ABSTRACT

JEFFREY L. KING. Application of an ANOVA Model To Evaluate Occupational Exposure to Formaldehyde. (Under the Direction of Stephen M. Rappaport, Ph.D.)

Occupational exposure to formaldehyde was evaluated at a large chemical facility. Of particular interest was the validity of so-called Homogeneous Exposure Groups (HEGs) in which it is assumed that all individuals are exposed, on average, to the same level of contaminant. As a preliminary step a field study was conducted comparing the use of diffusion monitors to sorbent tubes for personal air sampling. Results from 26 matched pairs showed the two methods to be comparable [mean difference (badge - tube) = 0.03 ppm; mean (badge) = 0.17 ppm]. Six HEGs were formed based on job tasks and location. Using a randomized design, multiple full-shift samples were collected (with monitors) from representative workers in each HEG (127 measurements from 44 workers). Application of an analysis of variance (ANOVA) model indicated that the total variation in exposure across the entire sample population was partitioned as follows: 79% within-worker, 8% between-worker (within HEG), and 13% between HEG. Thus, assignment of HEGs in this case had only a marginal impact (13% reduction in variance) on the exposure assessment and substantial effort could have been avoided by randomly sampling the entire population prior to grouping.

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INTRODUCTION

One of the primary duties of an occupational hygienist is monitoring the work environment to determine levels of exposure to airborne contaminants. Sampling campaigns are undertaken for a variety of reasons: to ensure compliance with governmental occupational exposure limits (OELs), to establish baseline levels of exposure, to evaluate the effectiveness of engineering controls, and to provide exposure information for future epidemiological investigations. Regardless of the reason for monitoring, it is important for the hygienist to collect samples which accurately reflect the level of exposure and which are sufficiently representative to allow meaningful decisions to be made regarding the exposures. Much progress has been made in the last fifty years to improve the accuracy and precision of environmental sampling methods. However, the issue of representative sampling in the field of occupational health has much room for improvement. While the idea of representative sampling is nothing new nor conceptually difficult, the how-to and application of a method of representative sampling still presents difficulties for the occupational hygienist.

The problem is two-fold: usually not every worker can be monitored at all times, and there exists a great deal of variability in the level of exposure across a population of workers in a given work environment. Furthermore, occupational hygienists have a limited amount of time and resources to devote to workplace monitoring. Thus it is important to structure the monitoring program such that a maximum amount of information regarding exposures can be obtained from a minimum number of samples, while maintaining an acceptable degree of representativeness. To help realize this objective, occupational hygienists have developed the concept of classifying workers into discrete exposure groups, sometimes termed homogeneous exposure groups (HEGs), where it is assumed that all workers within a group are exposed, on average, to the same level of contaminant.

Defining an HEG

The American Industrial Hygiene Association's (AIHA) Exposure Assessment Strategies Committee (1991) defines an HEG as follows:

> "A group of employees who experience agent exposures similar enough that monitoring agent exposures of any worker in the group provides data useful for predicting exposures of the remaining workers. Such groups are used in stratified sampling of workplace exposures, thereby improving the power of statistical decision tools. The categorization of workers into such groups often involves categorization by process, job description, and agents, although finer separation can be attained by further dividing on the basis of task analysis."

While this definition provides a useful qualitative description of an HEG, it gives the reader no guidance in terms of a quantitative description of such a group. In fact, even though the word "statistical" appears in the definition, to date this group, nor any other consensus group in the field of occupational health, has specifically dealt with the defining attributes of an HEG, from a statistical viewpoint.

Rappaport (1991) addresses the issue of defining discrete exposure groups from a statistical viewpoint by defining two other terms. First, the author defines a 'monomorphic' group as "a collection of individuals whose mean exposures can be adequately described by a single log-normal distribution (between-persons)." A 'uniformly exposed' group of workers is then defined as "a monomorphic group in which 95% of the individual mean exposures lie within a factor of 2." While this definition of a uniformly exposed group is arbitrary and possibly too restrictive, it does provide a quantitative framework with which to assess the homogeneity of a given HEG. A metric based on this definition is denoted by the author as $R_{0.95, B}$ and is presented in an upcoming section.

There are essentially two approaches one can use to establish HEGs. One involves classification of workers *a priori*, based on observational techniques. The other method groups workers subsequent to random sampling of exposures, and is hence considered *a posteriori* (Rappaport, 1991).

An *a priori* classification of workers into discrete groups called "exposure zones" was described by Corn and Esmen (1979). The concept involves prospective assignment based on task, agent, and work process similarities. A randomly selected sub-group of workers within each exposure zone is subsequently sampled and assumed to represent the level of exposure for the entire group.

Purpose

This study was initiated to evaluate occupational exposure to formaldehyde at a chemical manufacturing facility using HEGs based on an observational approach. Of particular interest is the uniformity of exposures to workers within such an established HEG. To address this issue, several HEGs were formed *a priori* using information on occupational title, job tasks, and work location. Multiple full-shift, breathing zone samples were subsequently collected using a randomized design from a representative sub-group of workers within each HEG. The homogeneity of the data is evaluated statistically by means of an analysis of variance (ANOVA) model, whereby the total variance in exposures is partitioned into three components: the within-worker, the between-worker, and the between-group (HEG) (Kromhout *et al.*, 1987; Rappaport, 1991). The analysis allows a judgment to be made regarding the success of the observational approach in this case, and provides valuable information on the distribution of exposures at this facility, to help guide future monitoring programs.

The work for this report was conducted during a ten week industrial hygiene internship served at this facility. Given the limited time and resources available, and the research nature of the project, it was not intended to be a comprehensive assessment of all exposures at this facility. The focus of the study was limited to potential formaldehyde exposure for a segment of the workforce, albeit that segment which was deemed to have the greatest potential.

First, results are presented from a field study comparing two methods of personal sampling for airborne formaldehyde. The preliminary study was initiated to demonstrate the efficacy of passive monitors relative to the pump-sorbent tube method, which traditionally had been the standard formaldehyde sampling method used by this corporation. The use of passive monitors for the random sampling of HEGs significantly increased the number of measurements possible by lowering the cost and labor associated with each sample.

METHODS and MATERIALS

Facility - Process Review

The workplace monitored for this project is a medium-sized chemical facility located in western New York State. The plant produces phenolic resin (approximately 30 million lbs./year) and phenolic molding compound (approximately 50 million lbs./year). The production of both materials involves batch-type operations, with the ability to produce hundreds of different formulations depending on the specific application. These resins are used, for example, in the aerospace industry as thermal barriers, in the abrasives industry as adhesives, and in the coatings industry as ingredients in paints and varnishes. Molding compounds are utilized extensively in the automotive industry as brake parts, pulleys, motor frames, and ashtrays.

The plant consists of about 40 buildings spanning 66 acres of land, though only a few are actively involved in production. Phenolic resin is produced in two separate buildings, while molding compound is produced in one building. The facility employs 120 salaried and 240 hourly personnel.

Phenolic resins, in general, are the polymerization product of a condensation reaction involving phenol and an aldehyde. The vast majority of phenolic resins consist of the phenol-formaldehyde variety, which is the type made at this facility. In particular, this plant produces two types of phenol-formaldehyde resin: a one-stage resole, and a two-stage novolac.

A resole is produced by reacting phenol and excess formaldehyde (50% formalin solution) in the presence of an alkaline catalyst in a resin kettle, which holds approximately 5000 gallons. It is a one-stage resin because the kettle is charged with all reactants needed for the final polymer; specifically, enough formaldehyde is added to make the resin thermosetting, or infusible once heated to a certain temperature. Production of a novolac, on the other hand, involves a two-stage process where an acid catalyst and a portion of the necessary formaldehyde (80%) are reacted with phenol. The first stage forms partially reacted, low molecular weight linear polymers. At this point the resin is considered thermoplastic, or fusible since application of heat will not chemically alter the material. The remainder of the formaldehyde necessary for final cure is added at a later time during the second stage, typically in the form of hexamethylenetetramine, which decomposes in the presence of heat and moisture to formaldehyde and ammonia. The latter acts as a catalyst.

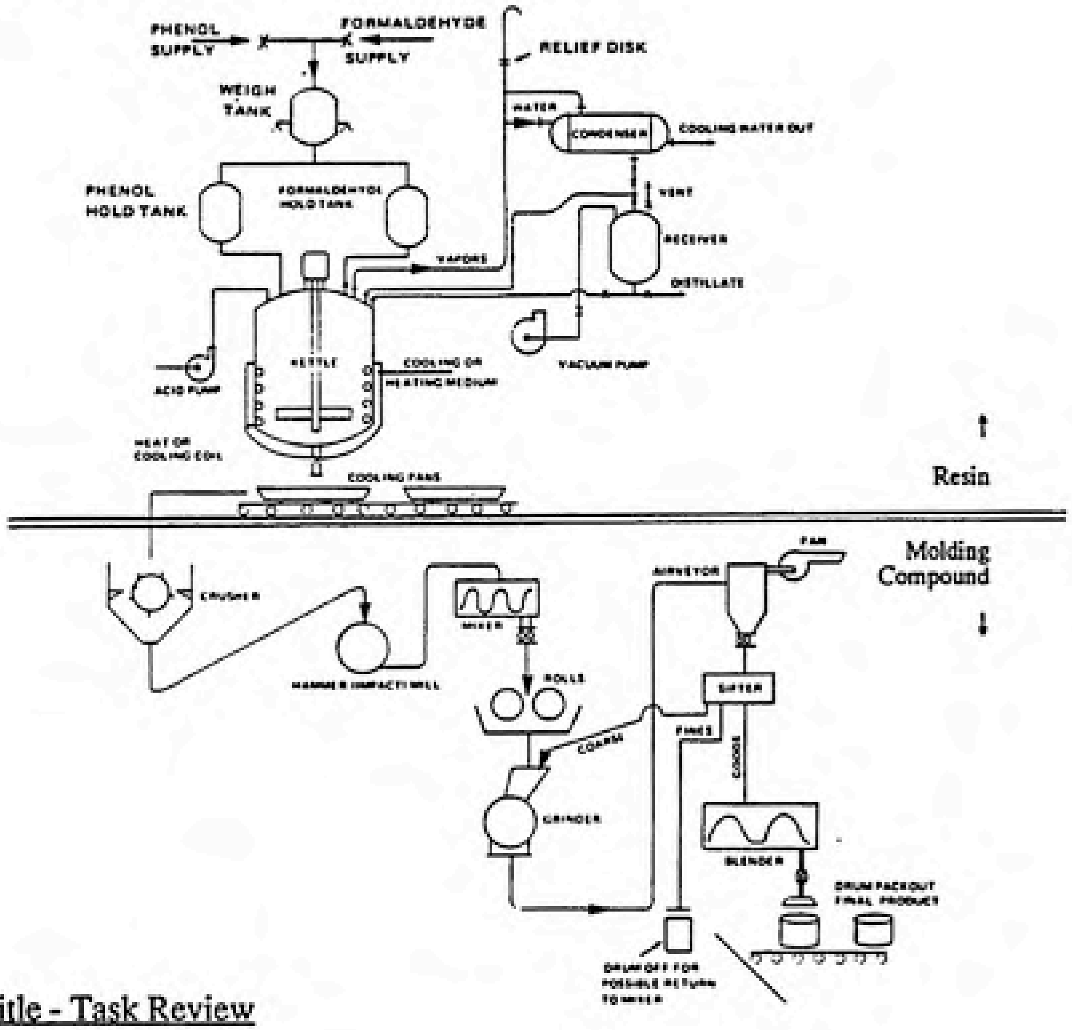
Once a kettle is charged with the reactants it is generally heated to a boil and refluxed for an amount of time determined by the given formulation. Upon reaching a desired end-point (e.g. viscosity or percent free formaldehyde remaining), the kettle is rapidly cooled and dehydrated to remove water and unreacted phenol, which prevents the resin from advancing beyond the desired stage. The cycle time for resin production at this facility ranges from several hours to several days, depending on the specific resin. Upon completion, the molten resin is transferred from the kettle and may or may not undergo further processing, again depending on the specific resin and customer specifications. If it is sold as a liquid resin, it will either be packed-out in 55 gallon drums, or transferred directly to a tank wagon for transport. It may also be transferred to a tank farm for storage as a liquid.

Alternatively, the resin can be converted to a solid form via additional cooling and/or dehydration. Solid resin can take two forms: pulverized or flake resin. Resin to be pulverized is typically dropped into large pans to cool and solidify. The solid mass is pulverized using a crusher and hammer mill. Once pulverized, it may be packed-out into boxes or bags, or used to make molding compound. Flake resin is formed using either a drum dryer or a belt flaker, depending on the type of resin (novolac or resole). Once formed, it too is either packed out or used for molding compound production.

