EVALUTION OF SUBSTITUTE MATERIALS FOR SILICA SAND IN ABRASIVE BLASTING

CONTRACT No. 200-95-2946

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INTRODUCTION

This report represents Phase 3 of a study commissioned by the Centers for Disease Control and Prevention (CDC) and the National Institute for Occupational Safety and Health (NIOSH). The study was outlined in an Invitation for Proposal entitled, "Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting," dated June 9, 1995. KTA-Tator, Inc. (KTA) responded to the invitation with a proposal entitled, "Technical Proposal for Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting," dated July 14, 1995. On September 29, 1995, Contract No. 200-95-2946, issued by the Centers for Disease Control and Prevention (Atlanta, Georgia), was awarded to KTA. The Contract directed KTA to conduct a three-phase study for the purpose of investigating relative levels of 30 different health-related agents and other attributes of surface preparation of alternative abrasives to silica sand.

Phase 1 involved a laboratory study. The Phase 1 results are contained in a KTA report to CDC/NIOSH dated September 1998. Phase 2 involved a field study. The Phase 2 results are contained in a KTA report to CDC/NIOSH dated December 1998. This Phase 3 report presents a comparison of the data collected during Phases 1 and 2.

PHASE 1 LABORATORY STUDY

The Phase 1 study involved 13 generic categories of abrasives (40 abrasives total) from suppliers and distributors located throughout the United States. The number of abrasives within each category ranged from 1 to 7. The abrasive types and the letter code assigned to each were as follows:

Expendable Abrasives

Coal Slag (CS)	7 products
Coal Slag with Dust Suppressant (CSDS)	2 products
Crushed Glass (CG)*	1 product
Nickel Slag (N)	2 products
Olivine (O)	1 product
Silica Sand (SS)	7 products
Silica Sand with Dust Suppressant (SSDS)	3 products
Specular Hematite (SH)	1 product
Staurolite (S)	2 products

*Crushed glass abrasive was mixed window and plate, post industrial.

Recyclable Abrasives

Copper Slag (CP)	4 products
Copper Slag with Dust Suppressant (CPDS)	1 product
Garnet (G)	7 products
Steel Grit (SG)	2 products

Phase 1 was conducted at the KTA-Tator, Inc. corporate headquarters and laboratories located at 115 Technology Drive, Pittsburgh, PA 15275. Forty abrasives were used in an environmentally-controlled laboratory blast room to blast clean bare carbon steel plates. The objective of the study was to collect industrial hygiene airborne levels and bulk ingredient data for 30 health-related agents as well as economic and technical data regarding the performance of the abrasives. KTA developed a detailed Study Design/Protocol which held constant many factors which affect an abrasive blast cleaning process so that a comparative evaluation of the abrasives could be made independent of the substrate, surface cleanliness, equipment set-up, or operator. The individual abrasives that were selected in Phases 1 and 2 were based on a higher volume of consumption within the blasting industry, and being able to produce the required profile criteria established by the Phase 1 and 2 protocols.

For Phase 1, controls were provided over the purchasing of the steel substrate test surfaces to insure homogeneity. The blast cleaning hose size and length (15 foot of 7/8 inch inside diameter) and nozzle type and size (Boride, 1/4 inch orifice venturi) were standardized for all runs. Blast pressure at the nozzle was maintained at 100 psi for each trial. The abrasive metering valve was adjusted from 1/4 inch to 1/2 inch in 1/16 inch increments based on recommendations of the abrasive supplier. If a recommendation was not made, the 1/2 inch size was used. The ventilation within the blast room was maintained at 50 to 75 feet per minute, and the blast room and blast cleaning equipment were thoroughly cleaned prior to each run.

Blasting was conducted until a total of 72 square feet of steel was used for each abrasive trial, or until the blast pot ran out of abrasive. The operator maintained a constant 18-inch nozzle to work-piece distance and held the nozzle perpendicular to the test surface.

Prior to initiating the study, it was also recognized that variability could exist between human operators. In an effort to reduce the variability between individual operators and within a single operator, a study was initially conducted to select a single operator for the project. Five abrasive blasting operators were evaluated while performing five abrasive blasting trials in accordance with the protocol. The operators were randomly scheduled for the trials and were evaluated based on four attributes: total abrasive blasting time, amount of surface area cleaned, rate of abrasive consumption, and abrasive cleaning rate. The objective was to select the operator who displayed the least variation across all four attributes combined. The results were statistically analyzed and a single operator was chosen for the blast cleaning study.

In order to improve the validity of the test results and the repeatability of the abrasive blast cleaning process, statistical process control measures were also implemented throughout the entire project. Five randomly scheduled process checks were used. The same abrasive material (coal slag) used for the operator variability study was used for the process control checks. The abrasive was incorporated into the test stream blindly. The same four attributes evaluated for the operator variability study were statistically analyzed for the process control checks. All checks showed the process to be in control.

During each abrasive trial, airborne samples were collected in the blast room as well as on the operator. A total of 29 samples were collected for each run (8 at the make-up air area, 8 in the operator area near the test surfaces; 8 in the exhaust area; 3 within the operator's breathing zone; and 2 passive samples for the collection of ricochet in the blast room operator area). All samples with the exception of those mounted on the operator were attached to fixed sample holders, assuring that the sample locations were identical for each abrasive trial.

Phase 1 evaluated each of the individual abrasives for seven performance-related characteristics: cleaning rate, consumption rate, surface profile, breakdown rate, abrasive embedment, microhardness, and conductivity. These performance attributes were clearly defined in the Phase 1 report. Bulk samples of the 40 abrasive products were analyzed for 30 potential contaminants prior to and after use. In addition, during use, the abrasives were evaluated for airborne concentrations of the same 30 contaminants. While data was collected for 30 contaminants, 11 of them were selected by NIOSH for a detailed analysis: arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, silver, titanium, vanadium, and respirable quartz.

