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*

COLUMN \ ROW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	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	19	84	90	20	20	50	87	74	93	51	62	10	23	30
6	60	46	18	41	23	74	73	51	72	90	40	52	95	41	20	89	48	98	27	38	81	33	83	82	94
	32	80	64	75	91	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	07	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	06	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	30	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	[illegible]	53	36	39	77	69	06	25	07
	[illegible]	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	13	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	80	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	93	47	41	38	36	33	95	05	90	26	72	85	23	23	30	70	51	56	93	23	84	80
	44	62	20	81	21	57	57	85	00	47	26	10	87	22	45	72	03	[illegible]	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	11	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

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

1. identify all employees who may be exposed at or above the action level, and
2. measure the exposure of the employees so identified.

The intent of this provision is to require exposure measurements only for those employees with significant exposures. The employer must define the population at risk and then measure the exposure of each of those employees. It is important to realize that the intent of the provision cannot be met by sampling a subgroup of workers and assigning the average exposure obtained to all workers except under unusual circumstances. This is because of the considerable variation in employee exposures, even between employees supposedly doing the same job. Further explanation of this is given in Technical Appendix B, Exposure Variation in Occupational Groups of Similar Expected Exposure Risk.

Whether a maximum risk individual may be identified or the equal-risk-group partial sampling procedure is used, the object remains the same — to determine if the measured exposure of any employee is above the action level. If the exposure of the most exposed employee, regardless of how he is identified, is below the action level, then it is reasonable to assume that measurements of exposure of the other employees in that operation would be below the action level. No further action is necessary until some change in the operation or control measures occurs. If the maximum risk measurement is above the action level, then it is necessary to proceed further to identify other employees whose exposures may be above the action level.

3.2 PERSONAL, BREATHING ZONE, AND GENERAL AIR SAMPLES

The proposed OSHA health regulations require that an employee's exposure be measured by any combination of long-term or short-term samples that represents the employee's actual exposure. Air samples should be taken in the employee's breathing zone (air that would most nearly represent that inhaled by the employee). There are three basic types of occupational environmental sample collection techniques:

1. Personal — The sampling device is directly attached to the employee and worn continuously during all work and rest operations.
2. Breathing Zone — The sampling device is held by a second individual who attempts to sample the air in the "breathing zone" of the employee.
3. General Air — The sampler is placed in a fixed location in the work area (also referred to as "area sampling").

The intent of the regulations is that samples taken for the purpose of measuring employee exposure normally be taken only by the "personal" or "breathing zone" methods. If samples taken by the "general air" method are to be used to determine employee exposure, then it is necessary to demonstrate that they accurately measure employee exposures. Generally this would involve a comprehensive job time and motion study for each employee repeated at least every 3 months. Then a comparison must be made with personal or breathing zone samples to show equivalency. Normally, this is very difficult to do. Refer to Technical Appendix C, The Inadequacy of General Air (Area) Monitoring for Measuring Employee Exposures, for further discussion of this subject.

3.3 EXPOSURE MEASUREMENT STRATEGIES

The decision procedures in the next chapter regarding compliance and noncompliance based on exposure measurements will differ depending on how the samples were obtained in relation to the period of the standard, duration of the samples, and number of samples. The following terminology is used to describe these various measurement types. See Figure 3.1 for a graphic depiction of the measurement types. The word "period" refers to the period of the standard. For an 8-hour TWA standard, the period is 8 hours, and for a ceiling standard, it is generally 15 minutes. An exposure "measurement" consists of one or more samples (personal or breathing zone) taken during the measurement period.

3.3.1. Full Period Single Sample Measurement

The sample is taken for the full period of the standard. This would be 8 hours for an 8-hour TWA standard and 15 minutes for a ceiling standard.