The other primary manufacturing process at this facility is the production of phenolic molding compound. In this process, pulverized resin is mixed with various fillers, lubricants, and plasticizers in large ribbon blenders. The resulting mixture is fed onto a set of counter-rotating heated rolls, where the material is transformed into a thermosetting compound. From there the material goes through a grinder, a sifter, and another blender prior to pack-out in drums, boxes, or bags. Figure 1 depicts the process, from resin production to molding compound production.

Finally, there are a multitude of other support activities performed by personnel at this facility. A quality control lab provides analytical services for raw materials and resins in various stages of production. Maintenance operations include a welding shop, an electrical shop, and a metal fabrication shop. Additional ancillary activities include shipping and receiving, raw materials and product storage, engineering services, boiler house operation, and clerical support.

Figure 1. Diagram of the Production Process



Job Title - Task Review

An analysis of job titles and associated tasks was performed, focussing on those which were judged to have the highest potential for formaldehyde exposure. Information on job titles was obtained from a 'weekly locator,' which listed all personnel (by job title) and their weekly shift assignment, and from interviews with personnel. Job task information was ascertained through observation and interviews with personnel. Table 1 provides a summary of the job titles and tasks included in the study.

Table 1. Job Titles and Associated Operation/Tasks

Job Title	Operation/Tasks	Location
Head Roll Operator (HRO)	• Molding compound production • Operate rolls from adjacent station - monitor roll temperature, feed rate - clean roll knives • Change sifter screens • Clear Airveyor lines, grinders	Bldg. 88
'A' Kettle Operator (AKO)	• Resin production (mostly resole) • Operate kettle from platform station - monitor temperature, pressure - obtain process samples - charge with reactants, catalysts • Clean and prep drum dryer • Operate drum dryer - monitor feed rate, temperature - oversee flake packout conveyor system • Liquid resin drum packout • Dress filter press • Transfer resin to tank farm • Obtain resin samples from tank farm • Load tank wagon with resin	Bldg. 19/57, Tank Farm, Loading Platform
'A' Floorman (AF)	• Load tank wagon with resin • Liquid resin drum packout • Dress filter press • Transfer resin to tank farm • Obtain resin samples from tank farm • Collect seal-water samples from vacuum pumps • Pump wastewater from dikes • Assemble wood packout boxes • Supply raw materials to kettle platform	Bldg. 19/57 (mostly groundfloor), Tank Farm, Loading Platform

Job Title	Operation/Tasks	Location
'A' Kettle Operator	• Resin production (mostly novolac) • Operate kettle from platform station - monitor temperature, pressure - obtain process samples - charge with reactants, catalysts • Clean and prep belt or drum flaker • Operate belt or drum flaker • Flake resin drum/box/bag packout • Liquid resin drum packout • Liquid resin pan job • Dress filter press • Load tank wagon with resin	Bldg. 3/12
Lift Truck/Conveyor Operator (LTO)	• Operate lift truck - material transport • Clean and prep belt or drum flaker • Operate belt or drum flaker • Flake resin drum/box/bag packout • Liquid resin drum packout • Liquid resin pan job • Dress filter press • Load tank wagons with resin	Bldg. 3/12 (mostly groundfloor)
Control Lab Specialist (SPT)	• Run routine analyses on raw materials and resins - cures, titrations, pH, freeze point, viscosity, refractive index, etc.	Control Lab

HEG Formation

After obtaining information on job title, task, and location, workers were assigned to HEGs. In developing these groups, consideration was given to the following four defining attributes of exposure zones (HEGs), as described by Corn and Esmen (1979):

1. Work similarity - workers in each HEG must perform similar job tasks.
2. Hazardous agent similarity - workers in each HEG must share potential exposure to the same agent(s).
3. Environment similarity - workers must perform job duties in similar environments, such that exposures are influenced by similar controls and processes.
4. Identifiability - there should exist a means of identifying workers within an HEG to facilitate any future tracking efforts.

Based on these criteria, six HEGs were established, as presented in Table 2.

Table 2: Summary of Formaldehyde HEGs

HEG No.	Job Classification	Location	No. of Workers
1	Head Roll Operator	Bldg. 88	6
2	A Kettle Operator	Bldg. 3/12	12
3	A Kettle Operator	Bldg. 19/57	28
4	Lift Truck/Conveyor Operator	Bldg. 3/12	4
5	A Floorman	Bldg. 19/57	6
6	Control Lab Specialist	Control Lab	12
		Total	68

Each HEG represents a group of workers perceived to have a unique potential for exposure to formaldehyde, given the job functions performed in the specific work environment. In this case, each HEG represents a different job title, or, for HEG 2 and 3, a different work location. It was not possible to further define HEGs within job classifications based on job tasks, because of task rotation at this facility. That is, within a given job classification all workers performed the same tasks based on a daily rotation procedure. Workers were not "pigeon-holed" into performing specific tasks every shift; all tasks were rotated. Therefore, it was assumed that all workers in a given job classification (and work environment) over time were uniformly exposed and hence represented by a discrete HEG.

HEG 1 is comprised of Head Roll Operators for Building 88, which produces molding compound (see Appendix A for floor plan). It was estimated that workers in this job classification are the only ones in the compound building to have any significant potential for formaldehyde exposure. Formaldehyde, as a raw product, is not present in this building. The job of a Roll Operator is to monitor a set of differential rolls from an adjacent work station. Exposure may occur as free-formaldehyde (unreacted) is vaporized during the heating of pulverized phenolic resin as it is applied to the hot rolls. The amount of free-formaldehyde present in a resin varies based on the given resin formulation and the particular batch. Estimates of the percent of free-formaldehyde in resins produced at this facility were as high as 14%, though the majority fall in the 0.5 to 5.0% range. Formaldehyde exposure for this job classification was also dependant on the efficacy of the local exhaust ventilation (LEV) system for this operation, which, it was noted, varied day to day. There were several factors which seemed to influence its ability to remove generated contaminants. One was process equipment operation, which itself was dependent on many factors, such as the relative proportion of resin to fillers, the temperature of the rolls, the relative humidity, and the feed rate. If conditions were not optimal, the process generated contaminants in excess of what the LEV system could handle, resulting in releases to the work environment. The other factor which influenced the LEV system was the presence of air-flow disturbances, primarily cross-drafts from large floor fans aimed at the platform to cool workers.

HEGs 2 and 3 are made up of Kettle Operators. Their job is to produce phenolic resins. This facility has two separate resin production buildings, each of which tends to make a different type of resin. Building 3/12 makes mostly two-step novolac resins, while Building 19/57 produces mostly one-step resoles (see Appendix A for floor plans). Given the different work locations and the fact that each building makes a different type of resin, two separate HEGs were formed, one for the Kettle Operators in each building. Because formaldehyde is one of two primary raw materials used in the production of phenolic resins, this job involves a number of exposure opportunities, even though it is primarily a closed system. For example, charging kettles with formaldehyde can result in releases to the work environment when the manway is opened to make a visual check or, as a result of minor leaks during transfer of the charge from the facility holding system to the weigh case or pressurized charge tank. Another task that may involve significant release to the work environment is when a kettle is charged with formaldehyde in solid form (paraformaldehyde). This requires addition through an open manway and hence more direct contact. Collecting raw material or process samples presents another opportunity for exposure. Kettle Operators in Building 19/57 also risk exposure while operating a drum dryer, which converts liquid resin into flake form through a dehydration process. Other tasks involving potential exposure opportunities include liquid resin packout and cleaning filter presses. The exposures relating to most of these tasks are influenced to some degree by LEV. However, the effectiveness of these systems is dependent upon the same factors mentioned previously for the LEV system in the compound building.

Lift Truck/Conveyor Operators in Building 3/12 make up HEG 4. This job requires operating a lift truck on the ground level of Building 3/12, as well as resin packout duties involving a resin drum flaker and a belt flaker. There are several exposure opportunities associated with this job, though not as numerous as for Kettle Operators. Tasks with the highest potential for exposure include cleaning the filter press and the belt flaker, liquid resin packout into drums, and liquid resin pan jobs. Also, these workers risk exposure simply by working on the ground floor of this resin production building.

HEG 5 is comprised of A Floormen in Building 19/57. This job is roughly analogous to the Lift Truck/Conveyor Operators in Building 3/12. It involves packout duties on the ground floor of Building 19/57, supplying raw materials to the kettle platform, and loading tank wagons with liquid resin. The main difference is that these workers spend significantly more time outside loading tankwagons and transferring resins to and from the tank farm.

Finally, HEG 6 includes Control Lab Specialists who work in the Control Lab in Building 21 (see Appendix A for floor plan). These workers conduct specification analyses on resin samples from Buildings 3/12 and 19/57. Samples taken from kettles at various production stages may arrive at the lab at high reaction temperatures, resulting in potential exposures for workers. Certain analytical procedures, such as cure tests, also involve potential formaldehyde exposure.

Random Selection of Workers and Sample Days

In order to make valid estimates of the distribution of formaldehyde exposures at this facility and to comply with assumptions inherent to the statistical model used for data analysis, randomization was incorporated into the sampling campaign. That is, workers to be sampled from each HEG were selected at random, as were the days on which to sample each worker. To ensure adequate representativeness, approximately two-thirds of the workers from each

HEG were selected, with the goal of collecting three measurements from each (see Table 3).

Table 3. Number of Randomly Selected Workers From Each HEG.

HEG	Total No. Workers	No. Selected
1	6	4
2	12	8
3	28	18
4	4	2
5	6	4
6	12	8
Total	68	44

The population of workers' exposures to be sampled from was defined as following:

- Day shift (8 am to 4 pm);
- Monday through Friday;
- July 15 through August 14, 1991.

The selection of workers was accomplished by first assigning a unique one or two digit number to each of the workers. The pre-determined number of workers from each HEG was then selected using the random number function on a Hewlett Packard 21S calculator. Once workers were selected, it was determined on which of the twenty-one sample days each given worker would be available for sampling (i.e. working the day-shift). Based on the total number of possible days, three were selected at random. Appendix B presents the results of the randomization process; Appendix C shows each sample day by date. In the event a primary selection was not available, alternate workers were also selected for some HEGs.

Field Study Comparing Sampling Methods for Airborne Formaldehyde

Prior to the random sampling of HEGs, a preliminary field study was conducted to compare two personal sampling methods for airborne formaldehyde. The study incorporated a matched-pair design and was initiated to demonstrate the efficacy of passive diffusion monitors relative to the pump-sorbent tube method.

The passive monitors utilized for this study were manufactured by Air Quality Research (AQR), model PF - 20 (PEL). This device uses a dry proprietary collector which converts formaldehyde to a stable intermediate, prior to regeneration and analysis by the chromotropic acid method. It is designed to monitor exposures for intervals ranging from one to eight hours. The monitors were compared to sorbent tubes manufactured by SKC, model XAD - 2 (Treated). These tubes also employ a dry collection media, but require the use of personal sampling pumps to draw air through the device at a uniform rate. Sampling pumps used were Gilian Personal Air Samplers with Constant Low Flow Modules. Nominal sampling rate for 4-hour samples was 100 cc/min, and 50 cc/min for 8-hour samples. Pumps were calibrated before and after each sample interval with a Mini-Buck Calibrator (Model M-5), and were checked periodically in the field with a precision low-flow rotometer. Two field blanks of each type were prepared each day and all samples were stored at 40-45°F. Soft bristle brushes were used to remove any visible dust from outer membrane on diffusion monitors prior to sealing. AQR monitors were analyzed by the manufacturer at their facility in Research Triangle Park, North Carolina, while the SKC sorbent tubes were analyzed by NATLSCO Environmental Sciences Laboratory located in Long Grove, Illinois.

