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The Application of Dustiness Tests to the Prediction of Worker Dust Exposure*

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Laboratory bench tests, known as dustiness tests, have been used to evaluate and compare the potential of various powders to cause occupational dust exposure. Dustiness tests are used to develop products with reduced dust emissions. The correlation between dustiness test results and dust exposures was evaluated at two bag dumping and bag filling operations. At one bag dumping and one bag filling operation, there was evidence of a relationship between dustiness test results and dust exposures. In one case, regression analysis showed that dust exposures could be predicted to within nearly one order of magnitude. The variability in this prediction was caused by the inherent variability in the occupational dust exposures. In the other case, there was evidence of a correlation after the data had been adjusted for the effect of varying drop height. At the remaining two operations, no correlation between dust exposures and dustiness test results were observed. These results indicate that the relevance of dustiness tests to occupational dust exposure needs to be evaluated at each site. Because a better option does not exist, manufacturers should continue to use empirical dustiness tests to develop better products in the laboratory. The conclusions reached in the laboratory need to be validated by dust exposure measurements in the field, however.

Laboratory dustiness tests have been devised[1] to provide a relatively quick and convenient means of estimating a material's relative dustiness. In using these dustiness tests, one assumes that the dust generation in the test simulates the dust generation in an actual powder handling operation. Because these tests are empirical, in that they do not measure a fundamental property or response of the material being tested, there can be no guarantee that dust generation in the dustiness testers adequately simulates dust generation in actual powder handling operations. In order to be useful, dustiness test results must be correlated with personal dust exposures at the operation of interest. The purpose of this paper is to report on the relationship between dust exposure and dustiness test results at two bag filling and two bag dumping operations.

The British Occupational Hygiene Society (BOHS) has published an extensive review of dustiness test procedures.[1] Dustiness tests consist of a means of generating dust and a means of quantifying the airborne dust. Their review illustrates 18 different dustiness testers. For a known amount of material, these tests generate dust by one of three techniques: (1) repeatedly dropping powder in a rotating drum (such as the Heubach Dust Measurement Appliance [Langelsheim 1, West Germany] pictured in Figure 1[2]); (2) dropping powder in a closed space (such as the MRI dustiness tester [Midwest Research Institute, Kansas City, Missouri] pictured in Figure 2); and (3) fluidizing the powder in a small fluidized bed. The amount of airborne dust generated is quantified by either gravimetric methods (filter or impactor) or by instrumental methods (aerosol photometer). In reviewing the available data, the BOHS report noted that there needs to be a practical relationship between dustiness test results and dust exposures. Such a relationship would allow one to estimate worker dust exposure from dustiness test results. Unfortunately, such information is not available in the published literature.

If there is a relationship between dustiness test results and dust exposure, dustiness tests could be used to facilitate the reduction of worker dust exposure. Most of the dustiness tests reviewed by the BOHS were developed by powder producers. Presently, they use dustiness tests to evaluate the efficacy of various dust suppression methods. One producer even uses dustiness test results to promote the purchase of a dust-suppressed form of a product.[2] If there is a useful relationship between dustiness test results and worker dust exposure, then powder producers can minimize occupational dust exposures by producing powders which inherently produce less dust. Potentially, the occupational health community and purchasers of powders could also use these tests. The occupational health community could use dustiness test results to evaluate the dust exposure

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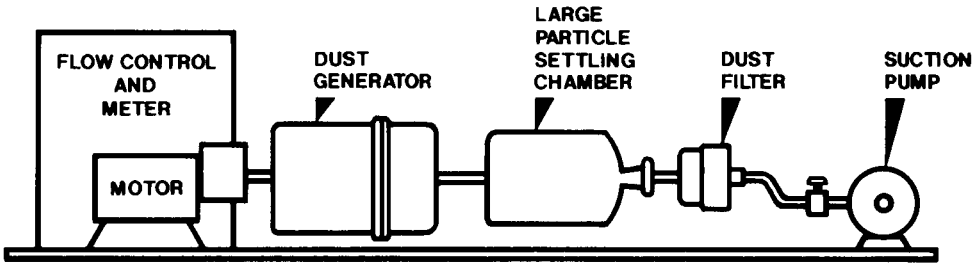

Figure 1—The Heubach Dust Measurement Appliance.

potential of various products before they are used in actual plants. Dustiness test results could also be used to specify the level of control needed in order to handle the product safely. Purchasers of powders could incorporate dustiness test results into their procurement specifications.

