EVALUTION OF SUBSTITUTE MATERIALS FOR SILICA SAND IN ABRASIVE BLASTING

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DISCLAIMER:

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Project: Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting

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INTRODUCTION

For over 50 years, silica sand has been the traditional media used for abrasive blast cleaning and has become an integral component of surface preparation operations for the removal of paint, rust, mill scale and other debris from steel surfaces prior to application of protective coatings. As a blasting abrasive, silica sand is naturally occurring, readily available, economical to use, and effective. It is a relatively hard media and is available in a variety of screen sizes that are capable of providing an angular roughness in the steel substrate ranging from shallow to deep. The degree of surface cleaning and roughening provided by the abrasive media is critical to the long term corrosion protection afforded by industrial protective coatings. Silica sand has economically satisfied these attributes for many years.

Silica sand does have inherent limitations and disadvantages. Silica sand is an expendable abrasive, as the breakdown rate after one use is considerable. Also, the quantity of airborne dust generated is high. More importantly, silica sand commonly contains high concentrations of free (crystalline) silica, which poses a health hazard to improperly protected workers and potentially to the surrounding public if they are in close proximity to the area of exposure.

The National Institute for Occupational Safety and Health (NIOSH) has long recognized the adverse health effects of overexposure to free silica. The friable characteristic of silica sand during abrasive blast cleaning results in the generation of respirable airborne particulate which, if inhaled can become deposited in lung tissue and can lead to silicosis. Bridge authorities such as Ohio Turnpike Commission[1] and The Port Authority of New York and New Jersey[2] do not permit the use of silica sand for preparation of steel surfaces in their project specifications due to concerns over the safety of workers performing abrasive blasting.

As a result of these concerns, the Centers for Disease Control and Prevention (CDC) and the National Institute for Occupational Safety and Health (NIOSH) issued an Invitation for Proposal entitled, "Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting", dated June 9, 1995. Subsequently, 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 the alternative abrasives to silica sand.

Phase 1 involved a laboratory study, Phase 2 a field study, and Phase 3 a comparison of the data collected during Phases 1 and 2. This report addresses the data collected during the laboratory study (Phase 1) of the Contract.

Phase 1 was conducted at the KTA-Tator, Inc. Corporate Headquarters and laboratories, located at 115 Technology Drive, Pittsburgh, PA 15275. The blast cleaning portions of Phase 1 were conducted beginning April 10, 1996, and were completed on August 30, 1996. Upon completion of blast cleaning, airborne particulate and bulk abrasive samples were analyzed, data entered and evaluated, and the report prepared.

The objective of the study was to collect (in an environmentally-controlled laboratory) industrial hygiene airborne levels and bulk ingredient data for thirty health-related agents; and economic and technical data; and compare the alternative abrasives' results to silica sand's results. It is critical that worker exposures to airborne dust, free silica, and other toxic metals during abrasive blast cleaning be assessed on a controlled basis to ensure reproducible results. This study characterizes the emissions generated by the various abrasives, enabling sound, scientific conclusions to be drawn relating to exposure hazards. This study compares the total operating costs of silica sand to the total operating costs of the alternative abrasives for the environmentally-controlled laboratory conditions used in this study.

Specifically, the study entailed the collection of airborne particulate (total and respirable fractions) generated during open nozzle dry abrasive blast cleaning operations conducted on hot rolled, mill scale bearing carbon steel. Additionally, the study investigated the production characteristics of silica sand, silica sand treated with dust suppressant and 11 alternative abrasive materials for surface cleanliness (visual), cleaning and consumption rates, breakdown rates and recyclability characteristics, surface profile generation, abrasive particle embedment, and water soluble contamination.

A total of 40 blast cleaning abrasive materials (selected by NIOSH) were studied under Phase 1. Specifically, 13 generic categories of abrasives from suppliers and distributors located throughout the United States were studied. This report addresses the methodologies employed during data collection, and the results of the abrasive media production characteristics and the bulk abrasive and airborne sample data acquired under Phase 1.

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 protocol was used to evaluate 13 generic types of abrasives, including:

- 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

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. Each of the abrasives was evaluated for 7 performance-related characteristics, including:

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

Bulk samples of the 40 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 significant 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.

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, nozzle to work piece distance). 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, resulted in a cost reduction of nearly 60%.

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 substantially 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. This 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.

STUDY DESIGN AND TEST METHODS

Description

The study was performed in strict accordance with the NIOSH-approved Phase 1 Study Design/Protocol developed specifically for this project (copy attached as Appendix 1). The protocol provided controls and documentation forms for:

- Purchasing and receipt of the steel substrate test panel material,
- Solvent cleaning and random numbering of the test panel material,
- Collection of both bulk and freshly fractured abrasive samples for additional analysis by NIOSH. A total of 40 different abrasives were included in the study (refer to the Products and Materials section of this report for a listing of the specific abrasives),
- Selection of a single operator to conduct all of the trial runs,
- Consistent operation of all blast cleaning and ventilation equipment,
- Consistent blast cleaning technique and cleanliness (SSPC SP-10, Near White),[3]
- Consistent cleaning of all equipment and facilities to prevent cross-contamination between runs,
- Analysis of particle size distribution, abrasive break-down rates, cleaning rates, abrasive consumption rates, surface profile, embedment, hardness, and water soluble content,
- Recyclability analysis with a design limitation of a maximum of 25 recycles,
- Collection of samples for total airborne dust, respirable crystalline silica, respirable radiochemical activity, total airborne radiochemical activity, and total airborne elements. A total of 28 metals/elements, and respirable quartz and cristobalite were evaluated by KTA (refer to the Industrial Hygiene Sampling portion of this report for a listing of the elements analyzed, and for information on the number of samples collected, locations of the sampling media, the type of media used, and pump flow rates. The analysis of the filters was managed by NIOSH, using other testing laboratories.), and
- Developing total cost calculations.

Abrasive suppliers expressed concerns with certain aspects of the protocol involving the restrictions on nozzle size, nozzle to substrate distance, angle of blast, nozzle pressures, the use of a predetermined metering valve settings, and restrictions on the number of recycles in the case of steel grit. Letters received from the suppliers are attached as Appendix 2.

Products and Materials

Steel Substrate Test Surfaces

The study was performed on 3/16" thick mill scale bearing carbon steel plates (2' x 2'). The plates were initially prepared in accordance with SSPC-SP 1 "Solvent Cleaning"[4] and numbered sequentially. Nine panels were used for each abrasive trial resulting in a maximum surface area of 72 square feet available for abrasive blast cleaning.

The influence of an abrasive on the preparation of metal surfaces is highly dependent on the physical and mechanical properties of the metal. These properties include hardness, ductility, yield strength, and density. In the case of hot rolled carbon steel, the presence of mill scale also effects the performance of blast cleaning abrasives. One of the most critical objectives in the study was to collect airborne particulate for subsequent analyses. In order to make valid comparisons between the abrasive media, the variability in the type and quantity of the particulate generated had to be restricted to the media itself, not within the substrate being cleaned. Therefore, all steel panels were purchased from the same supplier. The supplier furnished certification that the steel was supplied from the same heat or melt of steel. The homogenous nature of the steel ensured that the chemical constituents of the steel were similar, if not identical. The panels were also chosen from the same mill rolling to ensure consistency in the thickness and characteristics of the mill scale (see Appendix 3). The iron (97.3%), manganese (.96%), copper (0.01%), chromium (0.01%), nickel (0.01%), phosphorous (0.006%), molybdenum (0.004%), and vanadium (0.004%) content in these steel plates may influence the results of these same elements when analyzed for airborne concentrations. The above steps reduced to a minimum any variation that might be introduced to the testing process due to the substrate material. To further ensure homogeneity of the steel material, 10 randomly chosen sample panels were submitted to NIOSH for metallurgical evaluation, if needed.

Abrasive Selection

The study involved 40 different abrasives representing 13 generic types. While the abrasives selected for the evaluation represent a broad range of the types of products used for blast cleaning, all possible generic types were not evaluated. Further, additional products within a given generic category are also available. As a result, the results of the study should not be construed to represent all abrasive blast cleaning media.

All products were commercially available materials. Abrasives reported by the suppliers as typically being used more than one time to prepare steel surfaces for painting were classified as recyclable. All other abrasives were classified as expendable. One exception involves the specular hematite (crystalline iron oxide) which may be classified as a recyclable abrasive, but was treated as an expendable abrasive in this study. The abrasives containing dust suppressant had already been treated prior to purchase. The generic types of abrasive, the alpha code assigned to each type, and the number of individual products evaluated under each type are 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

Relatively large variations can exist within the same generic abrasive type with regard to factors such as productivity, consumption rate, breakdown rate, dust generation, embedment, and water soluble contamination. Variations can stem from the geographic locations where the material is mined or produced, in addition to differences in manufacturing, processing, and material handling techniques. Not only do products vary between manufacturers, but products provided by the same manufacturers can also exhibit differences. Because of these variations, several abrasives within each generic category were typically obtained from suppliers in different geographic regions. Exceptions include specular hematite, staurolite, and olivine. Since the number of companies supplying these abrasives is limited, only one of each type was evaluated. In addition, only one crushed glass abrasive and one copper slag treated with dust suppressant were utilized due to limitations in the size of the project.

The nominal size of the abrasive media can effect productivity, consumption rate, and resulting surface profile. Therefore, abrasive suppliers were requested to provide materials in a nominal mesh size to achieve a surface profile of 2 to 3 mils based on information provided to them regarding the blast cleaning equipment (1/4” nozzle) and operating conditions (100 psi nozzle pressure) that would be employed. The suppliers were also asked to provide the abrasive metering valve setting for their product and to express any concerns they had with the test protocol which was discussed with them in advance. A copy of the standard letter formally requesting the participation of the abrasive suppliers is attached as Appendix 4.

Blast Cleaning Equipment and Facilities

The blast cleaning facility at the KTA corporate offices in Pittsburgh, Pennsylvania was used to conduct all abrasive blast cleaning trials. Throughout all abrasive trials, variability of the blast cleaning environment was controlled by using the same blast room and abrasive blast cleaning equipment. A diagram of this facility is provided in Appendix 8 and photographs of the facility and equipment employed are provided in Appendix E. The equipment utilized for the study included:

- A clean, enclosed, illuminated 12' by 8' by 8' high walk-in blast room equipped with a 5800 cubic feet per minute (cfm) Torit-Donaldson dust collection system. Airflow through the blast room was controlled at 50 to 75 feet per minute average crossdraft for each trial run, measured using an Alnor Model RV rotating vane anemometer.

- A Clemco 6 cubic feet gravity feed abrasive hopper fitted with a specially designed abrasive metering valve. The metering valve plate designed by KTA utilized five fixed settings ranging from 1/4" to 1/2" in 1/16" increments. This allowed for the use of a precise valve setting for each trial run. Each abrasive supplier was asked to recommend the orifice for their product and mesh size. If the supplier did not furnish this information, the 1/2" size was used.

- A 170 cfm Atlas Copco air compressor. The compressed air line was equipped with moisture and oil separators. Prior to each abrasive trial, the supplied air was evaluated for moisture and oil in accordance with ASTM D4285, Standard Test Method for Indicating Oil or Water in Compressed Air.[5] No moisture, oil, or other visible contamination was detected during any of the blotter tests.

- Two 15 foot lengths of reinforced air/abrasive hose (7/8" inside diameter), and two Boride brand No. 4 (1/4 inch orifice size) venturi blast nozzles. After each abrasive trial, the blast hoses were flushed, washed inside and out with potable water, then dried with compressed air before the next trial. The use of two hose/nozzle assemblies allowed sufficient drying time of the washed hoses between trials.

- A Clemco nozzle orifice gage. The gage was used to monitor the nozzle orifice size prior to each abrasive blasting trial. Both nozzles maintained the 1/4"orifice size throughout the laboratory study, and neither nozzle showed signs of uneven wear. The 1/4" nozzle was selected for the Phase 1 laboratory study to obtain enough blast cleaning time during each trial to obtain accurate exposure monitoring data. While the use of a larger nozzle would have substantially increased productivity, the reduced operating time would have provided inadequate sampling time for the industrial hygiene data.

- A Clemtex Model 352-02 hypodermic needle pressure gage. The gage was used to measure the blasting pressure at the nozzle prior to each abrasive trial. The pressure was maintained at 100 pounds per square inch (psi) throughout the abrasive study. A fixed pressure of 100 psi was selected in order to minimize the number of variables involved with the collection of the data, in an effort to enhance the reproducibility of the test methods.

- A Dickson Model THDX 24 hour recording hygrometer for continuous monitoring of relative humidity and dew point, and an Atkins Model 33035-F digital thermocouple for monitoring the surface temperature of the steel panels. Barometric pressure was also documented. A sample Blast Cleaning Inspection Report is attached as Appendix 5. The completed reports are provided separately from this report.

- A Lunardini Vac-U-Claimer, an abrasive media vacuuming reclaiming system. The equipment was used to clean the interior surfaces of the blast room after each trial. After thorough vacuuming and cleaning, industrial hygiene personnel inspected the room in accordance with the procedures described later in this section.

  For trials involving abrasive recycling, the adjustable air curtain feature of the reclamation system was used to separate abrasive fines from larger, re-usable abrasive particles. A summary of blast room environmental data and ventilation velocity for each trial is summarized in Appendix 8.

Blast Operator Selection

The use of an "automated blast cleaner" for the Phase 1 study was considered in order to reduce the potential risk to human subjects and to reduce the variability between abrasive trials. However, it was concluded that although robotics could be designed for the laboratory study, it would not be representative of the manner in which the majority of blast cleaning operations are conducted in industry, nor is it representative of the nature of operations in the field. In addition, the Phase 2 study (field study) must be performed using human operators to assess exposures when cleaning under field conditions to properly assess productivity and effectiveness. The blast cleaning effort required to achieve the desired level of cleanliness in the field will vary from one point on a structure to the next. The human operator can immediately react to this difference, while a machine will not. Other variables such as operator visibility and its influence on productivity will not be appropriately recognized when using robotics. Finally, for Phase 3 (comparison of Phases 1 and 2) to be meaningful, Phases 1 and 2 need to be conducted in a similar manner, so that appropriate comparisons can be made. In order to gain meaningful data in Phases 1 and 2, it was essential that human operators be used for all phases of the study.

It is recognized that variability exists between human operators. In an effort to reduce the variability between individual operators and within a single operator (and thus increase the validity of both the production related and health related test results), a study was conducted to evaluate several operators in order to select one operator for the project.

Five abrasive blasting operators were evaluated. Each operator performed five abrasive blasting trials in accordance with the Phase 1 study design and protocol. Operators were randomly scheduled for these trials, and operators were not informed of the schedule. This was done to help ensure that the operators could not prepare (i.e., get more or less rest the previous day), and so that the operators' attitudes concerning their work would not be reflected in the results (i.e., operator having a good or bad day). The abrasive media used for the operator variability study was a coal slag abrasive of the same nominal size from one supplier to ensure that any variation in the results would be attributed to operator technique. Area and worker exposure monitoring data as well as abrasive and steel samples were collected during the operator variability study.

The operators were ranked from least to greatest variation in results for the following four attributes:

1. Total Abrasive Blasting Time (seconds)
2. Amount of Surface Area Cleaned (square feet)
3. Rate of Abrasive Consumption (pounds per square foot)
4. Abrasive Cleaning Rate (square feet per minute)

The objective was to select the operator who displayed the least variation across all four attributes combined. All attributes were given an equal weighting for the analysis. It should be noted that a demonstration of least variability in a given attribute does not always correlate with the most desirable performance characteristic. For example, the operator showing least variability in cleaning rate (productivity) may not be the most productive cleaner.

The test results for each of the above attributes are shown in the tables that follow:

TABLE 1
OPERATOR VARIABILITY STUDY – TOTAL BLAST CLEANING TIME (SECONDS)

Operator Number	1	2	3	4	5
Trial 1	4121	3365	2619	5325	3270
Trial 2	3592	3922	3583	3722	4754
Trial 3	4220	4590	3969	4328	4573
Trial 4	4545	5016	3699	4354	4577
Trial 5	4266	4844	4364	4330	4928
Average	4148.8	4347.4	3646.8	4411.8	4420.4
Standard Deviation	348.8	688.9	648.3	575.9	659.6
Ranking	1	5	3	2	4

TABLE 2
OPERATOR VARIABILITY STUDY – SURFACE AREA CLEANED (SQUARE FEET)

Operator Number	1	2	3	4	5
Trial 1	46.80	44.10	42.30	56.20	45.17
Trial 2	44.00	48.73	52.40	48.90	44.30
Trial 3	56.30	42.83	45.70	47.30	37.30
Trial 4	48.00	45.75	45.70	50.10	38.70
Trial 5	44.60	38.50	60.00	39.70	38.50
Average	47.94	43.98	49.22	48.44	40.79
Standard Deviation	4.95	3.78	7.05	5.93	3.65
Ranking	3	2	5	4	1

TABLE 3
OPERATOR VARIABILITY STUDY – CONSUMPTION RATE (POUNDS PER SQUARE FOOT)

Operator Number	1	2	3	4	5
Trial 1	10.60	11.25	11.73	8.83	10.18
Trial 2	11.27	10.18	9.47	10.14	12.83
Trial 3	8.81	11.58	10.85	10.49	13.30
Trial 4	10.33	10.84	10.85	9.90	11.20
Trial 5	11.12	12.88	8.27	12.49	10.98
Average	10.43	11.35	10.23	10.37	11.70
Standard Deviation	0.98	1.00	1.36	1.34	1.31
Ranking	1	2	5	4	3

TABLE 4
OPERATOR VARIABILITY STUDY – CLEANING RATE (SQUARE FEET PER MINUTE)

Operator Number	1	2	3	4	5
Trial 1	0.680	0.670	0.970	0.630	0.710
Trial 2	0.730	0.640	0.880	0.790	0.490
Trial 3	0.800	0.510	0.690	0.660	0.490
Trial 4	0.630	0.570	0.740	0.690	0.580
Trial 5	0.630	0.530	0.820	0.550	0.550
Average	0.694	0.584	0.820	0.664	0.564
Standard Deviation	0.072	0.069	0.111	0.088	0.090
Ranking	2	1	5	3	4

The results of the operator variability study were statistically analyzed for each abrasive trial to determine the arithmetic mean, and the standard deviation from that mean for each operator. The operators were given a ranking from 1 to 5 in each production category, with a ranking of 1 representing the least variation, and a 5 representing the most variation. Since the variance of any data set is equal to the standard deviation value squared, the variability each operator exhibited could be determined on the basis of standard deviation alone. The results of these rankings were summed to give each operator a "score". The following table illustrates the rankings and scores assigned to each operator.

TABLE 5
OPERATOR VARIABILITY STUDY – COMPOSITE RANKINGS PER OPERATOR

Operator Number	Total Blast Cleaning Time	Square Feet Cleaned	Consumption Rate	Cleaning Rate	**SCORE**
1	1	3	1	2	**7**
2	5	2	2	1	**10**
3	3	5	5	5	**18**
4	2	4	4	3	**13**
5	4	1	3	4	**12**

The results shown in the above table reveal only minor differences in the deviation between operator number 1 and operator number 2 for both consumption rate and cleaning rate. To further ensure that the most consistent operator for all four parameters was selected for use during the study, the analysis was performed using only four abrasive trials, with the value furthest from the mean eliminated from the data. The following table illustrates this approach:

TABLE 6
OPERATOR VARIABILITY STUDY – COMPOSITE RANKINGS BASED ON FOUR BEST TRIALS*
*(values furthest from the mean were eliminated)

Operator Number	Total Blast Cleaning Time	Square Feet Cleaned	Consumption Rate	Cleaning Rate	**SCORE**
1	3	1	1	2	7
2	4	2	2	3	11
3	2	5	5	5	17
4	5	4	3	4	16
5	1	3	4	1	9

Based on the results of the statistical analysis, Operator Number 1 was chosen for the Phase 1 abrasive blast cleaning study. NIOSH was in full agreement with the selection of the operator.

Abrasive Media Test Methods

A series of test methods was used to control the abrasive blast cleaning process and to evaluate the physical characteristics and performance of the abrasives. Each method is described below:

Blast Cleaning Procedure and Process Control Checks

Nine 3/16" x 2' x 2' mill scale bearing panels were used for each trial. The panels were mounted in a specially designed rotary holder which accommodated three sets of three panels each. This enabled the operator to abrasive blast clean both sides of the nine panels at a working height of 3 feet to 5 feet, for a total available surface area of 72 square feet. The operator blast cleaned one set of three panel faces then rotated the mounting fixture to expose the next group of three faces and resumed blast cleaning. After the last series of three panels was cleaned, the fixture was rotated 180 degrees to expose the back sides of the panels and the cleaning resumed.

The distance that the blast nozzle was held from the steel plates was maintained at a constant 18 inches for all abrasive blasting. This was accomplished through the use of a small rod attached to the blast hose that extended to the wall behind the operator. The operator kept the blast nozzle perpendicular to the steel substrate at all times. This was done to provide the maximum amount of abrasive ricochet, simulating a worst case airborne dust condition. All cleaning was performed to SSPC-SP 10 "Near-White Metal Blast Cleaning[3]" or better.

In order to improve the validity of the test results and the repeatability of the abrasive blast cleaning process, statistical process control measures were implemented throughout the entire project. Five randomly scheduled process checks were used. The process checks using a blind control abrasive were conducted following the exact testing protocols used for the actual abrasive trials. The same abrasive material (coal slag) used for the operator variability study was used for the process control checks. This allowed for a comparison of the process control check data with the same data produced by the same operator during the operator variability study. Control charts were established using the data from the five abrasive trials conducted by the operator (operator No. 1) during the operator variability study. Separate control charts were developed for the following process characteristics: cleaning rate, abrasive consumption rate, amount of surface area cleaned, and the elapsed trial time. As agreed upon with NIOSH, the upper control limit (UCL) and lower control limit (LCL) used for the control charts were set at +/- three standard deviations from the mean of the results for the initial five abrasive trials conducted for the operator variability study. The results for the selected operator (Operator 1) from the operator variability study are summarized in the table below for convenience.