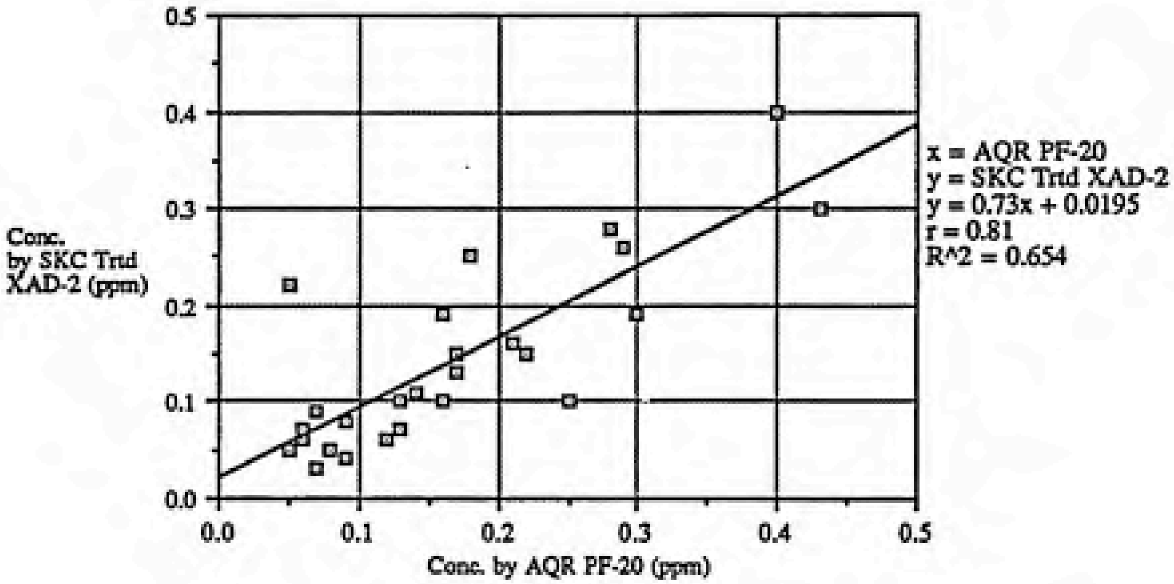
Simultaneous personal measurements were collected from a group consisting of mostly Kettle Operators. Both devices were placed in the breathing zone of the worker on the same side of the body. A deliberate attempt was made to sample during "worst case" conditions, to ensure that formaldehyde air concentrations were high enough for detection for both devices. A total of 50 side-by-side measurements were made: thirty-eight 4-hour and twelve 8-hour measurements. In spite of the attempt to sample during "worst case" conditions, 24 of the 50 sample pairs were excluded from the comparison analysis due to analytical results below the limit of detection for either device. Hence, 26 matched pairs were considered valid for comparison purposes.

Data from the field study are presented in Appendix D along with the statistical analysis. Table 5 and Figure 2 summarize the results.

Table 5. Summary Statistics Comparing Sampling Methods (n = 26 pairs)

Method	Mean Conc. (ppm)	95% Confidence Interval
AQR PF-20 (PEL)	0.17	0.13, 0.20
SKC Treated XAD-2	0.14	0.10, 0.18
Difference	0.03	0.005, 0.055
Paired Sample t-Test of Differences: p = 0.046		

Figure 2. Linear Regression Comparing Sampling Methods



As the results in Table 5 indicate, the two methods compare reasonably well, though a paired sample t-test on the distribution of differences does show marginal significance ($p = 0.046$). Figure 2 presents a linear regression analysis on the data. The fitted regression line is SKC = 0.73(AQR) + 0.0195, with a coefficient of determination (R^2) equal to 0.65 and a correlation coefficient (r) of 0.81. These results reveal a strong correlation between the methods and indicate that the diffusion monitors are good linear predictors of these sorbent tubes. Note the decision to use the diffusion monitors as the independent variable for the regression analysis was arbitrary.

Since the "true" concentration of formaldehyde was not known for this field study, the marginal difference was interpreted to mean that the two methods were comparable and, because of the convenience of use, worker acceptance, and lower cost, the diffusion monitor was employed for the remainder of the study.

Statistical Evaluation of Sampling Data

Sampling results were evaluated statistically with SAS software by means of an analysis of variance (ANOVA) based on the random effects model. This model can be used to determine means and variance components for a given variable based on repeated observations from a factor across numerous levels. For example, estimating average exposures within and across groups of workers based on repeated measurements from each worker. For this study, two versions of the model are used: a one-way classification, and a two-way nested classification.

The one-way classification ANOVA was used to evaluate the exposure variability within and between workers in each HEG. The equation for the model is,

$$Y_{ij} = \mu + A_i + \varepsilon_{ij}.$$

The term Y_{ij} represents the log-transformed exposure concentration received by the ith worker during the jth sample interval (shift). The symbol μ is the mean exposure for the population of workers, where A_i is the difference in mean exposure of the ith worker from that of the population as a whole and ε_{ij} is the difference between each individuals' mean exposure (μ_i) and the exposure received by that individual on any given day. The terms A_i and ε_{ij} are both assumed to be normally distributed with a mean of zero and variance σ_B^2 and σ_W^2 respectively, and are considered independent. Thus σ_B^2 represents the between-worker component of variation, and σ_W^2 the within-worker component. It is also assumed that μ_i is normally distributed with a mean μ and variance σ_B^2, and that the within-worker variance is uniform across all workers in the population. Another assumption inherent to this model is that each observation is a random sample from the population of interest.

The basic data layout for the one-way classification random effects model applied to the data from this study is shown in Table 6.

Table 6. Data Layout for One-Way Classification (within an HEG)

Obs.	Worker 1	Worker 2	...	Worker i = k
j = 1	Y_{11}	Y_{21}	...	Y_{i1}
j = 2	Y_{12}	Y_{22}	...	Y_{i2}
.	.	.		.
.	.	.		.
$j = n_i$	Y_{1n_1}	Y_{2n_2}	...	Y_{in_i}
	$\bar{Y}_1$	$\bar{Y}_2$	...	$\bar{Y}_i$

The term n_i refers to the total number of measurements collected for the ith worker and k is the total number of workers monitored. The general layout of the one-way classification ANOVA for a set of log-transformed repeated exposure measurements is presented in Table 7.

Table 7. One-Way Classification ANOVA

Source of Variation	df	SS_y	MS_y	Parameter Estimated
Between-worker	(k - 1)	${}_BSS_y$	$\frac{{}_BSS_y}{(k-1)}$	$\sigma_W^2 + n_o\sigma_B^2$
Within-worker	(N - k)	${}_WSS_y$	$\frac{{}_WSS_y}{(N-k)}$	σ_W^2

k = number of workers
N = total number of exposure measurements
${}_BSS_y$ = sum of squares of between-worker distribution
${}_WSS_y$ = sum of squares of within-worker distribution
MS_y = mean square
n_o = weighted number of measurements per worker

As Table 7 indicates, the ANOVA provides estimates for the two parameters of interest, σ_W^2 and σ_B^2. The estimator of σ_W^2 is derived as follows:

$$ {}_{W}s_y^2 = {}_{W}MS_y = \frac{[\sum_{i}^{k}\sum_{j}^{n_i}(Y_{ij} - \bar{Y}_i)^2]}{(N - k)}. $$

The quantity,

$$ \bar{Y}_i = \frac{\sum_{i=1}^{n_i} Y_i}{n_i}, $$

is the estimated mean of the i-th worker's log-transformed exposure measurements. The ANOVA estimator for the other component of variance, σ_B^2, is computed from the following equation:

$$ {}_{B}s_y^2 = \frac{[({}_{B}MS_y - {}_{W}s_y^2)]}{n_o}. $$

The term $n_o = N - (\sum_i^k n_i^2 / N)$ and represents the weighted number of measurements per worker. Finally, because the total variance is simply the sum of the within and between components, an estimate of the total variance is,

$$ {}_{T}s_y^2 = {}_{W}s_y^2 + {}_{B}s_y^2 . $$

The two-way nested classification for the random effects model is used to assess exposure variability not only within and between workers in a group, but also between groups or, in this case, HEGs. The random effects model is unchanged except for one additional term:

$$ Y_{hij} = \mu + B_h + A_{hi} + \varepsilon_{hij}. $$

For this model, Y_{hij} is the log-transformed exposure concentration received by the ith worker from the hth HEG during the jth sample interval. Again, the term μ is the mean across the entire group, but B_h represents random deviations of the mean of the hth HEG about the grand mean and is normally distributed with mean zero and variance σ^2_{HEG}. As with the first model, the A_{hi} term corresponds to between-worker deviations and ε_{hij} to within-worker deviations, and both are normally distributed with a mean of zero and variance σ^2_B and σ^2_W, respectively. Finally, each term is assumed to be an independent variable and all measurements are collected randomly. Table 8 displays the data layout for the two-way classification.

Table 8. Data Layout for Two-Way Nested Classification

HEG, h (h=1, ... ,a)	Worker, hi (i=1, ... ,k)	Ln Conc., Y_{hij} (j=1, ... ,n)	$Y_{hi.}$	$Y_{h..}$	$Y_{...}$
1	1	$Y_{111},..., Y_{11n_1}$	$(\Sigma Y_{hij})_{h,i=1}$		
	.	.	.		
	.	.	.		
	k_1	$Y_{1k1},..., Y_{1kn_{k_1}}$	$(\Sigma Y_{hij})_{h=1,i=k_1}$	$\Sigma(Y_{hi.})_{i=1,k_1}$	
.				.	
.				.	
.				.	
a	1_a	$Y_{a11},..., Y_{a1n_1}$	$(\Sigma Y_{hij})_{h=a,i=1_a}$		
	.	.	.		
	.	.	.		
	k_a	$Y_{ak1},..., Y_{akn_{k_a}}$	$(\Sigma Y_{hij})_{h=a,i=k_a}$	$\Sigma(Y_{hi.})_{i=1_a,k_a}$	$\Sigma(Y_{h..})_{h=1,a}$

The term $Y_{hi.}$ is the sum of the log-transformed exposure concentrations received by the ith worker from the hth HEG, while $Y_{h..}$ refers to the sum of every workers' $Y_{hi.}$ for a given HEG. Finally, $Y_{...}$ is the sum of each $Y_{hi.}$, or simply the sum of all log-transformed concentrations for the entire sample population. Table 9 displays the ANOVA for the nested classification, which partitions the variance into three components: between-group (HEG), between-worker, and within-worker.

Table 9. ANOVA for Two-Way Nested Classification

Source of Variation	df	SS_y	MS_y	Parameter Estimated
HEG	$(a - 1)$	${}_{HEG}SS_y$	$\frac{{}_{HEG}SS_y}{(a-1)}$	$\sigma^2_W + n_o\sigma^2_B + k_o n_o \sigma^2_{HEG}$
Between-worker	$a(k_o - 1)$	${}_{B}SS_y$	$\frac{{}_{B}SS_y}{a(k_o-1)}$	$\sigma^2_W + n_o\sigma^2_B$
Within-worker	$ak_o(n_o - 1)$	${}_{W}SS_y$	$\frac{{}_{W}SS_y}{ak_o(n_o-1)}$	σ^2_W

Where,

$$ {}_{W}SS_y = \sum_h^a \sum_i^k \sum_j^n Y^2_{hij} - \frac{\sum_h^a \sum_i^k Y^2_{hi.}}{n_o} , $$

$$ {}_{B}SS_y = \frac{\sum_h^a \sum_i^k Y^2_{hi.}}{n_o} - \frac{\sum_h^a Y^2_{h..}}{k_o n_o} , \text{ and} $$

$$ {}_{HEG}SS_y = \frac{\sum_h^a Y^2_{h..}}{k_o n_o} - \frac{(Y_{...})^2}{a k_o n_o} . $$

The term k_o refers to the average number of workers per HEG. For an unbalanced data set (i.e. unequal number of workers in each HEG, and unequal measurements per worker), n_o and k_o are estimated as follows:

$$ n_o = \frac{(N - (\sum_i^k n_i^2)/ N)}{K - 1} , \text{ and} $$

$$ k_o = \frac{\sum_h^a k_h}{A} . $$

Where, K is the total number of workers sampled for the entire population, and A is the total number of HEGs sampled. Thus, estimates of each component of variance are:

$$_{W}S_y^2 = {}_{W}MS_y = \frac{_{W}SS_y}{ak_o(n_o - 1)},$$

$$_{B}S_y^2 = \frac{_{B}MS_y - {}_{W}MS_y}{n_o},$$

$$_{HEG}S_y^2 = \frac{_{HEG}MS_y - {}_{W}MS_y - n_{o\,B}S_y^2}{k_o n_o}.$$

Finally, the total variance $\sigma_T^2 = \sigma_W^2 + \sigma_B^2 + \sigma_{HEG}^2$, hence ${}_{T}S_y^2 = {}_{W}S_y^2 + {}_{B}S_y^2 + {}_{HEG}S_y^2$.

To assess the degree of exposure homogeneity between workers within HEGs and across the total group, a metric described by Rappaport (1991) was used. The metric defines a 'uniformly exposed' group of monomorphic workers as a group in which 95% of the individual mean exposures are within a factor of 2. This implies that the ratio of the 97.5th percentile to the 2.5th percentile, denoted by ${}_{B}R_{0.95}$, is not greater than 2. Where,

$${}_{B}R_{0.95} = \exp\,[3.92\ \sigma_B],$$

and σ_B is the standard deviation of the between-worker distribution of the log-transformed exposures. In this study, the true value of σ_B was not known so the estimate of ${}_{B}R_{0.95}$ (designated ${}_{B}\hat{R}_{0.95}$) was used as the measure of uniformity. This estimate,

$${}_{B}\hat{R}_{0.95} = \exp\,[3.92\ {}_{y}s_B],$$

where ${}_{y}S_{B}^{2}$ is the between-person component of variance obtained from the random effects ANOVA on the log-transformed measurements.

