a full period sampling strategy as discussed by Leidel and Busch (L-1) and Chapter 3. Second, the day-to-day variation of the true 8-hour TWA exposures is also lognormally distributed. It is this day-to-day variation that creates a need for an action level based on only one day of required exposure measurement. The one day's measurement is used to draw conclusions regarding compliance on unmeasured days and is the sole basis for deciding whether further measurements should be made on a particular employee.

Environmental variation is expressed by the geometric standard deviation (*GSD*). A *GSD* of 1.0 represents absolutely no variation in the environment whereas *GSD*'s of 2.0 and above represent relatively high variation. When based on analysis of gas, vapor, and particulate data, it was concluded that very few industrial operations have day-to-day environmental *GSD*'s less than about 1.2.

If one particular day's exposure measurement showed an 8-hour employee exposure average less than the standard, we could not conclude that all other days' exposures are less than the standard. This is because the true daily exposure average on one day was drawn from a lognormal distribution of all other true daily exposures over a period of time. The long term exposure average is assumed to remain stable, but the sample on a particular day might have come from a low portion of the distribution. Even though the one daily exposure average is less than the standard, there is a risk of other daily averages exceeding the standard.

A statistical model was developed that showed the relation of the probability (risk) that at least a given percentage of true daily exposure averages will exceed the standard, as a function of

- 8-hour TWA employee exposure measurement on one day as a fraction of the standard, and
- day-to-day environmental variation of true daily exposure averages (*GSD*), and
- precision and accuracy of the sampling and analytical method used in the measurement process.

The graphic results of this model are shown in Figure L-1. For the graphic presentation, a 10% sampling and analytical coefficient of variation (CV_T) was assumed. This corresponds to an *accuracy* for the measurement method of about 20% at a confidence level of 95%. However, the curves are labeled for "pure" day-to-day variation. It is very important to realize that the random measurement errors due to the sampling and analytical procedure make a very minor contribution to the calculated employee risk of having a given percentage of true daily averages exceed the standard. This calculated risk is almost solely a function of the day-to-day variation.