All of these uses for dustiness tests presume that there is a relationship between dustiness test results and dust exposure. Because this relationship has not been evaluated, studies were conducted, using the two different dustiness tester, at two plant operations where powders were packed into bags and at two operations where powders were emptied from bags. The two dustiness test devices were the Heubach Dust Measurement Appliance (Figure 1) and the Midwest Research Institute (MRI) tester (Figure 2).[3] The Heubach test was originally developed to aid in process control work for the production of pigments. The MRI test was developed by MRI in response to a research project sponsored by the Environmental Protection Agency (EPA) to develop an inexpensive and quick test for dustiness.

FIELD STUDIES

At two bag filling and two bag dumping operations, the correlation between worker dust exposure and dustiness test results was evaluated. At each site, dustiness tests and personal dust exposure monitoring were conducted concurrently. The number of materials evaluated and the number of exposure measurements for each material studied varied with the operating conditions at each study site. Dust exposures were measured for a period of 30 to 120 min, while the workers were performing bag dumping or bag packing activities. The details of these field studies are available elsewhere.[4-6]

The dustiness testers used during these field studies are shown in Figure 1 and 2. The Heubach unit, depicted in Figure 1, consists of a horizontal rotating drum with internal baffles that produce a repeated dust fall through a regulated airstream. Air containing airborne dust from the drum enters a settling chamber and is then filtered. The test parameters (mass of material, airflow rate, and total flow) for the Heubach dustiness tester are not unique; they are set for each type of powder tested, so that a measurable quantity of dust is collected on the filter. High dust loadings on the filter, near 200 mg, can cause losses during handling and weighing. The approach suggested by Heubach is to select the dustiest material for setup, then set the airflow rate and the test time so as to collect the desired amount of dust.[2] A sample of about 20 g and a flow rate of 2 L/min was used at Sites A and B. Less dusty materials were encountered at Sites C and D. As a result, the dustiness tests were conducted at a flow rate of 15 L/min on a 100-g sample of the powder. The Heubach dustiness test index is 100 times the ratio of the mass of dust collected on the filter to the mass of material tested:

$$\text{Heubach dustiness index} = \frac{100\ (\text{dust collected on filter [grams]})}{(\text{mass of material tested [grams]})}.$$

The MRI tester, shown in Figure 2, simulates the pouring and dumping of fine solids under specified conditions within an enclosed chamber fitted with a sampling filter (47-mm glass fiber, Gelman type AE, Ann Arbor, Mich.) and constant flow exhaust pump system. The cup was rotated at a constant speed to dump the powder. A vibrator mounted to the cup shaft helps to dislodge the dust. The sample pump, operated at a nominal 10 L/min,