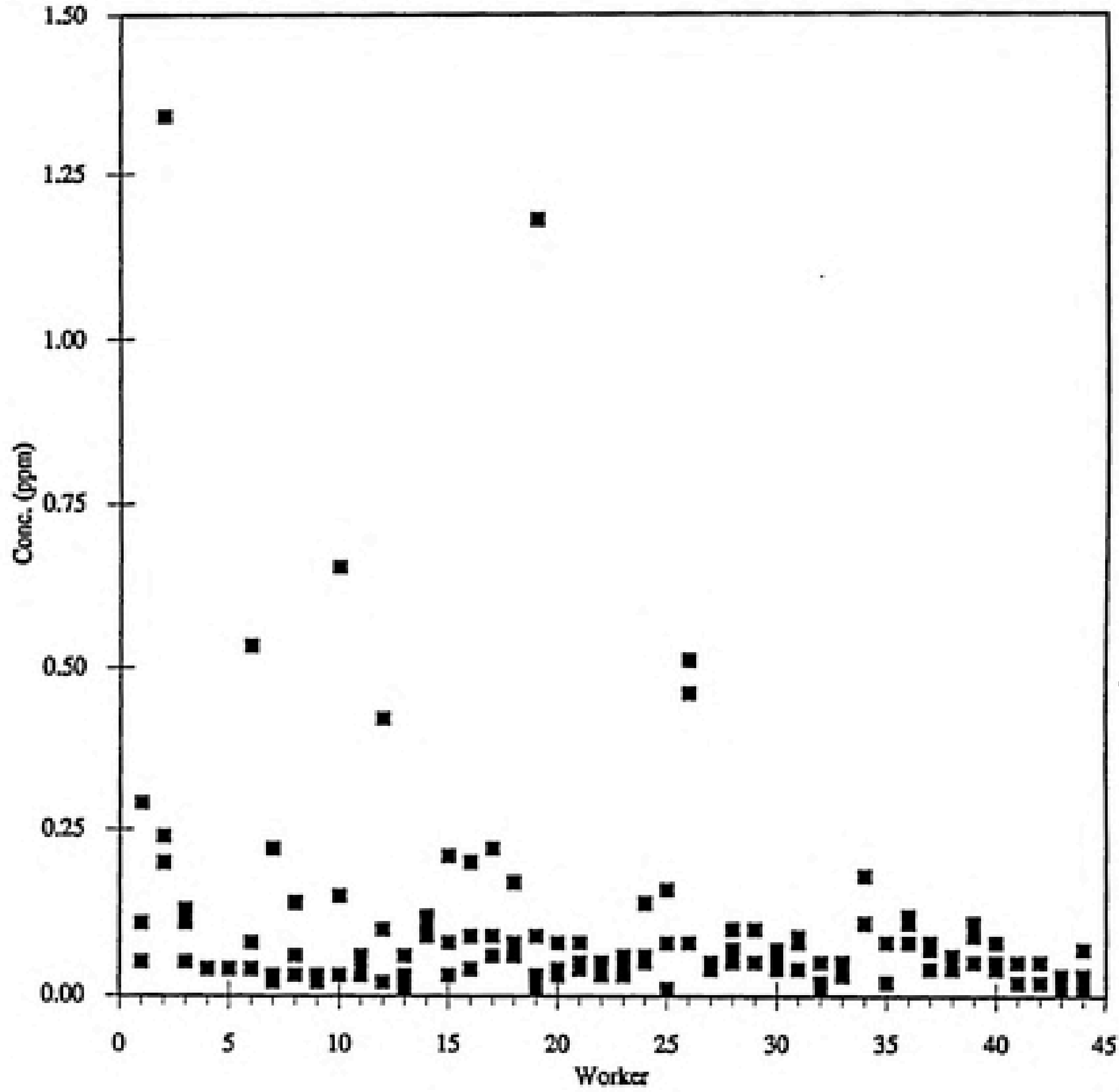
Clearly, the assumption that the exposure concentrations are lognormally distributed is an important one. To verify the validity of this assumption, a formal goodness-of-fit test was used, in addition to a less rigorous qualitative method. The goodness-of-fit test employed for this study was the Shapiro-Wilk W test, which is considered to be a statistically powerful and superior omnibus test of the fit to the lognormal model (Waters, *et al.*, 1991). A W statistic and corresponding p-value was computed for each HEG and for the population as a whole.

A visual representation of the fit was also made by means of a log-probability plot, where the cumulative probabilities are plotted against the corresponding geometric mean exposure concentration for each worker across the entire sample population. Each workers' cumulative probability was derived from [i / (k + 1)], where i is the rank from low to high of each mean from the between-worker distribution of k workers (Rappaport, 1992). Only balanced data were used, that is, only cases with three measurements per worker. Due to small sample sizes, plots were not generated for each HEG.

RESULTS

Results from the random sampling of the six HEGs are displayed in Figure 3 and are presented in tabular form in Appendix E. Each sample represents a full-shift, 8-hour time-weighted average (TWA) concentration.

Figure 3. Exposure Measurements for Total Sample Population



A total of 130 measurements were made, two less than the desired number. Table 10 accounts for the actual number obtained per HEG versus the number desired.

Table 10. Measurements Collected Per HEG

HEG	No. Desired	No. Collected
1	12	11
2	24	24
3	54	55
4	6	6
5	12	10
6	24	24
Total	132	130

For HEG 1, two of the four workers selected for monitoring were transferred to a different job after one measurement was made on each. Three samples were subsequently collected for the alternate, as well as for the other two workers originally selected. For HEG 3, a fourth measurement was made for one previously selected worker, when a no-show from HEG 5 made available an extra monitor on that day. Likewise, one other worker from HEG 5 did not show on their scheduled day, resulting in a total of two measurements less than desired for this group. It should also be noted that alternate workers, which were selected at random, were used for HEGs 2 and 6. Finally, the samples from a worker belonging to HEG 6 were excluded from the analysis because their job during the sample interval was in a location different from that of the other workers in this group. A temporary laboratory had been setup in one of the resin buildings. Hence, the total number of measurements included in the analysis was 127, which were obtained from 44 workers at this facility.

Tests of Lognormality

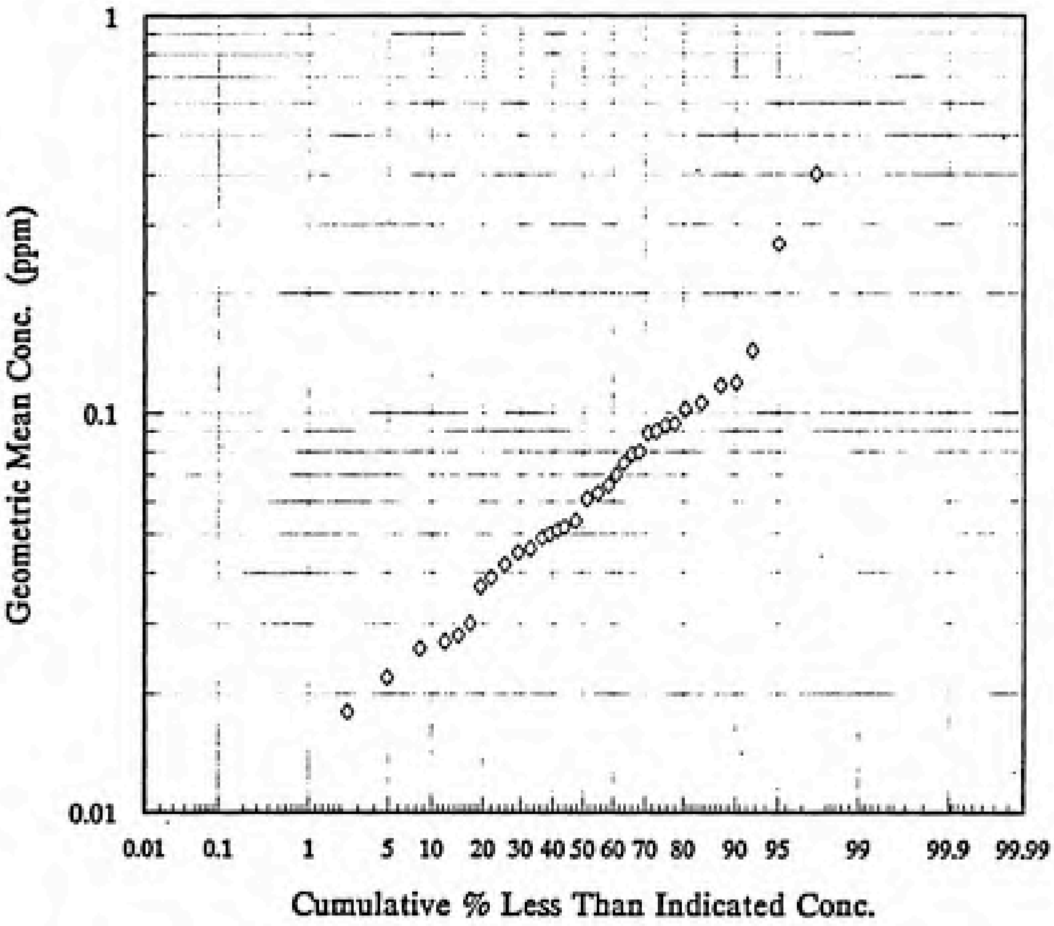
Table 11 presents the results of the Shapiro-Wilk W test on the goodness-of-fit of the data to the lognormal model.

Table 11. Results of Shapiro-Wilk W Test for Lognormality

HEG	k	W Statistic	P Value
1	3	0.8787	0.3207
2	8	0.9328	0.5462
3	18	0.9226	0.1472
4	2	1.0	1.0
5	2	1.0	1.0
6	7	0.9776	0.9458
Total Population	40	0.9737	0.5827

At an alpha level of 0.05, the null hypothesis of lognormality was not rejected for any group. Clearly the test results for groups 1, 4, and 5 are without meaning, given the small sample sizes. The degree of non-significance for the total group, however, does indicate that the assumption of lognormality was reasonable, at least for the total between-worker distribution of exposures. Further evidence that the total group was monomorphic can be seen in Figure 4, which shows a log-probability plot of the between-worker distribution for the total group. It appears to be approximately linear. Finally, the results for groups 2, 3, and 6 indicate that the assumption of lognormality was reasonable, thus each can be considered a monomorphic group.

Figure 4. Log-Probability Plot for Total Between-Worker Distribution



ANOVA Results

Complete results from the analyses of variance performed on the exposure measurements for these groups are presented in Tables 13 - 20. First, Table 12 provides a summary of the results. A total of seven one-way ANOVAs were completed, one for each HEG and one for the total population, in addition to a nested two-way analysis using HEGs as the primary factor. The one-way classifications partition the variance into estimates of the within and between components for each group and the population as a whole, allowing for an assessment of homogeneity of exposures for each case. The two-way classification reveals any reduction in between-worker variability as a result of the grouping scheme, and is used to gauge the success of the process for this population.

Table 12. Summary Statistics from One-Way Classification ANOVAs

HEG	N	k	$\bar{x}$ (± sd) [ppm]	$\bar{y}$	${}_{T}S_{y}^{2}$	${}_{W}S_{y}^{2}$ (% of Total)	${}_{B}S_{y}^{2}$ (% of Total)	${}_{B}\hat{R}_{0.95}$
1	11	5	0.24 (± 0.38)	- 2.08	1.129	0.712 (58.8)	0.498 (41.2)	15.9
2	24	8	0.12 (± 0.17)	- 2.82	1.226	1.215 (99.0)	0.012 (1.0)	1.5
3	55	18	0.11 (± 0.17)	- 2.66	0.685	0.714 (100.0)	- 0.030 (0.0)	1.0
4	6	2	0.04 (± 0.02)	- 3.50	0.431	0.369 (78.3)	0.102 (21.7)	3.5
5	10	4	0.09 (± 0.04)	- 2.56	0.381	0.241 (58.4)	0.171 (41.6)	5.1
6	21	7	0.05 (± 0.03)	- 3.28	0.439	0.308 (67.8)	0.146 (32.2)	4.5
Total	127	44	0.11 (± 0.18)	- 2.77	0.841	0.691 (81.9)	0.152 (18.1)	4.6

N = number of exposure measurements per group
k = number of workers monitored
$\bar{x}$ = arithmetic mean
sd = sample standard deviation
$\bar{y}$ = mean of log-transformed data
${}_{T}S_{y}^{2}$ = total variance of log-transformed data
${}_{W}S_{y}^{2}$ = within-worker variance component
${}_{B}S_{y}^{2}$ = between-worker variance component
${}_{B}\hat{R}_{0.95}$ = estimated ratio of 97.5^{th} and 2.5^{th} percentile from the between-worker distribution

Table 13. One-Way Random Effects ANOVA for HEG 1

Variance Source	df	SS	MS	Variance Component	Percent of Total
Between-Worker	4	7.0173	1.7543	0.4983	41.16
Within-Worker	6	4.2743	0.7124	0.7124	58.84
Total	10	11.2916	1.1292	1.2107	100.00