TABLE 7
TEST RESULTS OBTAINED BY OPERATOR NO. 1 DURING OPERATOR VARIABILITY STUDY

	Trial Time (seconds)	Surface Area (square feet)	Consumption Rate (pounds/square foot)	Cleaning Rate (square feet/minute)
Trial 1	4121	46.80	10.60	0.680
Trial 2	3592	44.00	11.27	0.730
Trial 3	4220	56.30	8.81	0.800
Trial 4	4545	48.00	10.33	0.630
Trial 5	4266	44.60	11.12	0.630
Mean	4148.8	47.94	10.43	0.694
Standard Deviation	348.8	4.95	0.98	0.072

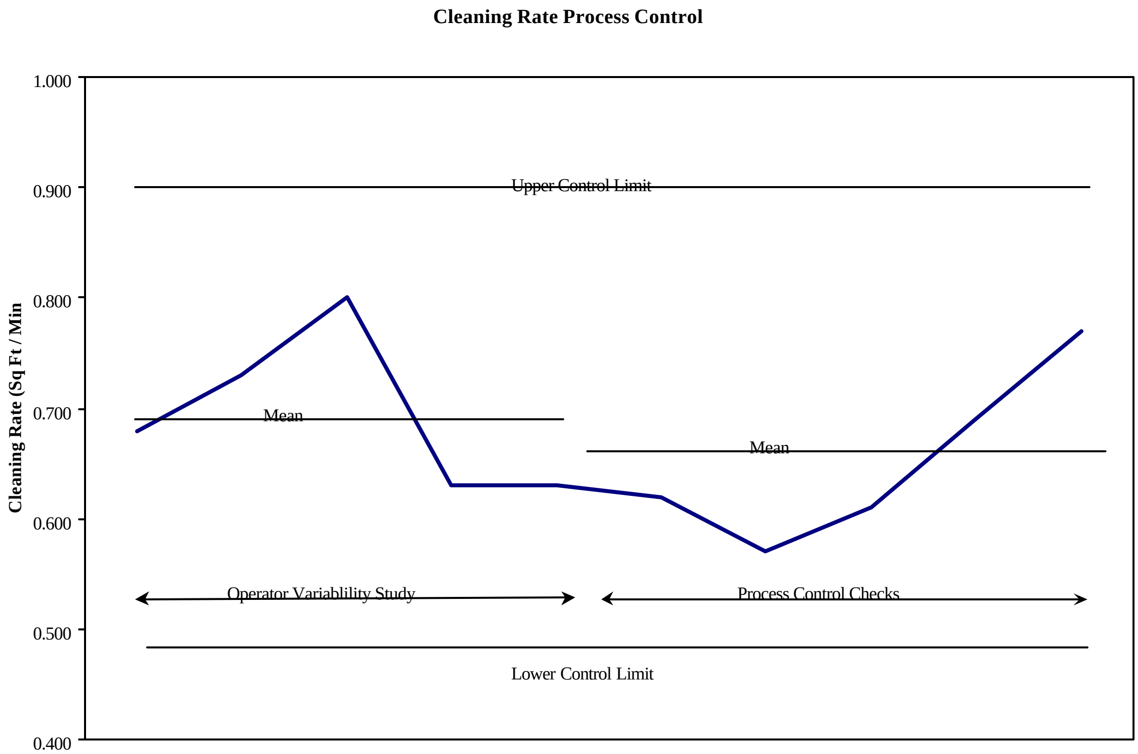
The results for each of the same attributes for the process control checks conducted during the actual study are summarized in the following table:

TABLE 8
TEST RESULTS OBTAINED BY OPERATOR NO. 1 DURING THE PROCESS CONTROL CHECKS

	Trial Time (seconds)	Surface Area (square feet)	Consumption Rate (pounds/square foot)	Cleaning Rate (square feet/minute)
Process Check 1	4824	49.80	9.92	0.620
Process Check 2	4722	45.10	11.09	0.570
Process Check 3	4110	41.50	12.05	0.610
Process Check 4	4692	54.30	9.12	0.690
Process Check 5	3888	50.00	10.00	0.770
Mean	4447.2	48.14	10.44	0.652
Standard Deviation	419.5	4.94	1.14	0.079

The control chart for blast cleaning rate is shown on the next page. The left half of the control chart shows the cleaning rate values obtained by the operator during the operator variability study. The right half of the control chart illustrates the cleaning rate values obtained during the five process control checks. Throughout the five process control checks, no values were found higher than the upper control limit or less than the lower control limit. This is true for all of the production categories (the control charts for trial time, surface area, and consumption rate are attached as Appendix 6. The control chart for cleaning rate shown below is also repeated in Appendix 6 for convenience). The data also did not reveal any trends that would indicate that the process was approaching a loss of control. Statistical analysis showing mean, standard error, median, mode, standard deviation, variance, kurtosis, skewness, range, minimum, maximum, and 95% confidence level for each production related attribute for the process checks is also attached as Appendix 6.

TABLE 9
PROCESS CONTROL CHART FOR CLEANING RATE



Cleaning Rate

Abrasive cleaning rate was calculated from the measured amount of area blast cleaned divided by the total elapsed time of the abrasive trial (square feet per hour). The surface cleanliness of each panel was verified using SSPC VIS1-89[6] pictorial standards. The abrasive trial time was defined as the amount of time to clean both sides of all 9 panels (72 square feet of surface area) or to clean as much of the panel surfaces as possible until all of the abrasive media had discharged from the abrasive hopper. The time was measured to the nearest second using a digital stopwatch. The total amount of time required to rotate the panels was typically 45 seconds. This time was not deducted from the totals. Since a small blast nozzle (No. 4) was used, cleaning rates, as expected, were much less than rates obtained during normal field abrasive blast cleaning operations. A smaller nozzle was intentionally used in order to obtain enough blast cleaning time for the collection of the industrial hygiene samples that were required.

Consumption Rate

A measured (weighed) amount of abrasive media was loaded into the abrasive blast pot for each abrasive trial. The abrasives were stored in a climate controlled shop prior to use to minimize differences that residual moisture may have on the weight. The initial weight of abrasive media varied due to differences in the bulk density of the types of abrasive, but a sufficient quantity of media was loaded to permit a continuous 30 to 40 minute blast sequence or to clean all surfaces of the steel panels, whichever occurred first. In the event that the entire amount of abrasive was not discharged during the abrasive trial (i.e. the entire 72 square feet of steel surface was blast cleaned without depleting the supply), the abrasive remaining in the hopper and blast hose was collected and weighed. The amount of abrasive consumed during each trial was calculated by deducting this amount from the initial amount loaded. The abrasive consumption rate was calculated as the weight of abrasive used during the trial divided by the measured surface area prepared (pounds per square feet).

As indicated above, the use of a 1/4" nozzle effected productivity. The small nozzle, together with the use of pre-established abrasive metering valve settings, also effected abrasive consumption rates.

Surface Profile

The surface profile resulting from each abrasive trial was measured in accordance with Method C of ASTM D4417-93 "Standard Test Method for Field Measurement of Surface Profile of Blast Cleaned Steel.[7]" Coarse and X-Coarse Testex replica tape and a spring micrometer were used. Two surface profile measurements were obtained on one side of three of the nine test panels (resulting in a total of 6 profile readings) for each abrasive run.

The nine panels used for each abrasive trial were assigned a number from one to nine. A computer-generated table of random numbers (numbers from one to nine in random order) was used to select specific panels for surface profile measurements. Surface profile measurements were obtained on the first three panels identified by the random number table. In the event the selected panel had not been completely blast cleaned, the random numbers were accessed in order, until three blast cleaned panels were selected. The side of the panel to be measured consistently alternated from front to back starting with the front side for the first abrasive run. That is, the measurements for the first abrasive run were taken on the front side of the first panel selected, back side of the second panel, and the front side of the third panel. The sequence continued for the measurements for the second run (i.e., starting with the back side of the first panel selected). A permanent identification number stamped into the steel designated the front side of the panel.

Abrasive Particle Size Distribution

A one hundred pound sample of each abrasive, as received from the supplier or distributor, was riffled three times to ensure a homogeneous mixture of abrasive particle sizes. A one hundred gram sample of this virgin abrasive was removed from the homogeneous mix and analyzed for particle size distribution in accordance with ASTM C136 "Standard Test Method for Sieve or Screen Analysis of Fine and Coarse Aggregates.[8]" The abrasive sample was tamped and shaken through a series of sieves for seven minutes. The sieve sizes used were 10, 12, 16, 20, 30, 40, 50, 60, 70, 100, 140, 200, 270, with a pan at the bottom. An electric Ro-Tap Model B aggregate shaker was used.

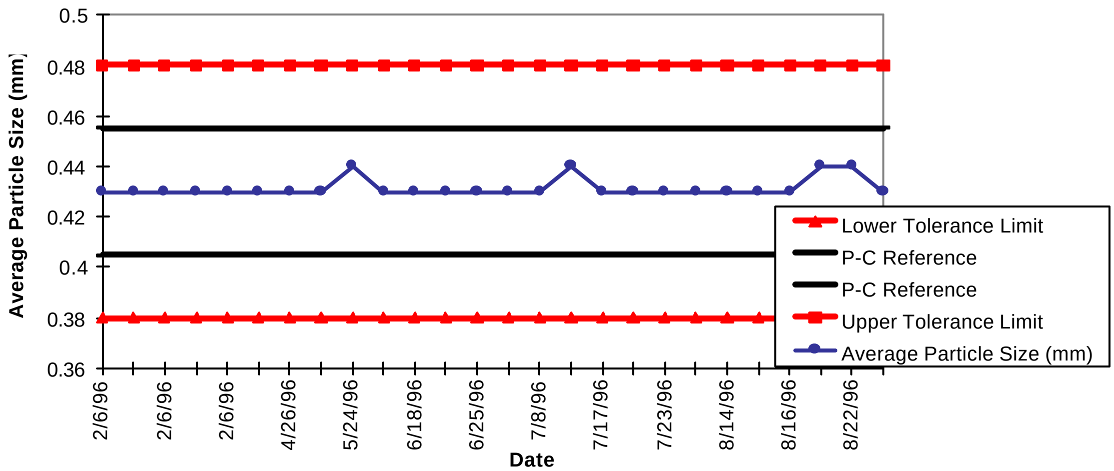
The abrasive retained on each screen was emptied into numbered and tarred sample cups. The underside of each screen was cleaned with a brass brush to loosen trapped particulate, and the particulate was added to the appropriate sample cups. The content of each sample cup was weighed to the nearest tenth of a gram and documented. This value (weight of particles retained on each screen) was multiplied by the screen size opening (in millimeters). These numbers were summed and divided by the cumulative weight of the sample to establish an average particle size for each lot of abrasive. The average value represents the size, above which and below which, approximately 50 % of the mass of the abrasive is found.

A statistical process control was used to ensure repeatability and validity of the sieve analysis portion of the abrasive testing. Since the screens used for sieve analysis are constructed of fine wires with very close tolerance spacing, it was critical to verify that the screen size openings were not affected by repeated use. Three 100 gram samples were drawn from the same riffled mixture of one of the abrasives at the beginning of the project. The samples were sieved five times to develop a control capability analysis for each sample. Sample A had an average particle size of 0.43 mm with no variation. Sample B had an average particle size ranging from 0.41mm to 0.42 mm, and Sample C was 0.42 with no variation.

After the first 15 analyses were performed, Sample A was sieved using the identical process. After sieving, the abrasive was collected in a sealed container and reintroduced into the process after the next 15 analyses were completed. These checks continued throughout the entire project. As indicated above, the results of the initial five sieve analyses of control Sample A were an average particle size of 0.43 mm with no variation. During approximately 370 individual sieve analyses performed during this study, the variation in average particle size of control Sample A was 0.01 mm. This is displayed in the control chart shown in Table 10 following this paragraph. Sample B was introduced after 75 and 150 analysis had been completed. In both cases, the average particle size was 0.42 mm, which was consistent with the initial five analyses that ranged from 0.41 mm to 0.42 mm. Sample B was also retained for additional use in the event two replicates of Sample A displayed non-conformance, but this never occurred. Sample C was used to ensure control at the completion of the testing. At the completion of testing, the analysis of Sample C showed an average particle size of 0.42 mm which is identical to its initial value.

The following figure displays a control chart for the first sieve control sample (Sample A).

TABLE 10
SIEVE ANALYSIS PRE-CONTROL CHART



The lines labeled P-C Reference are used in Pre-Control theory to indicate loss of control is approaching and adjustments to the process should be made. Based on the results obtained, it is evident that the screens used during sieve analysis displayed highly consistent measurements.

Abrasive Breakdown Rate

At the completion of each abrasive run, a one hundred pound sample of the spent abrasive was collected from several areas of the enclosed blast room floor and riffled three times to obtain a homogeneous mixture. A 100 gram sample was removed and analyzed for particle size distribution using the identical process as described in the section entitled "Abrasive Particle Size Distribution". The amount of abrasive breakdown was determined by comparing the average particle size of the pre-blast (virgin) abrasive to the average particle size of the post-blast abrasive. The abrasive breakdown rate was calculated and is reported as the percentage change in average particle size.

Abrasive Embedment

Abrasive embedment is defined as the percentage of abrasive particles that remain affixed to the prepared substrate and cannot be removed by cleaning with a stiff bristle brush or a focused stream of compressed air. The amount of abrasive embedment was evaluated on the same three panels selected for the surface profile measurements. A 12.7 mm (1/2") x 12.7 mm (1/2") piece of transparent mylar with a printed grid of 100 squares (each 1.3 mm x 1.3 mm in size) was placed on the surface and viewed through a 10X illuminated magnifier to make the determination. Each of the 100 squares was evaluated for the presence of embedded abrasive particles. In the event an embedded particle fell between two or more squares, only one of the squares was counted. The number of squares containing one or more embedded particles was summed to determine the number of squares out of 100 that exhibited embedded abrasive particles. This number was reported as a percentage. Five locations were evaluated on each panel. The locations were selected by dropping the mylar grid onto the panel surface from a distance of approximately one foot, and making the assessment at the point where the grid came to rest on the surface.

Abrasive Recyclablity Evaluation

Abrasives reported by the suppliers as typically being used more than one time to prepare steel surfaces for painting were evaluated for recyclablity. An initial run with each abrasive was made to determine cleaning rate, consumption rate, surface profile, particle size, embedment and relative industrial hygiene health-related agent levels. The spent abrasive was collected, weighed, and returned to the abrasive hopper. Without the use of an operator, the abrasive was impinged on a clean steel plate within a specially designed blast reclamation chamber. An illustration of this blast chamber is attached as Appendix 7 and photograph number 13 in Appendix E. The larger (thus heavier) particles of abrasive settled in the base of the chamber and fine particles were collected in the dust bag. The weight of both the settled material and the fine material captured in the dust bag was recorded after each trial run. In addition, samples of the settled abrasive were sieved to determine the particle size distribution. The material at the base of the chamber was then vacuumed, reclaimed and classified using the Lunardini air curtain classifier. The reclaimed abrasive was weighed prior to returning it to the blast pot for reuse, and a sample of the reclaimed abrasive was also sieved. All of the above information is recorded in the Blast Cleaning Reclaim report. A sample report is attached as Appendix 5. The completed reports are provided separately from this report.

This recycling process was repeated until the change in average particle size of the spent abrasive at the bottom of the blast chamber exceeded 50%, or for a maximum of 25 recycles for the steel grit abrasives, or 5 recycles for the copper slag and garnet abrasives. The limitation on the maximum number of recycles was established in advance for testing purposes. It is acknowledged that recyclable abrasives such as steel grit can be productively recycled many fold over the test design maximum. At the completion of the resulting number of recycles, the abrasive media was returned to the abrasive hopper for a final blast cleaning run using the blast operator and nine steel panels. The attributes of abrasive cleaning rate, consumption rate, surface profile, particle size, and embedment and relative industrial hygiene health-related levels were again evaluated for the final run.

Abrasive Bulk and Substrate Samples

One pound bulk samples of both pre-blast (virgin) abrasive material and post-blast abrasive material were obtained for each abrasive trial and submitted to NIOSH for analysis. Homogeneous pre-blast samples were collected as described above in the section entitled “Abrasive Particle Size Distribution.” Homogeneous post-blast samples were collected as described in the section entitled “Abrasive Breakdown Rate.”

One, 4"x 4" sample of the blast cleaned substrate from each abrasive trial was dry cut from one of the nine panels prepared in each trial. The panel selected and the sample location was determined using a computer-generated table of random numbers. The samples were sealed in plastic bags for future analysis if deemed essential by KTA or NIOSH in the future.

Abrasive Microhardness

The relative hardness of an abrasive can effect several production related characteristics including cleaning rate, consumption rate, and breakdown rate, and may also effect the amount of dust produced by an abrasive. Samples of each abrasive were removed from the riffled homogeneous mixture of pre-blast (virgin) abrasive and analyzed to determine the hardness of the abrasive particles in accordance with ASTM E384 "Standard Test Method for Microhardness of Materials"[9]. Results are reported in units of Knoop microhardness. Hardness increases as the Knoop number increases. 500 Knoop is approximately 6 on the Mohs hardness scale. Industrial Testing Laboratory Services Corporation in Pittsburgh, Pennsylvania performed the abrasive hardness testing.

Water Soluble Contaminants

Water soluble contaminants residing in abrasives in sufficient concentrations can be transferred to the substrate during cleaning, leading to reduced coating system performance. Conductivity analysis provides a means for determining whether water soluble materials are present in an abrasive. Conductivity assessments were performed on samples of the riffled pre-blast (virgin) abrasive in accordance with ASTM D4940 "Standard Test Method of Conductimetric Analysis of Soluble Ionic Contamination of Blasting Abrasives"[10]. This analysis involves combining approximately 300 milliliters of deionized water with 300 milligrams of the abrasive, and agitating the mixture for approximately one minute. The sample remains undisturbed for eight minutes, and is agitated again for approximately one minute. The sample is then filtered and the liquid portion is tested using a conductivity bridge. An Altex Model RC16C conductivity bridge was used for this analysis.

Industrial Hygiene Sampling

A proposed exposure monitoring protocol was developed to ensure collection of adequate data on airborne total dust levels of 28 metals/elements, and respirable quartz and cristobalite. The specific analytes included:

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

The protocol was also designed to ensure the reproducibility of the test methods and to prevent cross-contamination from abrasive media. The elements of the approved assessment protocol included:

- Protection of Human Subjects
- Sample Collection Methodology and Filter Media Positioning
- Calibration of Sampling Pumps
- Background Monitoring
- Preparation of Test Facilities
- Sample Collection During Abrasive Trials
- Post Sample Collection Procedure

A trial run was conducted over a two day period prior to the start of the actual study. The trial run was used to determine the optimum sampling duration necessary to obtain quantifiable data without overloading filters. The final test protocol was modified as necessary, based upon the results of the trial run.

Protection of Human Subjects

Protection of human subjects (e.g. blasters, laborers, quality control personnel) was monitored throughout the study. Prior to initiation of the operator variability study, assigned project personnel were trained in the health effects of arsenic, cadmium, chromium, copper, iron, lead, nickel, silica, and zinc. Proper use of personal protective equipment, respiratory protection, and decontamination procedures were also reviewed. Finally, a medical surveillance program was initiated to help ensure that project personnel were adequately protected during the study. Medical surveillance consisted of: blood lead and zinc protoporphyrn (ZPP) levels; cadmium in blood and in urine (grams of creatinine and beta-2 microglobulin); spirometry testing (FEV and FVC); blood chemistry profile; and complete blood count with differential. Pre- and post-project medical surveillance testing was performed by Health-on-Site of Youngstown, Ohio.

Personal protective equipment utilized by the blaster(s) included a Bullard Model 77 Type CE supplied air helmet (APF of 1000) with Grade D breathing air supply, cotton coveralls, gloves, boots and hearing protection (NRR 29). Separate work clothing was worn beneath coveralls, and no food, beverages, tobacco or cosmetics were permitted in the test facility. Support personnel were similarly outfitted, except that half-face, negative-pressure, air-purifying respirators with HEPA filtration were worn, (APF of 10), instead of the blast helmet. All project personnel washed hands and face prior to eating, drinking or smoking, and showered at the end of the workshift.

Sample Collection Methodology and Filter Media Positioning

During each abrasive trial, airborne samples were collected in the blast room as well as on the operator. Blast room samples consisted of: total airborne dust, 28 airborne metals/elements; respirable crystalline silica and cristobalite; respirable radiochemically active materials; and total airborne radiochemically active materials. Sampling was conducted under the NIOSH methods[11]: 7500 for respirable quartz, 7300 for elements, 0500 for total dust, 0600 for respirable dust; and the WR-IN-314 standard operating procedures entitled "The Determination of Radium-226 in Solids by Alpha Spectrometry" for respirable radioactivity[12].

A total of twenty-nine (29) samples (8 make-up air area; 8 operator area; 8 exhaust area; 2 passive samples for collection of ricochet in the blast room operator area; and 3 within the operator's breathing zone) were collected for each abrasive trial. A passive sample is one placed in the operator sampling area without a pump attached. The following samples were collected at each area (or fixed station) for each abrasive trial: four total dust samples, one elemental sample, one respirable crystalline silica sample, one respirable radioactivity sample, and one total airborne radioactivity sample. The following samples were collected within the operator's breathing zone for each abrasive trial: one total dust sample, one elemental sample, and one respirable crystalline silica sample. One virgin and spent bulk sample were collected for each abrasive trial and analyzed for thirty health-related agents. The airborne and bulk samples were analyzed by the following NIOSH methods:[11] 7500 (x-ray diffraction) for respirable quartz; 7300 for all elements, except the graphite furnace method for arsenic, beryllium, cadmium, and lead; the WR-EP-325 standard operating procedure entitled "Determination of Gamma Emitting Isotopes" for radioactivity in bulk samples[13] and WR-IN-314 standard operating procedures entitled "The Determination of Radium-226 in Solids by Alpha Spectrometry" for respirable radioactivity in airborne samples.[12] Greater than 75% of the total dust samples had filter weights greater than the recommended sample filter weight for NIOSH method 0500. Therefore, the total dust results will not be provided in this report.