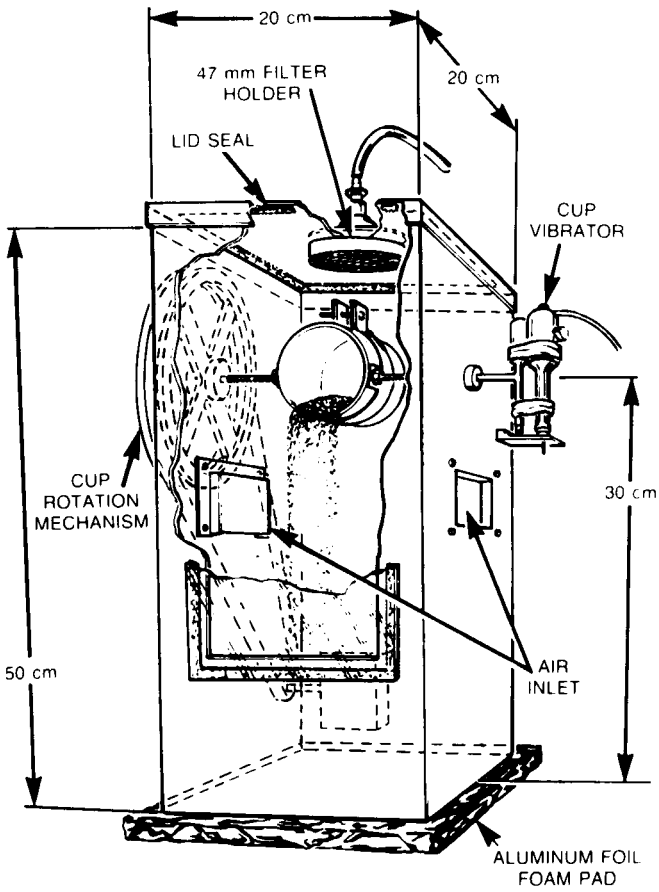

Figure 2—The MRI dustiness tester.

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was run for 10 min, starting when the rotation of the cup was initiated. The sample cup was filled by gently pouring the material into the stainless steel cup. It was slightly overfilled, scraped level with the top of the cup with a metal straight edge, and then the cup and material were weighed. The bulk density of the powder was calculated by dividing the mass of the powder in the cup by the cup's volume. A preweighed filter was placed in the filter holder. The apparatus was then assembled for the test. During the test, the time that the powder begins to pour and the time the pouring is complete were recorded. When the test was completed, the filter was removed from the apparatus and weighed. The MRI dustiness index is

$$\text{MRI dustiness index} = \frac{\text{dust collected on filter (mg)}}{\text{(weight of sample [Kg])}}$$

The study at Site A was conducted in the packaging room for a powdered acrylic resin production line. The plant produced a variety of resins which differ in bulk density, particle size, moisture content, and observed dustiness. The resin powders were auger fed into tuck-in valve bags. After the bags were filled with 22.7 kg (50 lb) of powder, they were sealed and dropped onto a conveyor belt which transported the bags to a palletizing operation elsewhere in the plant. The operator simultaneously controlled a number of bag packing machines. Several workers rotated between the bagging equipment and the palletizing equipment in an adjacent storage area. Local exhaust ventilation was applied to control the dust generated when the powder was fed into bags and when the bags were sealed. The dust generated during the bag filling process was exhausted by a hood placed around the feeding spout. The dust control measures appeared to be partially effective. The workers' dust exposure appeared to result from process leakage of the acrylic resin and from the bag filling process. In addition, workers routinely wore disposable respirators; for particularly dusty products, powered air-purifying respirators were utilized.

For six different products, personal monitoring and dustiness tests were conducted. For each product, the personal dust exposures of 3 to 6 workers were measured gravimetrically using Method 0500 from the *NIOSH Manual of Analytical Methods.*[7] Dustiness tests were conducted on bulk samples of the material that the workers were actually bagging.

Site B was on the fourth floor of a paint plant which was built in the early 1900s. As part of the process for making paints, a number of bags of crystalline silica, titanium dioxide, and talc were emptied into a 600-gal. mixing tank. Because the level of liquid in the mixing tank changed for each material, the heights through which the material fell varied. The fall distances for the crystalline silica, titanium dioxide, and talc were 85, 75, and 25 cm, respectively. The dust controls were minimal, consisting of a slot hood at the rim of the mixing tank. The workers' dust exposure appeared to be caused by every facet of the process of opening the bag, emptying the bag into the mixing tank, and discarding the emptied bag. There were no other sources of dust exposure at this plant.

Personal exposure monitoring was conducted on two days. On each day, the same worker charged the three materials into the mixing tank. While each material was being charged into the mixer, the total dust exposure was measured using Method 0500 from the *NIOSH Manual of Analytical Methods.*[7] Bulk samples of the material were collected for dustiness tests.