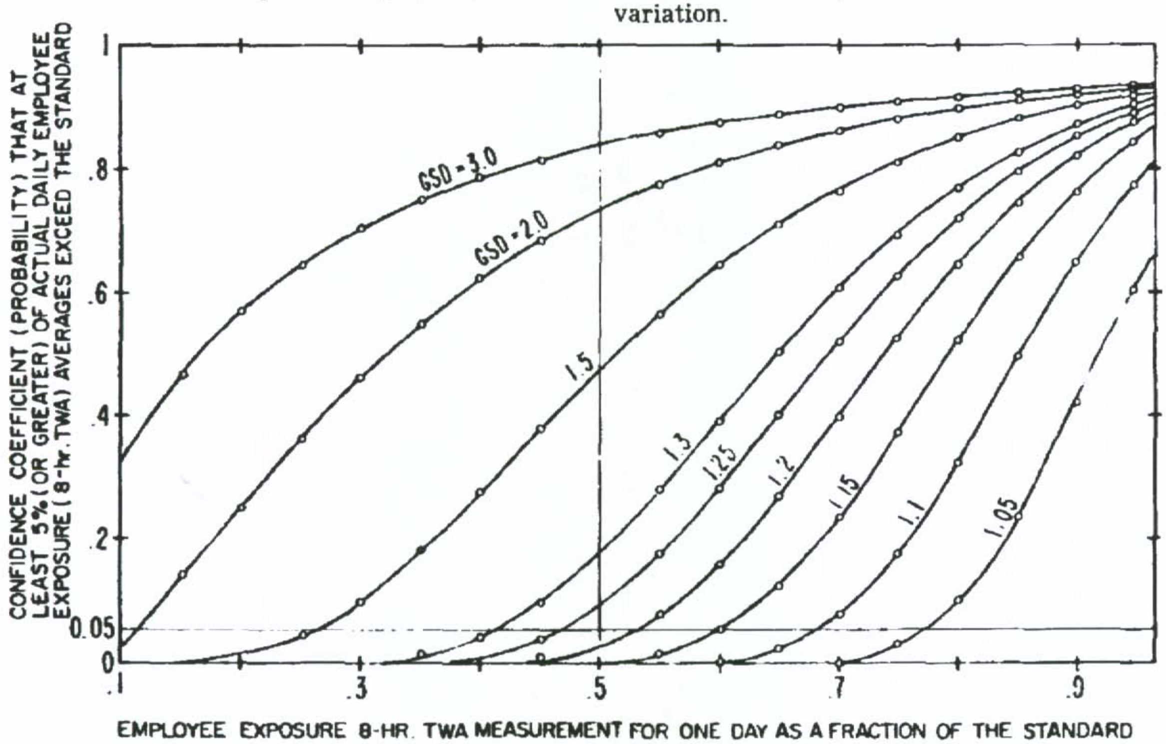

Figure L-1. Employee overexposure risk curves for one 8-hour TWA exposure measurement.

Thus, Figure L-1 shows the probability that at least 5% of an employee's unmeasured true daily exposure averages will exceed the standard given the fact that one day's measurement happened to fall below the standard. Declaring an employee as *safe* and never sampling again because one day's exposure measurement fell below the standard would be analogous to accepting a factory's entire production on the basis of only one tested product. That is why an action level of one-half the standard is necessary as a "trigger" to ensure further sampling of an employee. An exposure measurement as low as one-half the standard indicates sufficient probability of an employee's exposure exceeding the standard on other days so that additional measurements are needed to ensure adequate protection of that employee.

Figure L-1 shows that employees with day-to-day exposure average GSD's of less than about 1.22 (combined with a sampling/analytical CV_T of 10%) have less than 5% probability of having 5% of their true daily exposures exceed the standard on unmeasured days. It is likely that very few day-to-day GSD's are less than 1.22. Note that if one measured daily exposure average is at one-half the standard, then the following much higher probabilities exist that at least 5% of the unmeasured true daily averages exceed the standard:

Day-to-day variation	*Probability, %*
$GSD = 1.3$	17
$= 1.5$	47
$= 2.0$	72
$= 3.0$	83

Finally, it should be noted that the above considerations concerning the stability of the distribution of true daily exposures the employee encounters are very conservative. Only random variations are considered. We have not considered unpredictable upward trends or sudden increases in daily exposures caused by changes in the employee's environment, such as closed plant doors and windows in cold seasons, decreased efficiency of or failure of engineering control measures (e.g., ventilation systems), or changed production processes leading to increased exposure.

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TECHNICAL APPENDIX M*

NORMAL AND LOGNORMAL FREQUENCY DISTRIBUTIONS

The statistical methods discussed in this manual assume that concentrations in random occupational environmental samples are lognormally and independently distributed both within any particular workshift and over many daily exposure averages. Additionally, it is assumed that the sampling and analytical errors of an industrial hygiene measurement sample are normally and independently distributed. The technical reasons for the choice of these two distributions for modeling our data distributions are given below. There is nothing sacred about the choice of these distribution models. They were chosen because they occur very frequently in industrial hygiene applications, and they are easy to use because their properties have been thoroughly investigated. The empirical observation that the data usually are well-fitted by the normal and lognormal models is no guarantee that all data fit these models. If there is any doubt about the appropriate application of the normal or lognormal model, the first step in the data analysis should be to sketch a distribution histogram or use probability paper as discussed in Technical Appendix I. Also refer to Technical Appendix I for examples of data that might not be adequately described by the lognormal model.

Before sample data can be statistically analyzed, we must have knowledge of the frequency distribution of the results or some assumptions must be made. Roach (M-2–M-4) and Kerr (M-5) have assumed that environmental data are normally distributed. However, it is well established (M-6–M-9) that most community air pollution environmental data are better described by a lognormal distribution. That is, the logarithms (either base *e* or base 10) of the data are approximately normally distributed. Most importantly, Breslin et al. (M-10), Sherwood (M-11, M-12), Jones and Brief (M-13), Gale (M-14, M-15), Coenen (M-16, M-17), Hounam (M-18), and Juda and Budzinski (M-19, M-20) have shown that occupational environmental data from both open air and confined work spaces for both short (seconds) and long (days) time periods are lognormally distributed.