Airborne sampling was conducted using Gilian, SKC and GAST Hi-Flow sampling pumps, tygon tubing and the appropriate collection device/filter media. In order to prevent pump damage from airborne dust concentrations inside the blast facility, all area sampling was performed remotely by traversing 32' 4" lengths of tygon tubing (3/8" O.D.) through a dividing wall, across the top and down through the ceiling of the blast room to three fixed station locations. Head loss was tested for the 32'4" length tubes and compared to standard length 3' tubes at flow rates of 1.0, 1.7, and 2.0 liters per minute. The comparative head loss was determined to be minimal. Eight to ten sample holders were positioned inside the blast room in each of three (3) areas, identified as the make-up air area (fixed station #1), operator area (fixed station #2), and exhaust area (fixed station #3). Sample holders were mounted 12" from the blast room wall, at breathing zone height (5- 6 feet). Individual samples were separated from each other by a clearance of 6 inches (see drawing attached as Appendix 8). The sampling pumps were positioned on the opposite side of the dividing wall, on a laboratory bench top. Each tygon tubing was identified using a unique number (1-39); and each pump was identified using a unique letter (A-U). Independent of pump location and filter media position, all tygon tubing was of the same length and diameter.

Sampling within the blaster's breathing zone was conducted using three (3) SKC programmable sampling pumps mounted on the waist of the blaster. Tygon tubing traversed from the pump up the worker's back, over the shoulders and into the breathing zone, defined as a 6-9" hemisphere from the nose downward, and forward of the shoulders. All tygon tubing for the breathing zone sampling was the same length and diameter (3' x 3/8"O.D.). The filter media for elemental sample collection was positioned over the right shoulder for each abrasive trial. The filter media for collection of total dust was positioned over the left shoulder for each trial. A 10mm nylon cyclone equipped with PVC filter media for collection of respirable crystalline silica was positioned between the two other samples, centered beneath the chin area on the worker. All filter media was positioned outside the blast helmet in a downward position, forward of the shoulder, attached to the blast helmet cape using collar clips.

Calibration of Sampling Pumps

The Gilian, SKC and GAST sampling pumps were calibrated prior to each sampling period (through the filter media) using a Gilian Model 800271 Gilibrator precision flow bubble meter equipped with a standard flow cell (20cc to 6 l/m). Each sampling pump was equipped with the respective filter media, then connected to the Gilibrator. Adjustments to each pump were made using the flow adjustment screw or flow restrictor valve (GAST pumps) until the target flow was achieved. Subsequently, five (5) flow measurements were recorded, then averaged for each sampling pump. The data was recorded on a Pump Calibration Report (example attached in Appendix 5).

The sampling pumps equipped with 10mm cyclones for collection of respirable crystalline silica and respirable radiochemically active material were calibrated in accordance with the Occupational Safety and Health Administration (OSHA) Technical Manual Chapter 1, "Personal Sampling for Air Contaminants"; Section C, Technique 3.[14] Briefly, the filter media was mounted in MSA 10mm nylon cyclones. The filter media and cyclone were then placed in a one liter vessel with two (2) ports in the screw top lid. A 12" section of tygon tubing was connected from one port on the glass vessel to the Gilibrator precision flow bubble meter. The sampling pump was connected to the second port on the vessel using the appropriate length of tygon tubing (32' 4" for area sampling in the blast room and 3' for breathing zone monitoring on the worker) and the sampling pump adjusted to maintain a flow rate of 1.7 L/min.

The sampling pumps for collection of total airborne dust were targeted for calibration at 1.0 liter per minute through pre-weighed, 0.5 micron pore size, 37mm diameter polyvinyl chloride (PVC) filter media encased in 37mm plastic cassettes. The sampling pumps for collection of metals/elements were targeted for calibration at 2.0 liters per minute through 0.8 micron pore size, 37mm diameter, mixed cellulose ester (MCE) membrane filter media, also encased in 37mm plastic cassettes. The sampling pumps for collection of respirable dust and respirable radiochemically active material were targeted for calibration at 1.7 liters per minute through pre-weighted, 0.5 micron pore size, 37mm diameter PVC filter media encased in 37mm plastic cassettes. Finally, the sampling pumps for collection of total radiochemically active material were targeted for calibration at 4.0 liters per minute through pre-weighed, 0.5 micron pore size, 37mm diameter, PVC filter media encased in 37mm plastic cassettes.

Background Monitoring

Prior to initiation of the study, background sampling was conducted for eight (8) hours to determine the existing airborne concentrations of total dust, targeted metals/elements, respirable crystalline silica and radiochemically active materials, and total radiochemically active materials. The ventilation system was activated, drawing 50-75 feet per minute average cross-sectional air flow through the facility. Otherwise, the blast room remained undisturbed during background monitoring.

Preparation of Test Facilities

To prevent cross-contamination of abrasive media after each abrasive trial, the blast facility was vacuumed to collect spent abrasive debris and dust. Subsequently, the surfaces within the blast room were damp-wiped using sponges to collect any residual dust clinging to the walls, ceiling, floor, sample holders, test plate rack, or other surfaces. Subsequently, after drying and prior to each abrasive trial, the blast facility was visually inspected for the presence of abrasive debris from the previous blast trial. Additionally, a "white glove" examination was conducted on a minimum of five (5) random surfaces. The presence of "swipe marks" left by the glove was case for rejection and recleaning as necessary.

In addition to the blast facility, support equipment used for the blast cleaning process was also cleaned and visually examined for residual dust. This equipment included the blast nozzles, blast hoses, blast pot, abrasive reclaimer (when applicable) personal protective equipment (blast helmet and cape), protective clothing, and substrate material.

In addition to qualitative inspection for surface cleanliness, wipe samples were obtained to quantitatively assess surface cleanliness. Three (3) wipe samples were obtained after every fifth trial by randomly placing a one square foot template on the wall, ceiling, and floor and collecting a wipe sample from each square foot area using non-alcohol, non-aloe containing baby wipes. The wipe samples were collected, then stored in plastic screw-cap conical tubes.

After the cleanliness inspection, a ventilation system inspection was performed by measuring the cross-sectional air flow through the blast facility using an Alnor Model RV Rotating Vane Anemometer. Twelve (12) measurements of cross-draft air flow were obtained midway through the blast room. Four (4) measurements were obtained near the ceiling (7-8' above floor level), four (4) measurements were obtained at the breathing zone height (5' above floor level), and four (4) measurements were obtained 6-12" from the floor. The twelve measurements were averaged to ensure that the cross-draft ventilation was maintained at 50-75 feet per minute. The results of the ventilation assessment and blast facility cleanliness were recorded on a Mechanical Ventilation

Evaluation Form and Industrial Hygiene Report Form, respectively (examples attached in Appendix 5). The arithmetic mean for each group of measurements are presented in Appendix 8.

Sample Collection During Abrasive Trials

Prior to initiating each blast trial, the unique number assigned to each filter media by NIOSH was transcribed to the Industrial Hygiene Report Form. Concurrently, a position number was assigned to each filter media to ensure proper positioning/tygon tubing connection once inside the blast facility. Each filter cassette/cyclone assembly was carefully mounted in the holders inside the blast room. The inlet ports of the cassettes remained plugged until the operator was ready to begin blast cleaning (exception - cyclone-mounted media). Subsequently, the operator personal pumps were mounted on the blaster and the cassette inlet port plugs were removed.

The three (3) personal sampling pumps mounted on the blaster were programmable SKC personal sampling pumps. The pumps were programmed to initiate sampling 3 minutes after the abrasive trial began in order to provide time to allow airborne concentrations of dust to equilibrate, and to stop sampling 24 minutes into the sampling period (to prevent overloading of the filter media). The total elapsed time of 27 minutes was based on information collected in a pilot study to estimate the best sampling rates to avoid overloading of the sample filters for total dust and to allow enough time to collect a minimum of respirable crystalline silica dust.

Similarly, the sampling pumps collecting airborne debris in the make-up air, operator, and exhaust areas were also turned on after 3 minutes had elapsed and stopped 24 minutes later.

To reduce the quantity of "total dust" collected on the filter media located in the three areas inside the blast room, four (4) 6 minute samples of total dust were collected rather than one (1) 24 minute sample. To reduce the number of sampling pumps required to perform this task, the following procedure was utilized:

1. Pumps identified as A, B, G, H, M, and N were used together with hoses numbered 1, 2, 3, 4, 14, 15, 16, 17, 27, 28, 29, and 30.
2. After a 3 minute delay, pumps A, G, and M were connected to hoses 1, 14, and 27, and started.
3. After six minutes, pumps A, G, and M were stopped and pumps B, H, and N started (connected to hoses 3, 16, and 29).
4. Hoses 1, 14, and 27 from pumps A, G, and M were disconnected, and hoses 2, 15, and 28 were connected to pumps A, G, and M, respectively.
5. After the second six (6) minute sampling period, pumps B, H, and N were simultaneously stopped and pumps A, G, and M restarted.
6. Hoses 3, 16, and 29 were disconnected from pumps B, H, and N, and hoses 4, 17, and 30 were connected to pumps B, H, and N, respectively.

7. After the third - six (6) minute sampling period, pumps A, G, and M were simultaneously stopped and pumps B, H, and N started.
8. After the fourth - six (6) minute sampling period, pumps B, H, and N were stopped.

This procedure resulted in the collection of four (4) 6 minute samples, in each of three areas in the blast facility.

Finally, two (2) samples consisting of 0.5 micron pore size, 37mm diameter PVC filter media in 37mm plastic cassettes were mounted in the operator area without hose or sampling pump connection to determine if ricochet debris entered the filter cassettes during the trial runs.

Post Sample Collection Procedure

Post sample collection procedures included sample security, removal of samples from the operator and blast facility, pump flow rate verification and sampling equipment cleaning. Sample security was accomplished by plugging the inlet port of the filter media, then removing the media from the sampling hose and plugging the outlet port. This procedure was conducted on the operator first, then the blast facility samples. Support personnel were prohibited from entering the blast facility until all inlet ports were sealed. Subsequently, the cyclones were carefully removed, kept in a vertical position, then placed in a customized holder. The holder kept the cyclones vertical to ensure the large debris which accumulated in the grit pot at the base of the cyclones did not come in contact with the PVC filter media. The filter cassettes were removed from the blast facility, and the cassettes sealed using 9/16" x 3-7/16" labels, each containing the date and technician's initials. This was done to prevent tampering with the samples, as well as accidental dislodging of the inlet port caps. The samples were sorted according to required analysis, then boxed for transportation to NIOSH in Morgantown, West Virginia for analysis in accordance with the appropriate NIOSH analytical methods. Samples were routinely transported to NIOSH by KTA personnel. A Sample Submittal Form and Chain-of-Custody accompanied each batch of samples (example included in Appendix 5). Additionally, 20% field "blank" samples were added to each shipment (also categorized by type of analysis). Forty-nine field blanks were submitted and analyzed for each of the 30 health-related agents listed in Appendix B. For all of the 30 health-related agents, the analytical results were so low and sporadic that no adjustment for field blanks was implemented. Chromium, nickel, vanadium, respirable quartz, respirable cristobalite, and lithium were not detected in any of the forty-nine field blanks. The results for the remaining 24 agents would not have altered the rankings of any of the individual abrasives or categories of abrasives, but would slightly decrease the magnitude of the results for all of these 24 health-related agents. The adjustment would be the same for all samples associated within a given health-related agent, but the proportion of that adjustment would be substantially greater for the results near the limit of detection (LOD) or limit of quantification (LOQ) as opposed to results which were much greater than the LOD or LOQ.

After all samples were secure, post-sampling pump flow rate verification was conducted by connecting each pump to the Gilian Gilibrator precision flow bubble meter (through the respective media) and recording five flow rates as well as the average flow rate (in LPM) on the Pump Flow Verification Report Form. The pre- and post-sampling flow rates for each pump were averaged to create an average flow rate for the actual sampling period. This flow rate was reported to NIOSH to calculate the total volume of air sampled on each filter cassette.

If the post-sampling flow rate verification results were relatively unchanged, the results were used as the pre-calibration for the next abrasive trial, provided another trial was being conducted that same work day. If the flow rate changed significantly, a separate calibration procedure was conducted.

After post-calibration, operator breathing zone pumps and hoses were wiped with a dampened cloth to remove residual dust. The 10mm nylon cyclones were cleaned in accordance with the OSHA Technical Manual, Chapter 1, Section C.3(6)e. "cyclone cleaning"[14]. The grit pot was removed from the base of the cyclone and gently tapped on a counter top to remove the large particles. The size selective inlet was disassembled and the components were thoroughly rinsed using tepid tap water. Subsequently, all nylon components were cleaned in a 22-watt ultrasonic bath manufactured by Fisher Scientific (Model FS-3). A mild solution of Alconox detergent powder in tap water was used to clean the parts for approximately ten (10) minutes. Each component was then thoroughly rinsed with tepid tap water and dried in a laboratory oven pre-set at approximately 100°F. After drying, the cyclones were inspected for wear, then reassembled for the next abrasive trial.

Documentation

The following documentation report forms were used for the collection of all data. Examples of each form are included in Appendix 5. Actual forms completed during the study were provided to NIOSH under separate cover.

Blast Cleaning Inspection Report # QPF-WDC345R.1 – Report form is for collection and record keeping of all data and variables associated with first and last runs during abrasive testing.

Blast Cleaning Reclaim Report # QPF-346r.0 – Report form is for collection and record keeping of all data and variables associated with reclaiming of spent abrasives and any abrasive breakdown cycles performed.

Sieve Analysis Report # MATF 100R.2 – Report form is for the collection and record keeping of data associated with screening for particle size. Calculations to develop average particle size and charting results are also included on report form.

Industrial Hygiene Report – Report form is for collection of data and acts as a checklist to ensure completion of pretest industrial hygiene practices. The report records air filter cassette sample numbers, type of filter media, duration of air flow over cassette, and total volume of air to flow over air sample media.

Pump Calibration Report – Report of calibration and actual air flow prior to test.

Pump Flow Verification Report – Report to verify post run actual air flow.

Mechanical Ventilation Evaluation # J95331 – Form used for collection and calculation of air flow through the blast room.

Sample Submittal Form – Used to provide sample identification and sample collection parameters for submission to NIOSH for corresponding industrial hygiene analysis.

Chain-of-Custody – Used to verify the integrity of the samples and resulting data throughout the collection, transport, and analysis activities.

Concerns

The size and scope of the testing program resulted in a few deficiencies in both the development of the testing protocol and execution of the abrasive blasting trials. Each concern, its cause, and resolution is described in the sections that follow. Letters from individual abrasive supplies discussing these concerns are included in Appendix 2.

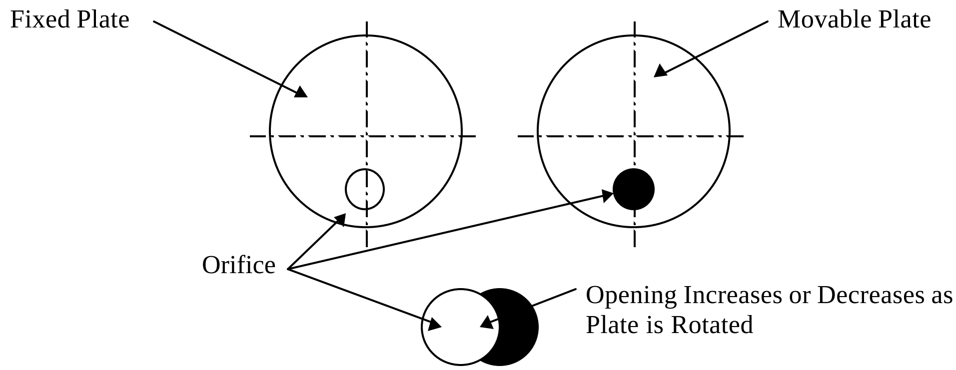
Abrasive Metering Valve

The abrasive metering valve is an integral part of any blast cleaning pressure pot. The purpose of valve is to meter the amount of abrasive that is fed into the stream of compressed air, which propels the abrasive particles.

The adjustment of the metering valve is critical to abrasive blast cleaning productivity. Too little abrasive introduced into the air-stream results in an incompletely filled blast pattern, which slows production and leaves areas on the substrate or item being cleaned untouched by the abrasive particles. Too much abrasive causes abrasive particles to collide, which wastes energy and disperses particles unevenly within the blast pattern. A metering valve setting that is too rich in abrasive also unnecessarily wastes abrasive. A properly adjusted metering valve ensures that the maximum amount of cleaning is gained from each abrasive particle. In typical field abrasive blast cleaning operations, the proper metering valve setting is determined by a trial and error procedure, which relies heavily on the experience of the blast machine operator. This procedure begins with the metering valve closed (only air is flowing through the blast hose and nozzle). The metering valve is then slowly opened. The proper setting is determined using both visual and audible experience. A proper setting will show slight discoloration of abrasive leaving the nozzle. Experienced blast operators can also hear a steady abrasive flow. Too little abrasive causes a high-pitched sound, while too much abrasive causes an erratic, pulsating sound. The metering valve adjustment process typically takes several minutes.

The typical construction of most abrasive metering valves is shown in Figure 1. Two concentric circular steel plates are used. Each plate has a one-inch diameter orifice. One of the plates is fixed in position, while the other is allowed to rotate. The valve is adjusted by rotating the plate. When the valve is fully open, the centers of each orifice are aligned.

FIGURE 1 – TYPICAL METERING VALVE CONSTRUCTION



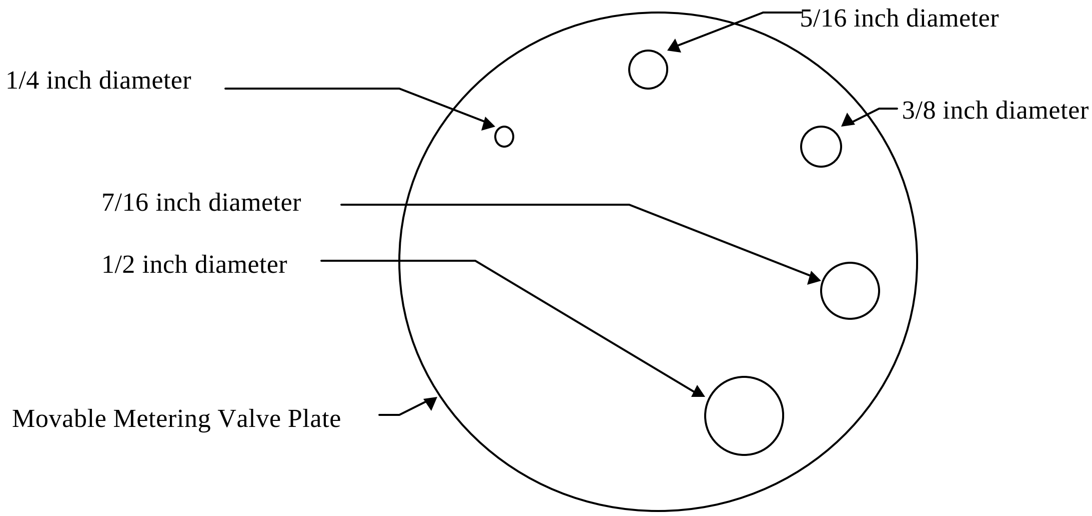
The study protocol developed for this abrasive testing program prohibited the use of traditional methods for setting abrasive metering valves for several reasons:

- Operator Variability Study – The purpose of this part of the study was to measure the difference in the blast operator's technique independent of the blast equipment setup. Therefore, constantly adjusting the metering valve to suit the operator's individual performance would not reliably evaluate the consistency of an individual blast operator or the performance of one operator versus another.

- Process Control Checks – Variability caused by abrasive metering valve adjustments would invalidate the in-process control checks of operator variability.

KTA designed and fabricated a metering valve plate and established a procedure which could address the deficiencies listed above. The new plate configuration is shown in Figure 2.

FIGURE 2 – SPECIALLY DESIGNED METERING VALVE CONFIGURATION



The metering valve plate has five fixed settings, which result in a much higher level of valve adjustment consistency. Each abrasive supplier was then asked to recommend the orifice for his or her product and mesh size. The sizes were as follows (if the supplier did not furnish this information, the 1/2 inch size was used):

CG-01	3/8”	S-02	1/4”	CP-2	3/8”
CS-01	1/2”	SH-01	5/16”	CP-3	3/8”
CS-02	7/16”	SS-01	1/2”	CP-4	5/16”
CS-03	1/2”	SS-02	1/2”	CPDS-1	3/8”
CS-04	7/16”	SS-03	1/2”	G-1	3/8”
CS-05	1/2”	SS-04	1/2”	G-2	7/16”*
CS-06	1/2”	SS-05	1/2”	G-3	3/8”
CS-07	1/2”	SS-06	1/2”	G-4	3/8”
CSDS-01	1/2”	SS-07	1/2”	G-5	1/4”
CSDS-02	1/2”	SSDS-01	1/2”	G-6	7/16”
N-01	7/16”	SSDS-02	1/2”	G-7	3/8”
N-02	3/8”	SSDS-03	1/2”	SG-1	3/8”**
O-01	1/2”	CP-1	3/8”	SG-2	3/8”
S-01	1/4”				

* Last abrasive run - metering valve reduced by 1/16” to promote abrasive flow.
** Last abrasive run – metering valve reduced by 1/8” to promote abrasive flow.

