FINAL REPORT:

CONTROL TECHNOLOGY FOR FALLING SOLIDS

AT

Rohm and Haas
Louisville, Kentucky

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NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
Division of Physical Sciences and Engineering
Engineering Control Technology Branch
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Cincinnati, Ohio 45226

PLANT SURVEYED:
Rohm and Haas
P.O. Box 32260
Louisville, Kentucky 40232

SIC CODE:
2821 Plastic materials, synthetic resins, and nonvulcanizable elastomers

SURVEY DATE:
August 11-12, 18-20, 25-29, and September 25-29

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I. INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services (formerly DHEW), it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering Control Technology Branch (ECTB) of the Division of Physical Sciences and Engineering has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

NIOSH has joined with the U.S. Environmental Protection Agency (EPA), Office of Toxic Substances, in an interagency agreement to study dust generation in the handling of powdered materials. Laboratory bench tests have been devised (by others) to provide a relatively quick and convenient means of estimating a material's relative dustiness.[1] In using these tests, one assumes that the dust generation in the tester simulates the dust generation in an actual powder handling operation.

The goal of the NIOSH/EPA joint effort is to develop a model that will serve as a predictor of potential workplace exposures associated with the handling of solid materials. This model will be used in the review of new chemical submitted as premanufacturing notices (PMNs) under the Toxic Substances Control Act[2] and in preliminary analyses of existing chemicals for which personal monitoring data is unavailable. As a first step in this project, NIOSH is evaluating the correlation between worker dust exposure and dustiness test results, and determining if material properties can be used to estimate exposures. If a good correlation exists, these tests could be used by manufacturers to develop treatments to reduce the dust exposures caused by powder handling.

The Rohm and Haas Company produces a variety of acrylic resins at their Louisville, Kentucky plant. The resins differ in bulk density, particle size, and moisture content. The company has noted differences in the dust exposures in the packaging area with these different product lines. Because of these reported differences and the cooperation of the plant staff, this site was selected as a test site for this study.

II. PLANT AND PROCESS DESCRIPTION

PLANT DESCRIPTION

The Louisville plant of the Rohm and Haas Co. was built in 1962. It employs a total of 300 hourly employees to produce an assortment of plastic resins. Production is scheduled 24 hours a day, 7 days a week.

Process Description

This study was conducted in the packaging room for the KV-2 (acrylic resin) production line. After polymerization, the acrylic resin is sprayed dried and stored in hoppers. From the hoppers, the resin powders are auger fed into tuck-in valve bags. After the bags have been filled with 50 pounds of powder, they are sealed and dropped onto a conveyor belt which transports the bags to a palletizing operation elsewhere in the plant. The bagging equipment at the KV-2 production unit was installed 18 months before the start of this study.

During this study, the correlation between the dust exposure of the operator of the bagging machinery and dustiness test results were evaluated. The operator simultaneously controls a number of bag packing machines. The bag filling sequence follows:

1. The operator places an empty bag upon the feed spout, and presses a button to start the auger.

2. Once filled, the stand on which the bag sits automatically vibrates to compress and to deaerate the bag contents.

3. The bag is automatically ejected after compaction and falls into position at the bag sealer.

4. The operator manually aligns the bag when necessary for proper sealing, then simultaneously presses two buttons to activate the heat sealer.

5. After sealing, the bag drops onto a conveyor for transport to the palletizer; enroute the bags are weighed and printed.

Every half hour, workers rotate between the palletizing operation in a near-by room and the packaging room. In addition to packaging powders in this room, over or underweight bags are emptied at a bag opening station. This operation is performed intermittently throughout the shift.

A number of different workers rotate between the bagging equipment and the palletizing equipment in an adjacent storage area. These workers take turns bagging the product. Usually, the workers rotate to different jobs every half hour. To accommodate the dust sampling, the workers remained at the bagging machines for an eighty-minute period.

Dust Release Sources

Practically every step in the packaging of the powders can creates some dust. Specific sources of dust release are:

1. During bag filling, dust-laden air leaks from the bag near the fill spout.

2. The platform of the vibrating bag stand is coated with spilled powder. When it vibrates, a dense cloud of dust is sometimes generated.

3. Dust leaks from the unsealed valve as the bag falls into position at the bag sealer.

4. When the operator manually aligns the bag for proper sealing, some dust escapes from the unsealed valve.

5. Bulk samples are perodically collected by placing a plastic bag over the outlet of the auger. This bag has the capacity of about 1 liter. When the auger feeder is turned-on, the bag is usually over-filled and resin falls through the air, generating dust and contaminating the vibrating filter.

6. Residual resin in the auger spout occasionally breaks free when the bag is removed from the spout.

7. Emptying of rejected bags results in dust exposure due to ineffective ventilation of the manual bag opening station. The filters in a self contained bag house at this station become clogged reducing the exhaust rate to a point where control is inadequate.

Dust Control Measures

A number of practices in the KV-2 unit were employed to do reduce worker dust exposures. These control measures include the process equipment design, local exhaust ventilation, and personal protective equipment.

The bagging equipment sits on a grated platform 28 inches above the concrete floor. During the bagging of certain products, the area under the grated platform was continuously flushed with water to remove settled dust, preventing it from being redispersed into the air.

Local exhaust ventilation was applied to control dust generated by feeding powder into the bags and by sealing the bags. The dust generated by feeding the bags was exhausted by a hood placed around the feeding spout. The air velocity around the feeding spout was 100 feet per minute (fpm). This hood is pictured in Figure 1. A slot hood (Figure 2) was located about two inches above the bag sealer. The slot was 18 inches by 6 inches and the slot velocity was measured at 200-300 fpm. Smoke tube traces showed that the slot captured the dust which was released up to six inches from the slot.

Because the dust control measures were not completely effective and did not address all of the dust exposure sources, respirators were used to control worker exposures to airborne dust. Workers routinely wore 3M model 8710 disposable respirators. When the products appeared to be excessively dusty, Racal Air Stream powered air purifying respirators were worn by some workers. A sign in the bagging room directed workers to wear respirators when bagging dusty products for a period of one hour or more during the day.