What are the differences between normally and lognormally distributed data? First, it should be remembered that a "normal" distribution is completely determined by the arithmetic mean μ and the standard deviation σ of the distribution. On the other hand, a lognormal distribution is completely determined by the median or geometric mean (*GM*) and the geometric standard deviation (*GSD*). For lognormally distributed data, a logarithmic transformation of the original data is normally distributed. The *GM* and *GSD* of the lognormal distribution are the antilogs of the mean and standard deviation of the logarithmic transformation. Normally distributed data have a symmetrical distribution curve whereas lognormally distributed environmental data are generally positively skewed (long "tail" to the right indicating a larger probability of very large concentrations when compared with a lower probability expected of normally distributed data). Figure M-1 compares a lognormal distribution to a normal distribution with the same arithmetic mean μ and standard deviation σ. The conditions conducive to (but not all necessary for) the occurrence of lognormal distributions are found in occupational

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*This material in part was originally presented in Leidel and Busch, *Exposure Measurement Action Level and Occupational Exposure Variability* (NIOSH Technical Information, HEW Publication No. (NIOSH) 76-131, Cincinnati, Ohio, December 1975) and Reference M-1.

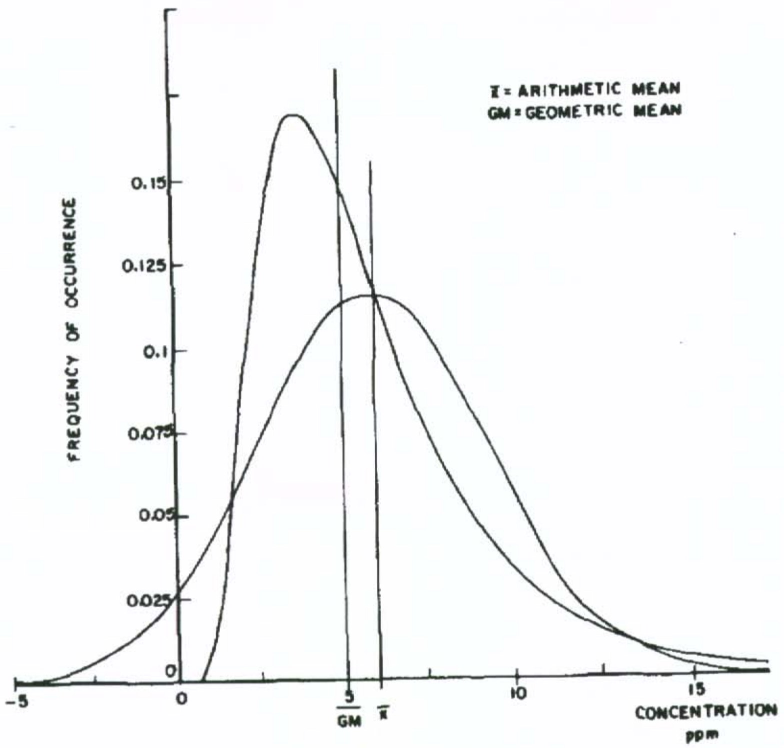

Figure M-1. Lognormal and normal distributions with the same arithmetic mean and standard deviation.

environmental data (M-16). These conditions are that

- the concentrations cover a wide range of values, often several orders of magnitude,
- the concentrations lie close to a physical limit (zero concentration),
- the variation of the measured concentration is of the order of the size of the measured concentration, and
- a finite probability exists of very large values (or data "spikes") occurring.

The variation of occupational environmental data (differences between repeated measurements at the same site) can usually be broken into three major components: random errors of the sampling method; random errors of the analytical method; and variation of the environment with time. The first two components of the variation are usually known in advance and are approximately normally distributed. The environmental fluctuations of a contaminant in a plant, however, usually greatly exceed the variation of known instruments (often by factors of 10 or 20). The above components of variation were discussed in an article by LeClare et al. (M-21).

