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Real-time, integrated, and ergonomic analysis of dust exposure during manual materials handling

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Past studies have shown that ventilation does not always provide complete dust control during the manual weigh-out and transfer of powders. However, these studies have not shown where the dust emission sources are located. A field study was conducted in a plastics manufacturing plant to evaluate factors affecting worker dust exposure at a ventilated booth which was used for the weigh-out and transfer of powdered materials. A unique study plan was formulated utilizing real-time air sampling and short-term air sampling in conjunction with an ergonomic evaluation to determine activities or factors associated with dust exposure. The factors and activities evaluated were depth of scooping, cleanliness of the workers' clothing, worker anthropometry, and work practices. Real-time air sampling and work cycle evaluation showed that dust concentrations were highest when the worker was scooping material out of the drum, and these levels increased dramatically when the worker placed his breathing zone inside the drum to scoop the powder from the bottom. Short-term dust sampling showed that worker and level of material in the drum significantly affected dust concentrations. Soiled clothing had no effect upon worker dust exposure. Anthropometry and work practices may have significantly affected the worker's dust exposure. This study plan proved to be quite useful and, with some modifications, may be helpful in identifying other types of exposure sources. **Gressel, M.G.; Heitbrink, W.A.; McGlothlin, J.D.; Fischbach, T.J.:** Real-time, integrated, and ergonomic analysis of dust exposure during manual materials handling. *Appl. Ind. Hyg.* 2:108-113; 1987.

Introduction

Manual weigh-out and transfer of powders is performed in many industries. Traditional dust sampling has shown that ventilation of these operations is only partially effective in controlling workers' dust exposure.⁽¹⁾ The filter sampling alone has not shown which operations in the process (i.e., scooping the powder or measuring it into a smaller container) are causing higher worker dust exposure. While

real-time instruments in conjunction with ergonomic analysis can indicate which operations in a process are causing an increase in worker dust exposure, they tend to indicate only relative exposure. Therefore, a unique study plan was formulated utilizing traditional air sampling, ergonomic analysis, and real-time instrumentation to identify factors causing incomplete dust control during the manual weigh-out process.⁽²⁾ The use of all three of

these methods provided many advantages over traditional methods by providing more detailed information about the factors affecting exposure in a shorter period of time.

Plant and process

The study was conducted in a plastics plant which manufactures a variety of polyvinyl chloride products. The raw materials were weighed at the weigh-out booths and then charged into mixers. After mixing, the plastics were extruded, milled, or calendared into their final form.

The powdered raw materials arrived at this plant in paper or poly-lined paper bags. The raw material used in the operation studied was an acrylic copolymer powder. This powder was assembled into batch lots at the weigh-out booth diagrammed in Figure 1. A hinged segment of the work platform could be raised to allow a drum of raw material to be placed inside the booth. An exhaust plenum formed the back wall of the booth. At the booth, the worker emptied 23 kg (50 lb) bags of powder into a fiber drum measuring 84 cm (33 in.) high and 55 cm (21 in.) in diameter. Then, using a scoop, the worker transferred the powder from the drum to a small paper bag. The bag was placed on the scale and the weight of powder in the bag adjusted. Usually, two scoops of the powder were required to achieve the proper weight. Finally, the filled bag was