PHASE 2 FIELD SITE STUDY

Phase 2 was conducted in order to evaluate 8 of the Phase 1 abrasives under field conditions. Phase 2 involved a single abrasive from 8 of the generic categories: coal slag, nickel slag, staurolite, silica sand, silica sand with dust suppressant, copper slag, garnet and steel grit. The specific abrasives were selected by NIOSH. Phase 2 was conducted at the Consolidation Coal Company's shipyard located in Elizabeth, PA. The object of Phase 2 was to collect data on airborne concentrations and bulk ingredient data for 30 health-related agents as well as economic and technical data under partially-controlled field conditions. The work involved open nozzle dry abrasive blast cleaning of the exterior hull of a coal barge. The hull was free of any coating and consisted of heavily rusted and pitted steel. The side of the barge was subdivided into eight (8) 14 foot x 5 foot sections resulting in a maximum surface area of approximately 72 square feet per abrasive. A portable containment was constructed that measured 16 feet long by 8 feet wide by 8 feet high in order to enclose one section at a time. Tarpaulins were used to cover the floor inside the containment. The containment was equipped with a dust collector with a capacity of 5,000 cubic feet per minute (cfm). An average cross-draft air flow of 40 feet per minute was maintained for each trial run. This was based on actual measurements rather than relying on theoretical calculations based on the stated capacity of the dust collector. The same blast cleaning equipment used in Phase 1 was utilized for Phase 2 except that a Boride 7/16 inch orifice venturi blast nozzle was used. In addition, the metering valve was uniquely adjusted for the abrasive based on the feel of the operator and the fullness of the abrasive blast pattern. The same operator from Phase 1 conducted the Phase 2 trials.

After each abrasive trial run, the containment was cleaned and moved to a new location on the barge to prevent cross-contamination between abrasives. A total of 14 airborne samples were collected inside the containment during each trial run (4 make-up air area; 4 operator area; 4 exhaust area; and 2 within the operator's breathing zone). The 12 area samples were mounted on fixed holders to assure that the position remained constant for each abrasive trial. The abrasives were evaluated for cleaning rate, consumption rate, surface profile, breakdown rate, and abrasive embedment. The same 30 contaminants evaluated in Phase 1 were evaluated in Phase 2, with the same 11 selected by NIOSH for a detailed analysis.

During both the Phase 1 and Phase 2 work, stringent controls over the calibration and operation of all of the test equipment including the sampling pumps was maintained. All of the calibration information and test data were recorded on project report forms.

EXECUTIVE SUMMARY

The Centers for Disease Control and Prevention (CDC), through the National Institute for Occupational Safety and Health (NIOSH), commissioned KTA-Tator, Inc. to conduct a study entitled "Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting." In conjunction with NIOSH, a project design protocol was developed to evaluate the characteristics that influence abrasive performance from a surface preparation viewpoint and the potential for worker exposures to airborne contaminants. The project involved a Phase 1 laboratory study and a Phase 2 field study. This report compares data from the Phase 1 laboratory study to the Phase 2 field study. Thirteen generic types of abrasives were evaluated in Phase 1, and the 8 generic types of abrasives marked with an asterisk (*) were evaluated in Phase 2:

- coal slag*
- coal slag with dust suppressant
- copper slag*
- copper slag with dust suppressant
- crushed glass
- garnet*
- nickel slag*
- olivine
- silica sand*
- silica sand with dust suppressant*
- specular hematite
- staurolite*
- steel grit*

For Phase 1, one to 7 individual products from within each of these generic categories (40 products total) were obtained from manufacturers and suppliers throughout the United States, and each of the abrasives was evaluated for the 7 performance-related characteristics listed below. Only one product from each generic category in Phase 2 was tested and each of the abrasives was evaluated for the 5 performance-related characteristics marked with an asterisk (*)below:

- cleaning rate*
- consumption rate*
- surface profile*
- breakdown rate*
- abrasive embedment*
- microhardness
- conductivity

Bulk samples of the abrasive products were analyzed for 30 potential contaminants prior to and following use. During use, they were evaluated for airborne concentrations of the same 30 contaminants:

aluminum	calcium	lead*	nickel*	sodium	yttrium
arsenic*	chromium*	lithium	phosphorous	tellurium	zinc
barium	cobalt	magnesium	platinum	thallium	zirconium
beryllium*	copper	manganese*	selenium	titanium*	quartz*
cadmium*	iron	molybdenum	silver*	vanadium*	cristobalite

* While data was collected for 30 contaminants, eleven of them were selected by NIOSH for detailed analysis.

In order to ensure that the only major variable being evaluated for each of the performance characteristics and airborne contaminants was the individual abrasive, stringent controls over operator work practices and equipment operation were implemented and maintained.

It is important to recognize that the Phase 1 results demonstrated that individual abrasives within each generic category exhibited characteristics that were often quite different than their counterparts. As a result, Phase 2 conclusions apply only to the specific abrasives evaluated and do not represent the entire generic category of abrasive. Each abrasive must be evaluated individually for its own characteristics.

For the Phase1 laboratory study, most of the alternative abrasives evaluated have performance characteristics that are equivalent to or better than silica sand. Average cleaning costs, based on blast cleaning steel in a blast room involving the stringent controls employed in the study, showed all of the alternative abrasives to be less expensive to use as a class with the exception of crushed glass and specular hematite. In both cases, only one abrasive was evaluated and in both cases there was at least one silica sand abrasive that proved to be more costly. It should also be recognized that all of the costs are artificially high due to the controls imposed on the study (blast nozzle size, operating pressure, metering valve settings, nozzle-to-work piece distance, and angle of abrasive impact). Adjustments to any of the study variables can be expected to result in substantial cost reductions for each of the abrasives. For example, increasing the nozzle size alone with a coal slag abrasive in Phase 1 resulted in a cost reduction of nearly 60%.

For the Phase 2 field study, the alternative abrasives evaluated were all capable of producing the desired degree of cleaning and a surface profile suitable for paint performance. Productivity of the abrasives evaluated was both better and worse than silica sand. Based on the specific abrasives tested, the operational controls imposed on the project, and the hypothetical project conditions established for cost-estimating, the cost to prepare the steel using the various abrasives ranged from $0.69 per square foot to $1.02 per square foot. The cost of coal slag abrasive was comparable to silica sand ($0.69 per square foot versus $0.72 for silica sand). Other abrasives were more expensive to use based on the test results (e.g., from 12 to 42% more expensive than silica sand), although without the constraints imposed on the equipment operator during the study, they will be more competitive to use in actual field applications. In addition, if hazardous waste is assumed to be present, the cost of use changes dramatically due to disposal costs, from $0.91/square foot to $1.67/square foot, with silica sand at $1.37 per square foot. Steel grit becomes the most cost-effective abrasive at $0.91/square foot.