Although the new metering valve plate was tested prior to the start of the operator variability study without fault, the valve clogged during two abrasive trials (OV-1 and OV-3). The metering valve plate used for these initial trials allowed abrasive to build up around the opening, restricting the flow of abrasive. The valve was redesigned to prevent the build up of material. Abrasive trials OV-1 and OV-3 were re-performed, and no further problems with the abrasive metering valve were encountered.

Production Rates

The cleaning rate and consumption rate results were much lower than published rates in the NSRP Report[15] and lower than what KTA has experienced in both field and laboratory projects. There are many factors that affect the cleaning and consumption rates of any abrasive blast cleaning system as previously discussed in this report and in the appended article "Achieving Productivity from Abrasive Blast Cleaning Systems" (Appendix 8). This article was published in the September 1989 edition of the Journal of Protective Coatings & Linings[16]. The factors that effect abrasive blast cleaning productivity are:

- Metering Valve Setting – As discussed above the use of a pre-determined meter valve setting, versus trial and error to account for the equipment set up can significantly affect the cleaning and consumption rates of the various abrasives.

- Nozzle Size – Abrasive blast nozzles with larger openings produce a larger blast pattern on the surface being cleaned. Blast nozzles typically range in size from 1/8 inch to 1/2 inch orifice diameter, in 1/16 inch increments. Larger sized nozzles also permit more abrasive impacts since more abrasive particles exit the nozzle over a given unit of time. Therefore, productivity increases as a function of the nozzle size. The limiting factor is that larger nozzles require larger volumes of compressed air. Each 1/16 inch increase in nozzle orifice diameter requires approximately twice as much air volume flow for a given blast pressure. During this study, KTA used a 1/4 inch nozzle to provide ample blast cleaning time to collect the industrial hygiene data. As a result the study resulted in lower cleaning rates.

- Nozzle Type – There are currently two types of blast nozzles used during field blasting operations. These are categorized by the nozzle geometry. Straight bore nozzles have a constant orifice diameter for the length of the nozzle. Venturi nozzles converge to the nozzle's size at a point approximately half of the nozzle's length and then diverge for the remainder of the nozzle. The converging portion of the nozzle accelerates the air and abrasive particles resulting in increased impact energy which, in turn, enhances productivity. The diverging portion of the venturi nozzle provides an increase blast pattern. KTA used a venturi nozzle for all abrasive trials.

- Standoff Distance – The standoff distance is the distance that the nozzle is held in relation to the item being cleaned. This distance is critical to abrasive blasting production. Blast operators typically optimize the distance to achieve the desired blast pattern and cleaning rate. This distance could range from 6 inches to 24 inches. Generally, nozzles are held closer to the substrate to clean tightly adherent mill scale or coatings which require a smaller blast pattern to achieve the specified surface cleanliness. When surfaces being cleaned exhibit loosely adherent coatings or flaking mill scale and rust, the larger blast pattern produced at greater standoff distances allows faster cleaning. During the abrasive trials the standoff distance was held constant for all abrasive trials at 18 inches to measure the effectiveness of the different abrasives independent of the operators skill or experience. This would also provide consistent, repeatable results, but the fixed distance will affect the ability of different abrasives to clean.

- Angle of Attack – The angle of attack is the angle that the nozzle is held to the work-piece. Most field abrasive blast cleaning is performed with the nozzle held between 60^o to 120^o to the surface. Nozzles held perpendicular (90^o) to the surface provide more impact energy, which fractures tightly adherent coatings and mill scale. Nozzles held at angles greater than or less than 90^o scour the surface. Experienced abrasive blast operators use a combination to achieve high productivity. During this abrasive study, the KTA operator held the nozzle perpendicular to the panels being cleaned so that the greatest amount of dust would be produced for industrial hygiene monitoring. Such restrictions, however, can affect cleaning rates.

- Dwell Time – Dwell time is the amount of time required to achieve the desired surface cleanliness before the nozzle can be moved to the next area on the substrate. This factor is highly influenced by the size of the blast pattern. For small blast patterns, where the nozzle is held close to the surface being cleaned, the dwell time is very short. When a larger blast pattern is used, the dwell time may be longer. Once again, the operator's skill and knowledge of the cleanliness specification help to reduce dwell time, thus increase productivity. Some of this control was removed from the operator by fixing the nozzle distance and angle of attack.

- Nozzle Pressure – The pressure of the air/abrasive stream during blasting operations greatly influence the cleaning productivity. For most abrasives, increased pressure results in increased production. Generally, abrasive blasting pressure is increased to the maximum capacity of the air compressor used with the exception of abrasives such as steel grit. Diminishing returns occur at pressures significantly above 100 psi. Some abrasives however, efficiently produce the desired surface cleanliness at lower pressures. Most of the garnet suppliers used during the study wanted KTA to use nozzle pressures in the range 60 to 80 psi in order to reduce breakdown rate and improve the reuse characteristics. During each abrasive trial run conducted as a part of this study, the nozzle pressure was held constant at 100 psi. This was necessary to limit the number of variables in the study.

Each of these factors affected the cleaning rate and consumption rate results. Many of the factors are dependent on the skill or experience of the blast nozzle operator. The goal of KTA's study design was to produce comparable abrasive blast cleaning results with the abrasive type being the only variable. Also, the operator used for the study was chosen based upon consistent results obtained during the operator variability study, not the operator displaying the highest productivity or having the most experience.

Number of Abrasive Recycles

Limitations were placed on the number of times that the steel grit abrasives would be recycled during the abrasive study due to time and cost restraints. The steel grit abrasives were recycled 25 times. Steel grit abrasive suppliers suggest that their products may be recycled in excess of 200 times. In fact, KTA uses steel grit abrasives for preparation of test panels for laboratory testing. The steel grit is used a minimum of three days per week all year long with no significant change in the surface profile obtained. The advantage to recycling any abrasive is reduced material cost and reduced waste disposal cost. Costs for each abrasive are addressed under the Test Results and Discussion section of this report.

The steel grit suppliers were also concerned with the setup and operation of KTA's abrasive reclamation and classification system. The suppliers felt that the Lunardini reclamation system removed too much abrasive fines (small particle sizes). The average particle size of SG-01 was 46.03 mm. The average size of the abrasive fines removed by the reclamation system was 0.34 mm. The average particle size of SG-02 was 51.38. The average size of the abrasive fines removed by the reclamation system was 0.23 mm.

Cost Analysis

The data regarding abrasive consumption, productivity, and the resulting cost/square foot are only valid as measures of the performance of each unique abrasive relative to the study parameters. A comparison of performance between abrasives is valid only as it relates to the study design. It is not an indication as to how one abrasive will perform relative to another when the optimum operating conditions are selected for each. The results have no relationship to true field performance, and should not be used for that purpose, either directly, or through relative comparisons.

In conclusion, KTA developed the Study Design/Protocol to measure the concentrations of health-related agents and effectiveness of 40 different abrasives. The factors affecting the abrasive blast cleaning process were held constant so that a comparative evaluation of the abrasives could be made independent of the substrate, surface cleanliness, equipment setup, or operator. KTA did not deviate from the Study Design/Protocol during the entire laboratory testing phase of the project.

TEST RESULTS AND DISCUSSION

This section presents and analyzes the results of the physical property evaluation of the abrasives and the industrial hygiene data that was collected. A total of 40 different abrasives representing 13 different generic types were evaluated in this study. For convenience, the generic abrasive types, an alpha code assigned to each, and the number of individual products evaluated under each type are 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

*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

The testing clearly demonstrated that a wide range in physical properties and in heavy metal content exists in the individual abrasives tested within all generic types. Although only 1 abrasive was evaluated for crushed glass, olivine, specular hematite, and copper slag with dust suppressant, it is expected that similar variability within these generic types of abrasive will exist as well.

Physical Property Evaluations

The results of abrasive media testing are summarized from the "Blast Cleaning Inspection Reports" prepared for each abrasive trial. The data was obtained in order to quantify the production and performance-related attributes of each of the abrasives tested. The specific attributes examined were:

- Abrasive cleaning rate
- Abrasive consumption rate
- Surface profile

- Abrasive breakdown rate (pre and post blast average particle size comparison)
- Abrasive embedment
- Abrasive recyclability (for abrasives designated as recyclable only)
- Microhardness
- Conductivity (water soluble contaminates)

Many of these attributes affect the amount of time that abrasive blast operators are subject to possible inhalation and ingestion hazards. Additionally, these attributes affect the cleanliness of prepared surfaces, the amount of waste generated, and cost of abrasive blast cleaning operations. Since abrasive blast cleaning is most often used for preparing surfaces to properly accept coating systems, an evaluation of particle embedment and water-soluble contaminants was performed because contaminants carried from abrasives to the surface being prepared can lead to premature coating failures. Premature failures of the paint system will unnecessarily subject workers to additional exposures by virtue of the unscheduled repair work that will be required.

The results of the testing for each of the individual abrasives are presented in the tables attached as Appendix A. Separate tables have been prepared for each of the attributes evaluated. This section describes the type of information found in each of the tables, and provides a general summary and discussion of the results.

The results are categorized by generic abrasive type and whether the abrasive is typically recycled (used more than one time). Refer to the Abrasive Media Test Methods section of this report for a description of the test methods and associated industrial standards used for each of the evaluations.

Abrasive Cleaning and Consumption Rates

Table A1 (Appendix A) provides the results of the cleaning and consumption rates for each of the expendable abrasives tested. Table A7 provides the results for the same testing conducted on the recyclable abrasives. Both tables present the length of time that each trial was conducted for each individual abrasive, the amount of abrasive used and surface area cleaned. From this data, the cleaning rate in square feet/hour and the abrasive consumption rate in pounds per square foot have been calculated. The results for the individual abrasives are combined according to their generic categories and summarized as a class in Table A13.

As indicated in the Study Design and Test Methods section of this report, the blast cleaning trials were conducted using a 1/4” orifice nozzle at 100 psi. Blast distance was fixed at 18” from the surface with the nozzle maintained at right angles at all times. Such restrictions were invoked in order to control as many variables as possible between each of the runs. One variable that was not held constant involved the metering valve setting. The metering valve was set uniquely for each abrasive at a predetermined opening based upon recommendations from the abrasive manufacturers. A 1/2” opening was used as the default setting when no recommendations were given. It became apparent that it is difficult, if even possible, for manufacturers’ to confidently pre-select metering valve settings. Instead, the settings need to be determined through experimentation for each equipment set up and unique project condition.

While all of the controls previously described were designed to allow for a more accurate comparison of the properties between abrasives, a disadvantage emerged. The equipment and operational controls proved to severely restrict productivity and adversely affect abrasive consumption rates when compared with industry data and experience. As a result, the information is only valid as it relates to the performance of a given abrasive relative to the stringent controls placed on the Study Design. The data should not be construed as being representative of field expectations, nor are relative comparisons between abrasives meaningful. When optimum operating conditions for each abrasive are selected for field use, dramatically different cleaning and consumption rates will result, both in an absolute and relative sense.

Cleaning Rates - As can be seen in Tables A1 (expendable) and A7 (recyclable), the cleaning rates derived from the study show:

- Crushed glass exhibited a cleaning rate of 33 square feet/hour.
- The cleaning rates for the 7 coal slag abrasives ranged from 28 to 42 square feet/hour. The abrasives can be categorized as follows: 1 sample at 28 square feet/hour; 4 samples from 31 to 34 square feet/hour; 2 samples at 41 and 42 square feet/hour.
- The cleaning rates for the 2 coal slag abrasives treated with dust suppressant were 35 and 38 square feet/hour. This was an increase over the untreated counterpart in one case (38 vs. 28 square feet/hour), and a decrease in the other (35 vs. 41 square feet/hour).
- The cleaning rates for the 2 nickel abrasives were 35 and 47 square feet/hour.
- The cleaning rate for the olivine abrasive was 44 square feet/hour.
- The cleaning rates for the 2 staurolite abrasives were 44 and 49 square feet/hour.
- The cleaning rate for the specular hematite abrasive was 32 square feet/hour.
- The cleaning rates for the 7 silica sand abrasives ranged from 25 to 37 square feet/hour.
- The cleaning rates for the 3 silica sand abrasives treated with dust suppressant ranged from 26 to 39 square feet/hour. This represents an increase over the untreated counterpart in one case (39 vs. 37 square feet/hour), a decrease in another (26 vs. 34 square feet/hour), and no change for the third (34 square feet/hour for both runs).

- The cleaning rates for the 4 copper slag abrasives ranged from 28 to 61 square feet/hour at the time of initial use (28, 40, 48, and 61). After uses, the cleaning rate increased in each case to a range from 33 to 92 square feet/hour (33, 52, 54, 92).

- The cleaning rates for the copper slag abrasive treated with dust suppressant was 31 square feet/hour. This increased to 40 square feet/hour after 2 uses. These rates show a decrease in cleaning rate compared with the untreated counterpart for the initial use (31 vs. 40 square feet/hour), and after reuse (40 vs. 54 square feet/hour).

- The cleaning rates for the 7 garnet abrasives ranged from 24 to 62 square feet/hour for the initial use. The abrasives can be categorized as follows: 2 samples at 24 and 26 square feet/hour; 2 samples at 31 to 34 square feet/hour; 2 samples from 43 to 44 square feet/hour; 1 sample at 62 square feet/hour.

- After 2 to 3 uses, the cleaning rates increased for 6 of the 7 abrasives to a range from 31 to 75 square feet/hour. The exception involved an abrasive that became too pulverized after 2 uses to evaluate.

- The initial cleaning rates for the steel grit abrasives were 27 and 39 square feet/hour. After 25 uses, the rates increased in both cases: 27 increased to 31 square feet/hour and 39 increased to 44 square feet/hour.

The cleaning rates for the 7 silica sand abrasives ranged from 25 to 37 square feet/hour. Industry data[15] suggest that cleaning rates for silica sand and the alternative abrasives tested will be 2 or more times the rates obtained from this study (due to the restrictions on equipment and operating procedures described above). Based on the study parameters, generic abrasive types having one or more products that exceeded the highest cleaning rate for silica sand included: (Again, it must be emphasized that when unique equipment and operating adjustments are made for each abrasive, the relative and absolute productivity of the abrasives will vary from the values obtained from the study. For example steel grit will be much more productive.)

- crushed glass (0 of 1 products exceeded)
- coal slag (2 of 7 products exceeded)
- coal slag with dust suppressant (1 of 2 products exceeded)
- nickel slag (1 of 2 products exceeded)
- olivine (1 of 1 products exceeded)
- staurolite (2 of 2 products exceeded)
- specular hematite (0 of 1 products exceeded)
- copper slag – initial use (3 of 4 products exceeded)
- copper slag – after 2 uses (3 of 4 products exceeded)
- copper slag with dust suppressant – initial use (0 of 1 exceeded)

- copper slag with dust suppressant – after 2 uses (1 of 1 exceeded)
- garnet – initial use (3 of 7 products exceeded)
- garnet – after 2 to 3 uses (4 of 7 products exceeded)
- steel grit – initial use (0 of 2 products exceeded)
- steel grit – after 25 uses (0 of 2 products exceeded)

Consumption Rates - As can be seen in Tables A1 (expendable) A7 (recyclable), the consumption rates derived from the study show:

- Crushed glass exhibited a consumption rate of 10.99 pounds/square foot.
- The consumption rates for the coal slag abrasives ranged from 9.05 pounds/square foot to 12.35 pounds/square foot.
- The consumption rates for the 2 coal slag abrasives treated with dust suppressant were 10.64 and 12.20 pounds/square foot. This represented an increase in the consumption rate compared with the untreated counterparts (12.20 vs. 11.63 pounds/square foot and 10.64 vs. 9.12 pounds/square foot).
- The consumption rates for the 2 nickel abrasives were 12.50 and 15.83 pounds/square foot.
- The consumption rate for the olivine abrasive was 8.02 pounds/square foot.
- The consumption rates for the 2 staurolite abrasives were 7.51 and 9.90 pounds/square foot.
- The consumption rate for the specular hematite abrasive was 6.60 pounds/square foot.
- The consumption rates for the 7 silica sand abrasives ranged from 9.05 to 13.48 pounds per square foot, with a single abrasive at 26.32 pounds/square foot. The abrasives can be categorized as follows: 4 abrasives from 9.05 to 11.36 pounds/square foot; 2 abrasives at 13.04 and 13.48 pounds/square foot; 1 abrasive at 26.32 pounds/square foot.
- The consumption rates for the 3 silica sand abrasives treated with dust suppressant ranged from 8.74 to 13.89 pounds/square foot. This represents a decrease in consumption rates for 2 of the abrasives compared with their untreated counterparts (8.74 vs. 9.05 pounds/square foot and 10.67 vs. 11.36 pounds/square foot), and an increase in the other (13.89 vs. 10.42 pounds/square foot).
- The consumption rates for the 4 copper slag abrasives ranged from 12.95 to 24.29 pounds/square foot for the initial use (12.95, 16.30, 19.44, 24.29). After 2 uses, the consumption rates for 2 of the abrasives decreased (15.37 vs.

16.30, and 15.47 vs. 19.44), 1 rate increased (25.80 vs. 24.29), and 1 remained constant (12.96 vs. 12.95).

- The consumption rate for the copper slag abrasive treated with dust suppressant was 15.64 pounds/square foot for the initial use, and 14.54 pounds/square foot after 2 uses. This is a reduction in consumption for the initial use (15.64 vs. 16.30) and a reduction in consumption after 2 uses (14.54 vs. 15.37).

- The consumption rates for the 7 garnet abrasives ranged from 7.43 to 14.42 pounds/square foot. The abrasives can be categorized as follows: 3 samples from 7.43 to 9.21 pounds/square foot; 2 samples at 10.64 and 10.80 pounds/square foot; 2 samples at 12.92 and 14.42 pounds/square foot.

  After 2 to 3 uses, the consumption rate decreased to a range from 7.12 to 9.60 pounds/square foot. One sample was too pulverized after the second use to be analyzed.

- The initial "consumption rates" for the steel grit abrasives were 27.71 and 21.53 pounds/square foot. These rates increased slightly after 25 uses: 27.71 increased to 28.75 pounds/square foot, and 21.53 increased to 21.77 pounds/square foot. Note that "consumption" refers to the amount of abrasive that was used to clean each square foot, rather than the amount actually consumed and disposed.

The consumption rates for the 7 silica sand abrasives on a weight basis ranged from 9.05 to 26.32 pounds/square feet. Industry data[15] suggest that the consumption rates for silica sand and the alternative abrasives tested are less than the rates obtained from this study (due to the restrictions on equipment and operating procedures described above). Based on the study parameters, generic abrasive types having one or more products that utilized less (or comparable) abrasive per square foot than the lowest silica sand on a weight basis included: (Again, it must be emphasized that when unique equipment and operating adjustments are made for each abrasive, the relative and absolute consumption rates will vary from the values obtained during the study.)

- crushed glass (0 of 1 rates less than the lowest silica sand)
- coal slag (3 of 7 had consumption rates similar to the lowest silica sand)
- coal slag with dust suppressant (0 of 2 had rates lower than the lowest sand)
- nickel slag (0 of 2 had rates less than the lowest silica sand)
- olivine (1 of 1 had rates less than the lowest silica sand)
- staurolite (2 of 2 had rates less than or comparable to the lowest silica sand)
- specular hematite (1 of 1 had rates less than the lowest silica sand)
- copper slag – initial use (0 of 4 had rates less than the lowest silica sand)
- copper slag – after 2 uses (0 of 4 had rates less than the lowest sand, but the ability to reuse the abrasive results in a net consumption rate less than silica sand)
- copper slag with dust suppressant – initial use (0 of 1 had rates less than sand)

- copper slag with dust suppressant – after 2 uses (0 of 1 had rates less than sand, but the ability to reuse the abrasive results in a net consumption rate less than silica sand)
- garnet – initial use (3 of 7 products had rates less than or comparable to the lowest silica sand)
- garnet – after 2 to 3 uses (6 of 7 products had rates less than or comparable to the lowest sand. The other product was reduced to an unusable powder after 2 uses)
- steel grit – initial use (waste per square foot not calculated, but will be substantially less than silica sand because of the multiple recycles)
- steel grit – after 25 uses (waste per square foot not calculated, but will be substantially less than silica sand because of the multiple recycles)

Cleaning and Consumption Rate Summary

The test results can be summarized as follows:

1 – The cleaning and consumption rates obtained from the study are not representative of industry standards and experience due to the study design's equipment and operating constraints. The cleaning rates are less than can be expected and the relative rankings between abrasives may not be applicable when transferred to field production operations.

2 - The cleaning and consumption rates for the individual abrasives within each generic type varied considerably. Typical cleaning and consumption rates for generic abrasive types did not emerge. Each abrasive needs to be evaluated individually for its own cleaning and consumption rates rather than rely on generalized characteristics.

3 - The data show that 13 of the 30 alternative abrasives exhibit cleaning rates equivalent to or in excess of the most productive silica sand (based on a 1 time use for the recyclable abrasives). When the cleaning rates after recycling are included in the analysis, 15 of the 30 alternate abrasives exhibit cleaning rates equivalent to or in excess of the most productive silica sand. All 30 of the alternative abrasives exhibited cleaning rates in excess of the least productive silica sand.

4 - The data show that 10 of the 30 alternative abrasives exhibit consumption rates (on a weight basis) less than or equivalent to the most efficient silica sand (based on a 1 time use for the recyclable abrasives). When the cleaning rates after recycling are included in the analysis, 20 of the 30 alternate abrasives exhibit consumption rates less than or equivalent to the most efficient silica sand. All 30 of the alternative abrasives exhibited consumption rates less than the least efficient silica sand.

5 - The productivity of the recyclable abrasives increased after reuse, while the consumption rate decreased with reuse.