Table 14. One-Way Random Effects ANOVA for HEG 2

Variance Source	df	SS	MS	Variance Component	Percent of Total
Between-Worker	7	8.7534	1.2505	0.0119	0.97
Within-Worker	16	19.4364	1.2148	1.2148	99.03
Total	23	28.1898	1.2256	1.2267	100.00

Table 15. One-Way Random Effects ANOVA for HEG 3

Variance Source	df	SS	MS	Variance Component	Percent of Total
Between-Worker	17	10.5860	0.6227	- 0.0300	0.00
Within-Worker	37	26.4253	0.7142	0.7142	100.00
Total	54	37.0113	0.6854	0.7142	100.00

Table 16. One-Way Random Effects ANOVA for HEG 4

Variance Source	df	SS	MS	Variance Component	Percent of Total
Between-Worker	1	0.6766	0.6766	0.1024	21.71
Within-Worker	4	1.4774	0.3694	0.3694	78.29
Total	5	2.1540	0.4308	0.4718	100.00

Table 17. One-Way Random Effects ANOVA for HEG 5

Variance Source	df	SS	MS	Variance Component	Percent of Total
Between-Worker	3	1.9882	0.6627	0.1711	41.56
Within-Worker	6	1.4438	0.2406	0.2406	58.44
Total	9	3.4320	0.3813	0.4117	100.00

Table 18. One-Way Random Effects ANOVA for HEG 6

Variance Source	df	SS	MS	Variance Component	Percent of Total
Between-Worker	6	4.4789	0.7465	0.1462	32.21
Within-Worker	14	4.3092	0.3078	0.3078	67.79
Total	20	8.7881	0.4394	0.4540	100.00

Table 19. One-Way Random Effects ANOVA for Total Population

Variance Source	df	SS	MS	Variance Component	Percent of Total
Between-Worker	43	48.6258	1.1308	0.1524	18.07
Within-Worker	83	57.3663	0.6912	0.6912	81.93
Total	126	105.9921	0.8412	0.8436	100.00

Table 20. Two-Way Nested Random Effects ANOVA for Total Population

Variance Source	df	SS	MS	Variance Component	Percent of Total
HEG	5	15.1253	3.0251	0.1151	13.20
Between-Worker	38	33.5005	0.8816	0.0660	7.56
Within-Worker	83	57.3663	0.6912	0.6912	79.24
Total	126	105.9921	0.8412	0.8723	100.00

DISCUSSION

The sampling results clearly indicate that the vast majority of formaldehyde exposures at this facility are well below the OSHA PEL of 1.0 ppm as an 8-hour TWA. In fact, out of 127 measurements, only two were above the OEL (Figure 3, Appendix E). The mean exposure across the entire sample population was 0.11 ppm with a standard deviation of 0.18 ppm.

Table 12 shows that the Head Roll Operators (HROs) in HEG 1 had the highest mean exposure of all six groups (0.24 ppm), while HEG 4 had the lowest (0.04 ppm). The analyses of variance reveal that for most groups and the population as a whole, the total variation in exposures was predominantly within-worker, that is, day-to-day. Estimates of the percent of total variation belonging to the within-worker component ranged from 58.4% to 100.0 %. The low degree of between-worker variation indicates relatively homogeneous exposure conditions at this facility. However, using the definition of a uniformly exposed group described earlier (i.e. ${}_B\hat{R}_{0.95} \leq 2$), only two of the six groups would be considered uniformly exposed: HEG 2 and 3. Given the extremely small components of between-worker variation for each of these groups, accounting for 1.0% and 0.0%, respectively, of the total variation, this result is not surprising. Compared to the total population, with a ${}_B\hat{R}_{0.95}$ of 4.6, the grouping scheme reduced the ${}_B\hat{R}_{0.95}$ and the between-worker variation in four of the HEGs. Yet, for groups 1, 4, and 5, with the total number of samples collected equaling 11, 6, and 10, respectively, the results must be considered somewhat tenuous.

These results also indicate that the between-worker variation across the entire sample population was relatively low. In fact, Tables 12 and 19 show that between-worker variance accounted for less than 20% of the total variance. This implies that the subclassification of workers into discrete exposure groups, in an effort to reduce variability between workers, would have limited effect for this population since a "perfect" grouping would only account for about 20% of the total variation across the population. Hence, a 20% reduction in exposure variability is the most that could have been achieved through the use of HEGs. As the nested ANOVA in Table 20 reveals, this effort was able to account for roughly 13% of the total variation or two-thirds of the 20% which could be dealt with in this manner.

In addition to providing information on the homogeneity of exposures, the analyses of variance also offer insight on the nature of exposures at this facility. Specifically, since the total variation in exposure across the entire population, and for each HEG, was predominantly within-worker, exposures are governed mostly by production processes or environmental conditions which are common to the entire group. This implies that in general, individual jobs or work tasks are not contributing to wide fluctuations in exposure to formaldehyde between workers at this facility. Given the practice of rotating tasks within job classes, this is, perhaps, to be expected.

However, the results indicating such a large degree of within-worker variation (accounting for 99.0% and 100.0% of the total, respectively) for HEGs 2 and 3 was surprising. At first glance, the sampling results displayed in Appendix E for these two groups do not appear to support this finding. Yet, upon closer inspection, the fact remains that there were indeed very large differences in levels of exposure from day to day for individual workers. These within-person differences were so large that for the statistical analysis, differences between the means of individual workers were obscured.

So, the relevant question is why were day to day fluctuations in exposure so great. One contributory factor may relate to the type of processes involved with the production of resin at this facility, specifically the intermittent nature of the operation. When resin undergoes production, kettles are charged, samples are collected and analyzed, and product is processed; there is opportunity for exposure. If kettles are not producing resin, there is minimal opportunity for exposure. Clearly, exposures will fluctuate based on the production of resin. Another factor which accounts for day to day variability is certain job tasks performed fairly infrequently, but which can impact the level of exposure for workers in an entire building. In particular, the task of charging a kettle with paraformaldehye is not performed every day, but leads to higher exposures for the majority of workers present in the building on those days when it is performed. For example, on the July 30, Worker 1 from HEG 2 started the shift that day by finishing the task of charging Kettle 323 with paraformaldehyde (see Appendix E). This operators' exposure on this day was 0.53 ppm, significantly higher than the other measurements made for this worker on other days. In addition, note that on this same day two other operators were monitored (Workers 2 and 3), and their exposures were also higher than those received on subsequent sample days. The end result is that this intermittent task contributed greatly to the within-worker variation for each operator, yet did not confer a large degree of between-worker variation.

Another factor which may have contributed to within-worker variance, by way of reducing between-worker variance, is overlapping job tasks between HEGs. In particular, it was not uncommon for Kettle Operators in both resin buildings to perform tasks similar to those performed by Lift Truck Operators and Floormen, from Buildings 3/12 and 19/57, respectively. However, the converse did not occur. That is, Lift Truck Operators or Floormen never performed tasks directly related to kettle operation. In any case, a potential consequence of task overlap is a reduction in between-worker variation, since performing similar tasks generally involves similar potential for exposure.

Finally, the fact that Head Roll Operators in HEG 1 received the highest exposures, on average, was unexpected, given that formaldehyde as a raw product is not present in Building 88. Formaldehyde is released, as described previously, during the heating of pulverized phenolic resin as it is applied to the nip of the heated rolls. Apparently, the process is capable of releasing more formaldehyde than the author thought possible, and the engineering controls are not adequately removing all of the contaminant generated. A brief investigation of the circumstances involved with the single exposure above the OEL received by a worker from this job class, revealed that the operator did experience difficulties with the process on that day. The other possibility which might account for the higher than expected results for this group is contamination of the monitor with resin dust, which is very prevalent for this process. It is possible that dust trapped in the outer membrane of the monitor after it is sealed, continues to off-gas any free formaldehyde which was present in the dust. However, there are two reasons why this possibility is thought to be unlikely. For one, measures were taken to remove all visible dust from the outer membrane of the monitor before sealing. Furthermore, if formaldehyde did continue to off-gas from trapped resin dust, one would expect to obtain results many orders of magnitude higher than the results which were obtained.

CONCLUSIONS

For this study, the use of diffusion monitors for full-shift personal sampling of formaldehyde exposure provided results comparable to sorbent tubes. Even though the monitors tended to read marginally higher compared to the sorbent tubes, the benefits outweigh any loss in accuracy, if it actually exists. The monitors require less labor, are more readily acceptable to workers, and are more cost efficient. The end result is an increased number of samples, which leads to a more accurate characterization of the distribution of exposures.

The observational approach used to assign workers to HEGs in this case was only marginally effective. In terms of reducing between-worker variability in exposures, the *a priori* groupings were successful for one-half of the groups based on an analysis of variance of sampling results. However, the most significant finding of this study was the fact that between-worker variability accounted for only 20% of the total variation for the population. Between-worker variation was obscured by the large degree of within-worker variation, or fluctuations day to day, which was likely a result of the batch nature of the operation and task overlap between groups.

Given the relatively uniform exposure conditions between workers within groups and across groups, much effort could have been avoided if the entire population had been randomly sampled prior to the assignment of workers into exposure groups which were perceived to be discrete. This illustrates the benefit of an *a posteriori* approach to assessing exposures across a population of workers.