While this study collected data on 30 potential contaminants, the analysis focused on eleven health-related agents selected by NIOSH including: arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, respirable quartz, silver, titanium, and vanadium. While no single abrasive category had reduced levels of all eleven health-related agents, all the substitutes offer advantages over silica sand with regard to respirable quartz. All but two (crushed glass and specular hematite) of the alternative abrasives have higher levels of some other health-related agents, as compared to silica sand. There is considerable individual product variability within the generic types of abrasives evaluated, which limits the possibility of developing recommendations regarding airborne concentrations of hazardous health-related agents based upon broad generic categories of abrasives.

The overall findings of this study are eye opening and potentially far reaching. In recent years, much of the industry focus has been directed at protecting workers from the hazards of lead and other metals in the coatings removed during abrasive blasting. NIOSH and OSHA have also directed increased attention to the hazards of silica sand. The findings of this study suggest that a much broader and holistic approach to protecting workers performing any form of abrasive blast cleaning needs to be taken. In addition to a continued focus on alternatives to silica sand abrasives or the hazard of lead in paint, consideration should be given to the establishment of a broad, vertical health standard encompassing all health hazards associated with abrasive blasting operations.

COMPARISON

SUMMARY OF PHASE 1 LABORATORY STUDY RESULTS

Phase 1 Laboratory Study – Physical Property Evaluations

The Phase 1 testing conclusively demonstrated that a wide range of physical properties exists in the individual abrasives tested within each generic type. Although only one abrasive was evaluated for crushed glass, olivine, and specular hematite, it is expected that similar variability within each of these generic types of abrasive will exist as well. Table 1 summarizes the range of results for each individual abrasive within a generic category, and the average result for the category as a whole for cleaning rate, consumption rate, surface profile, breakdown rate, embedment, maximum microhardness, and conductivity. The letter codes for the abrasive types are defined in the "Introduction" to this report.

Phase 1 Laboratory Study – Operating Cost Comparisons

Based on the cleaning rates obtained during the Phase 1 study, the costs per use are shown on Table 2. In order to obtain reliable industrial hygiene data, the test protocol placed restrictions on equipment and operating procedures used during the blast cleaning study. As a result, the cleaning and consumption rates for the abrasives rates are not representative of actual production. Restrictions included fixed metering valve settings, a small nozzle orifice size (1/4-inch) in order to obtain ample blast cleaning time to collect the industrial hygiene data, a fixed nozzle to work-piece distance (18 inches), a requirement to maintain the nozzle perpendicular to the surface at all times, and a fixed blasted cleaning pressure (100 psi). Because of these restrictions, the cost data that was developed (using the cleaning and consumption rates obtained during the study) is only representative of the hypothetical project under which the cost was derived: one blast operator working in a blast room under those unique operating conditions. Even when using the abrasive in a blast room, if the equipment and operating procedures are optimized, an increase in productivity and a reduction in costs with each of the abrasives will occur. The cost formula used for the analysis was:

$$\text{Cleaning Costs} = \frac{\left[\dfrac{A(P+D)}{R} + E + L\right]}{X}$$

Where: Cleaning Costs ($/square foot)
A = Abrasive Flow Rate (ton/hour)
P = Material Cost of Abrasive ($/ton)
D = Disposal Cost ($/ton)
E = Equipment Cost ($/hour)
L = Labor Cost ($/hour)
R = Number of Time the Abrasive is Used
X = Abrasive Cleaning Rate (square feet/hour)

TABLE 1 – GENERIC ABRASIVE SUMMARY, PHASE 1

TABLE 2 – ABRASIVE CLEANING COST SUMMARY, PHASE 1

Phase 1 Laboratory Study – Industrial Hygiene Data

KTA collected a total of 424 airborne dust samples and 106 bulk samples of abrasives (pre and post run) for the Phase 1 laboratory study. Two hundred and twelve of the airborne samples were analyzed for up to 28 metals/elements. In addition, 212 air samples of respirable dust were analyzed gravimetrically and for quartz and cristobalite. NIOSH selected eleven of these health-related agents for comparative analysis, including: arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, respirable quartz, silver, titanium and vanadium. A brief description of health hazards and recommended exposure limits for these selected eleven health-related agents are provided in Appendix 1.

The Comparison of Airborne Dust Concentrations to Bulk Concentrations Tables (Tables 3 to 14 which follow) provide a comparison of the airborne concentrations recorded for the specific contaminant at all of the fixed sampling stations (i.e., Make-up Air Area, Operator Area, and Exhaust Area) and the Operator's Breathing Zone to the concentration of the contaminant in the virgin abrasive. These tables provide an indication of the range of concentrations of the contaminant in virgin bulk materials that might be associated with airborne exposure levels. The letter codes used to designate the abrasive types are defined in the "Introduction" of this report. For the recyclable abrasives, an "A" suffix represents the results from the first run and "B" represents the results from the last run.

Table 15 summarizes the airborne monitoring results for each of these health-related agents by generic category of abrasive. Note that the data illustrated on the table may not be representative of each individual abrasive within the generic category.