Sites C and D were located at a lead chromate pigment production plant. At this plant, the company had used the Heubach dustiness test to develop and market a "low dust" form of their lead chromate pigments. Both the normal and low dust formulations of the lead chromate pigments were produced at this plant. Two distinct sites in the plant were selected for study. Site C was at a bag dumping station and Site D was at a bag packaging station. These two sites were in separate buildings.

At the bag dumping station (Site C), workers manually emptied 22.7-kg (50-lb) bags of lead chromate into a ventilated hopper. Depending upon process needs, the worker would empty 100 to 200 bags of lead chromate into the hopper. After emptying these bags, the workers discard the empty bags into a container which was located outside of the ventilated enclosure. Some workers would carefully compress the emptied bag in the enclosure, in order to minimize the amount of dusty air which is spilled from the emptied bag when it is placed in the trash containers. Others would simply crush the bag in the trash container. Based upon aerosol photometer measurements, this bag disposal activity caused most of the worker's exposure to lead chromate. There were no other significant sources of worker dust exposure in this area of the plant.

At the bag packing station (Site D), lead chromate is packed into 22.7-kg (50-lb) bags by a force flow packer. The operator places an empty bag on the packer spout and starts the bag filling process. Once the bag is nearly full, the worker moves the bag from the fill spout to a hood. Then, the worker adjusts the final weight of material in the bag by using a scoop to add or remove pigment. After tucking in the valve, the worker sets the bag on the pallet. Much of the workers' dust exposure is caused by leakage of lead chromate pigment from the equipment used to transport the pigment. The treatment was applied early in the process before the process leakage occurred.

At Sites C and D, personal dust exposure monitoring and dustiness tests were conducted concurrently for seven different materials at Site C and for six different materials at Site D. The workers' exposure to lead chromate was monitored for a period of 30 to 90 min, which was the duration of their activity. At the start of each sampling period, the worker collected a bulk sample of the powder which was being packed or emptied into bags. Dustiness tests were conducted on this bulk sample. The workers' exposures to lead chromate were measured by using NIOSH sampling and analytical Methods 7082 and 7300.[7] For each material, there were 1 to 6 different sampling periods. The number of sampling periods was dictated by plant operating conditions and the demand for the product which was being produced.

RESULTS

The field studies indicated an inconsistent correlation between worker dust exposure and dustiness test results. The findings from Sites A and B suggest that dustiness test results can, to

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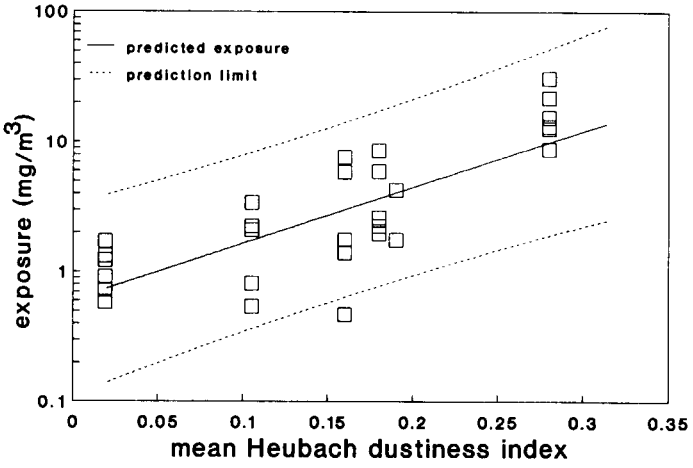

Figure 3—At Site A, dust exposure as a function of Heubach dustiness index.