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APPENDIX A

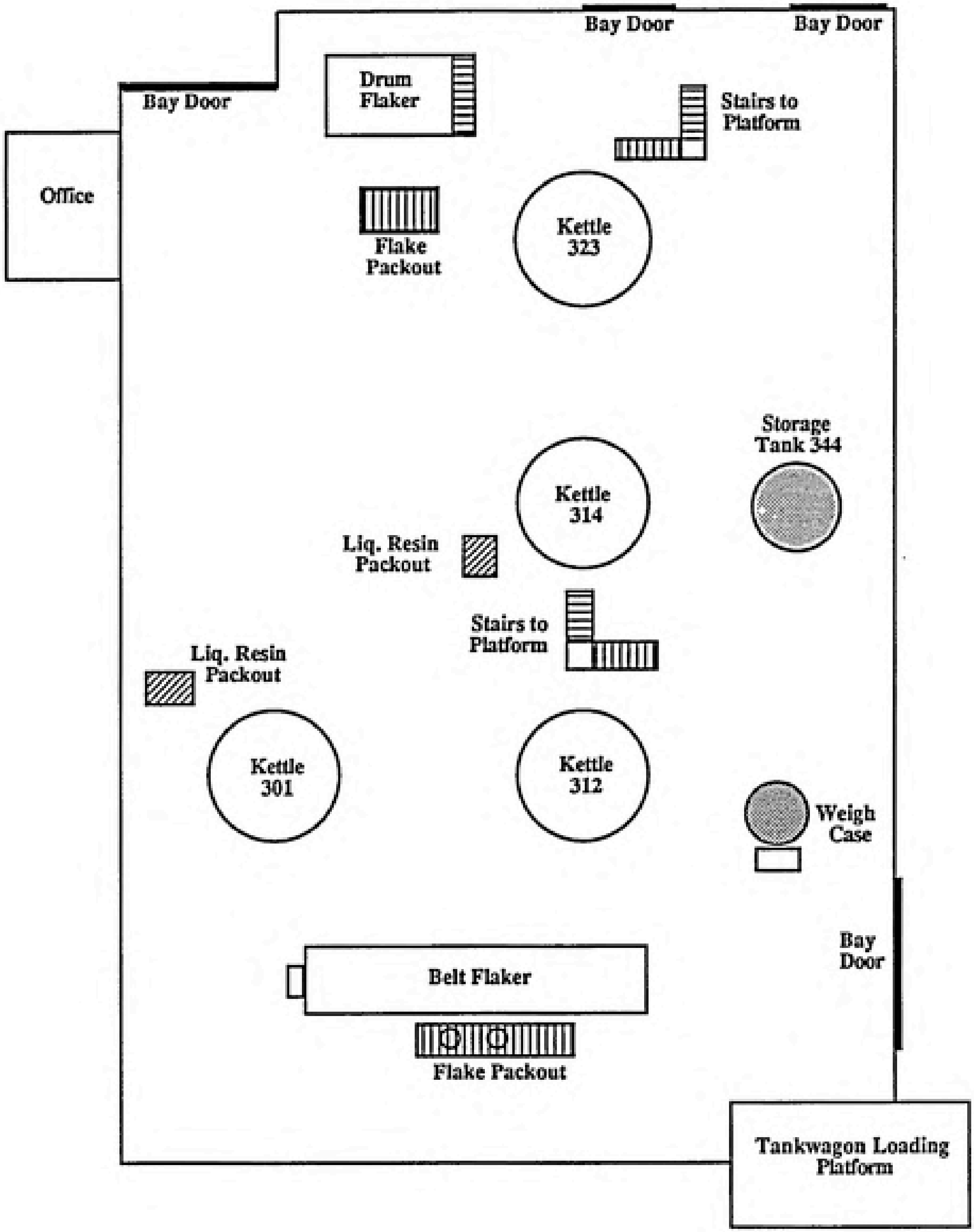
Floor Plans

OLD COUNCIL TREE

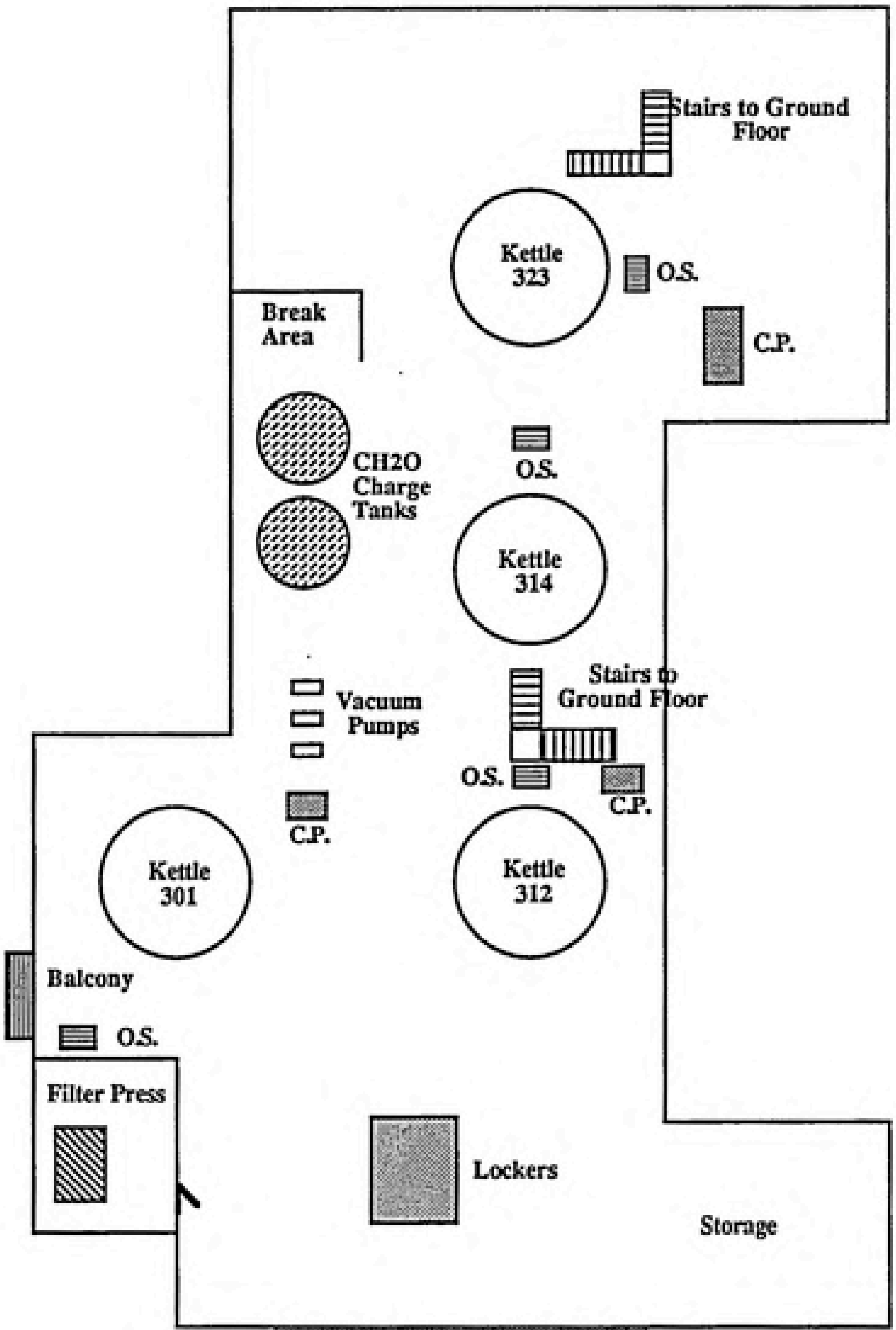
POND

[illegible]