TABLE 3 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – ARSENIC

TABLE 4 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – BERYLLIUM

Table 5 – Comparison of Airborne Concentrations to Bulk Concentrations – Cadmium

TABLE 6 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – CHROMIUM

TABLE 7 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – LEAD

Table 8 – Comparison of Airborne Concentrations to Bulk Concentrations – Manganese

TABLE 9 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – NICKEL

TABLE 10 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – RESPIRABLE QUARTZ

TABLE 11 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – SILVER

TABLE 12 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – TITANIUM

TABLE 13 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – VANADIUM

TABLE 14 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – RESPIRABLE DUST

TABLE 15: SUMMARY OF AIRBORNE SAMPLE RESULTS OF HEALTH-RELATED ELEMENTS BY GENERIC CATEGORY OF ABRASIVE

SUMMARY OF PHASE 2 – FIELD STUDY EVALUATIONS

Phase 2 Field Study – Physical Property Evaluations

Cleaning rate, consumption rate, surface profile, breakdown rate, and abrasive embedment were analyzed for 8 different abrasive products: coal slag, nickel slag, staurolite, silica sand, silica sand with dust suppressant, copper slag, garnet and steel grit. The individual abrasives represent 8 of the generic categories evaluated in Phase 1. The specific abrasive within each category selected by NIOSH for the Phase 2 evaluation was done without consideration of the performance of that abrasive in Phase 1 (i.e., the most productive coal slag abrasive in Phase 1 was not consciously selected for evaluation in Phase 2). Recyclable abrasives were used only one time for the Phase 2 study. The results of each of the above evaluations are presented in Table 16.

Phase 2 Field Study – Operating Cost Comparisons

The operating costs for Phase 2 were derived using the same formula as Phase 1, but the hypothetical project conditions changed. The project involved 40,000 to 50,000 square feet of rusted pitted steel with a crew of three workers: two abrasive blast nozzle operators, and one laborer. The results of the economic analysis are summarized in the attached Tables 17 and 18. Table 17 has been prepared assuming that the waste is non-hazardous. Table 18 provides costs assuming that the waste is hazardous (e.g., if a lead-containing paint is removed). The abrasive codes are identified in the “Introduction” to this report. The numerical suffix represents the identification of the specific product analyzed within the generic class.

TABLE 16 – GENERIC ABRASIVE SUMMARY – PHASE 2

TABLE 17 – ABRASIVE CLEANING COST SUMMARY, NON-HAZARDOUS – PHASE 2

TABLE 18 – ABRASIVE CLEANING COST SUMMARY, HAZARDOUS – PHASE 2

<u>Phase 2 Field Study – Industrial Hygiene Data</u>

KTA collected a total of 64 airborne dust samples and 16 bulk samples of abrasives (pre and post run) for the Phase 2 field study. Thirty-two of the airborne samples were analyzed for up to 28 metals/elements. In addition, 30 air samples of respirable dust were analyzed gravimetrically and for quartz and cristobalite. NIOSH selected eleven of these health-related agents for comparative analysis, including: arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, respirable quartz, silver, titanium and vanadium.

The Comparison of Airborne Dust Concentrations to Bulk Concentrations Tables (Tables 19 to 30 which follow) provide a comparison of the airborne concentrations recorded for the specific contaminant at all of the fixed sampling stations (i.e., Make-up Air Area, Operator Area, and Exhaust Area) and the Operator's Breathing Zone to the concentration of the contaminant in the virgin abrasive. These tables provide an indication of the range of concentrations of the contaminant in virgin bulk materials that might be associated with airborne exposure levels. ND represents results below the limit of detection. Any data reported in the "Notes" column as "<LOQ" means that the associated result reported in column 6 (μg/g) is less than the limit of quantification (LOQ), but greater than the limit of detection (LOD). These results are "semi-quantitative", meaning the respective agent could be detected, but the result can only be accurately quantified as being in a range between the LOD and LOQ.

Table 31 summarizes the airborne monitoring results for each of these health-related agents by category of abrasive. Note that the data illustrated on the table may not be representative of each individual abrasive within a generic category.

TABLE 19 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – ARSENIC

TABLE 20 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – BERYLLIUM

TABLE 21 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – CADMIUM

TABLE 22 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – CHROMIUM

TABLE 23 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – LEAD

TABLE 24 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – MANGANESE

TABLE 25 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – NICKEL

TABLE 26 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – RESPIRABLE QUARTZ

Table 27 – Comparison of Airborne Concentrations to Bulk Concentrations – Silver

Table 28 – Comparison of Airborne Concentrations to Bulk Concentrations – Titanium

TABLE 29 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – VANADIUM

TABLE 30 – COMPARISON OF AIRBORNE CONCENTRATIONS TO BULK CONCENTRATIONS – RESPIRABLE DUST

TABLE 31 – SUMMARY OF AIRBORNE SAMPLE RESULTS OF HEALTH-RELATED ELEMENTS BY GENERIC CATEGORY OF ABRASIVE

COMPARISON OF PHASE 1 AND PHASE 2

The goal of the laboratory study was to control blasting and environmental conditions so the difference between airborne sample results would primarily be attributed to the abrasive used. Therefore, the laboratory results may not have been representative of real world conditions, although the results for different abrasives could confidently be compared to each other, and specifically with the silica sand abrasive. Equally important, the results indicated that there was considerable variability between individual abrasives within a generic category.

The goal of the Phase 2 field study was to collect airborne samples under partially controlled field site conditions. As a result, there was less control over certain environmental factors (e.g., wind velocity and direction, relative humidity, air temperature, temperature of the substrate blasted, etc.) and some blast conditions (e.g., the steel substrate being blasted) than in the Phase 1 laboratory study. However, the Study Design/Protocol followed by KTA during the field study was designed to produce comparable abrasive blast cleaning results, with the abrasive type being the primary variable. Within Phase 2, the different abrasives could confidently be compared to each other, and specifically with the silica sand abrasive. However, in order to compare the results of the Phase 1 laboratory study directly with the Phase 2 field study, the comparison must take into account the inherent variability of individual abrasives, even those within a single generic category of abrasive.

Physical Property Evaluations

Eight of the 40 abrasives used in the Phase 1 laboratory study were selected by NIOSH for use in the Phase 2 field study. Table 32 compares the laboratory and field results obtained with the 8 abrasives. The table presents data for the cleaning rate, consumption rate, average surface profile, breakdown rate, and percent embedment. In addition, the Phase 1 values for maximum microhardness and conductivity are presented. These tests were not repeated on bulk samples of the same abrasive prior to use in the field. Although the products for the field study were purchased from the same source as the abrasives used in the laboratory phase, they were not purchased at the same time. As a result, product composition may not be identical. The data shows the following:

1) Cleaning rate – The laboratory cleaning rates ranged from 34 square feet/hour to 49 square feet/hour. The field cleaning rates showed a 113% to 409% increase over the laboratory rates, ranging from 83 square feet/hour to 146 square feet/hour. The dramatic increase in field cleaning rates is attributed to the use of a larger blast nozzle (7/16 inch versus 1/4 inch ID) and unique adjustments of the abrasive metering valve in the field based on the feel of the operator and the fullness of the blast pattern.