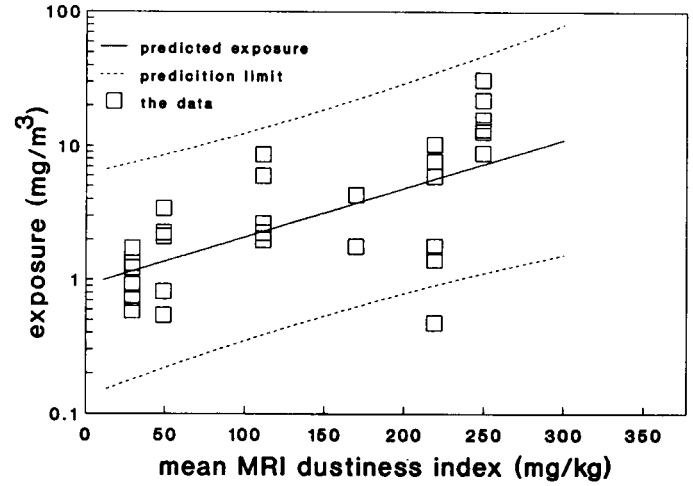

Figure 4—At Site A, dust exposure as a function of MRI dustiness index.

some extent, be used to predict worker dust exposure. At Sites C and D, there was no relationship between worker dust exposure and dustiness test results.

At Site A, a significant correlation between dustiness test results and worker dust exposure was found for both the MRI and Heubach dustiness test results. For both testers, the correlation was significant at a level of confidence greater than 99.9%. Figures 3 and 4 show observed and predicted dust exposures plotted as a function of dustiness test results. The limits about the predicted exposures indicate the range of individual dust exposures which is predicted for a given exposure. These limits (the 95% prediction limits for predicting individual exposures from the regression model) are interesting because they quantitatively illustrate the ability of dustiness test results to predict individual dust exposures. They indicate that the regression model developed from the data could predict worker dust exposures to within a factor of 12 for the Heubach dustiness test and to within a factor of 18 for the MRI dustiness test.

The width of these prediction intervals is proportional to the standard error of estimate, which is essentially the standard deviation about the regression line.[8] It is the sum of two sources of error: (1) the lack of fit of the model to the data and (2) the statistical sampling error in monitoring worker dust exposure. The second source of error is caused by the inherent variability of the workers' dust exposure. For the MRI dustiness tester, the first source of error was found to be statistically significant at a 98% level of confidence. This explains the wider prediction interval for the MRI tester. For the Heubach dustiness test results, the first source of error was not statistically significant. This means that the prediction interval for the results obtained from the Heubach dustiness tester cannot become much smaller. The error in using these regression equations is largely caused by the variability inherent to worker dust exposures.

The results from Site B indicated that dustiness test results need to be adjusted for the effect of drop height. Before adjustment of the data for the effect of drop height, the value of R^2 (which is the fraction of the variability in the data explained by the model) was less than 0.1. Empirically, dust generation is reported to be proportional to the square of drop height.[9] This

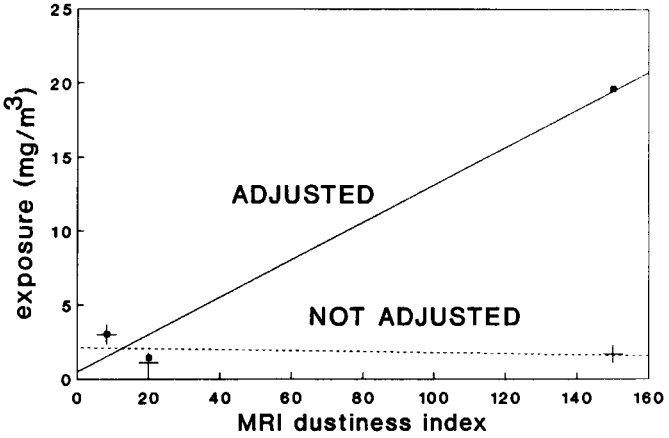

Figure 5—At Site B, dust exposure, before and after adjustment for the effect of drop height, as a function of MRI dustiness index.