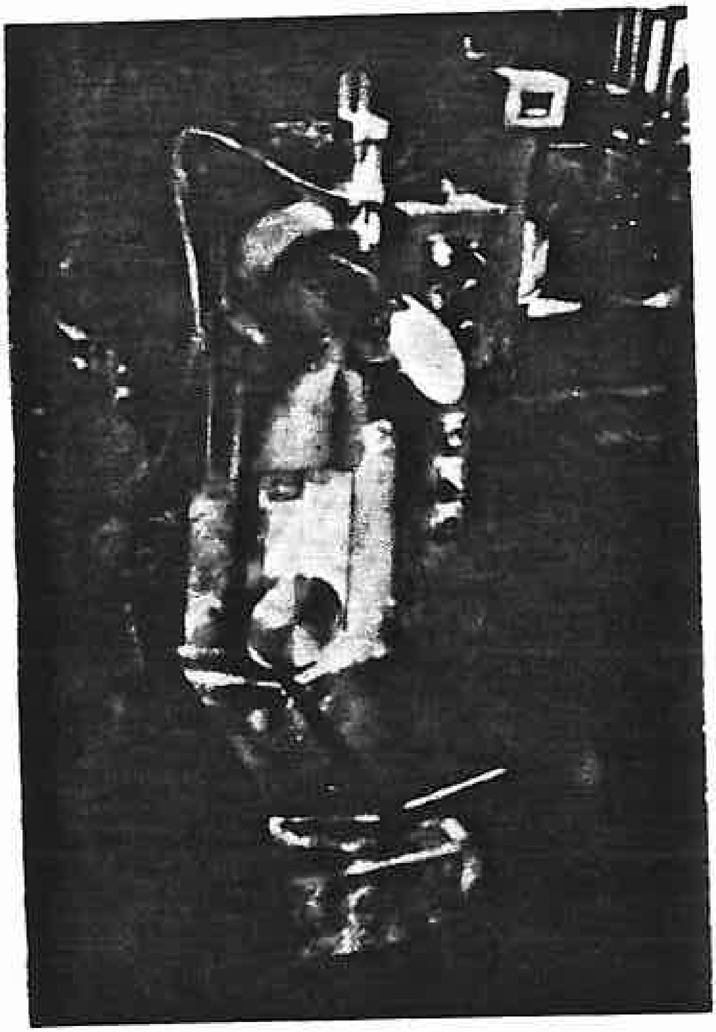

Figure 1. Outlet of Bag Filling Machine

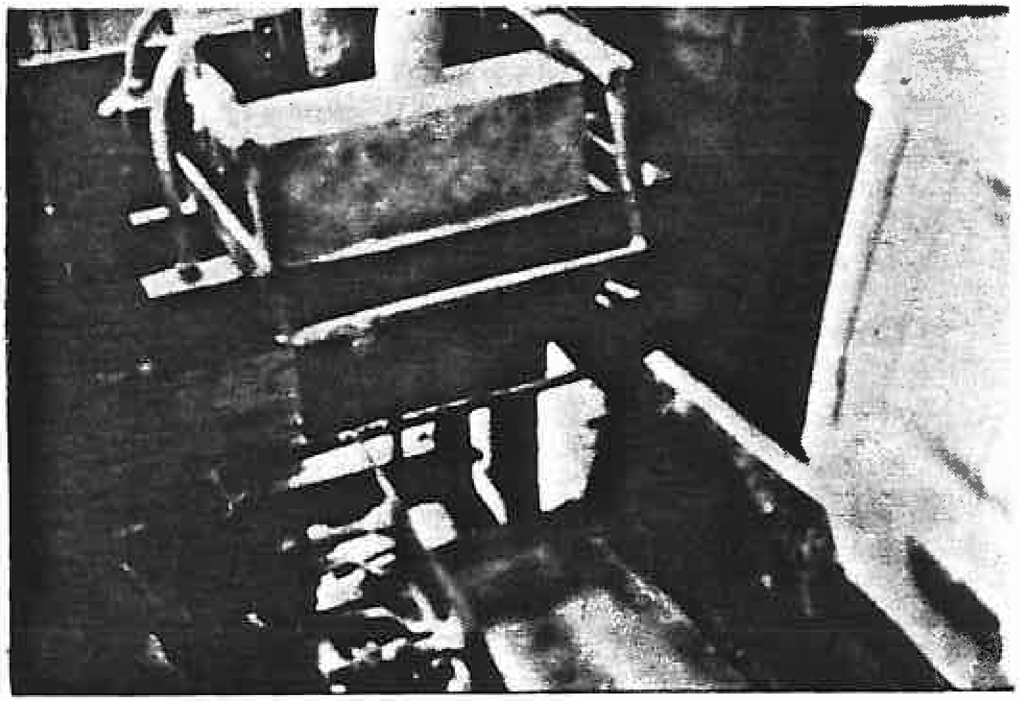

Figure 2. The Bag Sealing Mechanism

Summary of Health Standards for Air Contaminants

The occupational exposure to airborne dusts in this operation are not specifically addressed by OSHA standards or by ACGIH Threshold Limit Values. However, the workers' dust exposure should not exceed the recommended exposure limits for a nuisance dust. The exposure limits are listed in the following table are for an eight hour time-weighted-average:

Table 1. Summary of Occupational Exposure Limits

Substance	OSHA PEL[3]	ACGIH TLV[4]
Nuisance Dust		
Total	15 mg/m^3	10 mg/m^3
Respirable	5 mg/m^3	5 mg/m^3

III. METHODOLOGY

This study attempted to answer the following questions:

1. Are the Workers' dust exposures and dustiness test results are correlated?
2. Are dustiness test results and the workers' dust exposure correlated with bulk powder properties?

To answer the first question, the worker's dust exposure was measured and dustiness tests were conducted on bulk samples of the material. In addition to measuring the worker's dust exposure, dust concentrations were measured at several stationary locations listed in Table 2. These samples were taken to measure the background dust concentration at a height of 4-6 feet above the floor. Two dustiness test methods were used: the Heubach rotating drum dustiness tester and the MRI tester.

The Heubach Dustiness Test consists of a rotating drum that produces a repeated dust fall through a regulated air stream. This is not a device that directly simulates the pouring and dumping of fine solids but the repeated fall of the solids through the air stream seems to increase the quality of the tests compared to the MRI test.

The MRI Test simulates the pouring and dumping of fine solids by having the material dumped under specified conditions within an enclosed chamber fitted with a sampling filter and constant flow pump system. The cup rotates at a constant speed while dumping the dust and a vibrator helps to completely dislodge the dust. The sample pump is run at 10 liters a minute for 10 minutes to obtain a total sample volume of 10 liters.

In order to answer the second question, information on bulk material properties were obtained from the company. For the specific batches of material which were processed, the company supplied NIOSH with particle size distributions obtained by sieving and the moisture content of the bulk solids. The bulk density of the bulk solids were obtained as part of the dustiness test procedures.

Table 2. Dust Sampling Locations

Location	Description
1. Worker	The worker who is operating the bagging equipment
2. Near Door	This location is on the wall next to the west bagging machine, about five feet above the grated platform.
3. Between bagging machines	This location is between two bagging machines. It might be affected by the dust generated by the bagging operation.
4. Control panel	This panel is behind the bagging machines and dust measurements made at this location should represent background dust concentrations.

Air Sampling Methodology

The procedures described in Method 0500 of the NIOSH Manual of Analytical Methods were used to measure the total dust concentrations at the locations listed in Table 2.[5] Dupont P4000 pumps were used to draw 3.7 liters per minute of air through preweighed MSA FWSB filters. A sampling time of 60 to 80 minutes was used for each worker.

For each material packaged, dust concentrations were measured at the locations listed in Table 2. Separate sets of measurements were taken for different workers or pairs of workers who rotated through the bagging machines. Usually, 4-6 sets of measurements were taken for each powder. Typically, the sampling was done on a day shift and on an evening shift. A separate set of samples was taken for each worker. In order to obtain sample volumes of 200-300 liters, the filters were reconnected to the sampling pump and restarted each time an operator returned to the bagging machine.

Dustiness Testing Methodology

Two tests for dustiness were evaluated in this study. The tests were selected by EPA after an evaluation of many such tests developed by various companies and researchers. The Heubach test was developed by the Heubach Company of Germany to aid in process control work for the production of the company's pigments. The MRI (Midwestern Research Institute) Test was developed by MRI in response to a research project sponsored by EPA to develop an inexpensive and quick test for dustiness.

The MRI Dustiness Test

The MRI chamber shown in Figure 3 has a volume of 20 liters. The dustiness of the material is defined as the amount of dust collected during the time required for at least 4.2 air changes in the chamber.

At the beginning of each test series, the tare weight of the 250-ml stainless steel cup is recorded. The volume of the cup is measured by weighing it full of water (of known temperature) and calculating the volume. Glass fiber filters are used in the filter assembly to collect the suspended dust. The glass fiber filters are weighed on an analytical balance then placed in a 47 mm filter holder.