6 – Dust suppressant was used on 2 coal slag samples. The cleaning rate compared with the untreated counterparts showed an increase for one sample and a decrease for the other. The consumption rate showed an increase for both samples. Conclusions regarding the effect of dust suppressant on cleaning rates can not be made, but the

limited data suggests that consumption rates may increase with the use of dust suppressant.

7 - Dust suppressant was used on 3 silica sand abrasives. The cleaning rate compared with the untreated counterparts showed an increase for the first sample, a decrease for the second sample, and no change for the third sample. The consumption rates increased for one sample and decreased for the other two. Conclusions regarding the effect of dust suppressant on cleaning and consumption rates can not be made from the data.

8- Dust suppressant was used on 1 copper slag abrasive that was used 2 times. The cleaning rate compared with the untreated counterpart was reduced both on initial use and upon reuse. The consumption rate was also reduced for the initial use and after reuse. The limited data available suggests that the dust suppressant reduces cleaning and consumption rates.

Surface Profile

The results of the six individual and average surface profile measurement for each of the abrasives is shown in the attached Table A2 for expendable abrasives and Table A8 for the recyclable abrasives.

The abrasive manufacturers' were asked to provide an abrasive sized to provide a surface profile from 2 to 3 mils which is a typical profile for most paint systems. Deeper profiles will also generally reduce cleaning rates. The results of the expendable and recyclable abrasives as a class are summarized below:

- 14 of 26 expendable abrasives met the average profile requirement.
- 1 of 14 recyclable abrasives met the average profile requirement at the time of initial use. The profile for 13 of 14 of the abrasives exceeded the 2-3 mil design criteria. After recycling, with the exception of one steel abrasive, the average profile depths of the abrasives were reduced, with 8 of the 14 falling between 2 and 3 mils.

The results of the individual generic abrasive types are as follows:

- 1 of 1 crushed glass samples met the criteria with an average profile of 2.72 mils.
- 4 of the 7 coal slag samples met the criteria with the average profiles ranging from 2.67 mils to 2.97 mils. The average profiles of the remaining 3 samples from 3.13 to 3.72 mils.
- 0 of the 2 coal slag samples with dust suppressant met the criteria. The average profiles were 3.13 and 3.42 mils.

- 0 of 2 nickel slag samples met the criteria. The average profiles were 3.25 and 3.87 mils.

- 1 of 1 olivine samples met the criteria with an average profile of 3.03 mils.

- 2 of 2 staurolite samples met the criteria with average profiles of 2.02 and 2.08 mils.

- 1 of 1 specular hematite samples met the criteria with an average profile of 2.77 mils.

- 2 of 7 silica sand samples met the criteria with average profiles of 2.73 and 2.80 mils. The average profiles of 4 of the remaining samples ranged from 3.30 mils to 3.73 mils, and the profile of the final sample measured 4.40 mils.

- 3 of 3 silica sand samples with dust suppressant met the criteria with average profiles ranging from 2.83 to 3.02 mils.

- 0 of 4 copper slag samples met the criteria upon initial use with average profiles ranging from 3.68 mils to 3.92 mils. After recycling, the average profile of 1 of the samples was reduced to 2.98 mils, with the average profile of the remaining samples was reduced to a range of 3.15 to 3.43 mils.

- 0 of 1 copper slag samples met the criteria upon initial use with an average profile range of 3.95 mils. After recycling, the average profile was reduced to 2.93 mils.

- 1 of 7 garnet samples met the criteria with an average profile of 2.68 mils. The average profile of 4 of the remaining samples ranged from 3.10 to 3.40 mils, and the average profile of the 2 remaining samples measured 3.93 and 4.15 mils. After recycling, the average profile of 5 of the 7 samples was reduced to a range of 2.07 to 2.77 mils. Of the remaining 2 samples, 1 could not be measured (useable abrasive did not remain after 2 uses), and the other measured 3.32 mils.

- 0 of 2 steel abrasive samples met the criteria upon initial use with average profiles of 3.08 and 3.17 mils. After recycling, the average profile of one of the samples measured 2.88 mils. The profile of the other sample measured 3.4 mils (an apparent increase from the initial average profile of 3.08 mils).

The consistency of the 6 profile readings obtained with each product was evaluated. The data below shows the total spread in profile readings between the minimum and maximum measurements obtained for each generic abrasive type. When more than one abrasive was evaluated within a generic type, the results of the measurements for each of the individual abrasives are shown in parenthesis:

- crushed glass - 0.4 mils (0.4 mils)
- coal slag - 0.2 to 1.0 mils (0.2, 0.4, 0.4, 0.4, 0.5, 0.6, 1.0 mils)
- coal slag with dust suppressant - 0.6 to 0.7 mils (0.6, 0.7 mils)
- nickel slag – 0.6 mils (0.6, 0.6 mils)
- olivine – 0.6 mils (0.6 mils)
- staurolite – 0.2 to 0.4 mils (0.2, 0.4 mils)
- specular hematite – 0.5 mils (0.5 mils)
- silica sand – 0.1 to 0.9 mils (0.1, 0.2, 0.3, 0.4, 0.4, 0.6, 0.9 mils)
- silica sand with dust suppressant – 0.2 to 1.4 mils (0.2, 0.3, 1.4 mils)
- copper slag – initial use – 0.2 to 0.7 mils (0.2, 0.2, 0.7, 0.7)
- copper slag – after 2 uses – 0.3 to 0.6 mils (0.3, 0.4, 0.4, 0.6 mils)
- copper slag with dust suppressant – initial use – 0.3 mils (0.3 mils)
- copper slag with dust suppressant – after 2 uses - 0.4 mils (0.4 mils)
- garnet – initial use – 0.1 to 0.4 mils (0.1, 0.2, 0.2, 0.3, 0.4, 0.4, 0.4 mils)
- garnet – after 2 to 3 uses – 0.1 to 0.8 mils (0.1, 0.4, 0.4, 0.7, 0.7, 0.8, one pulverized)
- steel grit – initial use – 0.1 to 0.5 mils (0.1, 0.5 mils)
- steel grit – after 25 uses – 0.5 to 0.6 mils (0.5, 0.6 mils)

The surface profile results can be summarized as follows:

1 – Fifteen of the 40 abrasives evaluated provided an average surface profile from 2 to 3 mils (14 of 26 expendable abrasives and 1 of 14 recyclable abrasives after one time use). After recycling, the average profile depths for 8 of the 14 recyclable abrasives fell within the 2 to 3 mil range, resulting in 22 of the 40 abrasives meeting the criteria.

2 – Twenty-five of the 40 abrasives exceeded the target profile of 2 to 3 mils (12 of 26 expendable abrasives and 13 of 14 recyclable abrasives after one time use). The average profile of 23 of the 25 abrasives that exceeded the target profile ranged from 3.13 to 3.95 mils. The profile of 1 garnet abrasive was 4.15 mils, and 1 silica sand abrasive was 4.40 mils. After recycling, 5 of the 14 recyclable abrasives exceeded the target profile. The average profiles of the abrasives ranged from 3.13 to 3.73.

3 -Dust suppressant was used on 2 coal slag samples. The surface profile compared with the untreated counterparts showed an apparent increase in one sample (2.8 to 3.13 mils) and an apparent decrease in the other (3.72 to 3.42 mils). It can not be concluded from the limited data whether the use of dust suppressant effects profile.

4 - Dust suppressant was used on 3 silica sand abrasives. The surface profile compared with the untreated counterparts showed an apparent increase for the first sample (2.73 to 2.92 mils), an apparent decrease for the second sample (3.42 to 3.02 mils), and no change for the third sample (2.80 vs. 2.83 mils). It can not be concluded from the limited data whether the use of dust suppressant effects profile.

5- Dust suppressant was used on 1 copper slag abrasive that was used 2 times. The surface profile compared with the untreated counterpart showed an apparent increase upon initial use (3.68 to 3.95) and an apparent decrease after recycling (3.43 to 2.93). It can not be concluded from the limited data whether the use of dust suppressant effects profile.

6 – The consistency in surface profile readings across the surface varied considerable with the specific product. As a generic class, the consistency of the silica sand abrasives ranged from a profile spread of 0.1 mils to a spread of 0.9 mils (based on 7 individual products). All of the alternative abrasives fell within this range with the exception of 1 coal slag abrasive (1.0 mil spread). One silica sand with dust suppressant also exceeded this range (1.4 mil spread).

7 – The most controlled profiles as a class of abrasives were staurolite with a range of 0.2 to 0.4 mils (based on 2 samples only) and the initial use of garnet with a range of 0.1 to 0.4 mils (based on 7 samples). Comments can not be made for crushed glass as a class as only 1 sample was evaluated (but the range of 0.4 mils is in line with the above), or for copper slag with dust suppressant as only 1 sample was evaluated (but the range of 0.3 is in line with the above).

8 – After recycling, the control over the range in surface profiles for copper slag abrasives was similar to the initial ranges (0.2 mil to 0.7 mil spread in profile readings for given abrasives initially to a 0.3 to 0.6 mil spread after 2 uses). The control over profiles for garnet tended to worsen with recycling. The initial spread in profile measurements for given garnet abrasives ranged from 0.1 to 0.4 mils. After 2 to 3 recycles, the spread in profiles for given abrasives ranged from immeasurable (a pulverized dust was created in one abrasive after 2 uses) to 0.1 to 0.8 mils. The control over the range in surface profiles with the steel grit was slightly reduced from an initial spread of 0.1 and 0.5 mils (for the 2 abrasives evaluated) to a spread of 0.5 and 0.6 mils.

Breakdown Rate (pre-blast and post-blast average particle size comparison)

Tables A3 (expendable) and A9 (recyclable) show the change in average abrasive particle size after use. The breakdown percentages are reflected in two different manners in the last two columns of the tables. One column shows the spent abrasive in terms of percent reduction in average particle size (Average Particle Size is Reduced by X%). The other shows the average particle size of the spent abrasive as a percent of the original particle size (Average Particle Size is X% of Original). For the purpose of the discussion below, the data entitled, “Average Particle Size is Reduced by X%” is used (the lower the percentage, the more conducive is the abrasive for multiple uses. The lower percentages will also produce less airborne dust):

- The average particle size of the crushed glass was reduced by 51.36% after use.

- The average particle sizes of the 7 coal slag abrasives were reduced by 38.1 to 54.71% after use. The samples fell into two general ranges: 2 samples were reduced by 38.41 and 39.69%, and 5 samples were reduced by 49.97 to 54.71%.

- The average particle sizes of the 2 coal slag samples treated with dust suppressant were reduced by 52 and 53.46%. Both reductions in average particle size were greater than their untreated counterparts: 52% reduction vs. 39.69% and 53.46% vs. 51.36%. The virgin samples treated with dust suppressant also exhibited a greater initial average particle size than their untreated counterparts.

- The average particle sizes of the 2 nickel abrasives were reduced by 51.2 and 53.9% after use.

- The average particle size of the olivine abrasive was reduced by 33.58% after use.

- The average particle sizes of the 2 staurolite abrasives were reduced by 18.06 and 19.63% after use.

- The average particle size of the specular hematite abrasive was reduced by 40.72% after use.

- The average particle sizes of the 7 silica sand abrasives were reduced by 25.58 to 72.88% after use. The abrasives can be categorized as follows: 1 sample reduced by 25.58%, 2 samples reduced by 40.75 and 46.38%; 4 samples reduced by 59.65 to 72.88%.

- The average particle sizes of the 3 silica sand samples treated with dust suppressant were reduced by 31.28, 46.28, and 66.54% after use. This reduction was greater than the untreated counterpart in one case, equivalent in another, and less in the third: 66.54% reduction vs. 25.58%, 46.86% reduction vs. 46.38%, and 31.28% reduction vs. 40.74%. The samples treated with dust suppressant also exhibited a greater initial average particle sizes than their untreated counterparts.

- The average particle sizes of the 4 copper slag abrasives were reduced by 51.80 to 52.36% after initial use. After recycling 2 times, the average particle sizes were reduced by 58.14 to 69.53% from the original.

- The average particle size of the copper slag sample treated with dust suppressant was reduced 60.36% after use. This reduction was greater than its untreated counterpart: 60.36% vs. 51.80%. After recycling two times the average percentages were reduced by 69.46%. The sample treated with dust suppressant also exhibited a greater initial average particle size than the untreated sample.

- The average particle sizes of the 7 garnet abrasive were reduced by 20.74 to 60.05% after use. The abrasives can be categorized as follows: 1 sample reduced by 20.74%; 4 samples reduced by 36.49 to 47.03%; 2 samples reduced by 55.93 and 60.05%. After recycling (from 2 to 3 times) the average particle sizes were reduced by 40.11 to 75.81% from the original.

- The average particle sizes of the 2 steel grit abrasives were reduced by 4.30 and 7.86%. After recycling for the maximum test design of 25 times, the average particle sizes were reduced 8.72% from the original in one case. For the other sample, the data indicates an increase in size. The reason for this is unknown.

The results can be summarized as follows:

1 – The typical breakdown (average particle size reduction) percentage for silica sand is 40.75 to 72.88% (although 1 of the 7 abrasives showed a lower value of 25.58%). Using 25.58% as the lower limit, the abrasives showing lower breakdown percentages are the 2 staurolite abrasives (18.06 and 19.63% reduction in particle size), 1 garnet abrasive (20.74% reduction upon initial use), and both steel grit abrasives (4.30 and 7.86% reduction upon initial use and 8.72% reduction after 25 recycles).

2 – Based on breakdown percentages after first use, the hierarchy of abrasives most likely to be used more than one time (arbitrarily using 40.00% reduction in average particle size as the threshold) are: steel grit (4.30 and 7.86% reduction in average particle size), 2 staurolite abrasives (18.06 and 19.63% reduction), 2 garnet abrasives (20.74 and 36.49% reduction), 1 silica sand (25.58% reduction), 1 silica sand with dust suppressant (31.28% reduction), 1 olivine (33.58% reduction), and 2 coal slag abrasives (38.41 and 39.69% reduction).

3 – The initial particle sizes of the coal slag, silica sand, and copper slag abrasives treated with dust suppressant were greater than the untreated counterparts.

Abrasive Embedment

A total of 15 individual abrasive embedment evaluations were made for each blast cleaning run (5 evaluations on 3 separate panels). The results are attached in Tables A4 (expendable) and A10 (recyclable). The results represent the number of 1.3 mm x 1.3 mm squares out of 100 (covering a surface area of one-half square inch) which contained embedded abrasive particulate. The 5 individual measurements for each of the 3 panels are shown on the table. The results are presented as a percentage, summarized as follows (the lower the number, the less is the embedment):

- The crushed glass abrasive contained an average embedment of 2.1%.

- The 7 coal slag abrasives showed a wide variation in results, ranging from 3.6% to 25.3% embedment. The majority of the samples (5) contained average embedment ranging from 8.4 to 15.7%.

- The 2 coal slag abrasives treated with dust suppressant showed 4.7 and 10.3% embedment. Both are an approximate 50% reduction from their untreated counterparts (8.4 and 25.3% respectively).

- The 2 nickel abrasives showed wide variations in embedment, averaging 1.2 and 27.3%.

- The olivine abrasive showed an average embedment of 15.1%.

- The 2 staurolite abrasives showed an average embedment of 0.1 and 0.2%.

- The specular hematite abrasive showed an average embedment of 0.7%.

- The 7 silica sand abrasives showed average embedment ranging from 0.1 to 12.3%. The majority of the samples (5) ranged from 0.1 to 4.7%. The remaining 2 were 9.2 and 12.3%.

- The 3 silica sand abrasives treated with dust suppressant showed 0.8, 1.2, and 2.7% embedment. This represents essentially no change in two cases compared with the untreated counterparts (1.1 vs. 0.8%, and 2.9 vs. 2.7%), and a slight increase of 1% in the other (0.1% to 1.2%).

- The 4 copper slag abrasives showed two general conditions of embedment upon initial use. Two samples showed 12.5% and 17.0%, and two showed 31.1 and 41.5%. After recycling, the amount of embedment was decreased for 3 of the 4 abrasives: 17.0% decreased to 8.1%, 31.1% decreased to 23.1%, and 41.5% decreased to 21.9%. The increase involved the sample with the lowest amount of initial embedment: 12.5% increased to 17.3%.

- The copper slag abrasive treated with dust suppressant showed a similar amount of embedment initially and after recycling: 19.0 and 19.3%. This represents an increase in the amount of embedment compared with its untreated counterpart (12.5% initially and 17.3% after recycling).

- The 7 garnet samples showed average embedment to range from 0.1% to 36.7%. The majority of the samples (5) ranged from 2.1 to 9.7%. After recycling, the average embedment was reduced in every case except one (0.1% became 0.2%), resulting in a range of embedment from 0.2 to 3.3%.

- The 2 steel abrasives showed initial average embedments of 3.1 and 4.1%. After recycling, both dropped to 1.6 and 2.3% respectively.

The results can be summarized as follows:

1 – The typical embedment percentage for silica sand is 0.1 to 12.3% embedment (5 samples ranged from 0.1 to 4.7%, the remaining 2 were 9.2 and 12.3%). Using 0.1 to 4.7% as the target embedment range, the abrasives showing comparable or lower embedment percentages are crushed glass (2.1%), 2 coal slag abrasives (3.6 and 4.7%), 1 coal slag with dust suppressant (4.7%), 1 nickel abrasive (1.2%), 2 staurolite abrasives (0.1 and 0.2%), 1 specular hematite (0.7%), 3 silica sand abrasives with dust suppressant (0.8 to 2.7%), 3 garnet abrasives after initial use (0.1, 2.1, and 4.7%), 6 garnet abrasives after 2 to 3 uses (1.4 to 4.7%), steel grit after initial use (3.1 and 4.1%), and steel grit after 25 uses (1.6 and 2.3%).

2 – The amount of embedment was reduced after recycling for 3 of the 4 copper slag abrasives, 6 of the 7 garnet abrasives (the 7th abrasive was 0.1 to start with and essentially showed no change), and the 2 steel grit abrasives.

3 – The use of dust suppressant on the coal slag abrasives showed a major decrease in embedment over the untreated counterparts (8.4 to 4.7% and 25.3 to 10.3%), but firm conclusions regarding the influence of dust suppressant on embedment can not be made due to limited data.

4 - The use of dust suppressant on the silica sand abrasives showed essentially no change in embedment in two cases compared with the untreated counterparts (1.1 vs. 0.8%, and 2.9 vs. 2.7%), and a slight increase in the other (0.1% to 1.2%). Conclusions regarding the effect of dust suppressant on embedment can not be made from the limited data.

5 - The use of dust suppressant on the copper slag abrasive showed an increase in the amount of embedment compared with its untreated counterpart (19.0% vs. 12.5% initially and 19.3% vs. 17.3% after recycling), but firm conclusions regarding the influence of dust suppressant on embedment can not be made due to limited data.

Microhardness

Measurements of microhardness were made in accordance with ASTM E384[9]. This method provides results in Knoop units (the higher the number, the harder the abrasive). Tables A5 (expendable) and A11 (recyclable) show the results of the microhardness evaluations. For comparison, 6 on the Mohs hardness scale is approximately 500 Knoop. The results of 2 individual readings are shown together with the maximum reading obtained. In many cases, the two individual readings varied greatly. This is likely due to the selection of an abrasive particle for testing that contained porosity or other discontinuity, leading to an inappropriately low value. For this reason, when summarizing the results, the single maximum microhardness reading is used, rather than averaging the two together, to avoid biasing the data by virtue of the lower value.

- The crushed glass abrasive showed a maximum microhardness value of 457.5.
- The 7 coal slag abrasives showed maximum microhardness values ranging from 611 to 720.
- The 2 coal slag abrasives treated with dust suppressant showed maximum microhardness values of 594 and 760. This was an apparent increase in one case compared with the untreated counterpart (760 vs. 669), and an apparent decrease in the other (594 vs. 617).
- The 2 nickel slag abrasives showed maximum microhardness values of 545 and 984.
- The olivine abrasive showed a maximum microhardness value of 960.
- The 2 staurolite abrasives showed maximum microhardness values of 219 and 937.
- The specular hematite abrasive showed a maximum microhardness value of 1182.
- The 7 silica sand abrasives showed maximum microhardness values ranging from 1267 to 2469. The abrasives can be categorized as follows: 1 with a maximum microhardness of 1267; 4 with maximum microhardness ranging from 1537 to 1809; and 2 with a maximum microhardness values of 2008 and 2469.
- A total of 3 silica sand abrasives were treated with dust suppressant: 2 showed maximum microhardness values of 643 and 1924. The third could not be evaluated as the material was too porous to be analyzed. There was an apparent increase in one case compared with the untreated counterpart (2008 vs. 1587), and an apparent decrease in another (643 vs. 1809). A comparison for the third can not be made as the treated material sample was too porous to measure. Its untreated counterpart was 1809.
- The 4 copper slag abrasives showed maximum microhardness values ranging from 540 to 769.
- The copper slag abrasive treated with dust suppressant showed a maximum microhardness value of 656. This is an apparent decrease from its untreated counterpart (656 vs. 662).

- The 7 garnet abrasives showed maximum microhardness values ranging from 535 to1809. The abrasives can be categorized as follows: 1 with maximum microhardness values ranging from 535; 1 with a maximum microhardness value of 948; 4 with maximum microhardness values ranging from 1285 to 1587; and 1 with a maximum microhardness value of 1809.

- The 2 steel grit abrasives showed maximum microhardness values of 240 and 823.

The results can be summarized as follows:

1 – The microhardness of the 7 silica sand abrasives ranged from 1267 to 2469. All of the alternative abrasives are softer than silica sand with the exception of 5 of the 7 garnet abrasives (1537 to 2154.4).

2 – Two coal slag abrasives were treated with dust suppressant. One sample showed an apparent increase in microhardness compared with the untreated counterpart (760 vs. 669), and an apparent decrease in the other (594 vs. 617). Conclusions regarding the effect of dust suppressant on microhardness can not be made from the limited data.