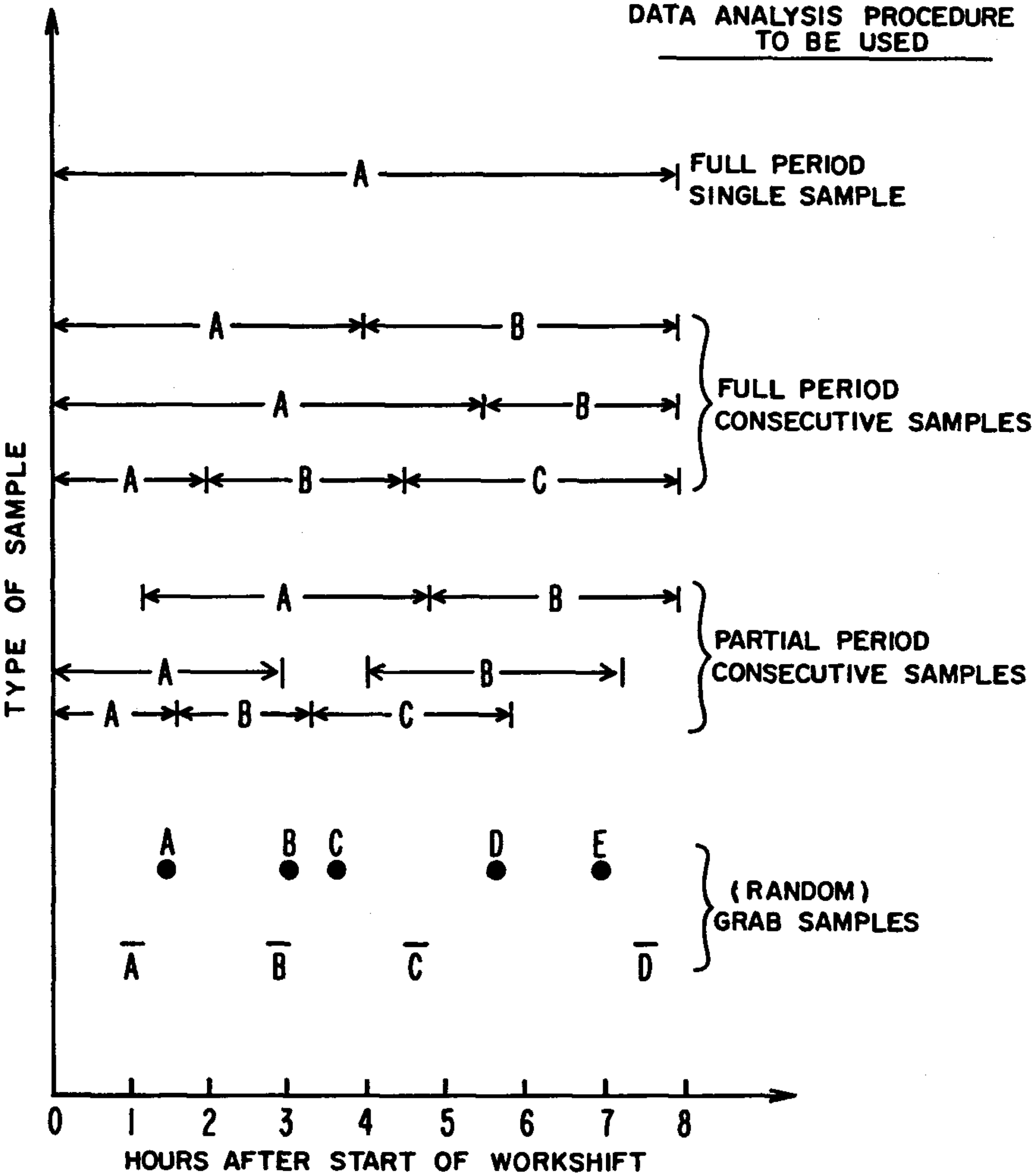

Figure 3.1. Reference chart of types of exposure measurements that could be taken for an 8-hour average exposure standard.

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.

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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 Industrial 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