Prior to each test, the test cup is cleaned and dried. The chamber is cleaned with a vacuum hose and damp laboratory tissues. The chamber is placed on a styrofoam sheet with and covered with a new sheet of aluminum foil. The sample cup is filled by pouring loosely the material into the stainless steel cup. It is slightly over-filled then scraped even with a metal straight edge, and the cup of material is weighed. The cup of material is then inserted into the chamber holder with its pour spout forward in the direction of rotation. The 47 mm glass fiber filter is placed into the stainless steel filter holder and it is screwed into the chamber lid. Finally, the chamber lid is replaced and sealed with tape and the vacuum line is attached. After the stopwatch has been zeroed, the test is begun by turning on, in rapid succession, the power to the vacuum pump, the cup vibrator and the cup rotor. The stopwatch is started simultaneously with the cup rotor. During the test, the following times are recorded:

1. Power to rotor, vibrator and pump.
2. Pour begins.
3. Pour ends.
4. Power off to the vacuum pump.

At the end of the test, the chamber lid is untaped, removed, and inverted before the power to the vacuum pump is turned off.

Immediately after the test, the filter holder is unscrewed from the chamber lid and the exposed filter is weighed immediately or it is transferred to a petri dish and transported with its exposed side up to await analysis. Finally, the chamber is removed from the aluminum foil surface and the dumped material is disposed of. The filter is weighed on an analytical balance. If precision work is desired, the filter and sample must be equilibrated in the same way the filter was initially prepared for weighing. Our experience is that sample variability is so great as to obscure minor variations such as due to sample equilibration.

The measure of "Dustiness" is the mass of suspended particulate collected during a 10 minute period beginning just before the dust pours from the cup. This sampling period corresponds to the time required for about 4.5 air changes in the test chamber. The Dustiness Index is a ratio of the dust collected to the total sample and divided by the air flow rate. In the NIOSH

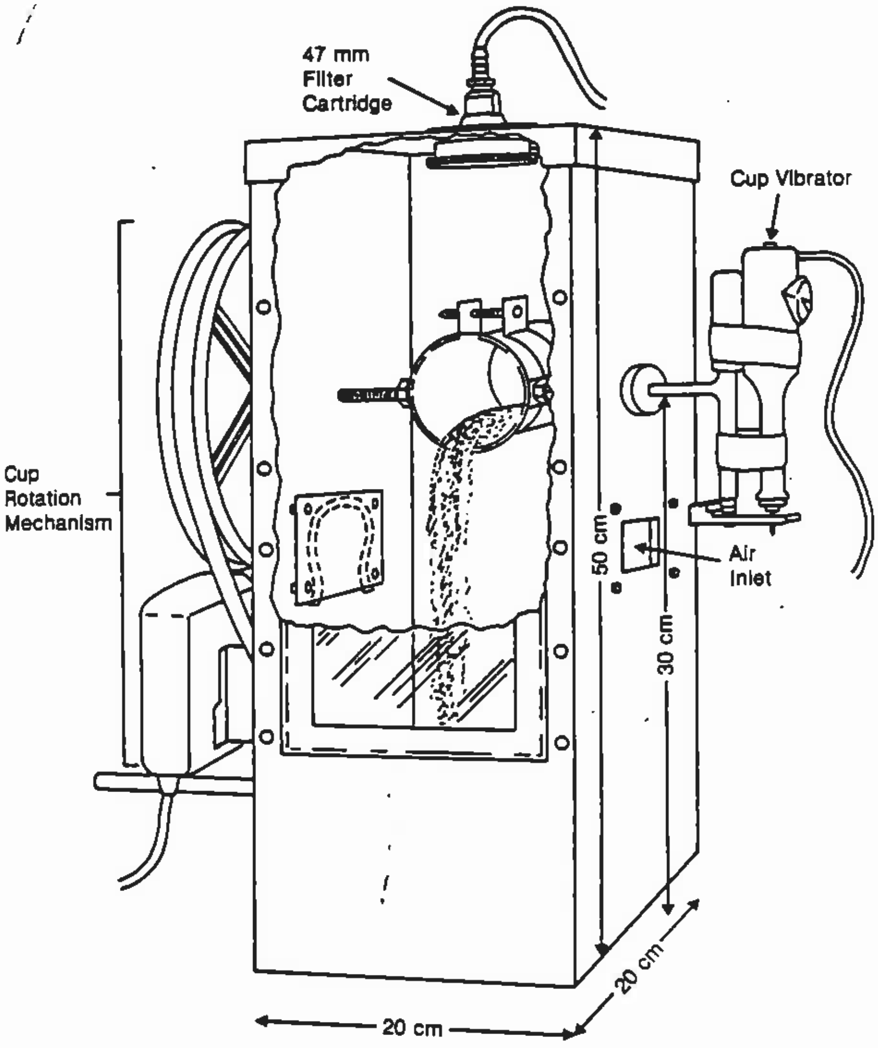

Figure 3. MRI Dustiness Tester

tests, a critical orifice controlling the flow at 10.8 L/min was used so the flow adjustment was made.

$$\text{Dustiness Index} = \frac{\text{Dust collected on filter (mg)}}{\text{Weight of Sample (Kg)} \quad \text{Flow Rate (L/Min)}}$$

The Heubach Dustiness Test

The test conditions for the Heubach dustiness tester (Figure 4) are set for each type of dust tested so as to obtain a collected dust sample on the filter of not more than 180 mg. An amount greater than this is apt to slough off during handling. The approach suggested by Heubach is to select the dustiest material for calibration then set the air flow rate and the test time so as to collect the desired amount of dust. For practical purposes it was suggested that a sample of about 20 grams and a flow rate of 4 liters/minute would be typical for a nuisance material in a transfer operation. These settings were selected for the resins to be tested in this study and found to be adequate.

The test requires the weighing of the test sample on a trip balance and the weighing of the collection filter before and after the test. The latter weighing is done on a precision laboratory balance accurate to four significant figures.

The weighed dust sample (20 grams) is placed in the rotor or particle generator, which is then mounted on the motor shaft. The filter is weighed and placed in the filter holder. The apparatus is then completely assembled for the test. Since the test conditions have been previously set, the test is initiated by pressing the START button. The test will then run until 20 liters of air have been metered. Sample buildup on the sample filter may slow the flow rate toward the end of the test, in which case the flow rate would need to be monitored and adjusted. It is our experience that this effect is not significant. When the test is completed, the filter is removed from the sample train and weighed to obtain the dust collected. The results are reported in terms of % Dust Lost of the 20 gram sample placed into the particle generator.

The apparatus is cleaned with detergent and warm water. Drying of the metal parts is speeded with the use of a small amount of acetone, especially the particle generator and the settling bottle which have areas not easily accessed by a towel. This clean up takes about 15 minutes at which time another test may be set up.

These tests are empirical in that they do not measure a fundamental property or response of the material being tested. The response of the test must be correlated with a related response to establish a baseline or index point. The related response in this study is the personal exposure samples of workers operating bagging equipment. The dustiness of the material results in airborne dusts due to residual material in spouts, air displaced from the bag during filling, bags falling onto conveyors, and leaks in lines and ducts. It is axiomatic that the more dusty the material, the more potential there is for dust exposure. The problem here however is to demonstrate that this actually occurs in a real work situation. One problem to confound this is that the

HEUBACH DUSTINESS TEST

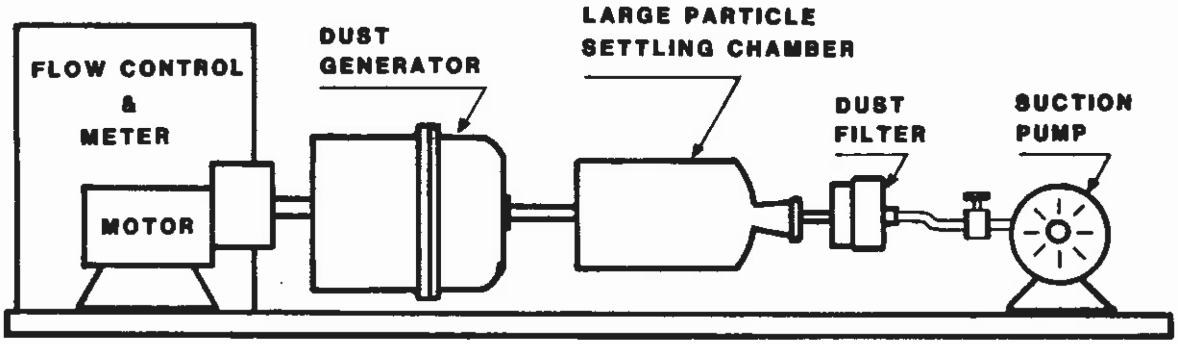

Figure 4. Heubach Dustiness Tester

process variation of factors related to dustiness of a material may vary significantly or that the exposure to dust may be controlled by environmental factors others than the dustiness. These additional factors may be significant enough to mask minor differences in the measured dustiness of two materials.