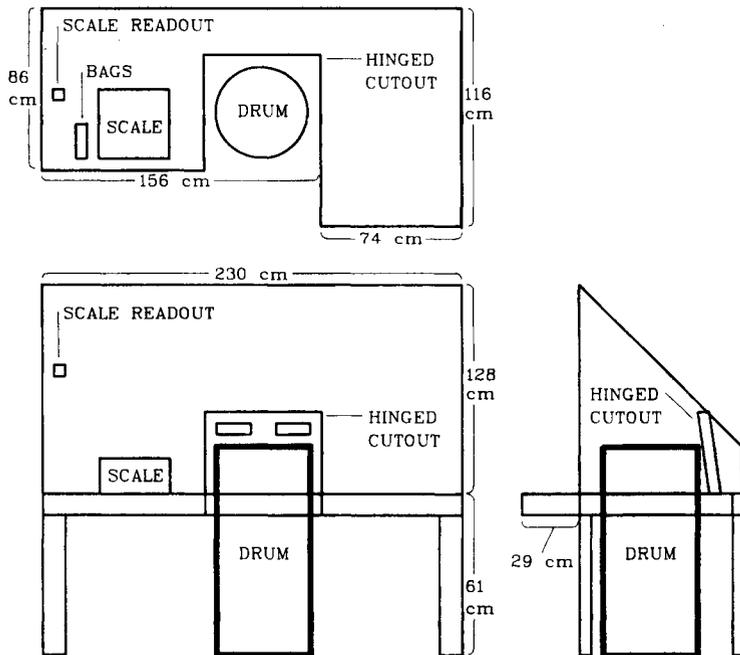


Figure 1—Diagram of work station. Not to scale. Exhaust plenum not shown.

closed and placed in a bin behind the worker. This process was repeated until the required number of batches were filled or the fiber drum was empty.

Methodology

Sampling strategy

Real-time instrumentation and gravimetric sampling were used in conjunction with an ergonomic evaluation to identify possible sources of dust exposure. For the gravimetric filter sampling, a 2×2 factorial experiment with two replications and three different workers was conducted to evaluate the effects of clothing and depth of scooping upon dust generation. A total of 24 sampling runs were conducted to assess the following: scooping from the bottom of the drum with dirty clothing, scooping from the top of the drum with dirty clothing, scooping from the bottom of the drum with clean clothing, and scooping from the top of the drum with clean clothing. The dirty clothing used was the worker's own coveralls, worn while performing some operations which were considered dusty such as emptying a bag of powder into the drum (sampling was not conducted while the bag was being emptied into the drum since this was beyond the scope of the study and had been studied previously).⁽¹⁾ The clean clothing consisted of disposable coveralls which were used once and then discarded. A drum was considered full if it was two thirds or more full, and considered

empty if one third or less remained in the bottom. For the filter sampling, air was drawn through a Mine Safety Appliances (MSA) FWSB 37-millimeter, 5.0 micrometer pore, closed face, filter and critical flow orifice by a carbon vane pump. The critical orifices were calibrated at 14-16 lpm (0.49-0.57 cfm). Six filter sampling locations were used: three on the worker, one at the face of the hood, one over the bin containing the filled bags, and one for background located about 9 m (30 ft) from the face of the hood. Of the three filters on the worker, one was fastened to the brim of his hat and the other two fastened to each lapel. A sampling run generally lasted ten to 20 minutes with 24 to 36 bags filled at 1.2 kg (2.6 lb) per bag.

Depth of scooping was evaluated further using real-time instrumentation. A single worker (worker #3), wearing dirty clothing, began with a full drum and weighed out the powder until the drum was nearly empty (less than one bag, or 1.2 kg of powder). During this period, two types of real-time instruments monitored respirable dust con-

centrations: hand-held aerosol monitors (HAM) (PPM Inc., Knoxville, TN) and real-time aerosol monitors (RAM) (GCA Inc., Bedford, MA). Two RAMs were used, one for background dust and one for dust within the hood, while a single HAM, attached to the worker, monitored the worker's breathing zone dust concentration. The RAMs' and the HAM's analog outputs were connected to an Apple II Plus computer through an A113 analog to digital converter (Interactive Structures Inc., Bala Cynwyd, PA). The computer was programmed to store digitized voltages from the converted analog signals. Readings were taken every two seconds and stored in several data files. The experiment was terminated when the drum was nearly empty (about 22 min).

Ergonomic evaluation

An ergonomic evaluation of the manual weigh-out and transfer process was conducted using a video camera ensemble and traditional job analysis techniques.^(3,4) This analysis included a breakdown of the process into job elements, the determination of the basic work cycle, and the identification of the selected hazardous elements in the work cycle. Also included in the ergonomic evaluation were selected descriptive and anthropometric measurements of each of the three workers, summarized in Table I. The descriptive data show that, while these workers were experienced with jobs involving materials weigh-out and transfer, this was not their regular job. Anthropometric measurements taken from these three workers show the female worker (worker #1) to be in the 35-40th percentile for stature, 5th percentile for height of hips, and 5th percentile for forward reach compared to a standard population. Worker #2, a tall male, measured in the 90-95th percentile for all anthropometric measurements taken. Worker #3, also a male and the most experienced of the three workers, measured in the 40-55th percentile for all anthropometric categories.⁽⁵⁾

TABLE I
Descriptive and anthropometric measurements

Measurement	Worker 1	Worker 2	Worker 3
Gender	Female	Male	Male
Length of employment	8.5 yr	9 yr	31 yr
Weight	51 kg (112 lb)	73 kg (161 lb)	91 kg (200 lb)
Body length	165 cm (65 in.)	184 cm (72 in.)	170 cm (67 in.)
Hip height	97 cm (38 in.)	111 cm (44 in.)	99 cm (39 in.)
Forward reach	72 cm (28 in.)	87 cm (34 in.)	83 cm (33 in.)