When several samples are taken in a plant to determine the average concentration of the contaminant and estimate the average exposure of an employee, the lognormal distribution should be assumed. However, the normal distribution may be used in the special cases of taking a sample to check compliance with a ceiling standard, and taking a sample (or samples) for the entire time period for which the standard is defined. In these cases, the entire time interval of interest in represented in the sample, with only normally distributed sampling and analytical variations affecting the measurement.

The relative variation of a normal distribution (such as the random errors of the sampling and analytical procedures) is commonly measured by the coefficient of variation (*CV*). The *CV* is also known as the relative standard deviation. The *CV* is a useful index of dispersion in that limits consisting of the true mean of a set of data, plus or minus twice the *CV*, will contain about 95% of the data measurements. Thus, if an analytical procedure with a *CV* of 10% is used to repeatedly measure some nonvarying physical property (such as the concentration of a chemical in a beaker of solution), then about 95% of the measurements will fall within plus or minus 20% (2 times the *CV*) of the true concentration.

Unfortunately, the property we are trying to measure — the employee's exposure concentration — is not a fixed physical property. The exposure concentrations are fluctuating in a lognormal manner. First, they are fluctuating over the 8-hour period of the TWA exposure measurement. Breathing zone grab samples (samples of less than about 30 minutes' duration, typically only a few minutes) tend to reflect the environmental variation within a day so that grab sample results have relatively high variation. However, this variation in the sample results can be eliminated by going to a full period sampling strategy as discussed by Leidel and Busch (M-1). Second, the day-to-day variation of the true 8-hour TWA exposures is also lognormally distributed.

Environmental variation is expressed by the *GSD*. A *GSD* of 1.0 represents absolutely no variation in the environment. *GSD*'s of 2.0 and above represent relatively high variation. Hald (M-22) states that the shape of lognormal distributions with low variations, such as those with *GSD*'s less than about 1.4, roughly approximate normal distribution shapes. For this range of *GSD*'s, there is a rough equivalence between the quantity $(GSD-1)$ and the *CV*, as follows:

GSD	$(GSD-1)$	*CV*
1.05	0.05	0.049
1.10	0.10	0.096
1.20	0.20	0.18
1.30	0.30	0.27
1.40	0.40	0.35

For those interested in a detailed study of the lognormal distribution, Aitchinson and Brown (M-23) is an excellent reference. Figure M-2 shows four different lognormal distributions that share a common arithmetic mean of 10 ppm. Four different variations are shown with *GSD*'s of 1.2, 1.5, 2.0, and 3.0.

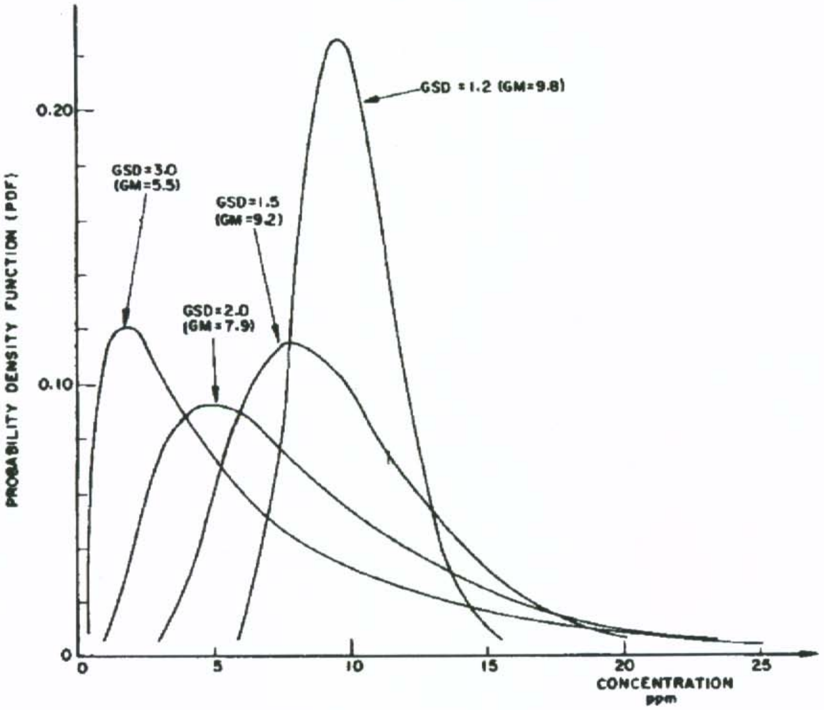

Figure M-2. Lognormal distributions for arithmetic mean concentration of 10 ppm.