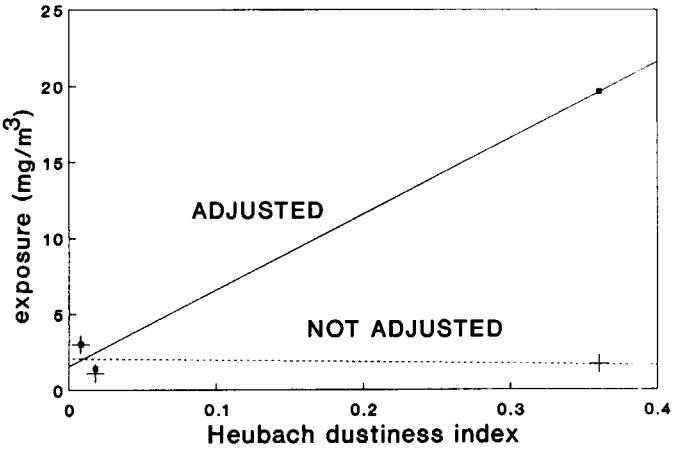

Figure 6—At Site B, dust exposure, before and after adjustment for the effect of drop height, as a function of Heubach dustiness index.

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assumes that the dust exposure is caused by the fall of the powder into the mixing tank. When the data were normalized by dividing the worker's dust exposure measurements by the square of the ratio of the drop height to the drop height of silica (arbitrarily selected as the reference), the value of R^2 increased to 0.98. Figures 5 and 6 show the data before and after the adjustment for drop height. At this site, the worker seemed to take more care in adding the talc to the batch. Talc was added last to the batch and handled with more care because the workers intuitively knew it would cause higher dust exposures. At this site, dustiness tests essentially indicated the order in which materials should be added to the mixing tank in order to minimize exposures. This situation, however, also indicates that there is a need to adjust dustiness test results for the effect of variables such as drop height. Although there is some empirical information as to identity of the variables which affect dust generation rates, there is no general approach for making such an adjustment. Furthermore, what is appropriate in one situation may not be appropriate in another.

At Sites C and D, there was no correlation between dustiness test results and dust exposures. This can be seen easily in Figures

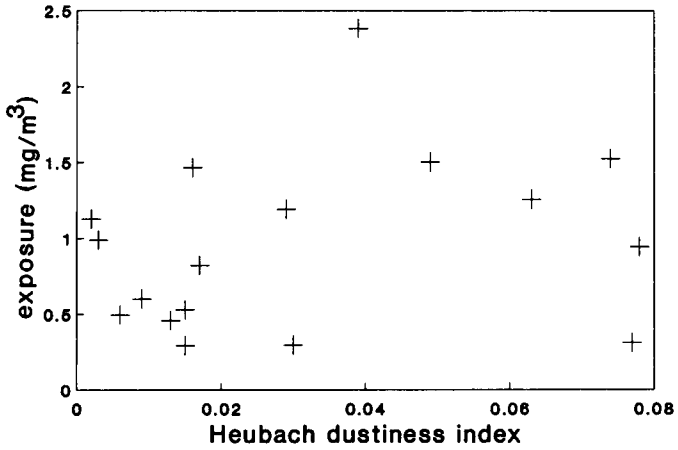

Figure 7—At Site C, lead chromate exposure as a function of Heubach dustiness index.

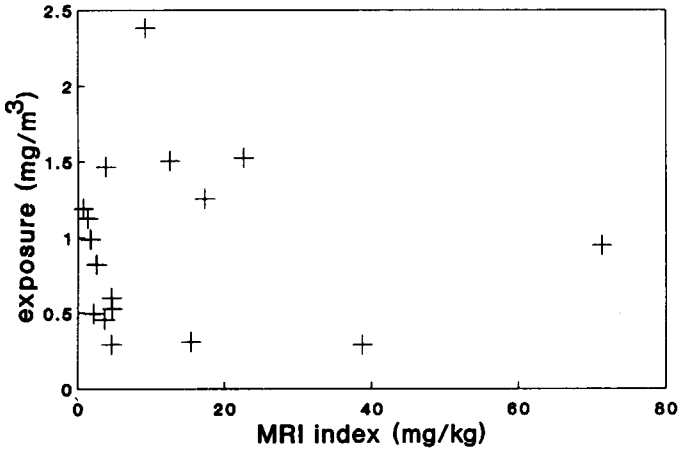

Figure 8—At Site C, lead chromate exposure as a function of MRI dustiness index.