The videotapes were played back in a laboratory in slow-motion and stop-action to provide detailed information on work practices, posture, and equipment, helping to determine which elements in the work cycle might have increased worker dust exposure. The clock of the video camera system was synchronized with the internal clock of the computer, allowing the videotape to be viewed alongside of a listing of the real-time data to determine which activities increased worker dust exposure. The job elements were also examined over time to determine what effect powder depth in the drum had on work practices. Self-selected pacing determined work cycle time, and this may be a factor in dust exposure. From the videotape, two time measurements, the first for total cycle time, the other for scooping time, were taken for various drum levels. The use of the videotaping system in conjunction with the real-time instruments provided a detailed look at the potential sources of worker dust exposure.

Based on the work analysis described above, there were several possible worker dust exposure factors associated with this process. The depth from which the worker must scoop the powder appeared to be important. Since the powdered material was stored in drums, workers had to reach inside the drum to scoop the powder. When the drum was less than one-third full, the workers' breathing zone was between the local exhaust ventilation and the dust emission sources. Differences in work practices between workers also may have caused variations in personal dust exposure. For example, the operation of transferring material from one container to another inevitably created dust which was not totally controlled by local exhaust ventilation. In such operations, exposure

may be affected by the individual's work practices.

Ventilation

The airflow patterns in the booth were measured using smoke tubes to determine the direction of the airflow and using a velometer to measure the velocity of the airflow. All measurements were made with a member of the survey team standing at the hood face, in a manner similar to the worker's position while weighing at the scale. Air velocities (Figure 2) varied from 10 to 67 m/min (35 to 220 FPM). Eddies existed in several places within the hood, the most important found in front of the worker. Air flowed straight up the worker's body and into his breathing zone. Thus, any dust generated close to the worker's waist would flow directly into his breathing zone. Another eddy was discovered inside the drum. The air entered the back area of the drum, moved down to the surface of the drum carrying with it some of the powder. The hinged cut-out deflected the dusty air upward toward the worker's breathing zone (Figure 3). Thus, the worker's breathing zone was in this flow of dusty air when scooping powder from the bottom of the drum.

Statistical methods

The air sampling data were statistically analyzed to determine which factors affect dust generation. The gravimetric dust samples were analyzed to determine whether depth of scooping, worker, and clothing affected dust concentrations. Measurements taken with the HAM and the two RAMs were analyzed to study the association between the dust exposure and the individual components of the job.

The voltage output of the real-time instrumentation was statistically ana-

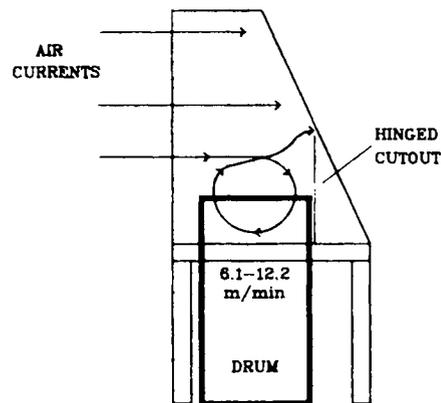


Figure 3—Eddies due to hinged segment of work platform.

lyzed to resolve whether scooping from the bottom of the drum increased worker dust exposure and, if so, which activities contributed the most to this increase. The strategy for this analysis was to fit a regression model involving the relation of the variable WORKER (a time-dependent measure of dust exposure) to the independent variables BAGCOUNT, SCOOPING, WEIGHING, and TURNING. WORKER was the voltage output of the real-time instrument which was mounted on the worker. BAGCOUNT was the cumulative number of bags which were weighed. SCOOPING was the cumulative time during each cycle spent scooping material from the drum and into the bag. WEIGHING was the cumulative time during each cycle spent weighing the bag at the scale and adjusting the amount of powder in the bag. TURNING was the cumulative time during each cycle spent placing the bag in the bin. The response was modeled closely enough to provide a fair representation of its relationship to the variables so that the objectives would be fulfilled. There was no attempt to continue to add terms until the lack of fit was not statistically significant.