2) Consumption rate – The consumption rate in pounds per square foot of each abrasive was higher in the laboratory than in the field for all of the abrasives with the exception of garnet. The consumption rates in the laboratory ranged from 7.43 pounds per square foot to 16.3 pounds per square foot (except for steel grit at 21.53

pounds per square foot). For the field work, the consumption rates ranged from 7.2 to 9.2 pounds per square foot (with steel grit at 15.6 pounds per square foot). The overall consumption rates of abrasives in the field were 52% to 94% of the consumption rates in the laboratory (with the exception of garnet, which showed an 8% increase in consumption rate in the field). The reduction in consumption rate is attributed to the adjustments to the abrasive metering valve and the increase in abrasive efficiency through the use of a larger nozzle size (which creates a larger abrasive blast pattern).

3) Surface Profile – The surface profile created by the 8 abrasives in the laboratory ranged from 2.02 to 3.68 mils. The surface profile in the field increased for every abrasive with a range from 3.9 to 4.4 mils. The increase in surface profile between the laboratory and field studies ranged from 20% to 93%. This increase is attributed to the rough pitted steel prepared in the field as compared with the smooth mill scale bearing steel prepared in the laboratory. The roughness of the steel itself in the field is likely contributing to the deeper profile measurements.

4) Breakdown rate – The breakdown rate of the abrasive in the field was greater than the breakdown rate in the laboratory for all of the abrasives with the exception of steel grit which showed a reduced breakdown rate. The laboratory breakdown rates ranged from 19.63% to 52.16%, except for steel grit at 7.86%. In the field, the breakdown rates ranged from 29.41% to 65.82%, with steel grit at 3.92%. The breakdown rate in the field increased from 13% to 60% (with the exception of steel grit which was reduced by 50%). The increase in breakdown rate is likely due to differences in hardness of the substrates being blast cleaned between the laboratory and field.

5) Percent Embedment – The embedment of the abrasive in the field was greater than the percentage of embedment in the laboratory for all of the abrasives except copper slag, which showed a reduction. The embedment in the laboratory ranged from 0.1% to 8.4%, with copper slag at 17%. The embedment in the field ranged from 1.6% to 16.6%. The increase in embedment in the field versus the laboratory ranged from 50% to 171%, except for staurolite at 1500%. The increase for staurolite is misleading because the amount of embedment in the field was only 1.6% which was the lowest level of embedment of all of the abrasives (the dramatic increase in percentage is because the embedment in the laboratory was essentially non-existent at 0.1%). The copper slag abrasive showed a reduction in embedment of 65% between the laboratory and field. Again, this is misleading because the laboratory embedment of the copper slag was substantially higher than all other abrasives at 17%, and the amount of embedment in the field at 11% was still higher than most of the abrasives. The trend for the increased embedment in the field is likely due to the pitted nature of the substrate being prepared which could be more conducive to the entrapment of abrasive particulate.

In summary, the field study showed a substantial increase in cleaning rate with the abrasives which is primarily due to the equipment adjustments that were made (larger blast nozzle size and uniquely adjusted abrasive metering valve). The consumption rates were also reduced. Although a larger nozzle size will utilize more abrasive per unit of time, the abrasive is used more efficiently by virtue of the larger blast pattern created by the increased nozzle orifice size. As a result, the amount of abrasive used per square foot decreases. Note that if the field study involved the blast cleaning of the same type of steel used in the laboratory (smooth mill scale bearing steel compared with heavily rusted and pitted steel), it is expected that the field cleaning rates would have shown an even greater increase, and the consumption rates a greater reduction. The surface profile created in the field was deeper than in the laboratory. This is more likely the result of the topography of the steel itself (heavily pitted steel) rather than the influence of the abrasive. If the field study utilized smooth steel, it is expected that the surface profile would have been comparable to that achieved in the laboratory. The breakdown rate of the abrasive as well as the amount of embedment were generally higher in the field. In both cases, it is believed that the rough, pitted steel substrate in the field, and possible differences in the hardness of the steel between the laboratory and the field have contributed to theses results.

TABLE 32 – ABRASIVE SUMMARY, PHASE1/PHASE 2 COMPARISON

Cost Comparison

The costs per square foot for the eight abrasives used in both the laboratory and field are presented in Table 33. The Phase 1 laboratory cost analysis was based on a hypothetical project using equipment similar to that employed in the study to blast clean steel plates in a walk-in blast room. The stringent controls utilized in the laboratory phase were included in the cost analysis (1/4 inch venturi blast nozzle, constant nozzle to work piece distance, 100 psi nozzle pressure, and fixed metering valve setting). It should be recognized that in actual blast room projects larger nozzle sizes would be selected and optimum adjustments of equipment would be made to maximize productivity. As a result, the cost per square foot in a walk-in blast room would be less than the costs derived from the study.

The field costs were based on the cleaning and consumption rates obtained during Phase 2. They are based on a hypothetical project involving 40,000 to 50,000 square feet of heavily pitted steel. The costs are substantially lower than the costs developed from the laboratory phase. Table 33 also presents the costs based on the Phase 2 field study when hazardous waste is generated (e.g., when lead-containing paint is being removed). The data revealed the following:

1) The laboratory costs ranged from \$1.35/square foot to \$1.97/square foot. The field costs were reduced in every case to a range from \$0.69/square foot to \$1.02/square foot (42% to 66% of the laboratory costs).

2) Steel grit (recycled 25 times) was the least expensive abrasive to use in the laboratory study at \$1.35/square foot. Copper slag (recycled two times), coal slag and silica sand (both used one time), showed comparable costs ranging from \$1.37/square foot to \$1.39/square foot. Staurolite was \$1.58/square foot. Silica sand with dust suppressant and nickel slag were comparable at \$1.70 and \$1.71/square foot. The most expensive abrasive in the laboratory study was garnet at \$1.97/square foot.