CONVERSION FORMULAS FOR A LOGNORMAL FREQUENCY DISTRIBUTION

If the variable ($\ln x$) is normally distributed (the variable x has a lognormal distribution), we can define

μ = true arithmetic mean of x-distribution
σ = true standard deviation of x-distribution
μ_l = true arithmetic mean of ($\ln x$) values
σ_l = true standard deviation of ($\ln x$) values
GM = geometric mean of x-distribution
GSD = geometric standard deviation = exp (σ_l) where ($\ln x$) was used to calculate σ_l
GSD = antilog$_{10}$ (σ_l) where ($\log_{10} x$) was used.

The conversion relations between the above six parameters are given in Table M-1.

Notes:

1. The relations apply *only* to the true parameter of the parent distribution. They *should not* be used for parameters of a sample except as a very rough approximation.
2. The GM and GSD are used to describe parameters of either a sample or the parent distribution, but they cannot be used in the relations unless they are calculated from the true parent distribution.
3. The GSD of the x-distribution is the same regardless of whether base 10 or base e logarithms were used to calculate σ_e.

TABLE M-1. CONVERSION RELATIONS BETWEEN LOGARITHMIC PARAMETERS AND ARITHMETIC PARAMETERS OF A LOGNORMAL DISTRIBUTION

Given	To obtain	Use
μ_l	$GM =$	$\exp(\mu_l)$
μ, σ	$GM =$	$\mu^2/\sqrt{\mu^2+\sigma^2}$
σ_l	$GSD =$	$\exp(\sigma_l)$
μ, σ	$GSD =$	$\exp\sqrt{\ln\left(1+\frac{\sigma^2}{\mu^2}\right)}$
μ_l, σ_l	$\mu =$	$\exp\left(\mu_l+\frac{1}{2}\sigma_l^2\right)$
GM, σ_l	$\mu =$	$(GM)\exp\left(\frac{1}{2}\ \sigma_l^2\right)$
μ_l, σ_l	$\sigma =$	$\sqrt{[\exp(2\mu_l+\sigma_l^2)]\,[\exp(\sigma_l^2)-1]}$
GM, σ_l	$\sigma =$	$\sqrt{(GM)^2\,[\exp(\sigma_l^2)]\,[\exp(\sigma_l^2)-1]}$
GM	$\mu_l =$	$\ln(GM)$
μ, σ_l	$\mu_l =$	$\ln\mu-\frac{1}{2}\sigma_l^2$
GSD	$\sigma_l =$	$\ln(GSD)$
μ, σ	$\sigma_l =$	$\sqrt{\ln\left(1+\frac{\sigma^2}{\mu^2}\right)}$
μ_l, σ_l	*mode*	$\exp(\mu_l-\ \sigma_l^2)$ = most frequent value

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TECHNICAL APPENDIX N

GUIDELINES FOR SELECTING AND USING AN INDUSTRIAL HYGIENE CONSULTANT

KNOWING WHEN A CONSULTANT IS NEEDED

Having read the previous chapters, you should have a feeling for the situations that you can deal with on your own. If you are still unsure of the solution or if preliminary control measures have proved unsatisfactory, it may be time to consider the use of a consultant. Industrial hygiene consultants are primarily used to accomplish two major objectives. The first is to identify and evaluate potential health and safety hazards to workers in the occupational environment. The second objective is to design and evaluate the effectiveness of controls to protect the workers in the workplace. The material and guidelines of this appendix are based on material presented in Chapter 6 of the *Industrial Noise Control Manual* (N-1). That manual should be referred to for guidelines for selecting a noise control engineering consultant.