A key assumption in the data analysis is the independence of measurements. Successive readings of the instrument response are not independent. When a dust generating event occurs, dust concentrations do not increase immediately; transportation time is needed for the air to move the dust cloud from the point of generation to the inlet of the instrument. Also, the HAM was operated with a time constant of one second and required some time to respond to fluctuating concentrations. Instrument response appeared to lag dust generating events by two to five

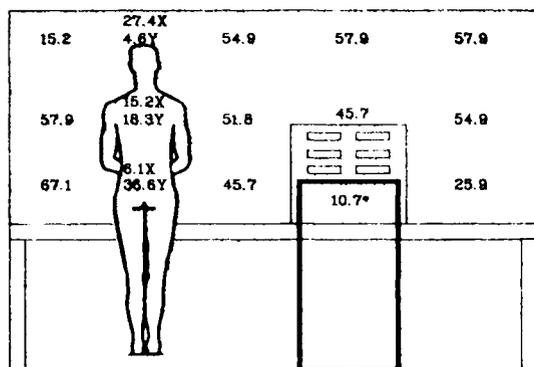


Figure 2—Face velocities of the booth. X direction is into the hood; Y direction is vertical. Velocities in m/min.

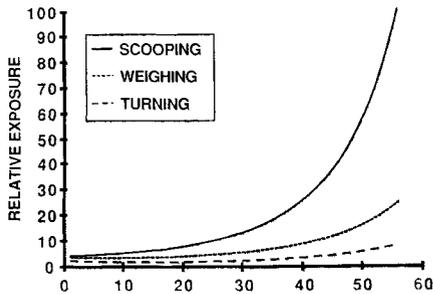


Figure 4—Modeled dust exposure of worker as a function of bag count for scooping, weighing, and turning at 8 seconds into an activity.

seconds. This suggests that autoregressive terms are needed in the analysis.

Terms were added in the following order only if the two-sided t-test indicated that the coefficient of a variable differed from zero at the 0.05 level of confidence.

BAGCOUNT
 SCOOPING, WEIGHING, TURNING
 BAGCOUNT², SCOOPING², WEIGHING²,
 TURNING²
 BAGCOUNT × SCOOPING, BAGCOUNT
 × WEIGHING, BAGCOUNT
 × TURNING

In cases in which three variables were added, the criterion, that the two-sided t-test of the hypothesis that the coefficient of a variable was zero, was rejected at the (0.05/3) level for at least one of the three variables. The SAS procedure AUTOREG was used for the analysis.^(6,7)

Statistical analysis of the filter data was conducted to address the study's hypotheses that the level of material in the drum and dusty clothing affected the worker's dust exposure. To test these hypotheses, a factorial experiment was conducted which involved the following variables:

Drum. The worker scooped material from either the bottom third of a drum or from the top third of the drum.

Clothing. The worker wore either dirty work clothing or clean Tyvek clothing.

Worker. The three workers who worked at the booth.

Location. The six sampling locations. The concentration data were analyzed as if they were a full factorial experiment involving the four variables listed above. Before analysis, the natural logarithms of the concentrations were taken to reduce the dependence of the variance on the mean. The SAS General Linear Models Procedure was used to

perform the analysis of variance, while multiple comparison tests were used to examine differences between treatment means.^(6,7)

Results

Real-time sampling

Based upon the analysis of the real-time data, the fitted model was found to be

$$\ln(E) = -4.56 + 0.00256B + 0.00083B^2 + 0.146S + 0.00035B - 0.0032S^2 - 0.044W - 0.0054WB + 0.038W^2 - 0.434T - 0.0089BT + 0.119T^2$$

where:

- E = relative worker dust exposure
- B = bag count
- S = time spent scooping/2 during scooping but was 0 during other operations
- W = time spent weighing/2 during weighing but was 0 during other operations
- T = time spent turning/2 during turning but was 0 during other operations

A plot of the predicted values using the model with the S, W, and T time terms constant is shown in Figure 4. This figure shows that the worker's dust exposure increased with bag count, a measure of the depth of material in the drum. During weighing and turning, the worker's dust exposure either remained constant or failed to increase as fast. Figure 5, a plot of three complete cycles, illustrates this point with a positive slope during the scooping activity and a negative slope during weighing and turning. This suggests that most of the worker's dust exposure is caused by the scooping of the powder from the drum. Dust exposures caused by weighing and turning are either controlled by the ventilation system or are much smaller than the dust exposures caused by scooping. The weighing activity appears to be associated with higher dust exposure than the turning activity. However, this difference may be an artifact caused by the delay of the HAM's response to the high dust exposures during scooping.