3) In the field study, coal slag was the least expensive abrasive at \$0.69/square foot with silica sand (with or without dust suppressant) comparable at \$0.71 and \$0.72/square foot. Copper slag (recycled 2 times) was \$0.82/square foot, with garnet (recycled 2 times) and steel grit (recycled 100 times) comparable at \$0.89/square foot. The most expensive abrasives were nickel slag at \$0.96/square foot and staurolite at \$1.02/square foot.

4) When the field cost scenario assumes that hazardous waste is generated, the Phase 2 field costs increase by 35% to 94% (with the exception of steel grit which only increased 2%), resulting in a cost ranging from \$0.91/square foot to \$1.67/square foot. In this case, steel grit (recycled 100 times) is the least expensive abrasive to use at \$0.91/square foot followed by copper slag (recycled 2 times) at \$1.15/square foot and garnet (recycled 2 times) at \$1.20/square foot. Coal slag is the least expensive of the expendable abrasives at \$1.25/square foot followed by silica sand with or without

dust suppressant at $1.37 and $1.38/square foot. The most expensive abrasives are staurolite at $1.65/square foot and nickel slag at $1.67/square foot.

The data show that even though the substrate in the field was much more difficult to clean by virtue of the extensive pitting, by increasing the nozzle size and making further adjustments to the metering valve, the efficiency of the abrasive increases and the costs are reduced by approximately 50%. The least expensive abrasive used in the shop was steel grit by virtue of its recyclability. In the field, the coal slag abrasive was the least costly to use followed by silica sand, and then the recyclable abrasives (copper slag, garnet, and steel grit). For field work when the generation of hazardous waste becomes an issue, the recyclable abrasives (steel grit, copper slag and garnet) become the least expensive, with steel grit demonstrating a considerable advantage in this area.

TABLE 33 – ABRASIVE CLEANING COST SUMMARY, PHASE 1 AND PHASE 2

Industrial Hygiene Data

Table 34 and Figures A to H present a comparison of the minimum, maximum, and geometric mean concentrations for 11 health-related agents for paired sets of abrasives. The results of the 8 abrasives run during the field study are compared to the same individual abrasive from the laboratory study. That is, products for the field study were purchased from the same source, according to the same product specifications. However, because the materials were purchased at different times, the product composition may not be identical.

Based upon 8 abrasives and 11 health-related agents, there are a total of 88 sets of paired data of geometric mean airborne concentrations. For these paired sets:

- 71 of 88 paired sets of data showed higher geometric mean concentrations of the health-related agents during the field study.

- Of the 17 paired sets of data showing lower geometric mean concentrations during the field study, 7 were from the copper slag abrasive and 7 were from steel grit. Coal slag had a lower concentration for one health-related agent and staurolite had a lower concentration for 2 health-related agents.

- The results for all 11 health-related agents were higher during the field study for nickel slag, silica sand with dust suppressant, garnet, and silica sand.

Several factors may have contributed to the trend for higher geometric mean concentrations during the field study than during the laboratory study. One possible source is the possible variation in the composition of the virgin abrasives, even though they were purchased from the same source. A comparison of the concentration of the 11 health-related agents in the virgin bulk abrasive for the laboratory and field materials follows on Table 35. While there are differences in concentrations between the laboratory and field materials, these differences do not correlate with the airborne concentrations. That is, the general trend for higher airborne concentrations during the Phase 2 field study do not necessarily correspond with an increase in the concentration of the health-related agent in the virgin bulk abrasive. In fact, in many instances, the concentration in the bulk material for the field study was the same (e.g., non-detectable) or less than the bulk material for the laboratory study.

Other factors that may have contributed to the trend for higher geometric mean concentrations during the field study include but are not limited to:

- The cross-sectional airflow through the containment was lower in the field study (average 40 feet per minute) than the laboratory study (50 to 75 feet per minute).

- A larger 7/16" nozzle was used in the field study versus the 1/4" nozzle for the laboratory study. Correspondingly, the metering valve setting would be changed.

- Because of the larger nozzle, more abrasive was used during each monitoring period.

The combination of increased volume of abrasive used per unit of time (because of the larger nozzle), in conjunction with the reduced cross-sectional airflow may have contributed to the generally higher geometric mean concentrations measured during the field study. Not withstanding this observation, the data clearly reflects the conservative nature of the laboratory results. That is, artificial constraints were placed upon the operating parameters during the laboratory study to improve the reproducibility of the data. Many of these constraints (e.g., nozzle size) were removed during the field study to more closely approximate actual work site conditions. In general, field conditions resulted in higher concentrations of the measured health-related agents.

TABLE 34 – COMPARISON OF AIRBORNE CONCENTRATION OF HEALTH-RELATED AGENTS FOR PAIRED ABRASIVES FROM THE LABORATORY (PHASE 1) AND FIELD (PHASE 2) STUDIES

Table 34

FIGURE A: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) COAL SLAG ABRASIVES

FIGURE B: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) NICKEL SLAG ABRASIVES

FIGURE C: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) STAUROLITE ABRASIVES

FIGURE D: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) SILICA SAND WITH DUST SUPPRESSANT ABRASIVES

FIGURE E: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) COPPER SLAG ABRASIVES

FIGURE F: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) GARNET ABRASIVES

FIGURE G: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) STEEL GRIT ABRASIVES

FIGURE H: GEOMETRIC MEAN AIRBORNE CONCENTRATIONS FOR PAIRED (LAB/FIELD) SILICA SAND ABRASIVES

TABLE 35 – CONCENTRATION OF HEALTH-RELATED AGENTS IN THE PAIRED (LAB/FIELD) VIRGIN BULK ABRASIVES

CONCLUSIONS

There was considerable variability in the results obtained with a given abrasive within each generic type. As a result, the attributes of each individual abrasive should be evaluated separately, rather than drawing conclusions based on a generic category as a whole. The conclusions below are based on a comparison of the attributes of the abrasive relative to silica sand.

Physical Property Data

Cleaning Rate

As a generic category, the cleaning rate for silica sand in the laboratory study averaged 31 square feet/hour. The average cleaning rates for all other generic abrasive types was higher than silica sand, ranging from 32 square feet/hour to 52 square feet/hour.