3 - A total of 3 silica sand abrasives were treated with dust suppressant. One sample showed an apparent increase in microhardness compared with the untreated counterpart (2008 vs. 1587), and an apparent decrease in another (643 vs. 1809). A comparison for the third sample could not be made as the treated sample was too porous to measure. Conclusions regarding the effect of dust suppressant on microhardness can not be made from the limited data.

4 - One copper slag abrasive was treated with dust suppressant. It showed an apparent decrease from its untreated counterpart (656 vs. 662). Conclusions regarding the effect of dust suppressant on microhardness can not be made from the limited data.

Conductivity (water soluble contaminants)

Conductivity measurements were made in accordance with ASTM D4940[10] in order to evaluate whether water soluble materials are present in the abrasive. Tables A6 (expendable) and A12 (recyclable) show the results of the conductivity measurements in microsiemens (1 microsiemen = 1 micromho/cm). A value less than 1,000 microsiemens is considered to be acceptable. A single test was run for each abrasive since all results were well below the 1,000 microsiemens threshold value. The results can be summarized as follows:

- The crushed glass abrasive measured 112.0 microsiemens.

- 6 of the coal slag abrasives measured from 23.8 to 96.7 microsiemens. One of the coal slag abrasives measured 833.3 microsiemens.

- One of the coal slag abrasives treated with dust suppressant measured 42 microsiemens, which was essentially the same as its untreated counterpart. The other coal slag treated with dust suppressant measured 400.3 microsiemens, which is essentially 50% of its untreated counterpart.

- The nickel abrasives measured 36.3 and 146.7 microsiemens.

- The olivine abrasive measured 96.7 microsiemens.

- The 2 staurolite abrasives measured 87.3 and 213.3 microsiemens.

- The specular hematite abrasive measured 63.3 microsiemens.

- 6 of the 7 silica sand abrasives measured from 18.2 to 96.7 microsiemens. The remaining abrasive measured 708.3 microsiemens.

- The 3 silica sand abrasives treated with dust suppressant measured from 25 to 99.3 microsiemens. Compared to the untreated counterparts, this resulted in an increase of 19.3 microsiemens in one case to decreases of 5.3 and 13 microsiemens in the two others.

- The 4 copper slag abrasives measured 31.8 to 135 microsiemens. After recycling, the values for 2 of the samples increased by 27.5 and 91.6 microsiemens, and the remaining 2 decreased by 1.0 and 15 microsiemens. The highest value after recycling was 223.3 microsiemens.

- The copper slag abrasive treated with dust suppressant measured 26.3 which was 5.5 microsiemens less than its untreated counterpart. After recycling, the value increased by 27 microsiemens.

- 4 of the 7 garnet abrasives measured from 9.0 to 47.0 microsiemens. The remaining 3 samples measured 95.7, 145.0, and 586.7 microsiemens. After recycling, the values for 4 of the samples increased from 0.6 to 26.3 microsiemens. The values for 1 of the samples decreased 41.7 microsiemens, and the sample with the original value of 586.7 microsiemens decreased by 336.7 microsiemens. The final sample was not measured because no usable material remained after recycling.

- The initial values for the 2 steel grit samples were 33.7 and 100.0 microsiemens. After recycling 1 sample remained essentially unchanged and the other (100) decreased by 20 microsiemens.

The results can be summarized as follows:

1 – SSPC AB1 " Mineral and Slag Abrasives"[17] and AB2 "Specification For Cleanliness of Recycled Ferrous Metallic Abrasives"[18] recommends that the conductivity of abrasives

be maintained below 1000 microsiemens. Based on this criteria, all of the abrasives exhibit acceptable levels.

2 – The conductivity of the silica sand abrasives is 18.2 to 96.7 microsiemens (6 of 7 abrasive samples) with 1 sample measuring 708.3 microsiemens. Using a maximum of 96.7 as the threshold, the following abrasives exhibit conductivity levels less than or equivalent to silica sand: 6 of 7 coal slag abrasives, 1 coal slag abrasive treated with dust suppressant, 1 of 2 nickel slag abrasives, 1 of 1 olivine abrasives, 1 of 2 staurolite abrasives, 1 of 1 specular hematite, 1 of 3 silica sand abrasives treated with dust suppressant, 2 of 4 copper slag abrasives prior to initial use, 2 of 4 copper slag abrasives after 2 to 3 uses, 1 of 1 copper slag abrasives treated with dust suppressant both initially and after 2 uses, 5 of 7 garnet abrasives prior to initial use, 4 of 7 garnet abrasives after 2 to 3 uses (1 sample pulverized to an unusable dust after 2 uses), 1 of 2 steel grit abrasives initially, and 2 of 2 steel grit abrasives after 25 uses.

3 – Two coal slag abrasives were treated with dust suppressant. One of the sample abrasives measured 42 microsiemens, which was essentially the same as its untreated counterpart. The other sample measured 400.3 microsiemens, which is essentially 50% of its untreated counterpart. Conclusions regarding the effect of dust suppressant on conductivity can not be made from the limited data.

4 – A total of 3 silica sand abrasives were treated with dust suppressant. The samples measured from 25 to 99.3 microsiemens. Compared to the untreated counterparts, this resulted in an increase of 19.3 microsiemens in one case, and decreases of 5.3 and 13 microsiemens in the other two. Conclusions regarding the effect of dust suppressant on conductivity can not be made from the limited data.

5 – One copper slag abrasive was treated with dust suppressant. The sample measured 26.3 microsiemens, which was 5.5 microsiemens less than its untreated counterpart. After recycling, the value increased by 27 microsiemens over the untreated counterpart. Conclusions regarding the effect of dust suppressant on conductivity can not be made from the limited data.

Comparisons Between Abrasive Types

A comparison of the general performance characteristics of the 40 abrasives is presented below. Since many characteristics of an abrasive effect its performance, selection of abrasive type should not be restricted to only a single characteristic. Experimental results were graphed in order to determine the influence that one abrasive attribute has on another. A linear regression was performed for various combinations of attributes to determine trends. These graphs are attached in Appendix C. The conclusions presented below are based upon this analysis for the removal of mill scale.

- Surface profile was directly proportional to the abrasive particle size (the larger the abrasive particle size, the deeper the profile)

- Cleaning rate was inversely proportional to the abrasive particle size (the larger the abrasive particle size, the slower the cleaning rate)

- Consumption rate was directly proportional to the abrasive particle size (the larger the abrasive, the greater was the abrasive consumption on a weight per square foot basis)

- Breakdown rate was directly proportional to microhardness (the harder the abrasive, the greater its friability)

Based upon these observations, optimal abrasive materials for the removal of mill scale would be as small as possible while maintaining the surface profile requirements. (It should be noted that when removing heavy rust scale and heavy paint, the size of the abrasive is often increased to benefit from the greater mass of the abrasive in removing the heavy material, rather than "wearing it" away as is would be the case with the smaller abrasive.) If the objective is to reuse the abrasive and/or reduce dusting, the hardness should be considered. Harder abrasives (with the exception of steel) tend to break down more rapidly than softer abrasives. Abrasives should also be low in soluble contaminants in order to minimize negative effects on coatings performance.

With consideration of the above, the attributes of the 12 alternative generic abrasive types are reviewed.

Crushed Glass

One crushed glass abrasive was evaluated, making it difficult to make conclusions regarding this class of abrasive as a whole. Based on the product evaluated, the cleaning and consumption rates (33 square feet/hour and 10.99 pounds/square foot) are similar to silica sand as a class (25 to 37 square feet/hour and 9.05 to13.48 pounds/square foot). The surface profile averaged 2.72 mils, which complied with the study target of 2-3 mils, and is acceptable for coating performance. The variation in profile across the surface (spread of 0.4 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils). The breakdown rate (51.36%) was consistent with silica sand as a class (25.58% to 72.88%). Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is much harder than crushed glass (1267 to 2469 Knoop vs. 457.5 Knoop). The amount of embedment (2.1%) was comparable to those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The conductivity (112 microsiemens) is slightly higher than most of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens), but still well below the 1000 microsiemen level of concern.

Coal Slag

A total of 7 coal slag abrasives were evaluated. The results demonstrate that there is a wide range in physical properties between the individual abrasives within this class. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results. Based on the products evaluated, the cleaning and consumption rates (28 to 42 square feet/hour and 9.05 to 12.35 pounds/square foot) are similar to silica sand as a class (25 to 37 square feet/hour and 9.05 to 13.48 pounds/square foot). The surface profile ranged from 2.67 to 3.72 mils which, although in excess of the target 2-3 mils, is not a problem for coating performance. The variation in profile across the surface (spread of 0.2 to1.0 mils) was outside of the tolerances of silica sand as a class (0.1 to 0.9 mils) because of one abrasive. If the single abrasive is eliminated, the remaining 6 abrasives exhibit a spread of 0.2 to 0.6 mils. The breakdown rate (38.1 to 54.71%) was consistent with silica sand as a class (25.58% to 72.88%). Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is much harder than coal slag (1267 to 2469 Knoop vs. 611 to 720 Knoop). The amount of embedment (3.6 to 25.3%) was in excess of those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The conductivity (23.8 to 96.7 microsiemens) is comparable to most of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens) with the exception of 1 coal slag that exhibited a value of 833.3 microsiemens. All coal slag abrasives were below the 1000 microsiemen level of concern.

Coal Slag with Dust Suppressant

A total of two coal slag abrasives treated with dust suppressant were evaluated. The results demonstrate a range in physical properties likely attributable to the coal slag rather than the dust suppressant. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results. Based on the products evaluated, the cleaning and consumption rates (35 and 38 square feet/hour, and 10.64 and 12.20 pounds/square foot) are similar to silica sand as a class (25 to 37 square feet/hour and 9.05 to 13.48 pounds/square foot). The surface profile ranged from 3.13 to 3.72 mils which, although in excess of the target 2-3 mils, is not a problem for coating performance. The variation in profile across the surface (spread of 0.6 to 0.7 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils). The breakdown rate (52 to 53.46%) was consistent with silica sand as a class (25.58% to 72.88%). Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is significantly harder than coal slag treated with dust suppressant (1267 to 2469 Knoop vs. 594 and 760 Knoop). The amount of embedment (4.7 and 10.3%) was in excess of those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The conductivity (42 and 400.3 microsiemens) is higher than most of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens), but still well below the 1000 microsiemen level of concern.

A comparison of the coal slag abrasives treated with dust suppressant versus the untreated counterparts shows no trend for any of the attributes except one. The dust suppressant appears to decrease the amount of embedment. For all other characteristics, the dust suppressant showed both increases and decreases in performance compared with the untreated material.

Nickel Slag

A total of 2 nickel slag abrasives were evaluated. The results demonstrate that there is a variation in physical properties between the individual abrasives within this class. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results. Based on the products evaluated, the cleaning and consumption rates (35 and 47 square feet/hour and 12.5 and 15.83 pounds/square foot) are similar to silica sand as a class (25 to 37 square feet/hour and 9.05 to 13.48 pounds/square foot). The surface profile measured 3.25 and 3.87 mils which, although in excess of the target 2-3 mils, is not a problem for coating performance. The variation in profile across the surface (spread of 0.6 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils). The breakdown rate (51.2 and 53.9%) was consistent with silica sand as a class (25.58% to 72.88%). Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is much harder than nickel slag (1267 to 2469 Knoop vs. 545 and 984 Knoop). The amount of embedment (1.2%) in one sample was comparable to those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The other was significantly greater (27.3%). The conductivity (36.3 and 146.7 microsiemens) is higher than some of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens), but still well below the 1000 microsiemen level of concern.

Olivine

One olivine abrasive was evaluated, making it difficult to make conclusions regarding this class of abrasive as a whole. Based on the product evaluated, the cleaning and consumption rates (44 square feet/hour and 8.02 pounds/square foot) are better than silica sand as a class (25 to 37 square feet/hour and 9.05 to13.48 pounds/square foot). The surface profile averaged 3.03 mils, which essentially complied with the study target of 2-3 mils, and is acceptable for coating performance. The variation in profile across the surface (spread of 0.7 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils). The breakdown rate (33.58%) was consistent with silica sand as a class (25.58% to 72.88%). Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is much harder than olivine (1267 to 2469 Knoop vs. 960 Knoop). The amount of embedment (15.1%) exceeded those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The conductivity (96.7 microsiemens) is comparable to most of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens), and well below the 1000 microsiemen level of concern.

Staurolite

A total of 2 staurolite abrasives were evaluated. The results demonstrate that there is a variation in physical properties between the individual abrasives within this class. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results. Based on the products evaluated, the cleaning and consumption rates (44 and 49 square feet/hour, and 7.51 and 9.90 pounds/square foot) are an improvement over silica sand as a class (25 to 37 square feet/hour and 9.05 to 13.48 pounds/square foot). The surface profile measured 2.02 and 2.08 mils, which complied with the study target of 2-3 mils, and is acceptable for coating performance. The variation in profile across the surface (spread of 0.2 to 0.4 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils). The breakdown rate (18.06 and 19.63%) was better than silica sand as a class (25.58% to 72.88%). Silica sand is also much harder than staurolite (1267 to 2469 Knoop vs. 219 and 937 Knoop). The amount of embedment (0.1 and 0.2%) was comparable to those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The conductivity (87.3 and 213.3 microsiemens) is higher than some of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens), but still well below the 1000 microsiemen level of concern.

Specular Hematite

One specular hematite abrasive was evaluated, making it difficult to make conclusions regarding this class of abrasive as a whole. Based on the product evaluated, the cleaning rate (32 square feet/hour) is comparable to, and the consumption rate (6.60 pounds/square foot) is better than, silica sand as a class (25 to 37 square feet/hour and 9.05 to13.48 pounds/square foot). The surface profile averaged 2.77 mils, which complied with the study target of 2-3 mils, and is acceptable for coating performance. The variation in profile across the surface (spread of 0.5 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils). The breakdown rate (40.72%) was consistent with silica sand as a class (25.58% to 72.88%). Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is harder than specular hematite (1267 to 2469 Knoop vs. 1182 Knoop). The amount of embedment (0.7%) was comparable to those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The conductivity (63.3 microsiemens) is comparable to most of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens), and is well below the 1000 microsiemen level of concern.

Silica Sand with Dust Suppressant

A total of 3 silica sand abrasives treated with dust suppressant were evaluated. The results demonstrate a range in physical properties likely attributable to the silica sand rather than the dust suppressant. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results. Based on the products evaluated, the cleaning and consumption rates (26 to 39 square feet/hour and 8.74 to 13.89 pounds/square foot) are similar to untreated silica sand as a class (25 to 37 square feet/hour and 9.05 to 13.48 pounds/square foot). The surface profile ranged from 2.83 to 3.02 mils, which complied with the study target of 2-3 mils, and is acceptable for coating performance. The variation in profile across the surface (spread of 0.2 to 0.3 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils), with the exception of 1 sample which exhibited a spread of 1.4 mils. The breakdown rate (31.28 to 66.54%) was consistent with silica sand as a class (25.58% to 72.88%). The silica sand abrasives tested were harder than the silica sand abrasives treated with dust suppressant (1267 to 2469 Knoop vs. 643 to 1924 Knoop). The amount of embedment

(0.8 to 2.7%) was greater than the silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). The conductivity (25 to 99.3 microsiemens) is comparable to the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens), and well below the 1000 microsiemen level of concern.

A comparison of the silica sand abrasives treated with dust suppressant versus the untreated counterparts shows no trend for any of the attributes. The dust suppressant showed both increases and decreases in performance compared with the untreated materials for each of the characteristics evaluated.

Copper Slag

Copper slag was classified as a recyclable abrasive for the purpose of the study. The various abrasives were recycled 2 times. The limit on recycling was defined as the point where a reduction in average particle size of 50% occurred. Once this value was obtained, recycling was ended. A total of 4 copper slag abrasives were evaluated. The results demonstrate that there is a wide range in physical properties between the individual abrasives within this class. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results.

Based on the products evaluated, the cleaning rates upon initial use (28 to 61 square feet/hour) are higher than silica sand as a class (25 to 37 square feet/hour). The consumption rates (12.95 to 24.29 pounds/square foot) are not valid comparisons since the abrasive can be recycled a few times, and as such, the value represents the amount of abrasive that impacts the surface rather than the amount of abrasive "consumed." As a point of reference, silica sand as a class is 9.05 to 13.48 pounds/square foot, which is less than copper slag if it is used only one time. After 2 uses, the cleaning rates showed further increases (33 to 92 square feet/hour) and "consumption" rates remained essentially unchanged (12.96 to 25.80 pounds/square feet).

The surface profile upon initial use ranged from 3.68 to 3.92 mils which, although in excess of the target 2-3 mils, is not a problem for coating performance. After 2 uses, the profile was reduced to a range of 2.98 to 3.43 mils. The variation in profile across the surface for the abrasives upon initial use (spread of 0.2 to 0.7 mils) and upon recycling (spread of 0.3 to 0.6 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils).

The breakdown rate upon initial use (51.80 to 52.36%) was consistent with silica sand as a class (25.58% to 72.88%). After 2 cycles, the breakdown rate increased to 58.14 to 69.53%. Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is much harder than copper slag (1267 to 2469 Knoop vs. 540 to 769 Knoop).

The amount of embedment upon initial use (12.5 to 41.5%) exceeded those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). After 2 uses, the embedment was reduced to a range from 8.1 to 23.1%. The conductivity upon initial use (31.8 to 135 microsiemens) is higher than a few of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens). After 2 uses, the conductivity increased to 59.3 to 223.3 microsiemens, but still well below the 1000 microsiemen level of concern.

Copper Slag with Dust Suppressant

Copper slag treated with dust suppressant was classified as a recyclable abrasive for the purpose of the study. The abrasive was recycled 2 times. The limit on recycling was defined as the point where a reduction in average particle size of 50% occurred. Once this value was obtained, recycling was ended. Only one abrasive was evaluated, making it difficult to make conclusions regarding this class of abrasive as a whole.

Based on the product evaluated, the cleaning rate upon initial use (31 square feet/hour) is comparable to silica sand as a class (25 to 37 square feet/hour). The consumption rate (15.64 pounds/square foot) is not valid a comparison since the abrasive can be recycled a few times, and as such, the value represents the amount of abrasive that impacts the surface rather than the amount of abrasive "consumed." As a point of reference, silica sand as a class is 9.05 to 13.48 pounds/square foot, which is less than copper slag if it is used only one time. After 2 uses, the cleaning rate increased to 40 square feet/hour and the "consumption" rate dropped slightly to 14.54 pounds/square feet.

The surface profile upon initial use was 3.95 mils which, although in excess of the target 2-3 mils, is not a problem for coating performance. After 2 uses, the profile was reduced to 2.93 mils. The variation in profile across the surface upon initial use (spread of 0.3 mils) and upon recycling (spread of 0.4 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils).

The breakdown rate upon initial use (60.36%) was consistent with silica sand as a class (25.58% to 72.88%). After 2 cycles, the breakdown rate increased to 69.46%. Although a few of the silica sand abrasives exhibited lesser breakdown rates, silica sand is much harder than copper slag treated with dust suppressant (1267 to 2469 Knoop vs. 656 Knoop).

The amount of embedment upon initial use (19.0%) exceeded those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). After 2 uses, the embedment remained constant at 19.3%. The conductivity upon initial use (26.3 microsiemens) is comparable to most of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens). After 2 uses, the conductivity increased to 53.3 microsiemens, but still well below the 1000 microsiemen level of concern.

A comparison of the coal slag abrasive treated with dust suppressant versus its untreated counterpart shows possible trend for four of the attributes tested. Although the data is quite limited, the dust suppressant appears to decrease cleaning and consumption rates initially and upon reuse, reduce the breakdown rate, and increase the amount of embedment.

Garnet

Garnet was classified as a recyclable abrasive for the purpose of the study. The various abrasives were recycled between 2 to 3 times. The limit on recycling was defined as the point where a reduction in average particle size of 50% occurred. Once this value was obtained, recycling was ended (or when 5 recycles was reached which was the limit of the study design). A total of 7 garnet abrasives were evaluated. It should be noted that 1 of the 7 abrasives became too pulverized after 2 uses to be of value in any of the follow up tests. As a result, all data after recycling is based on 6, rather than 7 abrasives. The results demonstrate that there is a wide range in physical properties between the individual abrasives within this class. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results.

Based on the products evaluated, the cleaning rates upon initial use (24 to 62 square feet/hour) are higher than silica sand as a class (25 to 37 square feet/hour). The consumption rates (7.43 to 14.42 pounds/square foot) are not valid comparisons since the abrasive can be recycled a few times, and as such, the value represents the amount of abrasive that impacts the surface rather than the amount of abrasive “consumed.” As a point of reference, silica sand as a class is 9.05 to 13.48 pounds/square foot, which is comparable to garnet if it is used only one time. After 2 to 3 uses, the cleaning rates showed further increases (31 to 75 square feet/hour) and “consumption” rates were further reduced (7.12 to 9.6 pounds/square feet).

The surface profile upon initial use ranged from 2.68 to 4.15 mils which, although generally in excess of the target 2-3 mils, is typically not a problem for coating performance. After 2 to 3 uses, the profile was reduced to a range of 2.07 to 3.32 mils. The variation in profile across the surface for the abrasives upon initial use (spread of 0.1 to 0.4 mils) and upon recycling (spread of 0.1 to 0.8 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils).

The breakdown rate upon initial use (20.74 to 60.05%) was consistent with silica sand as a class (25.58% to 72.88%). After 2 to 3 cycles, the breakdown rate increased to 40.11 to 75.81%. Silica sand is harder than garnet as a class (1267 to 2469 Knoop vs. 535 to 1809 Knoop).

The amount of embedment upon initial use (0.1 to 36.7%) exceeded those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). After 2 to 3 uses, the embedment was reduced to a range from 0.2 to 3.3%. The conductivity upon initial use (9.0 to 586.7 microsiemens) is higher than some of the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens). After 2 to 3 uses, the conductivity was reduced overall to 25 to 250 microsiemens, well below the 1000 microsiemen level of concern.