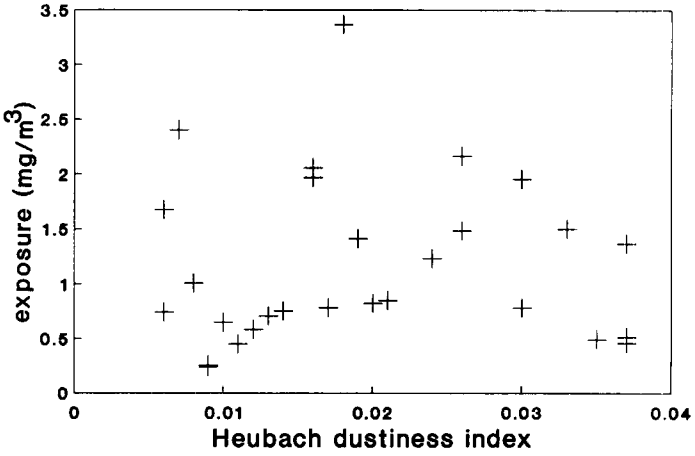

Figure 9—At Site D, lead chromate exposure as a function of Heubach dustiness index.

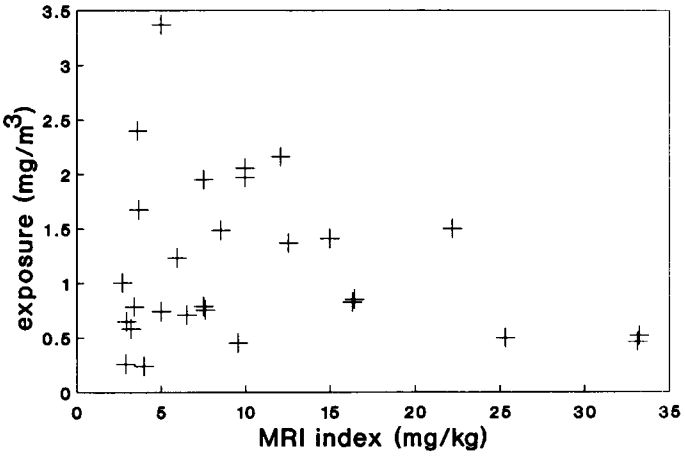

Figure 10—At Site D, lead chromate exposure as a function of MRI dustiness index.

7–10. These results could be caused by either the presence of confounding factors or by deficiencies in the dustiness test procedures. The dustiness test results covered a wider range than at Site A. At Site C there were no extraneous sources of dust exposure near the bag dumping station. (Area samples taken for lead were lower than the personal exposures to lead by a factor of 10). There are a number of potential confounding factors at this site which could explain the lack of correlation. The dust exposure appeared to be largely caused by the bag disposal operation. Analysis of aerosol photometer results indicated that the pigment remaining in the bag after it had been emptied caused this source of dust exposure. Possibly, the bag was adsorbing the agent used to treat the powder. As a result, the powder which was causing the dust exposure may have been less dusty than the bulk of the powder which is tested. Variations in work practices and body stature could also have affected worker exposure.

At Site D, process leakage appeared to cause much of the workers' dust exposure. The powders with the lower dustiness test results were treated with a dust suppression agent to reduce

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the powder's dustiness. The dust suppression treatment may have made the pigment more cohesive and difficult to handle. More force may have been used to handle treated powders which have lower dustiness test results than would have been used on untreated powders. This suggests that the dustiness tests may need to consider the flowability of powder, among other factors. At this site, there were no clear cut reasons for the lack of correlation between dustiness test results and dust exposures.

DISCUSSION

At Sites A and B, dustiness test results were observed to provide useful information about the relative dustiness of materials used. At Sites C and D, there was no relationship between material dustiness and worker dust exposure. Therefore, one can conclude that dustiness tests provide only a "somewhat" useful indication of material dustiness. For example, consider materials X and Y. If material X is inherently less dusty than material Y, then worker exposure to material X may be less than exposure to material Y in the field. The magnitude of the exposure difference between products X and Y, however, will probably vary from site to site, and in some cases there may not be a difference in exposure.