IV. RESULTS

The air sampling data and dustiness test data are listed in Appendices 1 and 2 and are summarized in Tables 3 and 4. In Table 3, the geometric mean and geometric standard deviation of the workers' dust exposure is listed for each material. The geometric means and geometric standard deviation of the data are reported because worker dust exposure data tends to be log-normally distributed. After taking the natural logarithms of the data, the SAS General Linear Models procedure was used to perform analysis of variance (ANOVA) and the Tukey Multiple Comparison Test was used to examine the significance of differences between individual means. These tests were used to examine whether there are significant differences in worker dust exposure between the the different materials. The grouping column in Table 3, which summarizes the results of the Tukey Test, shows that the P1 material created a much higher dust exposure than the other materials which were studied. The differences between the other materials are not as striking. A geometric standard deviation of 2.0 was computed from the root mean square error of the ANOVA. This variability is so large that two geometric means in Table 3 must be different by a factor of 4.22 in order for the difference to be considered significant in the multiple comparison test. Based upon an examination of the residuals from the analysis of variance by the SAS Univariate procedure, the worker exposure data was found to be log-normally distributed. In contrast, the dustiness test data is relatively precise. A pooled coefficient of variation, based upon replicate tests of bulk samples, was computed to be 11% for the Heubach dustiness test and 14% for the MRI dustiness test.

The Dustiness tester results are summarized in Tables 4 and 5. This data exhibits much less variability than the personal exposure data. Based upon judgment, two Heubach dustiness test results were deleted for the P2 material. This bulk sample was taken immediately after a shut-down period and the results were a factor of two higher than the value reported in Table 4.

Table 6 summarizes observations made during the collection of the air sampling data. Examination of Table 6 shows that the operation of the bag filling room did vary during the data collection. The number of packing machines in use varied and material flow rate varied by about 20%. This variability is a potential confounding factor in this study and probably causes the variability in worker dust exposures which is typical of personal dust exposure data. The air flow patterns in this room were not constant due to changes in ambient wind velocity and the use of a pedestal fan for some materials. In this room, dust generation is caused by both bag filling and the adjacent bag opening operation. The bag opening operation was intermittent and it probably contributed to the worker dust exposures in this room for two materials. For P2, new bags were placed in the bag house and the dust generated by bag opening appeared to be controlled. Thus, the bag opening operation may have inflated the dust exposures for P4 and P5.

Table 3. Summary of Worker Dust Exposures

Material[a]	GM[b] (mg/m^3)	GSD[c]	N[d]	Grouping[e]
P1	15.8	1.55	6	A
P2	3.56	1.9	5	B
P3	2.8	3.1	6	B
P4	2.36	1.66	3	B
P5	1.47	2.15	5	B
P6	1.07	1.49	6	B

Note:
[a] a - code for the material.
[b] GM - geometric mean
[c] GSD - geometric standard deviation
[d] N - number of samples
[e] Geometric Means with different letters under the grouping column differ significantly.

Table 4. Summary of Heubach Results

Material	Weight Fraction Lost average	s*	N	Grouping
P1	0.28	0.04	6	A
P2	0.18	0.008	2**	B
P3	0.16	0.034	6	B
P4	0.19	0.017	6	B
P5	0.105	0.026	8	C
P6	0.019	0.007	4	D

*s - standard deviation

** - two samples were deleted

Table 5. Summary of MRI Results

Material	MRI Dustiness Index average	s	N	Grouping
P1	23.1	3.7	6	A
P2	10.3	5.19	5	C
P3	20.3	2.49	6	A,B
P4	15.7	3.82	6	B,C
P5	4.53	1.25	8	D
P6	2.69	0.7	4	D

Table 6. Summary of Operations During Bag Filling

Material	bag dumping	Other activities
P1	0%	cooling fan on, water flush under floor platform
P2	10-20%	new filters in bag house, broken bag causing dust exposure, a packager appears to be leaking, wind into garage door.
P3	0%	cooling fan on, water flush floor under platform
P4	10-20%	
P5	20-30%	wind into garage door,
P6	0%	bulk bags were filled, cooling fan is in use

Table 7 lists properties of the powders tested. The bulk density was obtained as part of the MRI dustiness test. The fraction of fines, the size distribution, and moisture content were obtained from Rohm and Haas product data. The fines and size distribution information were obtained from by sieving the powder. The fines are the fraction of material which passed through a 325 mesh sieve. The geometric mean and geometric standard deviation were obtained by plotting sieve opening size as a function of cumulative weight fraction collected on the sieves.

Table 7. Summary of Physical Properties

Material	Bulk Density (g/cc)	Fines (fraction)	Particle Size Dist GM (microns)	GSD	Moisture Content %	Pour Time MRI test (seconds)
P1	0.40	0.29	63	1.8	0.69	13.1
P2	0.54	0.10	90	1.6	0.80	11.4
P3	0.43	0.12	80	1.4	0.55	13.3
P4	0.43	0.11	100	1.8	0.53	11.6
P5	0.39	0.10	96	1.8	0.40	10.7
P6	0.48	0.05	110	1.6	0.30	10.0

Correlation Between Dust Exposure and Dustiness Test Data

A significant correlation was found between MRI and Heubach dustiness test results and geometric mean (GM) dust exposures. The geometric mean dust exposures were the values listed in Table 3. The dustiness test results were the average values listed in Tables 4 and 5. The data was fit to a model of the following form:

$$\ln(GM) = a + b \text{ (dustiness test results)}$$

The above model was evaluated using the SAS Regression Procedure. Statistical results are listed in Table 8. In Table 8, the term "Probability of a larger F" expresses whether the model explains the dependent variable's behavior. A small significance indicates that some linear function of the parameters excluding the intercept is significantly different than zero. The term R^2, which ranges between 0 and 1, measures how much variation in the dependent variable is explained by the model.