Even though you may be familiar with the chemicals and processes used in your plant or shop, you may not believe you have the background or training to evaluate their health effects and recognize potentially hazardous exposure situations. Competent industrial hygiene consultants are able to perform these tasks because of their training and experience. Also, consultants can efficiently and economically evaluate the size of employee exposures, because of their knowledge of the proper sampling equipment and analytical procedures required.

Consultants can also recommend whether or not control measures are required and the alternatives available. They can design, supervise the installation of, and evaluate the effectiveness of control measures. Alternatives include substituting less toxic materials and changing the process, engineering controls, administrative controls, and personal controls such as respirators. Also, if you have installed control measures that don't work, you may have to use a consultant to resolve the problem. Although this may be a painful decision, it should occur only once. You should document the situation thoroughly and use the consultant to supply information on what went wrong, either through improper design, improper installation, or both.

Consultants can be used to keep you aware of the requirements of current Federal and state regulations in the area of occupational safety and health. They can inform you when medical examinations of your employees may be recommended or required by regulation. They should be able to recommend appropriate physicians or clinics in your area specializing in occupational medicine. The consultant can play a valuable role in providing the examining physician with information on the occupational exposures of each employee examined and alert the physician to particular medical tests either recommended or required by regulations. Consultants can also design employee training programs and provide information for them. A consultant can serve as an expert witness if you are involved in a lawsuit and data must be obtained, interpreted, and presented by a disinterested third party.

SELECTION OF A CONSULTANT

Now that you have decided to obtain a consultant, how do you proceed? You should first be aware that currently any person can legally offer services as an industrial hygiene consultant. Consequently, it is up to you to avoid those who are unsuitable because of lack of training, inexperience, or incompetence.

Individuals or firms billing themselves as industrial hygiene consultants can be broadly classified according to whether they recommend a particular monitoring procedure, medical examination service, or control process, or are independent consultants.

These product-oriented individuals or firms vary in their backgrounds from nontechnical product salespersons to experienced industrial hygiene professionals. Special interest consultants, who are most commonly identified by the degree of their association with manufacturing or retail sales of occupational health and safety products, should be used only if, by the use of the techniques described in the previous chapters, you have satisfied yourself that you know what sampling strategy or control procedure is applicable to your situation. In this case, "consulting" consists mainly of recommending appropriate exposure monitoring equipment and analytical facilities. This type of consultation may include assistance in soliciting proposals for the design and installation of control equipment, such as ventilation control systems or respirators. The main problem remaining is to write the contract in such a way that you are guaranteed (to the extent possible) a solution to your problem at a reasonable cost. The advantage of using this group directly is that you avoid consultant costs and pay only for the product or service. In effect, you are acting as your own consultant. The disadvantage in dealing with a product-oriented consultant is that a costly mistake, more expensive than the independent consultant's fees, is more likely since these consultants may not consider all options available. Examples abound of cases where thousands of dollars were spent in purchasing a particular type of monitoring equipment or in implementing a particular control system, only to discover that the desired results were not obtained.

If there are any doubts in your mind as to the proper method for solving your problem, then an independent consultant (one free from ties to a particular service or line of products) should be called in. It is this type of industrial hygiene consultant that will be discussed for the remainder of this appendix.

There are several sources one can go to for information and names of consultants available locally. The National Institute for Occupational Safety and Health (NIOSH) has 10 regional offices across the country located in large cities. Their phone numbers are listed under "United States Government, Department of Health, Education, and Welfare." NIOSH regional offices usually have lists of consultants in their region (consisting of several states). NIOSH offices can provide technical information on a wide range of occupational safety and health topics. The Occupational Safety and Health Administration (OSHA) has both regional offices and several area offices in each region. OSHA office phone numbers are listed under "United States Government, Department of Labor." OSHA offices can also provide technical information particularly regarding Federal occupational safety and health standards. OSHA offices are particularly valuable in assisting in the determination of what standards may be applicable to your firm and their proper interpretation.