For the 8 individual abrasives tested both in the laboratory and field, silica sand had a higher laboratory cleaning rate (37 square feet/hour) than nickel slag (35 square feet/hour), silica sand with dust suppressant (34 square feet/hour) and garnet (34 square feet/hour). The remaining abrasives (coal slag, staurolite, copper slag, and steel grit) demonstrated higher cleaning rates. When the 8 abrasives were used in the field, silica sand (cleaning rate of 127 square feet/hour) was higher than nickel slag (104 square feet/hour), copper slag (102 square feet/hour) and steel grit (83 square feet/hour). The cleaning rates for the other abrasives were higher than silica sand.

Consumption Rate

The consumption rate of silica sand as a generic class in laboratory studies was 13.4 pounds/square foot which is higher than the other abrasives with the exception of nickel slag (14.17 pounds/square foot), copper slag with dust suppressant (15.09 pounds/square foot), copper slag (17.82 pounds/square foot) and steel grit (24.94 pounds/square foot).

For the 8 abrasives used in both the laboratory and field, in the laboratory study the silica sand abrasive (consumption rate 9.05 pounds/square foot) was only higher than garnet (7.43 pounds/square foot). All other abrasives showed higher consumption rates. When used in the field, the consumption rate of silica sand (8.5 pounds/square foot) was equivalent to copper slag, and higher than coal slag (7.2 pounds/square foot), garnet (8.0 pounds/square foot) and staurolite (8.1 pounds/square foot). The remaining abrasives demonstrated higher consumption rates.

Surface Profile

The surface profile generated by the silica sand abrasives as a class in the laboratory study averaged 3.4 mils. The profile was higher than the other abrasives with the exception of copper slag with dust suppressant (3.44 mils), copper slag (3.49 mils), and nickel slag (3.56 mils).

For the 8 abrasives used in both the laboratory and field, the laboratory surface profile for silica sand was 2.80 mils. Staurolite (2.02 mils) was the only abrasive with a lesser profile. Coal slag (2.80 mils) was comparable to silica sand, with the remaining abrasives creating a deeper profile. In the field, silica sand created a 4.3-mill surface profile. All other abrasives were comparable to or less than silica sand with the exception of copper slag (4.4 mils) and garnet (4.4 mils).

<u>Breakdown Rate</u>

The breakdown rate of silica sand as a generic category was 54.13% in the laboratory study. This was higher than the other abrasives with the exception of copper slag (54.49%) and copper slag with dust suppressant (64.91%).

For the 8 abrasives used in both the laboratory and the field, the breakdown rate for silica sand in the laboratory was 46.38%. This was higher than the other abrasives with the exception of copper slag (52.16%) and nickel slag (51.20%). In the field, the breakdown rate of the silica sand was 54.17%. Three other abrasives demonstrated higher breakdown rates: nickel slag (57.69%), coal slag (58.82%), and copper slag (65.82%).

<u>Embedment</u>

The percent embedment of silica sand as a category was 4.9%. Five other abrasive categories showed lesser embedment than silica sand: staurolite (0.2%), specular hematite (0.7%), silica sand with dust suppressant (1.6%), crushed glass (2.1%), and steel grit (2.8%).

For the 8 abrasives used in both the laboratory and field, the silica sand in the laboratory demonstrated 2.9% embedment. This was higher than four other abrasives: staurolite (0.1%), nickel slag (1.2%), silica sand with dust suppressant (1.2%), and garnet (2.1%). In the field, embedment of silica sand was 4.5%. This was higher than three other abrasives: staurolite (1.6%), silica sand with dust suppressant (1.8%), and nickel slag (2.7%).

<u>Microhardness</u>

The maximum microhardness was evaluated on the samples of abrasive purchased for the laboratory work only. Silica sand as a generic class showed an average microhardness of 2,469 Knoop units. This was harder than all other abrasives as a generic category, which ranged from 185 to 1,809 Knoop units (silica sand with dust suppressant was 2,008).

For the 8 abrasives used in both the laboratory and field, the silica sand abrasive in the laboratory measured 1,267 Knoop units. One abrasive (garnet) was harder at 1,285 Knoop units. The remaining abrasives ranged from 219 to 984 Knoop units.

Conductivity

Conductivity of the abrasives used for the laboratory study were evaluated. As a generic category the conductivity of silica sand was 147.0 microsiemens. Three abrasive categories demonstrated higher conductivities: staurolite (150.3 microsiemens), coal slag (176.9 microsiemens), and coal slag with dust suppressant (221.2 microsiemens). The remaining abrasive categories showed lower average conductivities ranging from 39.8 microsiemens to 116.1 microsiemens.

For the 8 abrasives selected for the laboratory and field study, the conductivity of the silica sand used in the laboratory was 66 microsiemens. Two other abrasives demonstrated higher conductivity: staurolite (87.3 microsiemens) and nickel slag (146.7 microsiemens). The remaining abrasives ranged from 9 to 47 microsiemens.

Costs

The costs for using the abrasives in the laboratory are reflective of the constraints placed on the tests. A small diameter nozzle was used (1/4 inch venturi). The nozzle pressure was fixed at 100 psi, the nozzle to work-piece distance was maintained at a constant 18 inches, and a pre-assigned abrasive metering valve setting was used. By adjusting the equipment and operator techniques to optimize productivity, the cost of use will decrease. Furthermore, the relative rankings in the costs between the abrasives may also change. The laboratory study also demonstrated that substantial differences in cost will occur based on the individual abrasive within a given generic abrasive type. As a result, cost analysis should be based on the attributes of the specific abrasive, rather than generalizing costs based on a given category.

For the field, the nozzle size was increased to a 7/16 inch venturi and the abrasive metering valve was adjusted based on the feel of the operator, and to obtain a full blast pattern. The other blast cleaning controls remained in place. The laboratory study involved the cleaning of new steel plates containing intact mill scale. The field study involved the blast cleaning of heavily pitted and rusted steel on the side of a barge. Again, by optimizing the equipment adjustments and operator techniques in the field, the absolute costs and relative cost differences between the various abrasives are likely to change.

For the laboratory study, the cost for using silica sand ranged from $1.39 to $2.52/square foot. No other individual abrasive was more costly to use than the most expensive silica sand.