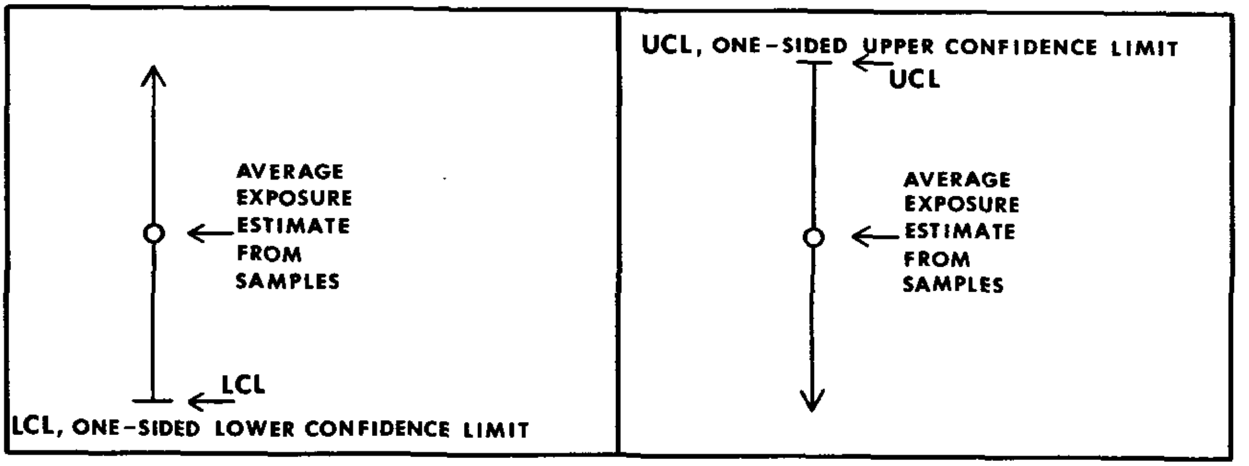

Figure 4.1. Example of one-sided LCL and UCL.

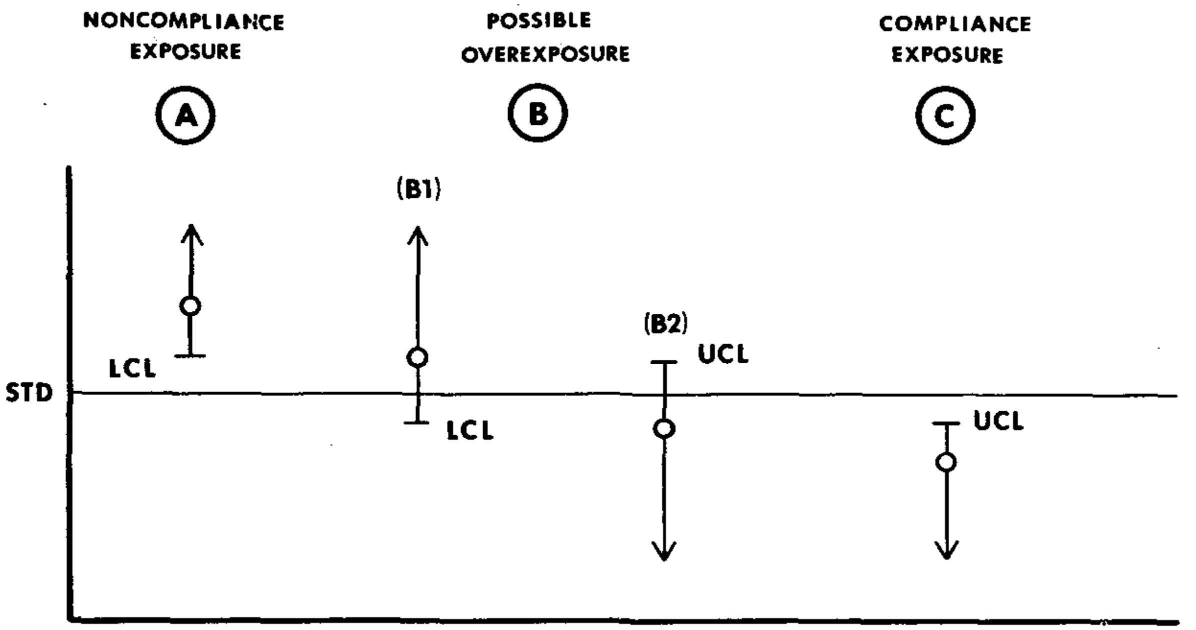

Figure 4.2. Classification according to one-sided confidence limits.

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%) ≲ 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

(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.

EXAMPLE

(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.

(2)

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

(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

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

(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) 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.

(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) (μ). 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 ≦ 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.

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.

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.

(5)

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.

4.2.2.2 Full Period Nonuniform Exposure Procedure

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 section 4.2.1 (step 1).