Steel Grit

Steel grit was classified as a recyclable abrasive for the purpose of the study. A total of 2 abrasives were evaluated. The abrasives were recycled 25 times. The limit on recycling was defined as the point where a reduction in average particle size of 50% occurred. Once this value was obtained, recycling was ended (or when 25 recycles was reached in the case of steel grit which was the limit of the study design). The results demonstrate that there is a wide range in physical properties between the individual abrasives within this class. Prior to use, the specific abrasive of interest should be investigated individually for its own merits rather than rely on generic results.

Based on the products evaluated, the cleaning rates upon initial use (27 and 39 square feet/hour) are comparable to silica sand as a class (25 to 37 square feet/hour). The consumption rates (21.53 and 27.71 pounds/square foot) are not valid comparisons since the abrasive is capable of being recycled well over 100 times, and as such, the value represents the amount of abrasive that impacts the surface rather than the amount of abrasive "consumed." As a point of reference, silica sand as a class is 9.05 to 13.48 pounds/square foot. After 25 uses, the cleaning rates increased (31 to 44 square feet/hour) and "consumption" rates remained essentially unchanged (21.77 and 28.75 pounds/square feet).

The surface profile upon initial use ranged from 3.08 to 3.17 mils which, although in excess of the target 2-3 mils, is not a problem for coating performance. After 25 uses, the profile ranged from 2.88 to 3.4 mils (the reason for the apparent increase is unknown). The variation in profile across the surface for the abrasives upon initial use (spread of 0.1 to 0.5 mils) and upon recycling (spread of 0.4 to 0.6 mils) was within the tolerances of silica sand as a class (0.1 to 0.9 mils).

The breakdown rate upon initial use (4.3 to 7.86%) was far less than silica sand as a class (25.58% to 72.88%). After 25 cycles, the breakdown rate increased slightly to 8.72% for one abrasive, and showed no breakdown for the other (size was comparable to the original size used). None of the silica sand abrasives exhibited lesser breakdown rates. Silica sand is much harder than steel grit abrasives (1267 to 2469 Knoop vs. 240 and 823 Knoop).

The amount of embedment upon initial use (3.1 and 4.1%) was comparable to those silica sand products that exhibited the lower percentages of embedment (0.1 to 4.7%). After 25 uses, the embedment was reduced to a range from 1.6 to 2.3%. The conductivity upon initial use (33.7 and 100 microsiemens) is comparable to the silica sand products (18.2 to 96.7 microsiemens, with 1 measuring 708.3 microsiemens). After 25 uses, the conductivity was reduced to 34 to 80 microsiemens, well below the 1000 microsiemen level of concern.

Calculation of Operating Costs

In order to develop costs for the use of the abrasives based on the production and consumption rates resulting from the study, the cost of cleaning steel plates in a walk in blast room has been calculated. The cost involves the use of one operator to blast clean the steel. The data is presented in Table D1. It is important that this cost data not be misused. In an actual project, larger nozzle sizes will be selected and optimum adjustments of the equipment made to maximize productivity. As a result, costs per square foot will be considerably less than the calculations provided herein. In fact, two additional blast trials involving coal slag abrasive were conducted and are reported in Table D1. The same abrasive used for the process control checks was employed. The average cost to clean the steel for the process control checks was $1.47/sq ft. Increasing the nozzle size from 1/4" to 3/8" reduced the cost to $0.73/sq ft. Note that additional changes (nozzle to work place distance, metering valve setting) could result in further reduction. A discussion of these factors, as well as a brief description of how each factor effects the costs, follows.

Industry Cleaning and Consumption Rates versus Study Rates

As discussed in the "Concerns" section of this report, because of the restrictions placed on the equipment used for the Phase 1 laboratory testing, the cleaning and consumption rates for the abrasives are not representative of field production. They are only representative of productivity and consumption rates for the blast cleaning of steel within a blast room with all variables tightly controlled. The costs are much higher than would actually occur during such a field project, and the relative differences between abrasive costs will also vary. A more accurate assessment of field blast cleaning costs can be found in SSPC NSRP Report 0511[15]. While the NSRP data is believed to be a better representation of actual field performance, there may also be questions regarding the applicability of the shipyard data to all industries. Within the NSRP report, cleaning and consumption rates are available for all of the abrasives included in this study with the exception of specular hematite and the abrasives treated with dust suppressant. The data in the NSRP report show that as the nozzle size increases, cleaning rates increase and consumption rates decrease for each of the generic categories of abrasives. The cleaning and consumption rates based on the Phase 1 Study are presented in Tables A1 and A7.

Abrasive Flow Rate

The abrasive flow rate is the amount of abrasive actually used during the blast cleaning operations. This is commonly expressed in units of tons of abrasive used per hour of operation. This factor is highly dependent on the abrasive material itself, the blast cleaning equipment utilized, nozzle sizes, pressures, equipment adjustments, the number of blast nozzle operators, the type and integrity of the paint coating being removed, and the configuration of the structure being cleaned.

Abrasive Material Cost

The cost of abrasive materials varies by generic type, manufacturer, geographic location, and the quantity of material purchased. Each manufacturer and/or supplier of abrasive media used for this study was interviewed to determine material costs. The unit cost was based on approximately 20 tons without any delivery charge. See Table D1 for an itemization of material costs.

The material costs ranged from $13.00 per ton to $494.00 per ton. Within a single class or type of abrasive, the cost of the most expensive material was up to 64 percent greater than the cost of the least expensive. In all but one case, dust suppressant increased the unit cost of the abrasive by an average of 30 percent. The exception involved one manufacturer's product treated with dust suppressant that was priced less than the same product without the suppressant (the material without the dust suppressant was supplied from a different plant). For the purpose of this cost analysis, the average material cost for each of the generic abrasive types was used. Many factors could affect the final purchase price of the products, but they were not investigated as part of this project.

Abrasive Disposal Cost

The cost to properly dispose of the surface preparation waste varies somewhat by location, but is not dependent on abrasive type. The disposal cost used for this economic analysis was for solid material categorized as non-hazardous. A non-hazardous classification was used since historically abrasive waste free of paint or other constituents has not been tested by the Toxicity Characteristic Leaching Procedure (TCLP).[19] Since TCLP was not used on the abrasive waste from this study, there is no basis under this cost analysis for assuming that any of the abrasives would test hazardous for disposal. A value of $30.00 per ton was used based upon previous experience with painting project cost estimating and the actual cost for disposal of the abrasive waste generated during this phase of the study.

Equipment Costs

The equipment used for dry abrasive blast cleaning operations is contingent upon whether abrasive recycling will be employed. In both cases, compressed air and a blast pot are required. When abrasives are recycled, highly specialized equipment is typically used to reclaim and clean the abrasive, as well as to remove fine particles in an effort to maintain consistent surface profile. For the purpose of this economic analysis, the equipment necessary to blast clean steel plates in a walk-in blast room was used (based on the equipment used for the study).

6 cubic foot abrasive blast pot – $713/month
125 CFM air compressor – $601/month

Reclaiming system for recyclable abrasives – $1,000/month[*20]

Equipment costs were obtained from rental rates published in the 1998 AEG Green Book[21], published by the Machinery Information Division of K-III Directory Corp. The Green Book averages national rental rates for construction equipment (the 1998 version was the latest book in print at the time of the writing of this report). The costs used for the analysis were based on a rental term of one month, and values were converted to units of dollars per hour assuming a 40 hour work week and a month consisting of four and one third weeks.

Labor Costs

Actual labor rates for an abrasive blast cleaning nozzle operator were averaged from eleven cities. The published prevailing wage rates for Pittsburgh, Pa. were used as the baseline. These rates were adjusted for the various cities using cost of living adjustments provided in Real Estate Tables[22]. The rates for a Pittsburgh painter was $30.15/hour. Adjusted labor rates for the other cities were as follows:

Pittsburgh, Pennsylvania	$30.15	Lincoln, Nebraska	$30.66
New York, New York (Manhattan)	$82.92	Helena, Montana	$28.39
Los Angeles, California	$42.66	Houston, Texas	$27.48
Jacksonville, Florida	$30.59	Bangor, Maine	$30.47
Montgomery, Alabama	$30.25	Seattle, Washington	$33.54
		Anchorage, Alaska	$35.46

The labor rates, in units of dollars per hour, include the costs for benefits and insurance. No provisions were made to account for overtime work.

Number Of Recycles

The number of times the abrasive is used effects the overall abrasive blast cleaning costs. Even if the material unit cost of a recyclable abrasive is higher, the overall cost per square foot will typically be lower due to savings in material quantities and lower waste disposal costs. This factor was recognized during the cost analysis. The following recycling rates were used based on the Phase 1 results: copper slag – 2x, garnet – 2-3x, steel grit – 25x, and all other abrasives – 1x.

Abrasive Cleaning Rate

The abrasive cleaning rate profoundly effects the surface preparation costs, as the cleaning rate influences nearly all of the other economic factors described above. The cleaning rate of an abrasive is dependent upon many variables, including abrasive particle size distribution, shape, hardness, specific gravity, the degree of substrate cleanliness, blast equipment operating conditions, and the type and condition of the substrate (i.e. mill

[*] Small recycling units are available on a purchase, not rental basis. For the purpose of this analysis, a manufacturers' published rental price of a vacuum blast unit is used as the cost of the reclaimer.

scale, light corrosion, heavy rust and pitting, coated, etc.). Generally, abrasive types and sizes are chosen to obtain an optimum cleaning rate while maintaining the surface profile required for adequate coating adhesion. The cleaning rates in this case were reduced by virtue of the restrictions placed on the Study design.

Cost Analysis

The overall abrasive blast cleaning costs were calculated using the following equation:

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

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)

The following is an example for the use of the formula based on abrasive SS-01.

A = 1 nozzle x 10.42 lb/sq ft (consumption rate) x 0.562 sq ft/min (cleaning rate) x 60 min/hour ÷ 2000 lb/ton
A = 0.176 ton/hour

P = $22.00/ton

D = $30.00/ton

R = 1

E = [$713/month (blast pot) + $601/month (air)] ÷ (4.33 weeks x 40 hours/week)
E = $7.59/hour

L = $36.60/hour

X = 1 nozzle x 0.562 sq ft/min (cleaning rate) x 60 min/hour
X = 33.72 sq ft/hour

$$\text{Cleaning Costs} = \frac{\left[\frac{0.176(22.00+30.00)}{1}+7.59+36.60\right]}{33.72}$$

Cleaning Costs = $1.58/sq ft

The results of the economic analysis are summarized in Table D1. The results are much higher than costs derived by incorporating the NSRP productivity and consumption rates into the same formula. The cost ranges using the laboratory data are as follows:

	Number of Samples	Cost Range Per Square Foot	Average Cost Per Square Foot
Crushed glass	1 sample	$2.06/sq ft	$2.06/sq ft
Coal slag	7 samples	$1.38 to $2.07/sq ft	$1.69/sq ft
Coal slag with dust suppressant	2 samples	$1.68 to $1.73/sq ft	$1.71/sq ft
Nickel slag	2 samples	$1.62 to $1.71/sq ft	$1.67/sq ft
Olivine	1 sample	$1.41/sq ft	$1.41/sq ft
Staurolite	2 samples	$1.58/sq ft & $1.58/sq ft	$1.58/sq ft
Specular hematite	1 sample	$1.90/sq ft	$1.90/sq ft
Silica sand	7 samples	$1.39 to $2.52/sq ft	$1.82/sq ft
Silica sand with dust suppressant	3 samples	$1.37 to $2.07/sq ft	$1.72/sq ft
Copper slag	4 samples	$0.81 to $1.76/sq ft	$1.34/sq ft
Copper slag with dust suppressant	1 sample	$1.62/sq ft	$1.62/sq ft
Garnet	7 samples	$1.12 to $2.14/sq ft	$1.56/sq ft
Steel grit	2 samples	$1.35 to $1.88/sq ft	$1.62/sq ft

Industrial Hygiene Results

KTA collected a total of 424 airborne dust samples and 106 bulk samples of abrasives (pre and post run) for this study in accordance with the protocol described in the Study Design and Methods portion of this report. Two hundred and twelve of the airborne samples were analyzed for up to 28 metals/elements. In addition, 212 air samples of total and respirable dust were analyzed gravimetrically and for quartz and cristobalite. The samples were submitted directly to NIOSH for analysis by their contract laboratory.

The results of all airborne dust and bulk abrasive sample results are presented in Appendix B, with tabs for each analyte evaluated. Within each tab, the results for a single specific analyte (e.g. aluminum) are summarized for all of the forty abrasives included in this study. In addition to a brief description of health hazards and recommended exposure limits[23,24], a total of 4 tables are used to present all of the data associated with each analyte. The general content of each table, and the sequence, in which they occur, is as follows.

Air Sample Results

The Air Sample Results table for each contaminant provides basic information on sampling parameters (e.g. sample number, sample volume; and abrasive code), as well as laboratory analytical results (e.g. mass per filter, detection/quantification limits, and concentration). The results are reported as average concentrations over the sampling period. Any data reported in the "Filter Notes" column 6 as "<LOQ" means that the associated result reported in column 7 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 LOD and LOQ.

Airborne Sample Data Analysis

The Airborne Sample Data Analysis table is used to present a comparison of the airborne sample results collected at three fixed stations (Make-up Air Area, Operator Area, and Exhaust Area), and Operator's Breathing Zone (OBZ), for each unique abrasive used in the study. While the data presented is not for an 8 hour (time weighted average) period, it provides an indication of the relative concentrations collected during the sampling period.

Bulk Elemental Analysis

The Bulk Elemental Analysis table within each tab provides data on the concentration of the specific analyte (as well as laboratory limits of detection/quantification) in the virgin abrasive and in the post-blast abrasive for each of the individual abrasive media evaluated. In addition, for recyclable abrasives, bulk samples were collected of the virgin abrasive and post-blast "final run" (following the appropriate number of runs to reduce the average particle size to 50% of the original particle size as determined through sieve analysis or for a maximum of 5 uses for copper slag and garnet abrasive, or 25 uses for steel abrasives). Any data reported in the "Notes" columns as "<LOQ" means that the associated results in columns 3 and 6 are 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.

Comparison of Airborne Dust Concentrations to Bulk Concentrations

The Comparison of Airborne Dust Concentrations to Bulk Concentrations table within each tab provides a comparison of the airborne concentrations recorded for the specific analyte 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 analyte in the virgin abrasive. This table provides an indication of the range of concentrations of the analyte in virgin bulk materials that might be associated with airborne exposure levels.

Identical tabular presentations of all of the data for each of the 28 metals/elements, as well as respirable quartz and cristobalite, are presented in Appendix B. Greater than 75% of the total dust samples collected during trial runs had filter weights greater than the recommended filter weight for NIOSH method 0500 or had loose particulate present. Therefore, the total dust results are not provided in this report. Background air samples were collected and submitted to NIOSH for analysis. In addition, all samples collected for radiochemically active materials were analyzed and are reported by NIOSH in this report.

Health-Related Agent Summary

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 different abrasives used. Therefore, the laboratory results may not be representative of real world conditions, but the results for different abrasives can confidently be compared to each other, and specifically with the silica sand abrasive. For comparison purposes, NIOSH selected 12 health-related agents for comparative analysis, including: arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, respirable quartz, silver, titanium, vanadium, and radium-226.

Figures 3 to 13 on pages 89 to 99 show the range of measured and geometric mean concentrations for the airborne levels of eleven hazardous health-related agents for each of the 40 abrasive products and the associated generic category of abrasives tested. The airborne levels, derived from the airborne sample data analysis tables in Appendix B, include results of four samples that were collected for each blast run conducted for each abrasive product: make-up area sample, operator area sample, exhaust or dust collector area sample, and the personal sample collected in the operator's breathing zone, but outside of the blasting helmet. The recyclable abrasives include the samples collected from both the initial blast run (indicated by the letter A – i.e. Garnet-07A represents the initial blast run conducted for Garnet abrasive #7) and the blast run that was conducted after tests for the recycling capability of the abrasive was completed (indicated by the letter B – i.e. Garnet-07B represents the final blast run conducted for Garnet abrasive #7 after the recycling tests were completed). The range and geometric mean are indicated by a bar chart and a small square, respectively. The shaded bars indicate the range and geometric mean of the entire generic category of abrasive. Radium-226 is reported separately.

Any abrasive product or generic category of abrasive with all airborne samples having results below the limit of detection (LOD) for the given health-related agent are represented by only a small square (these abrasives will have no bar since there is no range to display). For abrasives having any samples below the limit of detection for the given health-related agent, the geometric mean was calculated by using LOD÷2, which is the method used to estimate the average concentration in the presence of nondetectable values described by Hornung and Reed[25]. The limits of detection for abrasive products sometimes varied slightly when analyzing a given health-related agent. Therefore, it is possible that an airborne concentration for one abrasive detected above the limit of detection could be less than the LOD÷2 for another abrasive which had a higher limit of detection associated with it analysis. The standard for comparison of all health-related agents will use the geometric mean for the silica sand generic abrasive category.

Arsenic

Figure 3 illustrates the range and geometric mean for the airborne levels of arsenic for each of the 40 abrasive products and the associated generic category of abrasive. The following generic categories of abrasives had all airborne results below the limit of detection for arsenic: crushed glass, olivine, staurolite, specular hematite, and silica sand treated with a dust suppressant.

The following generic abrasive categories had at least one airborne sample with results above the limit of detection for arsenic, and in order form the highest to the lowest geometric mean level of arsenic include: copper slag, copper slag with dust suppressant, steel grit, nickel slag, coal slag, coal slag with dust suppressant, silica sand, and garnet. The variability of results for individual abrasives within a generic category must be considered in addition to comparisons of combined data for an entire generic category of abrasives.

The silica sand generic abrasive category had 2 out of 28 airborne samples (both with abrasive SS-06) with results above the limit of detection for arsenic. The arsenic levels for these samples were 2.07 and 6.92 $\mu g/m^3$. The geometric mean concentration of arsenic for the silica sand generic abrasive category was 2.039 $\mu g/m^3$. This will be used as the standard of comparison.

The copper slag generic abrasive category had all 32 airborne samples with results above the limit of detection for arsenic. The range and geometric mean levels of arsenic varied considerably within the copper slag generic abrasive category. Copper slags CP-01 and CP-02 have similar ranges and geometric mean levels of arsenic. Copper slag CP-01 had levels of arsenic ranging from 5.98 to 75.35 $\mu g/m^3$ with a geometric mean of 17.84 $\mu g/m^3$ which is nearly 9 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$. Copper slag CP-02 had levels of arsenic ranging from 6.6 to 99.54 $\mu g/m^3$ with a geometric mean of 21.78 $\mu g/m^3$, which is over 10 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$. Copper slag CP-03 had levels of arsenic ranging from 51.63 $\mu g/m^3$ to 1.1 mg/m^3 with a geometric mean of 299.5 $\mu g/m^3$, which is over 145 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$. Copper slag CP-04 had levels of arsenic ranging from 79.56 $\mu g/m^3$ to 24.5 mg/m^3 with a geometric mean of 540.8 $\mu g/m^3$ which is 265 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$. The geometric mean level of arsenic for the copper slag generic abrasive category of 89.1 $\mu g/m^3$ is 444 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$.

The treated copper slag (with dust suppressant) generic abrasive category had 7 out of 8 airborne samples with results above the limit of detection for arsenic, ranging from 2.05 to 107.37 $\mu g/m^3$. The geometric mean level of arsenic for the treated copper slag generic abrasive category of 14.942 µg/m3 is 7 times higher than silica sand's geometric mean relative level of 2.039 $\mu g/m^3$.

The steel grit generic abrasive category had 12 out of 16 airborne samples with results above the limit of detection for arsenic. The range and geometric mean levels of arsenic varied considerably for the steel grit generic abrasive category. Steel grit 1A/B had four out of eight samples with results above the limit of detection for arsenic, ranging from 0.96 to 49.52 $\mu g/m^3$, with a geometric mean level of 5.15 $\mu g/m^3$. Steel grit 2A/B had all eight samples with results above the limit of detection for arsenic, ranging from 8.09 to 187.7 $\mu g/m^3$, with a geometric mean level of 22.31 $\mu g/m^3$, which is 10 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$. The geometric mean level of arsenic for the steel grit generic abrasive category of 10.714 $\mu g/m^3$ is 5 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$.

The nickel slag generic abrasive category had 4 out of 8 airborne samples with results above the limit of detection for arsenic. The range and geometric mean levels of arsenic varied considerably within the nickel slag generic abrasive category. Nickel slag N-01 had all four samples with results below the limit of detection for arsenic. Nickel slag N-02 had all four samples with results above the limit of detection for arsenic, ranging from 19.81 to 170.80 $\mu g/m^3$, with a geometric mean level of 45.97 $\mu g/m^3$, which is nearly 23 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$. The geometric mean level of arsenic for the nickel slag generic abrasive category of 9.728 $\mu g/m^3$ is 5 times higher than silica sand's geometric mean level of 2.039 $\mu g/m^3$.

The coal slag generic abrasive category had 9 out of 28 airborne samples (associated with four coal slag abrasives: CS-01, CS-02, CS-06, and CS-07) with results above the limit of detection for arsenic. The relative arsenic levels for these nine abrasives ranged from 2.08 to 29.13 $\mu g/m^3$. The geometric mean relative arsenic levels for the coal slag generic abrasive category of 2.902 $\mu g/m^3$ is 1.4 times higher than silica sand's geometric mean of 2.039 $\mu g/m^3$.

The treated coal slag generic abrasive category had 1 out of 8 airborne samples (abrasive CSDS-02) with results above the limit of detection for arsenic. The arsenic level for this sample is 4.8 μg/m3. The geometric mean arsenic level for the treated coal slag generic abrasive category of 2.304 $\mu g/m^3$ is slightly greater (13%) than the silica sand's geometric mean of 2.039 $\mu g/m^3$.