Building 3/12 Floorplan - Ground Level

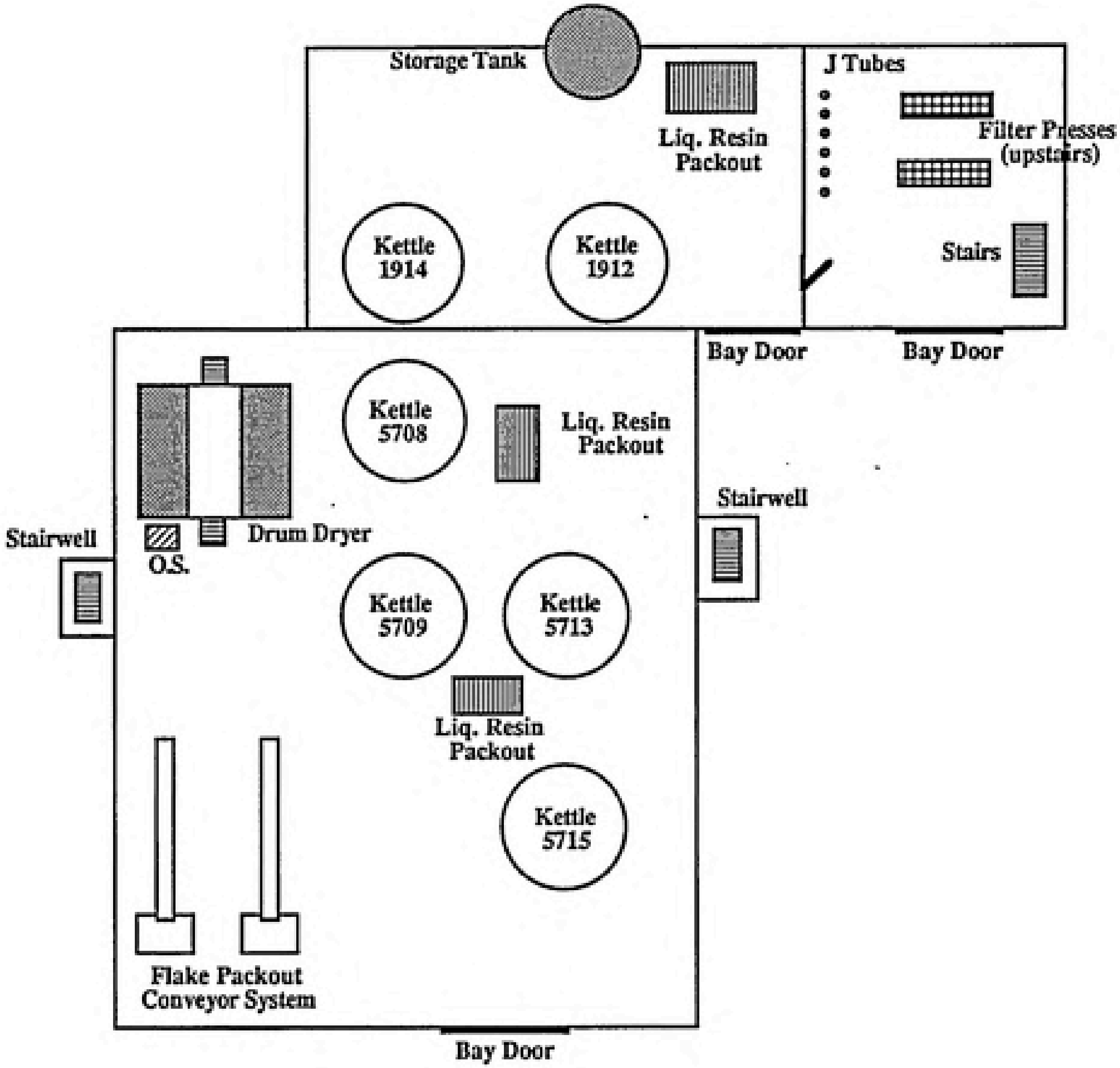


Building 3/12 Floorplan - Platform Level

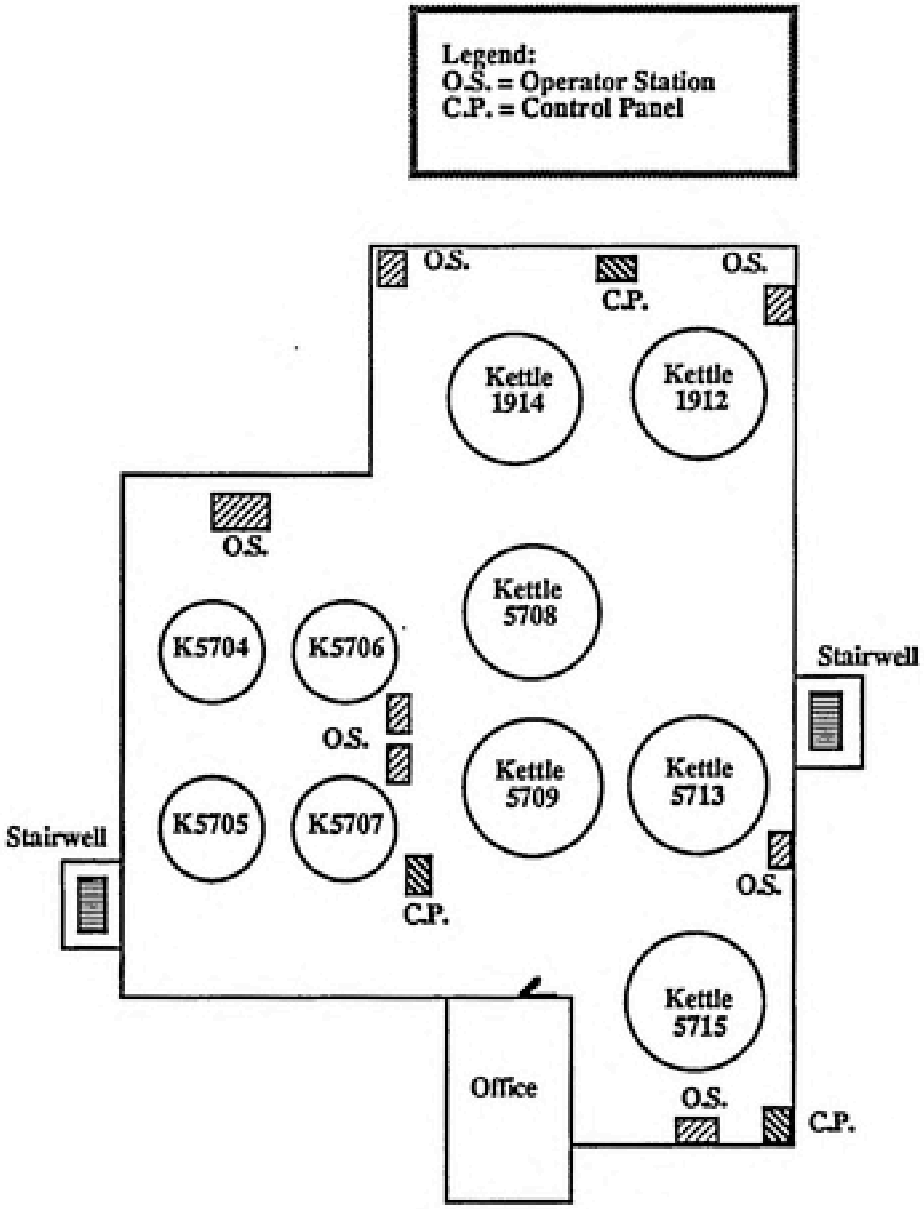


Legend:
O.S. = Operator Station
C.P. = Control Panel

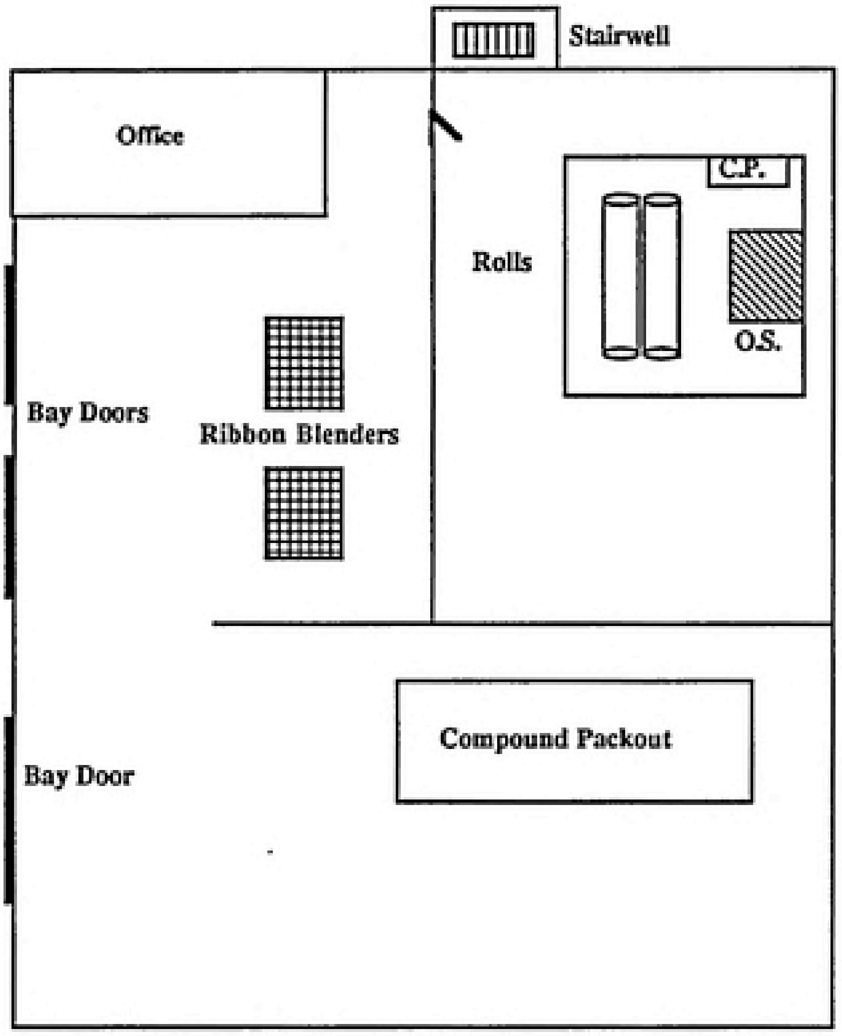
Building 19/57 Floorplan - Ground Level



Building 19/57 Floorplan - Platform Level

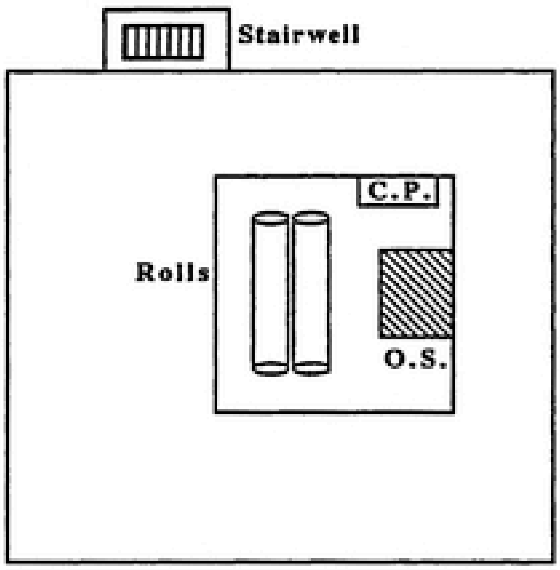


Building 88 Floorplan - Ground Level



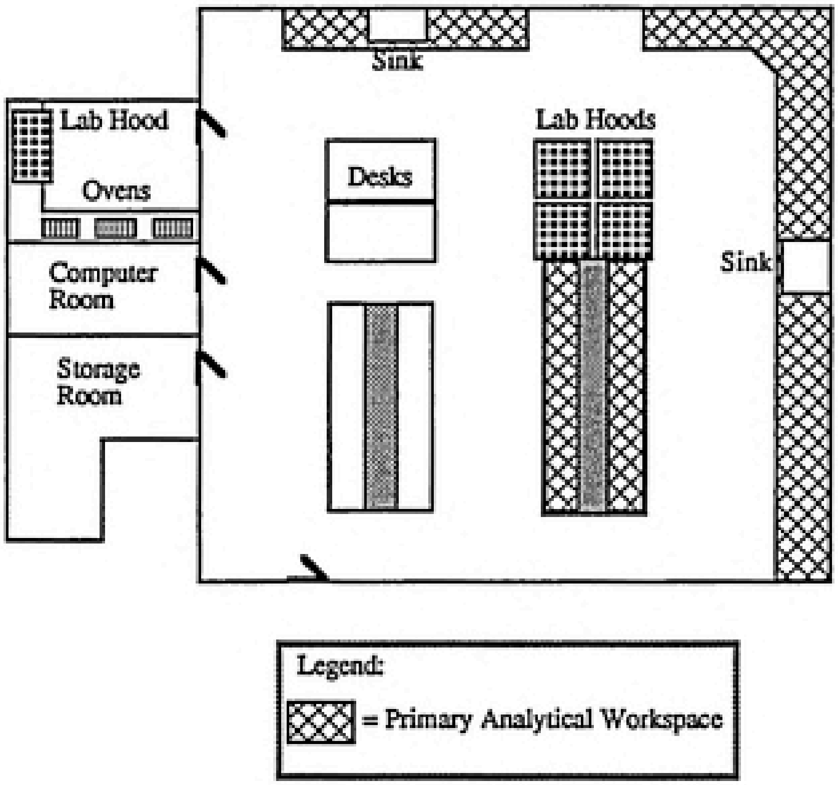
Legend:
O.S. = Operator Station
C.P. = Control Panel

Building 88 Floorplan - Upper Level



Legend:
O.S. = Operator Station
C.P. = Control Panel

Control Lab - Floorplan



APPENDIX B

Randomization Procedure

Appendix B Random Selection of Workers and Sample Days; Number of Samples Collected Per Worker

HEG	Worker ID No.	Shift	Selected (√)	Sample Days on Day Shift	Randomly Selected Sample Days	Actual No. Samples Collected
1	1	1	√	10 - 13	11, 12, 13	3
1	2	1				
1	3	2	√	1 - 5, 14 - 18	3, 16, 17	3
1	4	2	√ (Alt)	14 - 18	16, 17, 18	3
1	5	3	√	6 - 9, 19 - 21	6, 9, 20	1
1	6	3	√	6 - 9, 19 - 21	8, 19, 20	1
2	01	1	√	10 - 13	10, 11, 12	3
2	02	1	√	10 - 13	10, 12, 13	3
2	03	1	√	10 - 13	10, 11, 13	3
2	04	1	√	10 - 13	11, 12, 13	3
2	05	2				
2	06	2	√	1 - 5, 14 - 18	4, 5, 14	3
2	07	2	√	1 - 5, 14 - 18	2, 3, 17	3
2	08	2				
2	09	3	√	6 - 9, 19 - 21	7, 8, 9	3
2	10	3	√ (Alt)	6 - 9, 19 - 21	9, 19, 21	3
2	11	3				
2	12	3	√	6 - 9, 19 - 21	6, 9, 19	0
3	01	J	√ (Alt 1)	1 - 5, 19 - 21	1, 5, 20	
3	02	J				
3	03	J	√	1 - 5, 19 - 21	2, 4, 19	3
3	04	J	√	1 - 5, 19 - 21	3, 5, 19	3
3	05	J	√	1 - 5, 19 - 21	1, 5, 19	3
3	06	J	√	1 - 5, 19 - 21	1, 4, 20	3
3	07	J	√	1 - 5, 19 - 21	1, 5, 20	3
3	08	K	√	14 - 18	14, 15, 16 (17*)	4
3	09	K	√ (Alt 2)	14 - 18	15, 16, 18	
3	10	K	√	14 - 18	15, 17, 18	3
3	11	K				
3	12	K	√	14 - 18	14, 15, 17	3
3	13	K				
3	14	K	√	14 - 18	14, 15, 16	3
3	15	L	√	6 - 9	7, 8, 9	3
3	16	L	√	6 - 9	6, 7, 8	3
3	17	L	√	6 - 9	6, 7, 9	3
3	18	L	√	6 - 9	7, 8, 9	3
3	19	L				
3	20	L				
3	21	L				
3	22	M				
3	23	M	√	10 - 13	10, 11, 12	3
3	24	M	√	10 - 13	10, 11, 13	3
3	25	M	√	10 - 13	10, 11, 12	3
3	26	M	√	10 - 13	10, 11, 12	3
3	27	M	√	10 - 13	10, 11, 13	3
3	28	M				

HEG	Worker ID No.	Shift	Selected (√)	Sample Days on Day Shift	Randomly Selected Sample Days	Actual No. Samples Collected
4	1	1				
4	2	2	√	1 - 5, 14 - 18	3, 14, 16	3
4	3	3	√	6 - 9, 19 - 21	19, 20, 21	3
4	4	3				
5	1	J	√	1 - 5, 19 - 21	3, 4, 19	2
5	2	K	√	14 - 18	14, 16, 17	2
5	3	K				
5	4	L	√	6 - 9	6, 7, 9	3
5	5	M	√	10 - 13	10, 12, 13	3
5	6	M				
6	01	J				
6	02	J	√	1 - 5, 19 - 21	1, 3, 21	0
6	03	J	√ (Alt 1)	1 - 5, 19 - 21	4, 5, 20	3
6	04	K	√	14 - 18	14, 15, 17	3
6	05	K				
6	06	K	√	14 - 18	15, 17, 18	3
6	07	L	√	6 - 9	6, 7, 8	3
6	08	L	√	6 - 9	6, 8, 9	3
6	09	L	√	6 - 9	6, 7, 8	3
6	10	M	√	10 - 13	10, 12, 13	3
6	11	M	√ (Alt 2)	10 - 13	11, 12, 13	
6	12	M	√	10 - 13	11, 12, 13	3

Alt = Alternate in the event any selected worker was not available

* = Indicates day on which 4th sample was collected; worker was randomly selected to wear monitor after Floorman scheduled for that day did not show

APPENDIX C

Sample Day By Date

Appendix C Sample Day by Date

Sample Day	Date	
1	July	15
2		16
3		17
4		18
5		19
6		22
7		23
8		24
9		25
10		30
11		31
12	August	1
13		2
14		5
15		6
16		7
17		8
18		9
19		12
20		13
21		14

APPENDIX D

Field Study Data and Analysis

Appendix D Data from Sampling Methods Field Study and Statistical Analysis

AQR PF-20 (PEL) Conc. (ppm)	SKC Treated XAD-2 Conc. (ppm)	Difference [AQR - SKC] (ppm)
0.09	0.04	0.05
0.14	0.11	0.03
0.18	0.25	- 0.07
0.08	0.05	0.03
0.17	0.13	0.04
0.13	0.10	0.03
0.25	0.10	0.15
0.13	0.07	0.06
0.16	0.10	0.06
0.30	0.19	0.11
0.40	0.40	0.00
0.29	0.26	0.03
0.07	0.09	- 0.02
0.07	0.03	0.04
0.43	0.30	0.13
0.22	0.15	0.07
0.16	0.19	- 0.03
0.28	0.28	0.00
0.17	0.15	0.02
0.12	0.06	0.06
0.21	0.16	0.05
0.05	0.05	0.00
0.09	0.08	0.01
0.05	0.22	- 0.17
0.06	0.07	- 0.01
0.06	0.06	0.00

n = 26 Matched Pairs

Sample Mean:

AQR = 0.17 ppm

SKC = 0.14 ppm

Difference ($\bar{d}$) = 0.026 ppm

Sample Standard Deviation:

AQR = 0.10 ppm

SKC = 0.09 ppm

Difference (s_d) = 0.062

Paired Sample t-Test on Differences:

$$t = \frac{\bar{d} - \mu_o}{\frac{s_d}{\sqrt{n}}}$$ where $\mu_o = 0$ under the null hypothesis

$t = 2.105$

Probability that $|t| > 2.105 = 0.046$

Result: At a 0.05 level of significance, borderline rejection of the null hypothesis of no significant difference between the two methods.