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

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

EXAMPLE

(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) $TWA =$

$$\frac{(300 \text{ min})\ (30 \text{ ppm}) + (180 \text{ min})\ (140 \text{ ppm})}{(300 + 180) \text{ min}}$$

$= 71.$ ppm

(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

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

b) Employer's test for compliance. Compute

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

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

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

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

(4)

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

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

$$= 0.71 + 0.07 = 0.78$$

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

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.

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 $LCL \leqq PPL$, classify as Possible Overexposure.
- If $(TWA/STD) \leqq PPL$, 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).

PROCEDURE

(1) Collect data.

The available contaminant data consist of less than 30 exposure grab samples X_1, . . ., 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, . . ., 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, . . ., 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

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

Or, in a simpler form, s is

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

(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.

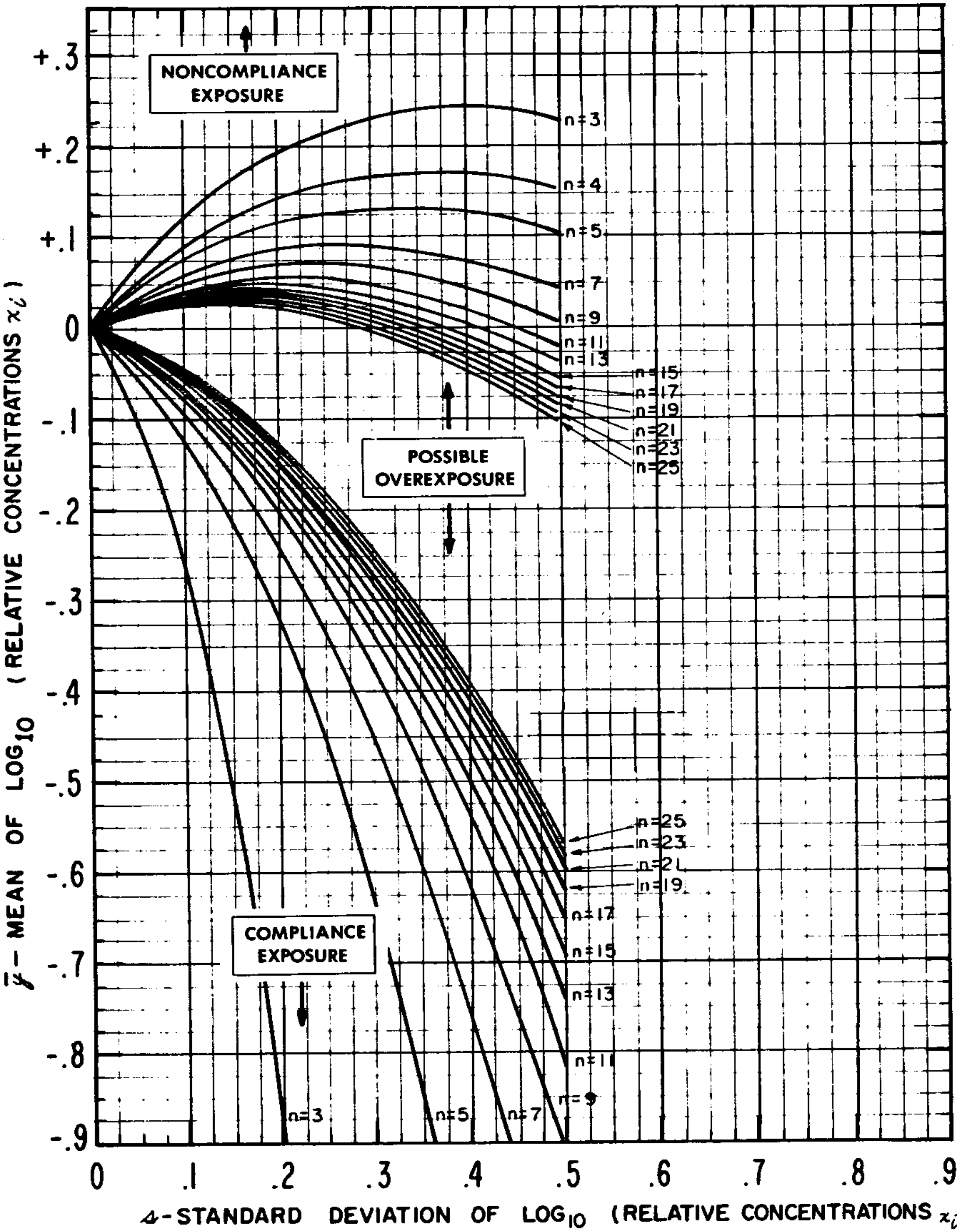

Figure 4.3. Grab sample measurement average classification chart.