Figures 5 and 6 show the tolerance intervals about the predicted concentrations obtained from the regression equation. The half-width of the tolerance interval is computed from the following formula[7]:

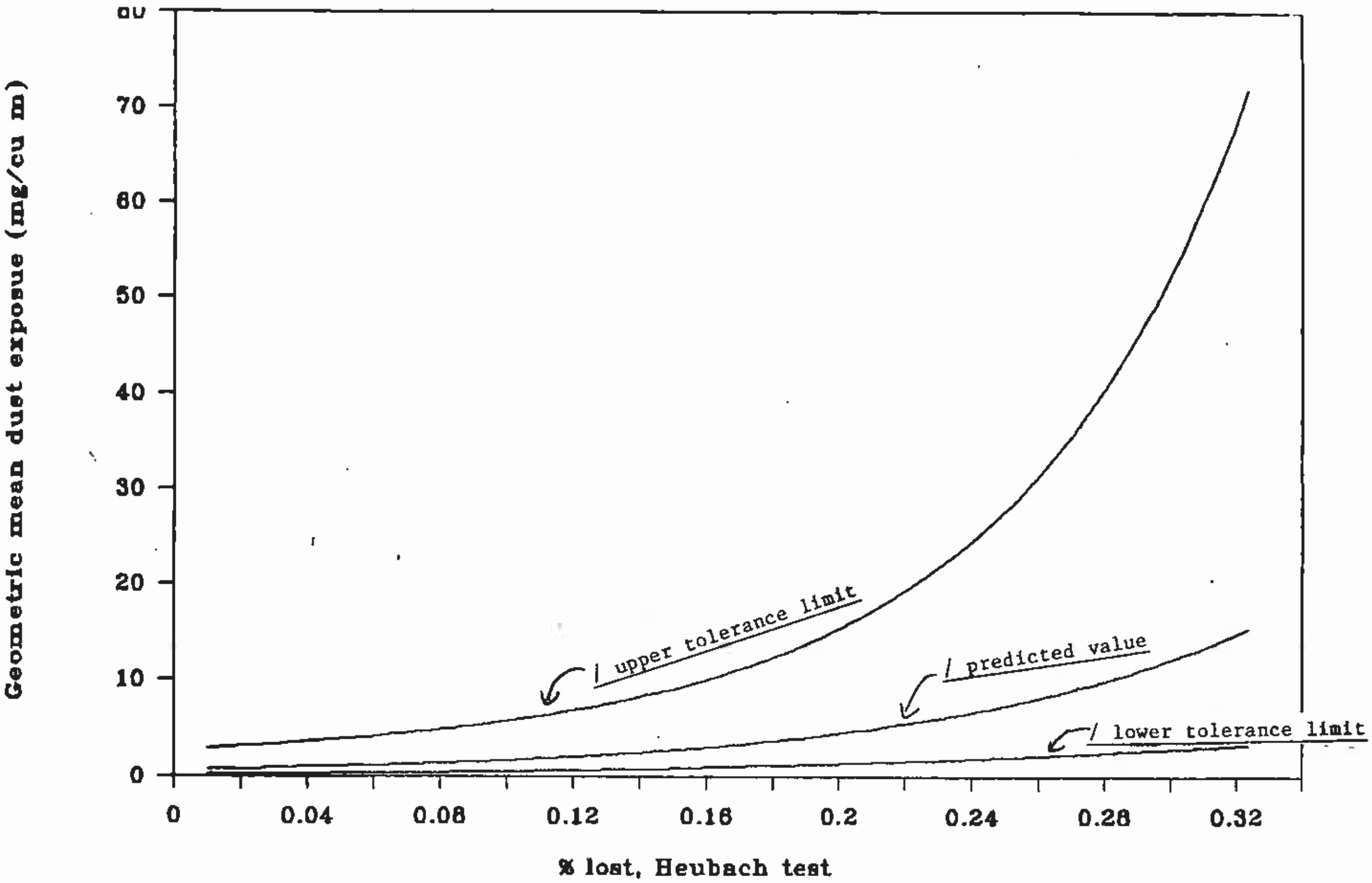

Figure 5. Predicted geometric mean dust exposure and tolerance intervals plotted as a function of % lost Heubach test.

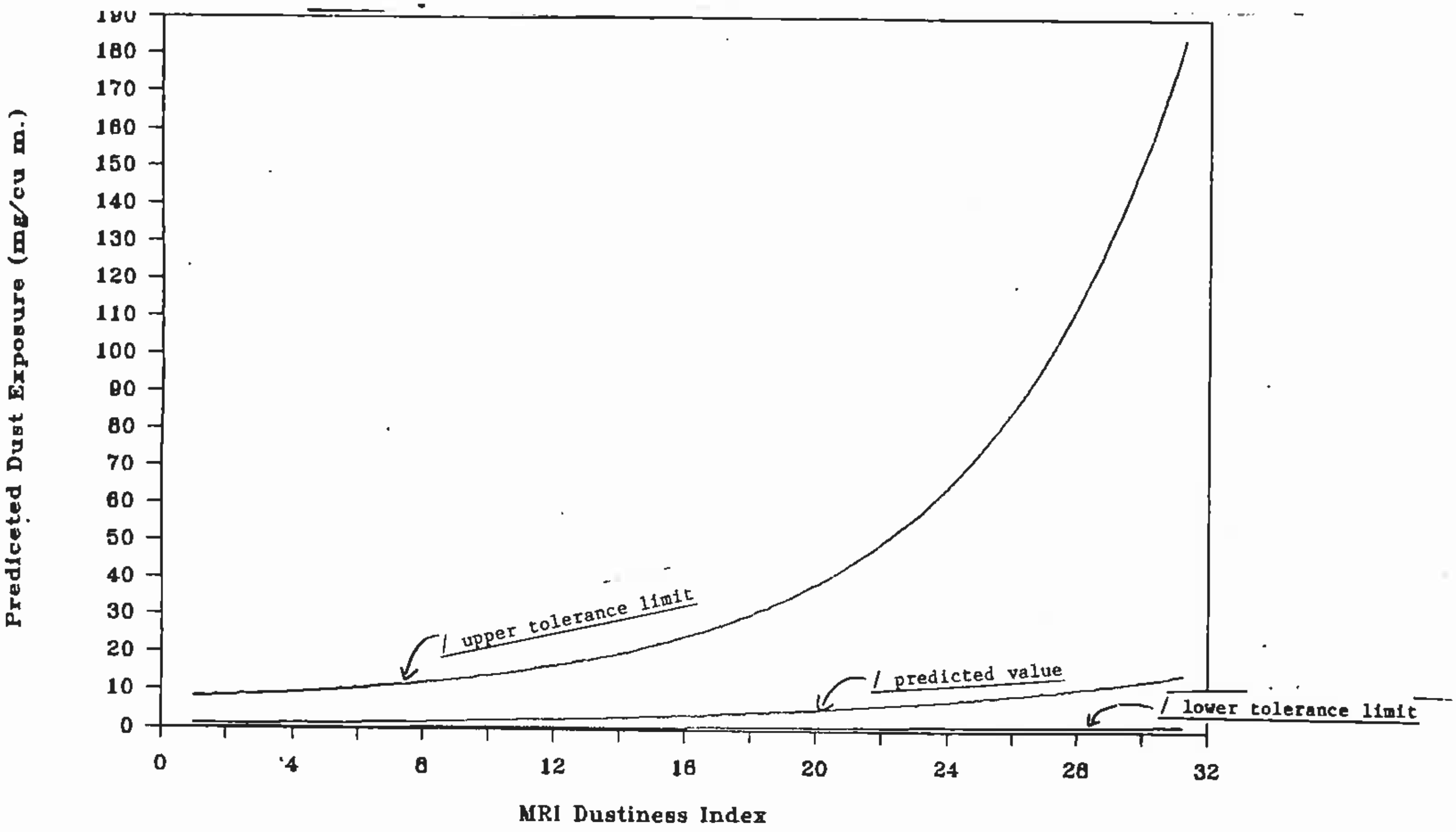

Figure 6. Predicted geometric mean dust exposure and tolerance intervals as a function of MRI Dustiness Index.

$$ts_e(1+1/n + n(x-\bar{x})^2/S_{xx})^{0.5}$$

where: s_e = the standard error of estimate (computed from the square root of means square error from regression analysis)

t = student's t statistic

n = number of data points

$S_{xx} = n \sum x^2 \quad - \quad (\sum x)^2$

x = independent variable.