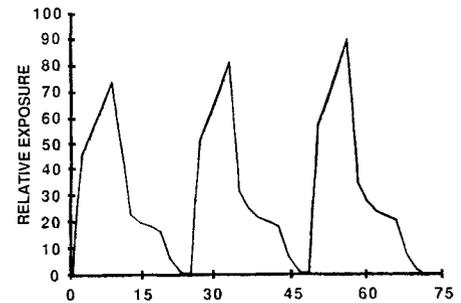


Figure 5—Modeled dust exposure of worker for filling bags 51-53.

Integrated sampling

An analysis of variance of the filter samples showed that location of sample, worker, and depth of scooping from the drum significantly affected concentration. The terms involving the workers' clothing did not appear to affect concentration (probability of a greater F = 0.5). As a result, clothing was excluded from subsequent analysis. The total dust concentration data were analyzed further as if it were a full factorial experiment involving sampling location, worker, and depth of scooping from the drum. The analysis showed that the height of material in the drum had a very significant effect upon concentrations (probability of a larger F = 0.0001). In addition, both the drum-sampling location interaction and the drum-worker interaction were significant at the 0.02 level. This implies that the effect of level of material in the drum varies with the sampling location and the worker. As a result, a separate analysis of variance was conducted for the different levels of material in the drum.

The results of the analyses of variance are listed in Table II. The table shows that both sampling location and worker significantly affected dust concentrations for both full and empty drums. The results of the multiple comparison tests conducted to examine differences in concentration due to sampling location are shown in Table III. For both empty and full drums, the

TABLE II
 Summary of analysis of variance of dust concentrations obtained from filter samples when drum is full and empty

Source of variation	Degrees of freedom	Probability of seeing such large differences due to chance	
		Full Drum	Empty Drum
Location	5	0.0001	0.0001
Worker	2	0.018	0.0013
Location-worker interaction	10	0.5	0.12
Degrees of freedom for the error term		41	37

TABLE III
Comparison of total dust concentrations by location

Location	Full Drum			Empty Drum		
	GM ^A (mg/m ³)	N ^B	Grouping ^C	GM (mg/m ³)	N	Grouping
Right lapel of worker	16	10	A	57	10	A
Left lapel of worker	7.6	10	A,B	31	11	A
Worker's hat	4.6	9	B	12	7	B
Bin	0.43	10	C	0.74	7	C
Background	0.43	11	C	0.46	9	C
Face of hood	0.33	9	C	0.43	11	C

^AGM = Geometric Mean.

^BN = Number of samples.

^CThe grouping is based upon the Waller-Duncan multiple comparison test.⁽⁷⁾ This test is conducted at approximately an overall level of confidence of 95%. Means which have the same letter do not differ significantly. Separate analysis was performed for the full and empty drum.

workers' dust exposure was significantly larger than area sampling results. Further, worker #3, who was more experienced, tended to have lower dust exposures than the other two workers.

There was a significant drum-sampling location interaction and worker-sampling location interaction. The drum-sampling location interaction implies that at some sampling locations, the level of material in the drum affected the geometric mean worker dust exposure. The results presented in Table IV show that the effect of level of material in the drum upon dust exposures varied with the worker. The geometric means were based upon the three sampling locations on the worker.

Discussion

Based upon the gravimetric filter results, the workers' dust exposure was not significantly affected by dirty clothing. Although not significant in this study, the effect of workers' clothing may have been overwhelmed by the other dust sources. Both the real-time data and the gravimetric filter data indicated that depth of scooping from the drum significantly affected the workers' dust exposure. Scooping from the bottom of the drum tended to increase dust exposure. Based on the very limited data presented in Table IV, workers' size appeared to be related to dust exposure when scooping from the bottom of the drum. While the tallest worker had no significant increase in dust exposure when scooping from the bottom, the shorter workers (worker #1 and #3) experienced a very noticeable increase in dust exposure. It is hypothesized that, because of the small arm length, the faces of these workers were closer to the drum opening when scooping from the bottom, and, there-

fore, their breathing zones were closer to the dust source. Self-pacing may also play a role in personal dust exposure.