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.

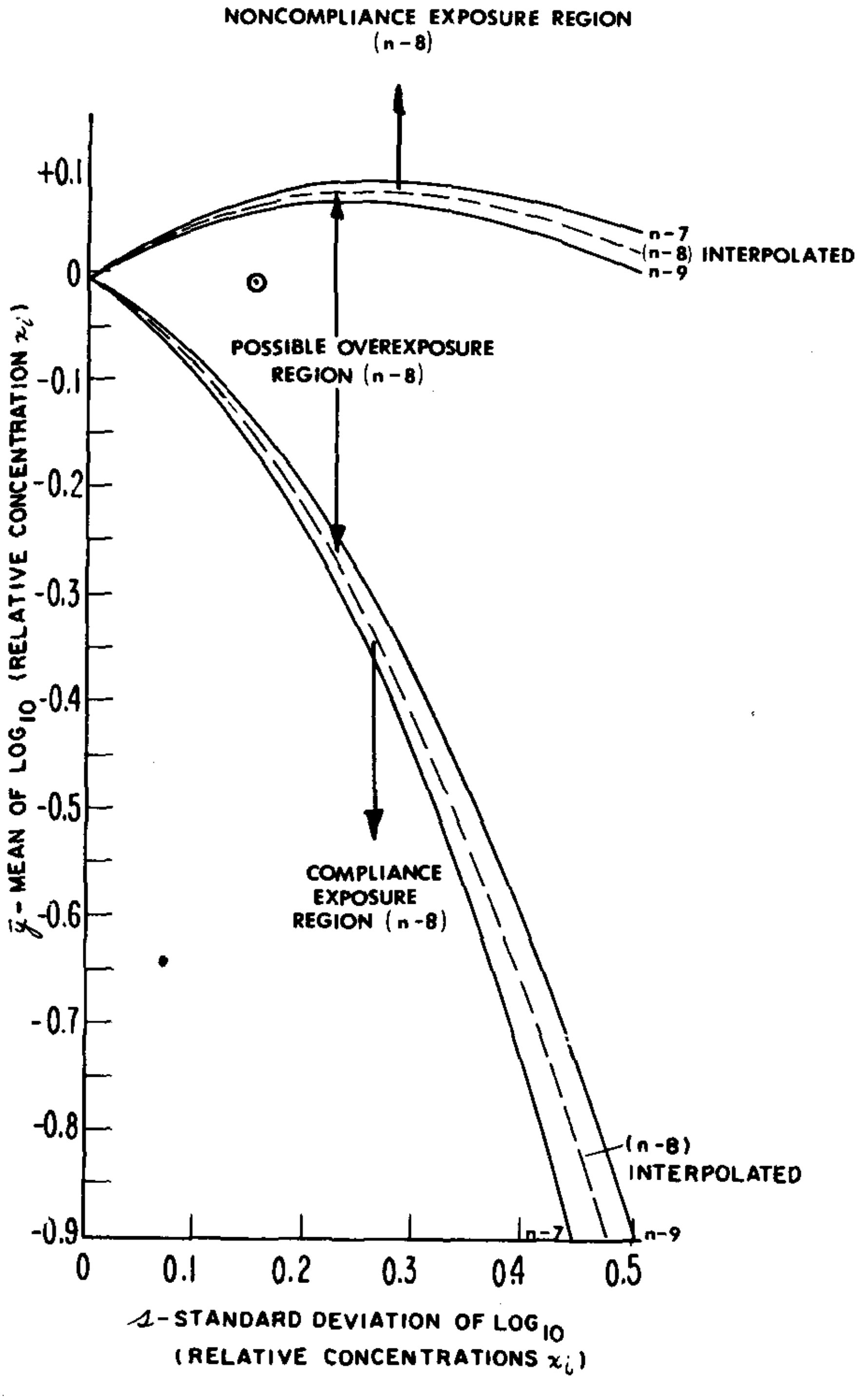

Figure 4.4. Grab sample classification chart for example of section 4.2.3.