When the laboratory data is examined by generic category (rather than by individual abrasive), the average cost for the silica sands evaluated was $1.82/square foot. Two other abrasive types were more costly to use: crushed glass at $2.06/square foot and specular hematite at $1.90/square foot. It should be noted however, that in both cases only a single abrasive was evaluated. The analysis of multiple abrasives within these categories may alter these results.

For the field study, the silica sand abrasive was $0.72/square foot. In this case, silica sand proved to be the least expensive abrasive to use (with the exception of silica sand treated with dust suppressant at $0.71/square foot). The remaining abrasives (coal slag, nickel slag, staurolite, copper slag, garnet and steel grit) were more costly at a range of $0.82 to $1.02/square foot.

When the field cost scenario is modified to assume that a hazardous waste is generated (e.g., lead containing paint is removed), silica sand is no longer the least costly. In this case, silica sand ($1.37/square foot) is only more cost-effective than silica sand with dust suppressant ($1.38/square foot), staurolite ($1.65/square foot) and nickel slag ($1.67/square foot). The remaining abrasives are less expensive to use with steel grit (recycled 100 times) the most cost effective at $0.91/square foot.

Industrial Hygiene Data

As indicated previously, there was considered variability in measured results for airborne concentrations of health-related agents among the individual abrasives within a generic category of abrasive. Therefore, conclusions relative to expected levels of these contaminants in airborne dust must take into account this inherent variability. To accomplish this, Table 36 presents the minimum, maximum, and geometric mean concentrations for each individual abrasive, as well as each generic category as a whole for Phase 1 laboratory data. Similar data for the Phase 2 field study was previously presented in Table 34. Table 37 provides a summary of the frequency wherein individual abrasives within each generic category had geometric mean concentrations above the geometric mean concentration for the silica sand generic category of abrasive, for each health-related agent, for both Phases 1 and 2. This data is used as the basis for the following conclusions.

Arsenic

All crushed glass, specular hematite, olivine and staurolite abrasives had geometric mean concentrations of arsenic that were less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Beryllium

All crushed glass, olivine, staurolite, specular hematite, and steel grit abrasives had geometric mean concentrations of beryllium that were less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Cadmium

Crushed glass and olivine abrasives had geometric mean concentrations of cadmium that were equal to or less than silica sand. The remaining generic categories of abrasives had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Chromium

Only specular hematite had a geometric mean concentration of chromium that was less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Lead

Olivine and specular hematite abrasives had geometric mean concentrations of lead that were less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Manganese

All of the generic categories of abrasives had one or more individual abrasives with geometric mean concentrations of manganese that were greater than silica sand.

Nickel

All crushed glass, staurolite, and specular hematite abrasives had geometric mean concentrations of nickel that were less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Quartz

All of the individual abrasives and generic categories had geometric mean concentrations of respirable quartz that were less than silica sand.

Silver

All crushed glass, nickel slag, olivine, staurolite, and specular hematite abrasives had geometric mean concentrations of silver that were equal to or less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Titanium

All crushed glass, olivine, specular hematite, and steel grit abrasives had geometric mean concentrations of titanium that were less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

Vanadium

All crushed glass, olivine, and specular hematite had geometric mean concentrations of vanadium that were less than silica sand. The remaining generic categories of abrasive had one or more individual abrasives with geometric mean concentrations greater than silica sand.

TABLE 36 – AIRBORNE CONCENTRATIONS OF HEALTH-RELATED AGENTS FOR INDIVIDUAL ABRASIVES AND GENERIC CATEGORIES

Table 36

Table 36

TABLE 37 – FRACTION OF INDIVIDUAL ABRASIVES WITHIN A GENERIC CATEGORY WITH GEOMETRIC MEAN CONCENTRATIONS GREATER THAN THE GEOMETRIC MEAN FOR THE SILICA SAND GENERIC CATEGORY OF ABRASIVES

RECOMMENDATIONS

A series of recommendations were submitted in both the Phase 1 laboratory study report and the Phase 2 field study report. In most instances, there was a similar basis and content to these recommendations. Therefore, it is not surprising that the recommendations resulting from this Phase 3 comparison report follow a similar theme. As a result, the principle recommendations that are germane to both Phase 1 and 2 are repeated below.

1. While no direct correlation can be established at this time, comparison of the relative concentration of health-related agents in the virgin abrasive, and assessment of the source of the raw materials and/or the manufacturing process, should be used as initial selection criteria for all of the abrasives and in particular for coal slag, nickel slag, copper slag, garnet, and steel grit abrasives.

2. Given the potential exposures to multiple contaminants from both the abrasive, as well as a painted steel surface, worker protection programs should be expanded to address all potential metals (e.g. as opposed to the current focus on worker lead protection programs). Perhaps a comprehensive vertical health standard for industrial maintenance painting operations addressing the use of abrasives, or classes of generic abrasives, should be developed. The standard would automatically invoke the necessary levels of protection and work practices without the need to uniquely evaluate each abrasive for all possible metals.

In addition to the fundamental recommendations described above, these studies identified the need for additional research. The recommended studies should be used to:

3. Investigate the relationship between the concentration of quartz in silica sand abrasives with airborne concentrations of other hazardous health-related agents, including an assessment of relative health risks.

4. Evaluate the potential for correlations between the concentration of health-related agents in all virgin abrasives, and the resulting airborne concentrations, for use as a selection criteria.

5. Conduct further evaluations of crushed glass, staurolite, specular hematite and olivine because this study evaluated only 1 supplier of each of these abrasives (note that staurolite and specular hematite are each provided from only one source).

6. Improve the quality of data regarding cleaning rate, consumption rate, and cost. The protocol should be modified to allow selection of blast nozzle size, meter valve setting, and nozzle pressure for each individual abrasive, set experimentally in conjunction with the suppliers. While such variations limit the strict reproducibility of the study and introduce subjective design criteria, these detractions will result in improved cleaning rate, consumption rate, and cost data.

7. It is recommended that additional field studies be conducted to collect information on other types of steel structures in order to expand the available database. Representative structures in the marine, water/wastewater, transportation, and industrial sectors should be included in these studies.