Other sources of information are the professional associations and public service organizations related to occupational safety and health. Three national groups are the American Industrial Hygiene Association (AIHA), American Society of Safety Engineers (ASSE), and the National Safety Council (NSC). These three have local chapters, sections, or offices in major cities which are a source of information and assistance. The AIHA publication *American Industrial Hygiene Association Journal* contains a list of industrial hygiene consultants in several issues each year.

Additional sources are a little more difficult to pursue. Useful information may be found in the Yellow Pages of your phone book. The headings to look under are Safety Consultants, Safety Equipment and Clothing Suppliers, Air Pollution Control, and so on. Many insurance companies now have loss prevention programs that employ industrial hygienists. Make inquiries of your present insurer and perhaps compare the services they offer to those of other insurance companies. Finally, there may be a university or college in your area that has an environmental health program. Generally their staff professionals are available for consultation.

GUIDELINE QUESTIONS TO ASK PROSPECTIVE CONSULTANTS

The best protection against an incompetent consultant is to question the prospective consultant yourself. A series of questions is given below. They should not be given equal weight since some are minor in importance. (The list is organized roughly in descending order of importance.)

EXPERIENCE

1. For how many years have you been professionally active in industrial hygiene?
2. Please supply a list of recent clients that you have served, preferably in my geographical area, and on problems similar to those in which I am interested. Are you retained by any clients on a continuing basis? (Be sure to call a few of these references to obtain their opinion on the consultant's services.)
3. What teaching have you done or training have you had in industrial hygiene? What groups were involved: university, industry, trade associations, civic groups, engineers, symposia?

CONSULTATION STATUS

1. Are you now an independent consultant? For how many years? Full time or part time?
2. If part time:
   a. Who is your chief employer or in what other business ventures are you involved?
   b. Is your employer aware and does he approve of your part time activity as an industrial hygiene consultant?
   c. May we contact your employer concerning you?
   d. What restrictions does your employer place on you as a part time consultant?
3. Are you associated with the manufacture or sale of a product that could create a conflict of interest in your activities as a consultant?

EDUCATION

1. What schools did you attend and what courses did you take related to industrial hygiene?
2. What degrees did you receive and when?
3. What special conferences, seminars, symposia, or short courses have you attended (especially recently) to stay current with industrial hygiene technical information and governmental regulations?
4. What other sources of information do you use to stay current with the field of industrial hygiene?

PROFESSIONAL AFFILIATIONS

1. What professional associations do you belong to? (Representative ones are the American Industrial Hygiene Association, American Conference of Governmental Industrial Hygienists, American Society of Safety Engineers.) What is your present grade of membership and length of time in that grade for each association?
2. Are you certified by any of the following?
   a. American Board of Industrial Hygiene (specify area of certification)
   b. Board of Certified Safety Professionals
   c. Environmental Engineering Intersociety Board (as an industrial hygiene engineer)
3. Are you a registered professional engineer? In what states and disciplines?
4. Of what professional engineer associations are you or your firm a member?
5. Of what trade associations, chambers of commerce, or similar business groups are you or your firm a member?

SPECIAL CAPABILITIES

1. In what areas of industrial hygiene do you specialize?
   —Comprehensive plant studies and/or analyses
   —Ventilation
   —Noise control
   —Audiometry
   —Biological monitoring
   —Heat stress
   —Ergonomics
   —Occupational medicine
   —Safety
   —Product safety and labeling
   —Radiological control
   —Training instruction
   —Air pollution
   —Meteorology
   —Waste disposal
   —Water pollution
2. What equipment do you have for conducting industrial hygiene evaluations in my plant or shop?
3. What laboratories do you use for the analysis of your exposure measurement samples? Are they accredited by the American In-

dustrial Hygiene Association? Do they participate in the NIOSH Proficiency Analytical Testing Program (PAT) and for what materials? (The AIHA Journal periodically publishes a list of accredited laboratories.)