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

The classification variables $\overline{y}$ 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 $\overline{y}$ 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 $\overline{X}^*$/STD.

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

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

is to be used to estimate the standardized average exposure.

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

- Plot the variables $\overline{y}$ and s, with $\overline{y}$ on the vertical axis and s on the horizontal axis.
- Follow the graph curve nearest to the plotted point to the $\overline{X}^*$/STD axis on the right-hand side of the graph.
- Interpolate between two values of $\overline{X}^*$/STD to obtain the appropriate $\overline{X}^*$/STD. If the value of $\overline{X}^*$/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

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

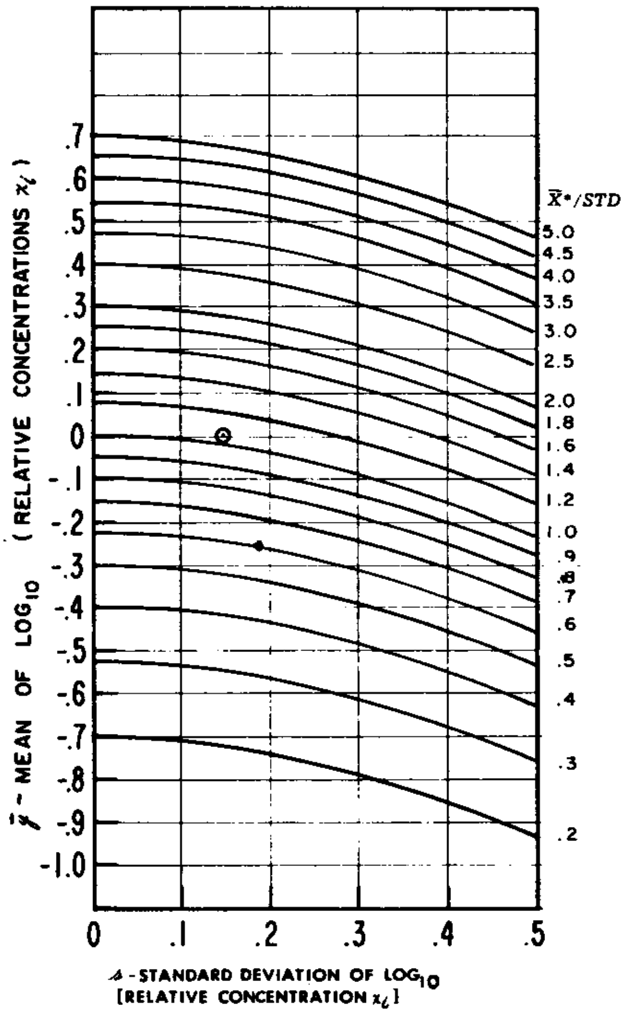

Figure 4.5. Estimation graph for X/STD.*

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

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

b) Employer's test for compliance. Compute

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

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

(4)

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

$= 0.89$

(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 $\leqq$ 1, classify as Possible Overexposure.
- If $\bar{x} \leqq 1$, no statistical test for noncompliance would be made.

b) Employer's test for compliance:

- If UCL $\leqq$ 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

(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).

b) Select the largest measurement and refer to it as X.

c) Calculate the maximum relative ceiling value

$$x = X/CSTD$$

where CSTD is the ceiling standard.

(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.

(3) If the classification is Compliance Exposure, go to section 4.3.2. Otherwise, this terminates the ceiling classification procedure.

EXAMPLE

(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:

$$X_1 = 12 \text{ ppm}, X_2 = 14 \text{ ppm}, X_3 = 13 \text{ ppm}, X_4 = 16 \text{ ppm}, X_5 = 15 \text{ ppm}$$

b) $X = 16$ ppm

c) $x = (16 \text{ ppm})/(20 \text{ ppm}) = 0.80$

(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) 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 $\log_{10}$s:

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

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

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 $\bar{y} \geqq 0$, 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 $0.1 \leqq P_c \leqq 0.9$, 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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