The tolerance interval includes 95% of the geometric mean worker dust exposures which would be observed for a large number of materials. Inspection of these figures shows that the Heubach dustiness tester could be used to predict worker dust exposures to with in a factor of 3 and the MRI dustiness tester could be used to predict the worker's geometric mean worker dust exposure to within a factor of 5.5 over the range of observed dustiness test results. The half-width of the tolerance interval for this data is dominated by ts_e. Once the number of data points exceeds six, the value of t slowly decreases from 2.77 to 1.96 as sample size increases to thirty. The term s_e is the result of two sources of error in the regression analysis:

1. The sampling error in measuring the geometric mean dust exposure. This term is the standard error of the mean and it is estimated from the standard deviation (s) of replicate samples and the number of replicate samples (n) by use of the formula $s/(n^{0.5})$.

2. The errors in fitting the model to the data.

Table 8. Evaluation of Model

Statistical terms	Heubach	MRI
Probability of a larger F	0.0083	0.0502
Geometric Standard Deviation estimated from model's mean square error	1.5	1.8
R^2	0.85	0.65
intercept (a)	- 0.5	-0.12
slope (b)	10.01	0.091

If the value of s_e is not different from the standard deviation of the means, then the errors in fitting the data to the model are small. If there is a significant difference, then there is significant lack of fit of the model to the data. Table 9 lists the value of s_e and a tolerance factor which is the minimum ratio of the upper tolerance limit to the geometric mean for several cases. The first two values of s_e are for the two regression analyses for the prediction of worker dust exposure from dustiness test results. For the third value of s_e, the standard error of the mean was used. This standard deviation was computed by pooling the standard deviation of replicate samples and dividing the pooled standard deviation by the square root of the harmonic mean sample size. This third value of s_e is for a hypothetical perfect fit of the model to the data. The tolerance factor which would result if this occurred is close to the tolerance factor which is computed for the correlation between the Heubach dustiness test and the personal dust exposure. However, the value of s_e for the correlation between MRI dustiness test results and personal dust exposures is significantly larger than the standard deviation of the mean (Probability of a larger F = 0.02). As a result, tolerance intervals for predicting geometric mean dust exposures from MRI dustiness test results are noticeably wider than for the Heubach dustiness tester.

Industrial hygiene air sampling data usually exhibits considerable variability. While reviewing replicate sampling results from NIOSH studies, Leidel et al found that industrial hygiene air sampling data is usually log normally distributed and with a geometric standard deviation between 1.25 and 2.[8] The median value of geometric standard deviation was 1.65. If the experiment were repeated at a another facility and the personal exposure data had a geometric standard deviation of 1.65, the tolerance factor would be no smaller than 1.94.

Table 9. Tolerance Factors for Various Values of S_e

Value of S_e	Degrees of freedom	S_e	Tolerance Factor
regression equation to predict dust exposure from Heubach tester	4	0.407	3.3
regression equation to predict dust exposure from MRI tester	4	0.62	6.3
pooled standard deviation of means	26	0.32	2.6

Powder Properties

The second question addressed is whether worker dust exposure and dustiness test results can be predicted from bulk powder properties. This possibility was explored using regression analysis. The dependent variables were: the natural logarithm of the geometric mean worker dust exposure, Heubach dustiness test results, and MRI dustiness test results. The independent variables were the following powder properties: bulk density, moisture content, the geometric mean of the particle size distribution, the geometric standard deviation of the particle size distribution, and the percentage of fines collected on the pan during sieve analysis. Regression analysis was used to fit all combinations of the dependent variables and independent variable to a model of this form:

$$Y = b_0 + b_1 X$$

where:

Y = dependent variable
X = independent variable
b_0, b_1 = the regression coefficients.

When the geometric mean particle size and the the fines content were the dependent variables, the regression model explained a significant fraction of the variability in the dependent variable. These results are summarized in Table 10. In Table 10, the term " probability of a greater F" is the probability that the model would explain such a large fraction of the variability in the dependent variable by chance. For the other independent variables, moisture content, geometric standard deviation of the particle size distribution, and bulk density, this probability was greater than 0.05 and the correlation was assumed to be insignificant. Figure 7 is a plot of geometric mean dust exposure as a function of fines content. This plot also includes the upper and lower tolerance limits.

As part of the MRI dustiness test, the pour time was recorded. Regression analysis was used to show that there is a significant correlation between the MRI dustiness index and the pour time. For the six different materials studied, the average MRI index and pour time were computed. The MRI index was modeled as a linear function of pour time. Parameters from the regression analysis are summarized in Table 11. Examination of these results suggests that the MRI test is not consistent from material to material. Figure 8 shows the model and the tolerance interval about the model.

Under contract to EPA, Midwest Research Institute developed a model for predicting MRI dustiness test results from the powders bulk density, moisture content, and the particle size distributions geometric mean and geometric standard deviation. This model for calculating predicted MRI results (PMRI) is shown below:

$$\mathrm{PMRI} = 16.6(M^{-0.75}) s_g^{3.9} D^{-1.2} M_g^{-0.45};$$

where:

M = moisture content in %
D = bulk density (g/cc)
M_g = mass median diameter of powder (micrometers)
S_g = geometric standard deviation of powder size distribution

Table 12 shows the comparison between predicted and observed MRI results for the different materials. There is very little agreement and the value of R for a linear regression line is -0.21 which was not significantly different than zero. The following model resulted from the regression analysis:

$$\mathrm{MRI} = 15 - 0.02(\mathrm{PMRI})$$

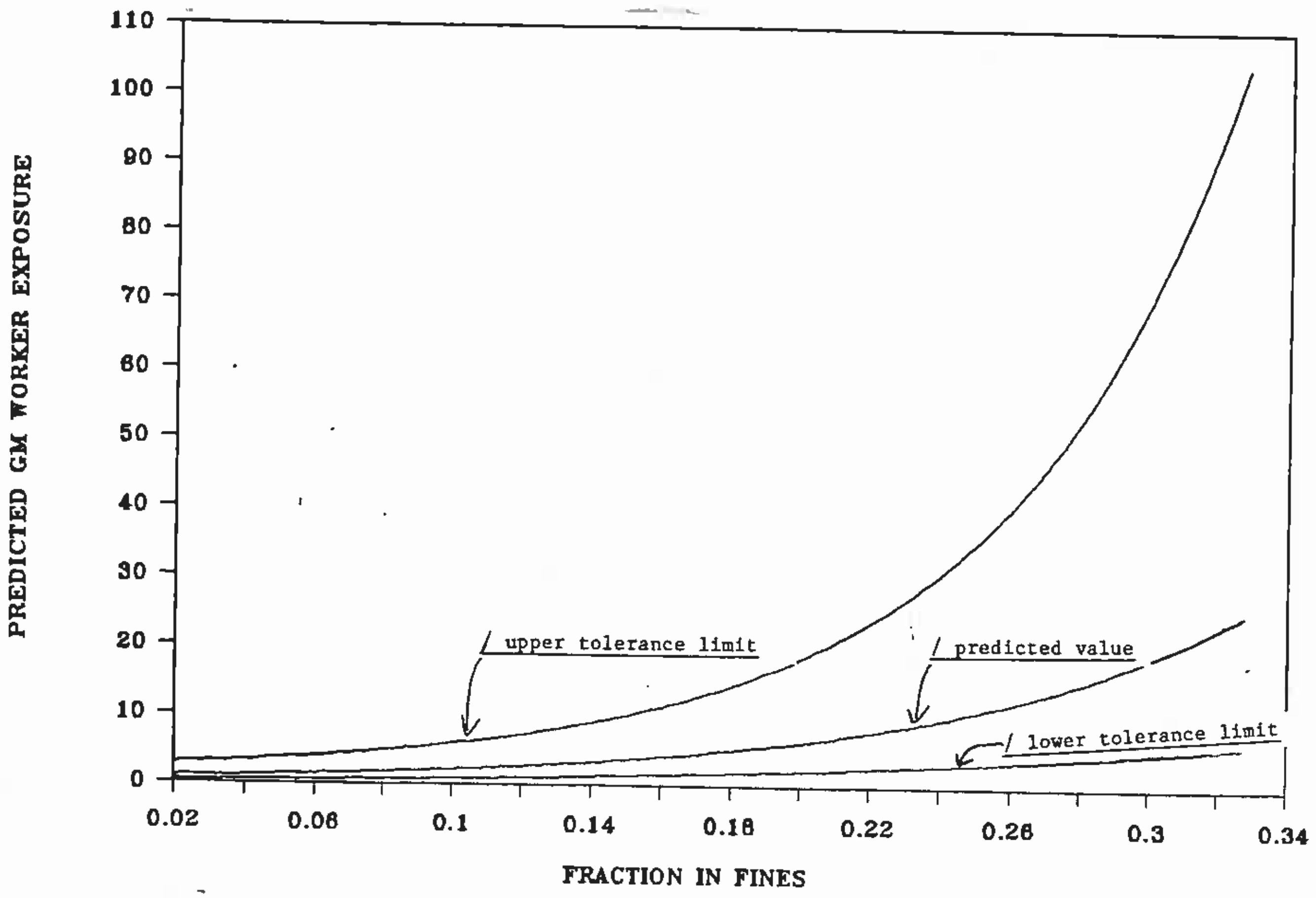

Figure 7. Predicted geometric mean dust exposure and tolerance intervals as a function of fines content.

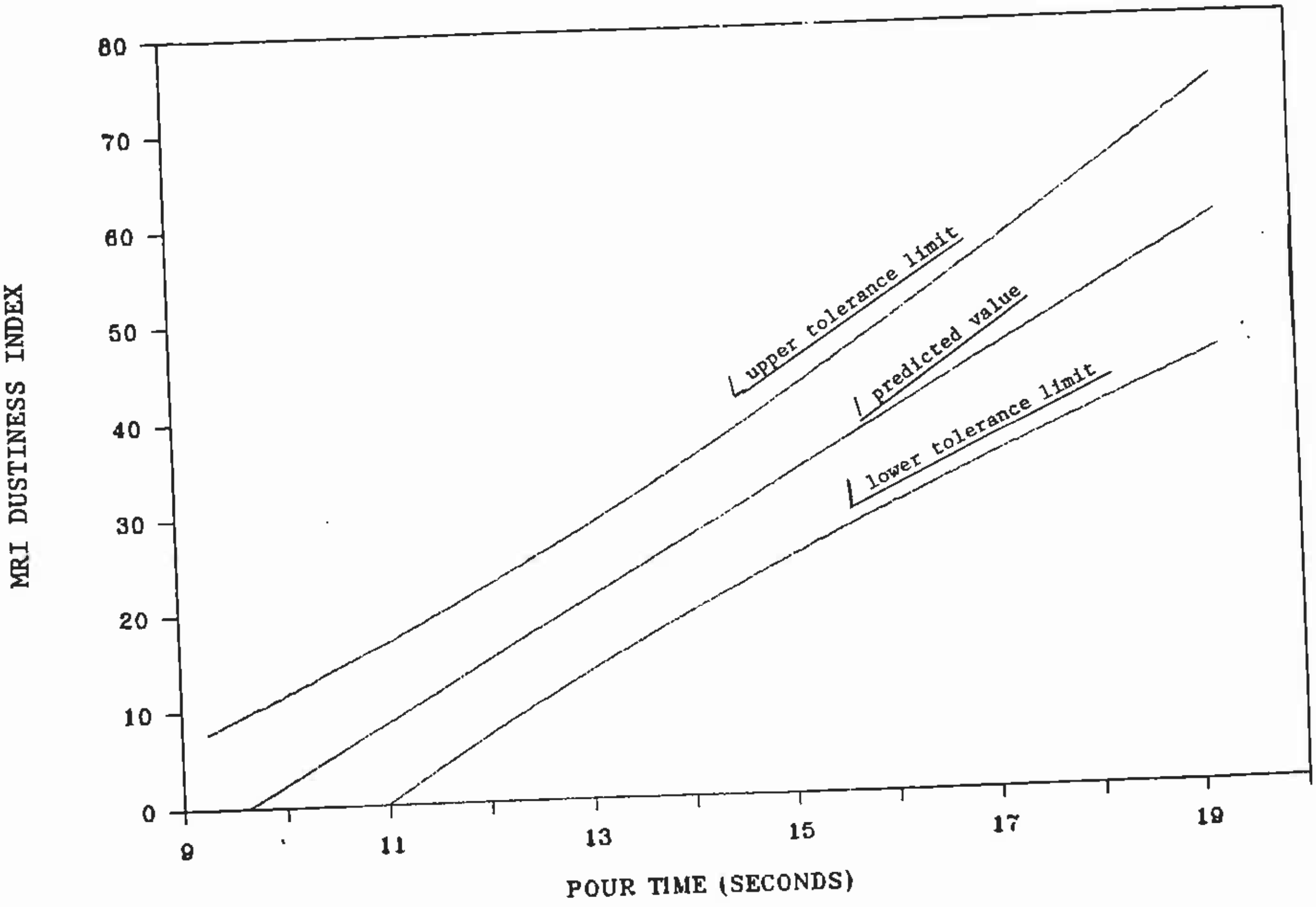

Figure 8. Predicted MRI dustiness index and tolerance intervals as a function of pour time.

Table 10. Statistical Evaluation of Models involving fines content and geometric mean of particle size distribution.

Statistics	Dependent Variables ln(GM of worker dust exposure)	Heubach results	MRI results
	independent variable - fines content		
Probability of a greater F	0.004	0.03	0.08
R^2	0.9	0.71	0.57
intercept	- 0.3	0.04	2.94
slope	10.9	0.8	77.1
	independent variable - Geometric mean of particle size distribution		
Probability of a greater F	0.008	0.04	0.04
R^2	0.85	0.69	0.69
intercept	5.8	0.55	51
slope	-0.05	-0.0044	- .42

Table 11. Summary of Regression analysis of MRI index as a function of MRI index

Terms	Values
Model	MRI Index = 6.15(pour time (in seconds)) - 59.3
s_e	2.43
probability of a larger F	0.0017
R^2	0.93

Table 12. Comparison of Predicted and Observed MRI Dustiness Indices

Material	MRI Index	PMRI
P1	23.1	99
P2	10.3	37
P3	20.7	42
P4	15.7	77
P5	4.53	113
P6	2.69	68

V. DISCUSSION

The workers dust exposure during bag opening exceeded the exposure limits listed in Table 1 when the material P1 was bagged. However, the exposure limits listed in Table 1 are for an eight-hour time weighted average. The workers operated the bag filling equipment for about 3-4 hours per shift. Assuming that bag filling was there only source of dust exposure, the workers' dust exposure on the basis of an eight-hour time weighted average, are below the limits specified in Table 1. The workers were observed to have other sources of dust exposure besides bag filling. The bag emptying operation created a short term, high dust exposure for the worker. This exposure source should be evaluated. During our visit, the plant industrial hygienist told us that the bag-house filters in this manual bag dumping station were becoming clogged. As a result, the airborne dust generated during bag opening was not controlled. Any effort to correct this problem would reduce worker dust exposure.

Although there is a large amount of experimental error inherently present in this field study, worker dust exposures are correlated with Heubach and MRI dustiness test results. When dustiness test results are used to estimate geometric mean dust exposures, the tolerance intervals are relatively wide as can be seen in Figures 6 and 7. At best, worker dust exposure can be estimated to within an order of magnitude. If a geometric mean dust exposure of 3.3 mg/m^3 is predicted from Heubach dustiness test results, the geometric mean dust exposures will be between 1 and 11 mg/m^3 (95% tolerance limits). The wide tolerance limits are caused by the high variance of the workers' dust exposure. In addition, the operation of the bag filling equipment was not entirely consistent from material to material. This also acts to increase the size of the error term in the regression analysis.