For worker #3, scooping further than half-way into the drum significantly increased dust exposure, as measured by the HAM. While this increase in worker dust exposure occurs predominantly during scooping, it generally decreases (or fails to increase as fast) during weighing and turning.

The tallest worker had no significant exposure increase between the full and empty drums. However, he had a higher dust exposure than worker #3 when scooping from a full drum. This suggests that dust exposure may have been affected by work practices and slight changes in work cycle time.

While most of the breathing zone samples did exceed the Threshold Limit Value (TLV) for total dust (10 mg/m³),⁽⁸⁾ and the Permissible Exposure Limit (PEL) for nuisance dust (15 mg/m³),⁽⁹⁾ all three workers wore respirators during the experiment to protect themselves from these high levels. This study strongly suggests that booth ventilation contains the dust emissions generated by this job, but does not adequately control personal dust exposures without the addition of personal protective equipment. In addition, work practices and worker anthropometry may be key fac-

TABLE IV
Comparison of geometric mean dust exposures for full and empty drums

Worker	Empty drum (mg/m ³)	Full drum (mg/m ³)	Probability of seeing such a large difference due to chance*
1	46	8	0.2
2	14	14	1.0
3	16	1.4	0.006

*Significance of difference estimated using linear contrasts.

tors in controlling personal dust exposure when engineering controls such as ventilation and work station are fixed. All statistical inferences of the real-time data apply to the specific worker used in the study, and caution should be used when extrapolating to other workers involved in similar material weighing and transfer processes.

This study shows that real-time instrumentation can be used to clearly identify sources of worker dust exposure. Figure 4 shows that dust exposure increases with bag count, which is a surrogate variable for depth of scooping. The data were collected in a 20-minute period. The same conclusion was obtained from the short-term measurement of dust concentrations with pumps and filters. However, the filter data required three full shifts to collect. The filter data did not provide any insight as to which part of the job cycle was elevating the workers' dust exposure. Knowledge of the specific task which elevated the workers' dust exposure may be crucial to the redesign of booths for the weigh-out of powders. This suggests that future study of engineering controls could be conducted with direct-reading instruments and a limited number of air samples used to calibrate these instruments.

Conclusions

The results show that the booth used for the weigh-out needs to be redesigned to provide better dust control. The design of the booth should eliminate eddies which force contaminated air into the worker's breathing zone. In spite of the small number of workers who were studied, the data show that the dust controls for this operation will be more effective when ergonomic principles, such as anthropometric factors, are implemented. In particular, operations such as this should be redesigned so that workers are not required to put their faces into pockets of highly contaminated air. This situation suggests that the booth should be considered as a workstation which is designed on the basis of both ventilation and ergonomics.

Real-time instrumentation can be used to study sources of worker dust exposure during the work cycle. It is possible to qualitatively and quantitatively study sources of worker dust exposure which are too short and quick to be studied with integrating air sampling methods.

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American Board of Industrial Hygiene Fall 1987 examinations

The ABIH has approved the following cities/geographic areas for the holding of its examinations in Fall, 1987, subject to the Board's requirement for a minimum of ten examination candidates at each location. Specific dates and test sites will be announced as arrangements are completed.

<i>Atlanta, GA</i>	<i>Houston, TX</i>	<i>Toronto, Ont</i>
<i>Boston, MA</i>	<i>Philadelphia (area)</i>	<i>Vancouver, BC</i>
<i>Chicago, IL</i>	<i>Portland, OR (PacNW Conf.)</i>	<i>Washington, DC</i>
<i>Cincinnati, OH</i>	<i>Raleigh, NC</i>	<i>Wiesbaden, FRG</i>
<i>Denver, CO</i>	<i>San Diego, CA (PCIH)</i>	

Applications and related information can be obtained from the Board's office.

ABIH
4600 W. Saginaw, Suite 101
Lansing, MI 48917

The deadline date for completed applications for the Fall examinations will be June 1, 1987.