The findings from the field studies probably follow from the empirical nature of dustiness tests. Dustiness tests are used to physically model dust generation in an actual powder handling operation. There is no guarantee that dust generation in the tester closely simulates dust generation in an actual process, however. In some cases, dust generation in the tester may be so different from dust generation in an actual process that there is no correlation between dustiness test results and dust exposure. Because of this situation, each user of dustiness test results needs to conduct studies which evaluate the relationship between dustiness results and dust exposure. Furthermore, such studies need to be conducted for every site of interest. When there is a correlation between dustiness test results and worker dust exposure, dustiness test results can be used to provide an order of magnitude estimate of worker dust exposure.

When there is no apparent relationship between dustiness test results and dust exposures, there are numerous possible explanations for such results. Frequently, it will be impossible to determine why there is no correlation. To some extent, each of the three possible scenarios can occur at all plants.

(1) Other variables such as work practices, equipment maintenance, and process leakage may have a greater effect upon dust exposure. The successful dust exposure control strategy should address the variables which have the greatest effect upon dust exposure.

(2) The effect of material dustiness upon exposure may be confounded with other factors. For example, work practices or the operation of the plant may vary during the time of the study. Process upsets in other parts of the plant may be occurring while a particular material is being manufactured. Any process upset or deviation from usual operating conditions can have an effect upon exposure and can affect the observed correlation between dustiness test results and dust exposure.

(3) In some cases, the mechanism of dust generation in the dustiness tester is very different from the mechanism of dust generation in the process of interest. As a result, there can be no correlation between dust exposures and dustiness test results.

Because dust generation by powder handling operations is too poorly understood to foster the development of scientifically based dustiness tests, empirical dustiness tests will continue to be used. Powder producers will need to continue to use dustiness tests to develop products with low dust emission rates and to compare the relative dustiness of different materials. As a final step in the development of a low-dusting product, producers should conduct personal dust exposure monitoring to show that a certain formulation does result in reduced dust exposures.

When there is a correlation between dustiness test results and dust exposures, prediction interval width cannot become smaller than the observed range in worker dust exposures. Typically, this range is about a factor of 10. (Leidel et al.[10] found that dust exposure data was lognormally distributed with geometric standard deviations between 1.1 and 2.3, with a median value of 1.55.) This situation suggests that dustiness only need to approximately simulate dust generation in the workplace. Furthermore, it suggests that substantial differences in dustiness test results are needed in order for the difference in dust exposures to be noticeable at an actual powder handling operation.

Although research recommendations are usually the trite and threadbare part of a research paper, the need for research is the most important observation in this paper. In order to avoid the problems caused by the empirical nature of the present dustiness tests, these tests need to be put on a more scientific basis. This will require fundamental research into the nature of dust generation by powder handling operations. The literature on dust generation by falling powders is scant and mostly empirical.

There are no theoretical models that have been evaluated to describe how a powder becomes an aerosol—a particle suspended in the air. As a result, one cannot rationally choose among the different dustiness tests which were mentioned in the introduction to this paper and described in the British Occupational Hygiene Society report.[1] A better understanding of powder handling operations would allow the individual to devise, develop, or choose the most appropriate dustiness test based upon established facts. Presently, one can only choose dustiness tests based upon professional judgment and past experiences.

RECOMMENDATION

Presently, empirical dustiness tests should continue to be used in product development. In addition, these tests can be used to compare the relative dust exposure potential of different products. Findings based upon dustiness test results need to be validated, however, by monitoring personal dust exposures in actual plants.

Dustiness testing can play a role in occupational health. Dustiness tests do provide a somewhat useful indication of the relative exposure potential of different powders. The occupational health professional must be aware that other factors besides material dustiness can affect worker dust exposure. In order to devise successful dust control strategies, one must control the variables which have the greatest effect upon workers' dust ex-

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posure. If dust exposures are known to vary significantly with the material being processed, then controlling material dustiness may result in significant exposure reduction. If other factors, such as process leakage or work practices, are more important than material dustiness, however, one must address the other factors to achieve a significant exposure reduction.

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