4. What equipment do you have for calibrating test apparatus such as pumps and direct-reading instruments? Do you have a calibration program for your equipment?
5. Can you refer me to a physician or clinic capable of doing preplacement examinations, periodic examinations, or diagnostic examinations of my employees if these may be required? Do you have any business connection with these individuals or firms?
6. Can you refer me to engineering firms capable of installing controls such as local exhaust ventilation systems if these may be necessary? Do you have any business connection with these firms?
7. Can you refer me to appropriate safety equipment supplies if personal protective equipment is necessary for any of my employees? Do you have any business connection with these firms?
8. Can you serve as an expert witness, either for your client or as a friend of the court? What experience have you had as an expert witness?

BUSINESS PRACTICES

1. Please indicate your fee structure. Do you work by hourly charges, estimates for the total job, retainer charges, or any of these?
2. In your charges, how do you treat such expenses as travel, subsistence, shipping, report reproduction, and computer time?
3. Can you supply a list of typical laboratory analytical fees?
4. If you use a contract form, please supply an example.
5. What insurance and bonding do you have?
6. What statements do you have in your contracts covering commercial security, liability, and patent rights?
7. What restrictions are there on the use of your name in our reports, in litigation, or in advertisements?
8. What is the character and extent of reports that you prepare? Can you supply an example?
9. What facilities do you have for producing design drawings for control systems that may be necessary?
10. What is the size of your staff? What are their qualifications? Who will be working on this project?
11. Do you have branch offices? Where?
12. Are you operating as an individual, partnership, or corporation?

THE PROPOSAL

Once you have selected a consultant, you can arrange to obtain his services in several ways. A verbal commitment is sometimes all that is necessary. However, you may wish to request a written proposal that spells out the steps to be taken in the solution of your problem.

Often, in a larger job, proposals from several points of view are evaluated and used as one of the bases for the final selection of the consultant. In this case, answers to pertinent questions in the preceding section may be sought in the proposal rather than in the interview. If so, evaluation of the proposal from this point of view is self-evident from the above discussion. If the questions you are interested in are not answered to your satisfaction, don't hesitate to ask for further clarification. In the discussion below, we are concerned with the section of the proposal that outlines the consultant's approach to your problem.

Aside from background qualifications of the consultant, the proposal should answer the questions:

1. How much is the service going to cost? Smaller jobs are often bid on an hourly basis, with a minimum of one-half day's work, plus direct expenses commonly specified. Larger jobs are usually bid at a fixed amount, based on the work steps described.
2. What is the consultant going to do? The answer to this question may range all the way from a simple agreement to study the problem to a comprehensive step-by-step plan to solve it.
3. What will be the end result? The answer to this question is all too often not clearly understood; the result is usually a report that specifies the consultant's recommendation. If you do not want to pay for the preparation of a written report, and a verbal one will do, specify this in advance. Since recommendations often call for construction to be carried out by others, whose

work is not subject to the consultant's control, results can usually not be guaranteed. Rather, an estimate of the exposure control to be attained is all that can be expected. If the consultant is to provide drawings from which the contractor will work, one must specify sketches or finished drawings. Generally, sketches are sufficient. If special materials are required, the consultant should agree to specify alternative selections, if possible. If you want a guaranteed result, experimental work will usually be necessary.

OTHER SERVICES

If you wish, the consultant can also monitor construction to determine compliance with specifications. The consultant can also measure after installation to confirm predictions and supply oral briefings as needed.

If the consultant is to serve as an expert witness for you, you will find that he is not automatically on your side. Rather, he is more like a friend of the court, devoted to bringing out the facts he has developed, with careful separation of fact from expert opinion. Complete frankness is needed if you want to avoid unpleasant surprises. For example, the consultant may be asked by the opposing attorney for a copy of his report to you. Thus, the report should be prepared with this possibility in mind.

If the consultant is retained to develop a specific control device for you, work out an agreement on patent rights. Ordinarily the patent is assigned to the client, with perhaps a royalty arrangement for the inventor.

For many situations, the consultant will need photographs and plans of machines and shop layout for his evaluation. Permission to obtain these can be granted in a manner consistent with your industrial security system.

The comments in this chapter should be read with the understanding that, where legal aspects are involved, appropriate legal counsel will be obtained to work with you and your consultant.

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