APPENDIX E

HEG Sampling Data

HEG	Worker ID No.	Date	8-Hr TWA (ppm)	Job Title	PF-20 ID No.	Location (Bldg.)	Operation/Job Task
1	1	073191	0.13	HRO	1090359	88	Downstairs Rolls
1	1	080191	0.05	HRO	1090371	88	Downstairs Rolls/General Cleanup
1	1	080291	0.11	HRO	1090383	88	Cleaned Pulverizers/General Cleanup/Downstairs Rolls
1	3	071791	0.29	HRO	1090288	88	Upstairs Rolls/Cleaned Sifters
1	3	080791	0.11	HRO	1090415	88	Upstairs Rolls
1	3	080891	0.05	HRO	1090425	88	Upstairs Rolls
1	4	080791	0.24	HRO	1090416	88	Main Floor Materials Handling/Downstairs Rolls
1	4	080891	0.20	HRO	1090424	88	Downstairs Rolls
1	4	080991	1.34	HRO	1090431	88	Downstairs Rolls
1	5	072591	0.04	HRO	1090337	88	General Cleanup/Upstairs Rolls
1	6	072491	0.04	HRO	1090327	88	Packout Duties
2	1	073091	0.53	AKO	1090347	3\12	K323-Finished Charging With Paraform
2	1	073191	0.04	AKO	1090360	3\12	Pan Job on Gelled Resin
2	1	080191	0.08	AKO	1090380	3\12	K323
2	2	073091	0.22	AKO	1090354	3\12	K301-Charged With Phenol and Sulfuric Acid
2	2	080191	0.03	AKO	1090372	3\12	Drained T344 into Pans/K301
2	2	080291	0.02	AKO	1090384	3\12	K323/Relieved Drum Flaker Packout
2	3	073091	0.14	AKO	1090348	3\12	K314
2	3	073191	0.06	AKO	1090367	3\12	K323
2	3	080291	0.03	AKO	1090385	3\12	K312
2	4	073191	0.02	AKO	1090361	3\12	K301
2	4	080191	0.03	AKO	1090373	3\12	Drained T344 into Pans/K312
2	4	080291	0.03	AKO	1090386	3\12	K312-Caustic Wash
2	6	071891	0.65	AKO	1090295	3\12	K323-Charged With Paraform
2	6	071991	0.15	AKO	1090303	3\12	K301
2	6	080591	0.03	AKO	1090395	3\12	K323
2	7	071691	0.05	AKO	1090286	3\12	K312-Phenol Boil/K301-Charged With Xylene
2	7	071791	0.06	AKO	1090289	3\12	Belt Flaker Packout/Cleaned Roof Dust Collector

HEG	Worker ID No.	Date	8-Hr TWA (ppm)	Job Title	PF-20 ID No.	Location (Bldg.)	Operation/Job Task
2	7	080891	0.03	AKO	1090419	3\12	K312-Transferred Resin to Tankwagon
2	9	072391	0.42	AKO	1090324	3\12	K314-Charged With Formalin Via Pressurized T341
2	9	072491	0.10	AKO	1090334	3\12	K323-Charged With Formalin Via Pressurized T341
2	9	072591	0.02	AKO	1090338	3\12	Ground Floor-Transferred Acid Rework to Drums
2	10	072591	0.01	AKO	1090339	3\12	K314
2	10	081291	0.06	AKO	1090434	3\12	K301
2	10	081491	0.03	AKO	1090446	3\12	K314-Finished Charging With Formalin/Belt Flaker Packout
3	3	071691	0.11	AKO	1090285	19\57	K5706/Relieved on Drum Dryer
3	3	071891	0.12	AKO	1090296	19\57	Liq. Resin Packout Ground Floor/K5709-Started Charging w/ Formalin
3	3	081291	0.09	AKO	1090435	19\57	Operated Drum Dryer
3	4	071791	0.08	AKO	1090290	19\57	5715-Charged w/ Phenol and Caustic
3	4	071991	0.21	AKO	1090305	19\57	Operated Drum Dyrer/K5706
3	4	081291	0.03	AKO	1090436	19\57	K1912/K1914
3	5	071591	0.09	AKO	1090281	19\57	K5715
3	5	071991	0.20	AKO	1090306	19\57	K5709/Liq. Resin Packout
3	5	081291	0.04	AKO	1090437	19\57	Transferred Resin to Tankwagon/Supplied Raw Materials to Platform
3	6	071591	0.09	AKO	1090282	19\57	K5706-Charged w/ Phenol and Formalin/Relieved on Drum Dryer
3	6	071891	0.22	AKO	1090297	19\57	K1912-Charged w/ Caustic, Sampled Continuosly
3	6	081391	0.06	AKO	1090438	19\57	Transferred Resin to Storage Tank/K5708-Prepped and Charged w/ Formalin
3	7	071591	0.08	AKO	1090283	19\57	K1914-Setup and Recirculated Through Filter Press
3	7	071991	0.17	AKO	1090304	19\57	K5708/Helped Charge K5715 w/ Paraform
3	7	081391	0.06	AKO	1090441	19\57	K5715-Completed, Transferred to Storage Tank/Helped Drop K5713 Brittle
3	8	080591	0.09	AKO	1090394	19\57	Liq. Resin Packout/Cleaned and Prepped Drum Dryer
3	8	080691	0.03	AKO	1090403	19\57	K5708-Charged w/ Phenol and Formalin
3	8	080791	0.01	AKO	1090411	19\57	K5709-Charged w/ Phenol and Formalin
3	8	080891	1.18	AKO	1090422	19\57	K1912-Charged w/ Paraform
3	10	080691	0.03	AKO	1090404	19\57	General Cleanup Duties/Relieved K5713 and K1914
3	10	080891	0.08	AKO	1090420	19\57	K5708/Relieved K5709 and K5715

HEG	Worker ID No.	Date	8-Hr TWA (ppm)	Job Title	PF-20 ID No.	Location (Bldg.)	Operation/Job Task
3	10	080991	0.04	AKO	1090429	1957	K5709-Setup and Circulated Resin Through Filter Press
3	12	080591	0.04	AKO	1090396	1957	K1912-Caustic Boil
3	12	080691	0.05	AKO	1090405	1957	K5713/Relieved K5715
3	12	080891	0.08	AKO	1090421	1957	Operated Drum Dryer
3	14	080591	0.05	AKO	1090397	1957	Cleaned and Prepped Drum Dryer
3	14	080691	0.04	AKO	1090406	1957	K1914
3	14	080791	0.03	AKO	1090412	1957	K5708/Relieved K5709/Prepped For Liq. Resin Packout
3	15	072391	0.06	AKO	1090317	1957	K5715-Charged w/ Phenol and Formalin
3	15	072491	0.04	AKO	1090328	1957	K5713/Relieved K5715
3	15	072591	0.03	AKO	1090340	1957	Drummed Off Caustic Wash From K5713
3	16	072291	0.05	AKO	1090309	1957	K5708/General Cleanup Duties
3	16	072391	0.06	AKO	1090318	1957	K5709
3	16	072491	0.14	AKO	1090329	1957	K1912-Charged w/ Phenol and Formalin
3	17	072291	0.16	AKO	1090310	1957	K1914-Transferred to Storage Tank/Cleaned Dike
3	17	072391	0.08	AKO	1090319	1957	General Cleanup Duties/Helped Load Tankwagon w/ Resin
3	17	072591	0.01	AKO	1090341	1957	K5709-Dehydrating Caustic Solution/Relieved K5708
3	18	072391	0.46	AKO	1090320	1957	Liq. Resin Packout/General Cleanup Duties
3	18	072491	0.51	AKO	1090330	1957	Cleaned and Redressed Filter Press
3	18	072591	0.08	AKO	1090342	1957	K5708
3	23	073091	0.04	AKO	1090349	1957	K1912
3	23	073191	0.05	AKO	1090362	1957	K1914/Relieved K1912
3	23	080191	0.05	AKO	1090376	1957	K5715
3	24	073091	0.10	AKO	1090350	1957	K1914-Transferred Resin to Storage Tank/Charged w/ Phenol and Formalin
3	24	073191	0.05	AKO	1090363	1957	K5715-Transferred Resin to Storage Tank/Washed and Rinsed Kettle
3	24	080291	0.07	AKO	1090388	1957	Cleaned and Prepped Drum Dryer/Relieved on Drum Dryer
3	25	073091	0.10	AKO	1090351	1957	K5706-Charged w/ Phenol and Formalin/Relieved on Drum Dryer
3	25	073191	0.05	AKO	1090364	1957	K5708/Relieved K5709
3	25	080191	0.05	AKO	1090374	1957	Liq. Resin Packout
3	26	073091	0.07	AKO	1090352	1957	Operated Drum Dryer

HEG	Worker ID No.	Date	8-Hr TWA (ppm)	Job Title	PF-20 ID No.	Location (Bldg.)	Operation/Job Task
3	26	073191	0.05	AKO	1090365	19\57	Cleaned and Prepped Drum Dryer/Relieved On Drum Dryer
3	26	080191	0.04	AKO	1090375	19\57	Liq. Resin Packout/K5708-Caustic Wash and Rinse
3	27	073091	0.09	AKO	1090353	19\57	K5715-Caustic Wash and Rinse/Relieved K5709
3	27	073191	0.08	AKO	1090366	19\57	Cleaned and Prepped Drum Dryer/Operated Drum Dryer
3	27	080291	0.04	AKO	1090387	19\57	K5708-Charged w/ Phenol and Formalin
4	2	071791	0.05	LTO	1090291	3\12	Belt Flaker Packout/Cleaned Roof Dust Collector
4	2	080591	0.01	LTO	1090398	3\12	Drum Flaker Packout/Cleaned Belt Flaker
4	2	080791	0.02	LTO	1090413	3\12	Cleaned and Prepped Belt Flaker/Operated Belt Flaker
4	3	081291	0.03	LTO	1090439	3\12	Chipped Gelled Resin For Drum Disposal
4	3	081391	0.05	LTO	1090443	3\12	Belt Flaker Packout/General Cleanup Duties
4	3	081491	0.05	LTO	1090448	3\12	Belt Flaker Packout
5	1	071791	0.18	AF	1090292	19\57	Liq. Resin Packout/General Cleanup Duties
5	1	071891	0.11	AF	1090298	19\57	Transferred Acid Wash to Railcar/Loaded Tankwagon w/ Resin
5	2	080591	0.02	AF	1090399	19\57	Pumped Dike/Loaded Tankwagon w/ Resin
5	2	080791	0.08	AF	1090414	19\57	Supplied Raw Materials to Platform/Loaded 2 Tankwagons w/ Resin
5	4	072291	0.11	AF	1090311	19\57	Supplied Materials For Packout/General Cleanup Duties
5	4	072391	0.08	AF	1090321	19\57	Loaded Tankwagon w/ Resin
5	4	072591	0.12	AF	1090343	19\57	Loaded 2 Tankwagons w/ Resin
5	5	073091	0.08	AF	1090355	19\57	Loaded 2 Tankwagons w/ Resin/Relieved on Drum Dryer
5	5	080191	0.07	AF	1090377	19\57	Loaded 2 Tankwagons w/ Resin
5	5	080291	0.04	AF	1090389	19\57	Supplied Raw Materials/Loaded Tankwagon w/ Waste Water/Drum Dryer Packout
6	3	071891	0.05	SPT	1090299	Control Lab	Conducted Routine Lab Analyses
6	3	071991	0.06	SPT	1090302	Control Lab	Conducted Routine Lab Analyses
6	3	081391	0.04	SPT	1090442	Control Lab	Conducted Routine Lab Analyses
6	4	080591	0.03	SPT	1090400	Control Lab	Conducted Routine Lab Analyses
6	4	080691	0.02	SPT	1090407	Control Lab	Conducted Routine Lab Analyses
6	4	080891	0.01	SPT	1090426	Control Lab	Conducted Routine Lab Analyses
6	6	080691	0.03	SPT	1090408	Control Lab	Conducted Routine Lab Analyses

HEG	Worker ID No.	Date	8-Hr TWA (ppm)	Job Title	PF-20 ID No.	Location (Bldg.)	Operation/Job Task
6	6	080891	0.01	SPT	1090423	Control Lab	Conducted Routine Lab Analyses
6	6	080991	0.07	SPT	1090430	Control Lab	Conducted Routine Lab Analyses
6	7	072291	0.06	SPT	1090312	19\57 Lab	Conducted Routine Lab Analyses/Spent Time On Kettle Platform
6	7	072391	0.55	SPT	1090322	19\57 Lab	Conducted Routine Lab Analyses/Spent Time On Kettle Platform
6	7	072491	0.06	SPT	1090331	19\57 Lab	Conducted Routine Lab Analyses/Spent Time On Kettle Platform
6	8	072291	0.05	SPT	1090313	Control Lab	Conducted Routine Lab Analyses
6	8	072491	0.11	SPT	1090332	Control Lab	Conducted Routine Lab Analyses
6	8	072591	0.09	SPT	1090344	Control Lab	Conducted Routine Lab Analyses
6	9	072291	0.04	SPT	1090314	Control Lab	Conducted Routine Lab Analyses
6	9	072391	0.05	SPT	1090323	Control Lab	Conducted Routine Lab Analyses
6	9	072491	0.08	SPT	1090333	Control Lab	Conducted Routine Lab Analyses
6	10	073091	0.05	SPT	1090356	Control Lab	Conducted Routine Lab Analyses
6	10	080191	0.05	SPT	1090378	Control Lab	Conducted Routine Lab Analyses
6	10	080291	0.02	SPT	1090390	Control Lab	Conducted Routine Lab Analyses
6	12	073191	0.05	SPT	1090368	Control Lab	Conducted Routine Lab Analyses
6	12	080191	0.02	SPT	1090379	Control Lab	Conducted Routine Lab Analyses
6	12	080291	0.02	SPT	1090391	Control Lab	Conducted Routine Lab Analyses