For the data collected during this study, the Heubach dustiness tester was a better predictor of geometric mean worker dust exposure than the MRI tester. The standard error estimate for the regression equation relating Heubach dustiness test results to personal exposure was essentially the statistical error caused by measuring the geometric mean dust exposure. This implies that further improvement in this model is unlikely. This is not the case for the

MRI tester. For the regression equation relating the MRI dustiness index to geometric mean personal dust exposures, the standard error of the estimate was significantly larger than the standard error of the means. This indicates that additional terms might be able to significantly improve the fit of the model to the data. Because the MRI regression equation has a larger standard error of estimate than the Heubach regression equation, the tolerance intervals about the MRI regression equation are wider.

The MRI tester did not treat materials consistently. A significant correlation between pour time and MRI dustiness index was observed. This indicated that materials which had a higher mass flow rate while being poured from the cup had a lower dustiness index. For coal free-falling through air, Cheng observed that dust generation per mass of material handled decreases with increasing mass flux.[9] Thus, differences in the MRI dustiness index could be caused by differences in pour time rather than a true difference in material dustiness.

Heubach dustiness test results and personal dust exposures were found to increase with increasing fines content and decreasing particle size. However, these results contradict Higman et al's results.[10] They studied dust generation rates of silica flour in a rolling drum tester similar to the Heubach device. For silica flour with a mean particle size of 15 to 40 micrometers, dust generation increased with increasing particle size and decreasing fines content. They observed that cohesion, as measured with a shear cell, increased with decreasing particle size. Cohesion is directly proportional to the interparticle adhesive forces which increase with decreasing particle size. Both the results of this study and the results of Higman et al could be valid. The variation of material dustiness with size distribution may be a complicated function of the particle size, fines content, and the adhesive forces between particles. If the powder remains free-flowing, dust generation may increase with increasing fines content. However, if the fines content increases enough to make the solid cohesive, then dust generation may decrease with increasing fines content. Further research is needed to discover the role of the fines content upon dust generation.

The results of the regression analysis must be used carefully. The equations which predict worker dust exposure from dustiness test results are only valid to the extent that the conditions of this study are duplicated. Some regression equations which were developed could be used to predict dustiness test results and personal exposures from bulk powder properties. There is no physical basis for these models; the slopes and intercepts were chosen to minimize the standard error of estimate. This explains the poor agreement between observed and predicted MRI indices.

VI. CONCLUSIONS

A significant correlation was found between geometric mean dust exposures and dustiness test results. The fact that this correlation was observed in an actual plant shows that addressing material dustiness is important in predicting and controlling worker dust exposure. Because geometric mean dust exposures are quite variable, the regression equations used to relate dust exposures to dustiness test results involve variability which is no smaller than the variability in the geometric mean dust exposures. Additional refinement of dustiness testing procedures will probably require a substantial laboratory effort to avoid the variability associated with field work. However, the ultimate utility of dustiness testing is its ability to predict worker dust exposures and workplace dust concentrations.

The data collected during this study suggests that the MRI tester is inferior to the Heubach tester. The MRI tester was not consistent from material to material. Furthermore, the regression equation relating the MRI Dustiness Index to dust exposures involved a significant lack of fit of the model to the data.

VII. REFERENCES

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Appendix I
Listing of Worker Exposure Data

LISTING OF CONCENTRATION MEASUREMENTS

MATERIAL	SHIFT	PERSONAL (MG/CU M)	DOOR (MG/CU M)	MIDDLE (MG/CU M)	BACKGROUND (MG/CU M)	
P5	1.00	0.54	0.99	1.16	0.68	8/19/6
P5	2.00	3.38	1.76	1.69	1.76	8/19/86
P5	2.00	2.09	2.64	0.88	1.55	8/19/86
P5	1.00	0.81	0.40	0.49	0.55	8/19/86
P5	1.00	2.24	0.58	1.63	1.23	8/19/86
P4	1.00	1.76	0.72	1.11	0.60	8/12/86
P4	1.00	1.76	2.04	1.66	0.97	8/12/86
P4	1.00	4.26	0.81	0.88	0.34	8/12/86
P2	1.00	8.54	11.78	5.55	4.18	8/26/86
P2	1.00	5.91	0.00	0.00	0.00	8/26/86
P2	2.00	2.23	2.53	31.45	3.34	8/26/86
P2	2.00	1.96	8.75	4.39	0.78	8/26/86
P2	2.00	2.60	8.21	2.32	0.81	8/26/86
P6	1.00	1.32	0.44	0.47	2.09	8/29/86
P6	1.00	1.22	0.37	0.47	0.24	8/29/86
P6	1.00	0.91	0.34	0.40	0.27	8/29/86
P6	1.00	0.58	0.40	0.58	0.50	8/28/86
P6	1.00	1.71	1.19	1.17	0.52	8/28/86
P6	1.00	0.72	0.54	0.36	0.99	8/28/86
P1	1.00	15.54	6.40	7.61	6.53	9/15/86
P1	1.00	12.70	4.55	6.80	5.23	9/15/86
P1	1.00	8.78	0.29	7.48	6.67	9/15/86
P1	1.00	21.92	17.96	55.50	4.20	9/16/86
P1	1.00	30.93	15.55	7.35	7.80	9/15/86
P1	1.00	13.24	7.30	18.65	1.53	9/16/86
P3	1.00	10.16	2.14	4.94	0.47	9/17/86
P3	1.00	7.59	1.42	2.13	0.28	9/17/86
P3	1.00	0.47	2.66	2.13	3.03	9/17/86
P3	2.00	5.86	2.83	2.66	1.00	9/17/86
P3	2.00	1.76	1.42	0.34	0.13	9/17/86
P3	2.00	1.40	0.99	0.90	0.32	9/17/86

Appendix II
Listing of Dustiness Test Results

LISTING OF DUSTINESS TEST RESULTS

DATE	MATERIAL CODE	HEUBACH %LOST	MRI INDEX
12-Aug-86	F4	0.179	16.73
12-Aug-86	F4	0.193	11.81
12-Aug-86	F4	0.185	15.04
12-Aug-86	F4	0.190	13.87
12-Aug-86	F4	0.182	20.72
12-Aug-86	F4	0.226	16.53
19-Aug-86	F5	0.110	5.34
19-Aug-86	F5	0.122	4.53
19-Aug-86	F5	0.101	3.63
19-Aug-86	F5	0.107	3.41
19-Aug-86	F5	0.115	6.01
19-Aug-86	F5	0.114	6.31
19-Aug-86	F5	0.069	4.19
19-Aug-86	F5	0.064	2.86
26-Aug-86	F2	0.334M	15.33
26-Aug-86	F2	0.432M	16.51
26-Aug-86	F2	0.193	6.07
26-Aug-86	F2	-----	5.44
26-Aug-86	F2	0.178	8.63
28-Aug-86	F6	0.012	2.69
28-Aug-86	F6	0.013	2.05
29-Aug-86	F6	0.023	2.86
29-Aug-89	F6	0.027	3.18
15-Sep-86	F1	0.264	24.40
15-Sep-86	F1	0.253	16.31
15-Sep-86	F1	0.251	27.47
15-Sep-86	F1	0.275	22.35
16-Sep-86	F1	0.330	25.12
16-Sep-86	F1	0.359	22.99
17-Sep-86	F3	0.110	20.86
17-Sep-86	F3	0.149	17.30
17-Sep-86	F3	0.162	23.59
17-Sep-86	F3	0.171	19.38
17-Sep-86	F3	0.160	23.70
17-Sep-86	F3	0.216	19.89

Note: M indicates value excluded from analysis because during process upset.