The garnet generic abrasive category had 1 out of 52 airborne samples (abrasive G7A/B) with results above the limit of detection for arsenic. The relative arsenic level for this sample was 2.09 $\mu g/m^3$. The geometric mean relative arsenic level for the garnet generic abrasive category of 1.970 $\mu g/m^3$ is slightly lower (3%) than the silica sand's geometric mean of 2.039 $\mu g/m^3$. The geometric mean arsenic level for the garnet abrasive G-07 of 1.48 $\mu g/m^3$ is less than the geometric mean of the other garnet abrasives which had all sample results less than the limit of detection, since the geometric mean was calculated by using LOD÷2 for all samples which were below the limit of detection (three of the samples associated with garnet abrasive G-07 have lower limits of detection for arsenic than all of the other garnet abrasives).

Beryllium

Figure 4 illustrates the range and geometric mean for the airborne levels of beryllium for each of the 40 abrasive products and the associated generic category of abrasive. None of the generic categories of abrasive had all airborne beryllium results below the limit of detection. However, the individual abrasives silica sand SS-02, silica sand with dust suppressant SSDS-03, and steel grit SG-1A/B had all results below the limit of detection for beryllium.

All of the generic abrasive categories had at least one airborne sample with results above the limit of detection for beryllium, and in order from the highest to the lowest geometric mean level include: coal slag with dust suppressant, coal slag, copper slag, copper slag with dust suppressant, nickel slag, garnet, silica sand, crushed glass, specular hematite, staurolite, silica sand with dust suppressant, steel grit, and olivine. The variability of results for individual abrasives within a generic category must be considered in addition to comparisons of combined data for an entire category of abrasives.

The silica sand generic abrasive category had 17 out of 28 airborne samples with results above the limit of detection for beryllium. The beryllium levels for these samples ranged from 0.03 to 0.36 $\mu g/m^3$. Silica sands SS-01, 02, and 03 had relatively low concentrations of beryllium, ranging from below the limit of detection to 0.10 $\mu g/m^3$. Silica sands SS-04, 05, 06, and 07 had relatively higher concentrations of beryllium, ranging from below the limit of detection to 0.36 μg/m3. The geometric mean concentration of beryllium for the silica sand generic abrasive category was 0.09 $\mu g/m^3$. This will be used as the standard of comparison.

The coal slag and coal slag with dust suppressant generic abrasive categories had all 36 airborne samples with results above the limit of detection for beryllium. The range and geometric mean levels of beryllium varied considerably. Individual airborne concentrations ranged from a low of 0.19 $\mu g/m^3$ to a high of 25.0 $\mu g/m^3$. The geometric mean for the individual abrasives varied by as much as a factor of 8. The geometric mean concentration for the coal slag with dust suppressant generic category of abrasive of 2.23 $\mu g/m^3$ is nearly 26 times higher than the geometric mean concentration for the silica sand generic category of abrasives of 0.09 $\mu g/m^3$. However, when a comparison is made between specific pairs of treated and untreated coal slags, this dramatic variance diminishes. The geometric mean concentration for paired data is as follows: untreated CS-06 at 1.93 $\mu g/m^3$ and treated CSDS-01 at 2.27 $\mu g/m^3$; untreated CS-01 at 2.29 $\mu g/m^3$ and treated CSDS-02 at 2.19$\mu g/m^3$. The geometric mean concentration for the coal slag generic category of abrasive of 2.040 $\mu g/m^3$ is slightly more than 23 times higher than the corresponding geometric mean concentration for the silica sand generic category of abrasives.

The copper slag generic abrasive category had 31 of 32 sample results above the limit of detection for beryllium. The range and geometric mean levels of beryllium varied considerably within the copper slag generic category. Copper slag CP-1A/B showed a wide range of measured concentrations, from below the limit of detection to 2.26 $\mu g/m^3$. However, it resulted in the lowest geometric mean level within the generic category at 0.24 $\mu g/m^3$. Copper slags 2A/B and 4A/B showed comparable results, ranging from 0.165 to 6.12 $\mu g/m^3$. The geometric mean concentrations of 0.74 $\mu g/m^3$ and 0.98 $\mu g/m^3$, respectively, are comparable. Copper slag CP-3A/B resulted in the highest range of concentrations of beryllium, from 0.50 to 6.41 $\mu g/m^3$, as well as the geometric mean of 2.19 $\mu g/m^3$. The geometric mean level of beryllium for the copper slag generic abrasive category of 0.78 $\mu g/m^3$ is 9 times higher than silica sands geometric mean level of 0.09 $\mu g/m^3$. The data for the copper slag with dust suppressant is comparable to these results. Measured concentrations of beryllium ranged from 0.24 to 2.89 $\mu g/m^3$, with a geometric mean concentration of 0.64 $\mu g/m^3$, which is over 7 times higher than silica sand's geometric mean level 0.09 $\mu g/m^3$. Geometric means for the paired treated and untreated copper slag were comparable; untreated CP-02 at 0.74 $\mu g/m^3$ and treated CPDS-01 at 0.64 $\mu g/m^3$.

The nickel slag generic abrasive category had 5 of 8 airborne samples with results above the limit of detection for beryllium. The range and geometric mean levels of beryllium varied considerably within the nickel slag generic category. Nickel slag N-01 had only one sample above the limit of detection at a concentration of 0.11 $\mu g/m^3$. In contrast, nickel slag N-02 had all 4 samples with results above the limit of detection for beryllium, ranging from 0.17 to 1.73 $\mu g/m^3$. The geometric mean level of beryllium for the nickel slag generic abrasive category of 0.14 $\mu g/m^3$ is 1.6 times higher than silica sands geometric mean level of 0.09 $\mu g/m^3$.

The garnet generic abrasive category had 30 of 52 airborne samples with results above the limit of detection for arsenic. Garnets G-1A/B, G-2A/B, G-3A, G-5A/B and G-7A/B had relatively consistent measured ranges of concentrations (from less than the limit of detection to 0.25 $\mu g/m^3$) and geometric mean concentrations (0.04, 0.07, 0.05, 0.07, and 0.04 $\mu g/m^3$, respectively). Garnet G-4A/B had measured concentrations of beryllium ranging from 0.20 to 1.27 $\mu g/m^3$ and a geometric mean of 0.53 $\mu g/m^3$. Garnet G-6A/B had measured concentrations of beryllium ranging from 0.10 to 2.29 $\mu g/m^3$ and a geometric mean of 0.34 $\mu g/m^3$. The geometric mean level of beryllium for the garnet generic abrasive category of 0.10 $\mu g/m^3$ is only slightly higher than silica sands geometric mean level of 0.09 $\mu g/m^3$.

The crushed glass generic category of abrasives had 3 out of 4 airborne sample results with results above the limit of detection for beryllium. Results ranged from 0.03 to 0.13 $\mu g/m^3$, with a geometric mean of 0.08 $\mu g/m^3$. Specular hematite generic category had 1 of 4 samples with results above the limit of detection for beryllium. The measured airborne concentration of 0.44 $\mu g/m^3$ resulted in a geometric mean concentration of 0.06 $\mu g/m^3$. The staurolite generic abrasive category had 3 of 8 airborne samples with results above the limit of detection for beryllium. Samples ranged from 0.03 to 0.30 $\mu g/m^3$, with a geometric mean concentration of 0.06 $\mu g/m^3$. The steel grit generic category of abrasive had 3 of 16 airborne samples above the limit of detection for beryllium. However, all of these measured concentrations were associated with steel grit SG-02, where concentrations ranged from below the limit of detection to 0.52 $\mu g/m^3$. The geometric mean level of beryllium for the steel grit generic abrasive category was 0.05 $\mu g/m^3$. The olivine generic abrasive category had 2 of 4 airborne samples with results above the limit of detection for beryllium. Concentrations ranged from below the limit of detection to 0.12 $\mu g/m^3$, with a geometric mean concentration of 0.03 $\mu g/m^3$. The geometric mean concentrations for each of these generic category of abrasives was less than the geometric mean level of 0.09 $\mu g/m^3$ for the silica sand generic category of abrasives.

Cadmium

Figure 5 illustrates the range and geometric mean for the airborne levels of cadmium for each of the 40 abrasive products and associated generic categories of abrasive. The crushed glass and olivine generic categories of abrasive had all airborne cadmium results below the limit of detection.

The following generic abrasive categories had at least one airborne sample with results above the limit of detection for cadmium, and in order from the highest to the lowest geometric mean level include: copper slag, nickel slag, coal slag, garnet, specular hematite, silica sand with dust suppressant, staurolite, steel grit, silica sand, coal slag with dust suppressant, and copper slag with dust suppressant. The variability of results for individual abrasives within a generic category must also be considered in addition to comparisons of geometric mean data for an entire generic category of abrasive.

The silica sand generic abrasive category had 7 out of 28 airborne samples with results above the limit of detection for cadmium. Six of the seven detectable concentrations ranged from 0.1 to 0.17 $\mu g/m^3$. Silica sand SS-01 had a sample result with a measured concentration of 1.99 $\mu g/m^3$. The geometric mean concentration of cadmium for the silica sand generic abrasive category was 0.08 $\mu g/m^3$. This will be used as the standard of comparison.

The copper slag generic abrasive category had 27 of 32 airborne samples with results above the limit of detection for cadmium. The range and geometric mean levels of cadmium varied widely for the individual copper slag abrasives within the generic category. Copper slag CP-2A/B had the lowest range of measured concentrations, from less than the limit of detection to 0.5 $\mu g/m^3$. Copper slags CP-1A/B and CP-3A/B had comparable ranges and geometric means, with airborne concentrations ranging from 0.27 to 3.93 $\mu g/m^3$ and geometric means of 0.88 and 1.68 $\mu g/m^3$, respectively. Copper slag CP-4A/B had the highest range and geometric mean, with measured airborne concentrations ranging from 2.06 to 71.41 $\mu g/m^3$, and a geometric mean of 10.21 $\mu g/m^3$. The geometric mean level for cadmium for the copper slag generic abrasive category of 1.04 $\mu g/m^3$ is 12 times higher than silica sands geometric mean level of 0.08 $\mu g/m^3$.

The nickel slag generic abrasive category had 4 out of 8 airborne samples with results above the limit of detection for cadmium. The range in geometric mean levels of cadmium was widely different between the two individual abrasives within the generic category. Nickel slag N-01 had all four sample results below the limit detection for cadmium. Nickel slag N-02 had all 4 results with concentrations above the limit of detection for cadmium, ranging from 0.52 to 10.21 $\mu g/m^3$. The geometric mean level of cadmium for the nickel slag generic abrasive category of 0.246 $\mu g/m^3$ is nearly 3 times higher than silica sands geometric mean level of 0.08 $\mu g/m^3$.

The coal slag generic abrasive category had 10 out of 28 airborne samples above the limit of detection for cadmium. The range and geometric mean levels, while variable, were considerably more consistent than copper slag or nickel slag. Coal slags CS-01 to 06 had relatively consistent geometric mean concentrations, although measured ranges were notably broader for coal slags CS-05 and CS-06. Copper slag CS-07 had the broadest range of measured concentrations, from less than the limit of detection to 2.71 $\mu g/m^3$. The geometric mean level of cadmium for the coal slag generic abrasive category of 0.13 $\mu g/m^3$ is about 1.6 times higher than silica sand's geometric mean level of 0.08 $\mu g/m^3$.

The garnet generic abrasive category had 25 out of 52 airborne samples with results above the limit of detection for cadmium. While the results range from below the limit of detection to 2.69 $\mu g/m^3$, the individual ranges and geometric means for each of the individual garnet abrasives were relatively consistent. The geometric mean level of cadmium for the garnet generic abrasive category of 0.13 $\mu g/m^3$ is about 1.5 times higher than silica sand's geometric mean level of 0.08 $\mu g/m^3$.

The specular hematite, silica sand with dust suppressant, staurolite, and steel grit generic abrasive categories resulted in somewhat different ranges of measured airborne concentrations, but relatively consistent geometric mean levels between the generic categories of abrasives: 0.10, 0.10, 0.09, and 0.08 $\mu g/m^3$, respectively. The geometric mean levels for cadmium for each of these generic abrasive categories are slightly higher than silica sand's geometric mean level of 0.08 $\mu g/m^3$.

The coal slag with dust suppressant and copper slag with dust suppressant generic categories of abrasive resulted in relatively consistent measured ranges of concentrations and geometric mean levels. The geometric mean levels of 0.08 and 0.08 $\mu g/m^3$, respectively, were essentially identical to silica sand's geometric mean level of 0.08 $\mu g/m^3$.

Chromium

Figure 6 illustrates the range and geometric mean for the airborne levels of chromium for each of the 40 abrasive products and the associated generic category of abrasive. One of the generic categories of abrasives, specular hematite, had all chromium results below the limit of detection.

The following generic abrasive categories had at least one airborne sample with results above the limit of detection for chromium, and in order from the highest to the lowest geometric mean level include: nickel slag, steel grit, olivine, copper slag, copper slag with dust suppressant, coal slag with dust suppressant, coal slag, garnet, crushed glass, staurolite, silica sand, and silica sand with dust suppressant. The variability of results for individual abrasives within a generic category must also be considered in addition to comparisons of geometric mean concentrations for the entire generic category of abrasives.

The silica sand generic abrasive category had 8 out of 28 airborne samples with results above the limit of detection for chromium. The chromium concentrations for these samples ranged from 5.02 to 27.16 $\mu g/m^3$. The geometric mean concentration of chromium for the silica sand generic abrasive category was 7.12 $\mu g/m^3$. This will be used as the standard of comparison.

The nickel slag generic abrasive category had 8 out of 8 airborne samples with results above the limit of detection for chromium. The range and geometric mean levels of chromium varied considerably for the individual nickel slags within the generic category. Nickel slag N-01 had levels of chromium ranging 345 to 7036 $\mu g/m^3$ with a geometric mean of 1996 $\mu g/m^3$. Nickel slag N-02 had levels of chromium ranging from 139 to 1270 $\mu g/m^3$, with a geometric mean of 330 $\mu g/m^3$. The geometric mean level of chromium for the nickel slag generic abrasive category of 812 $\mu g/m^3$ is nearly 114 times higher than silica sand's geometric mean level of 7.12 $\mu g/m^3$.

The steel grit generic abrasive category had 14 of 16 airborne samples with results above the limit of detection for chromium. The range and geometric mean levels of chromium varied widely between the individual abrasives. Steel grit SG-1/AB had levels of chromium ranging from below the limit of detection to 227 $\mu g/m^3$, with a geometric mean of 38.2 $\mu g/m^3$. Steel grit SG-2A/B had levels of chromium ranging from 311 to 8551 $\mu g/m^3$, with a geometric mean of 1398 $\mu g/m^3$. The geometric mean level of chromium for steel grit generic abrasive category of 231 $\mu g/m^3$ is nearly 33 times higher than silica sand's geometric mean level of 7.12 $\mu g/m^3$.

The olivine generic abrasive category had 4 out of 4 airborne samples with results above the limit of detection for chromium. The results ranged from 65.9 to 247 $\mu g/m^3$. The geometric mean level of chromium for olivine abrasive of 117 $\mu g/m^3$ is 16 times higher than silica sand's geometric mean level of 7.12 $\mu g/m^3$.

The copper slag generic abrasive category had 32 of 32 airborne samples with results above the limit of detection for chromium. Three of the individual copper slags, CP-1A/B, CP-2A/B, and CP-3A/B, had relatively consistent ranges and geometric mean levels of chromium. Concentrations ranged from 11 to 290 $\mu g/m^3$ and geometric means were 55.6, 56.0, and 40.8 $\mu g/m^3$, respectively. Copper slag CP-4A/B had a considerably higher range of measured concentrations and geometric mean. The CP0-4 had levels of chromium ranging from 104 to 2244 $\mu g/m^3$ and a geometric mean of 360 $\mu g/m^3$. The geometric mean level of chromium for the copper slag generic abrasive category of 82.2 $\mu g/m^3$ is about 11.5 times higher than silica sand's geometric mean level of 7.12 $\mu g/m^3$.

The copper slag with dust suppressant generic abrasive category had 8 of 8 airborne samples with results above the limit detection for chromium. The measured range of concentration of 24.3 to 227 $\mu g/m^3$ closely parallels the range of concentration for the untreated version of this specific product (i.e. CP-2A/B) with a range of concentrations of 20.01 to 290 $\mu g/m^3$. The geometric mean level of chromium for copper slag with dust suppressant of 66.8 $\mu g/m^3$ is slightly over 9 times higher than the geometric mean level of silica sand of 7.12 $\mu g/m^3$.

The coal slag with dust suppressant had 7 out of 8 airborne samples with results above the limit of detection for chromium. The range of concentration and geometric means within the generic category were relatively consistent. Measured concentrations ranged from 5.19 to 137 $\mu g/m^3$. The geometric mean level of chromium for the coal slag with dust suppressant generic category of 39.5 $\mu g/m^3$ is about 5.5 times higher than silica sands geometric mean level of 7.12 $\mu g/m^3$.

The coal slag generic category of abrasives had 26 out of 28 airborne samples with results above the limit of detection. The range and geometric mean levels of chromium varied considerably for the coal slag generic abrasive category. Coal slag CS-01, CS-02, CS-03, CS-06, and CS-07 show relatively consistent ranges and geometric mean concentrations. The overall range for the group was from 10.7 $\mu g/m^3$ to 333 $\mu g/m^3$. CS-04 and CS-05 had very consistent and lower range and geometric mean levels. The range of measured concentrations was from below the limit of detection to 46 $\mu g/m^3$. The geometric mean level for the coal slag generic abrasive category of 38.7 $\mu g/m^3$ is about 5.5 times higher than silica sand's generic mean level of 7.12 $\mu g/m^3$.

The garnet generic abrasive category had 37 out of 52 airborne samples with results above the limit of detection for chromium. The ranges and geometric mean concentrations for each of the individual abrasives varied widely, with garnet G-2/AB showing the lowest range (less than the limit of detection to 13.1 $\mu g/m^3$) and G-6/AB showing the highest range (13.1 to 206 $\mu g/m^3$). The geometric mean level of chromium for the garnet generic abrasive category of 18.2 $\mu g/m^3$ is slightly more than 2.5 times higher than silica sand's geometric mean level of 7.12 $\mu g/m^3$.

The crushed glass generic abrasive category had 3 of 4 samples with results above the limit of detection for chromium. Crushed glass had levels of chromium ranging from 5.15 to 22.7 $\mu g/m^3$. The geometric mean level of chromium for the crushed glass generic abrasive category of 12.5 is slightly more than 1.5 times silica sands geometric mean level of 7.12 $\mu g/m^3$.

The staurolite generic abrasive category had 3 of 8 samples with results above the limit of detection for chromium. Results ranged from 5.19 to 33.4 $\mu g/m^3$. The geometric mean level of chromium for staurolite abrasive of 8.62 is slightly higher than silica sand's geometric mean level of 7.12 $\mu g/m^3$.

The silica sand with dust suppressant generic category of abrasive had 2 of 12 airborne samples with results above the limit of detection for chromium (10.7 and 15.3 $\mu g/m^3$). The range for the group was from 5.0 to 15.3 $\mu g/m^3$. The geometric mean level of chromium for the silica sand with dust suppressant generic category of 5.96 $\mu g/m^3$ is slightly less than the silica sand geometric mean level of 7.12 $\mu g/m^3$. However, direct comparison of the individual treated and untreated abrasives (SSDS-01 with SS-01; SSDS-02 with SS-04; and SSDS-03 with SS-03) illustrate similar ranges and geometric means.

Lead

Figure 7 illustrates the range and geometric mean for the airborne levels of lead for each of the 40 abrasive products and the associated generic category of abrasive. Only specular hematite had all airborne results below the limit of detection for lead.

The following generic abrasive categories had at least one airborne sample with results above the limit of detection for lead, and in order of the highest to the lowest geometric mean level include: copper slag, crushed glass, staurolite, copper slag with dust suppressant, nickel slag, coal slag with dust suppressant, coal slag, silica sand, steel grit, garnet, olivine, and silica sand with dust suppressant. The variability of results for individual abrasives within a generic category must also be considered in addition to comparisons of the combined data for an entire generic category of abrasive.

The silica sand generic abrasive category had 17 of 28 airborne samples with results above the limit of detection. The lead levels for these samples ranged from 0.80 to 10.4 $\mu g/m^3$. The geometric mean concentration of lead for the silica sand generic abrasive category was 2.74 $\mu g/m^3$. This will be used as a standard of all comparisons.

The copper slag generic abrasive category had 29 out of 32 airborne samples with results above the limit of detection for lead. Each of the individual abrasives within the generic category had highly variable ranges and geometric means. Copper slag CP-2A/B had the lowest reported range, from below the limit of detection to 9.75 $\mu g/m^3$. Copper slag CP-4A/B had the highest reported range from 391 to 120,384 $\mu g/m^3$. The geometric mean level of lead for the copper slag generic abrasive category of 92 $\mu g/m^3$ is 33.5 times higher than silica sand's geometric mean level of 2.74 $\mu g/m^3$. The geometric mean level of lead for the copper slag generic abrasive category is nearly an order of magnitude or more greater than the corresponding mean concentrations for all of the remaining generic categories of abrasive.

The crushed glass category of abrasive had 4 out of 4 samples with results above the limit of detection for lead. Crushed glass had levels of lead ranging from 3.91 to 26.8 $\mu g/m^3$. The geometric mean level of lead for the crushed glass generic category of 12.2 $\mu g/m^3$ is nearly 4.5 times higher than silica sand's geometric mean level of 2.74 $\mu g/m^3$.

The staurolite generic category of abrasive had 7 out of 8 airborne samples with results above the limit of detection for lead. While there was some variability in the range of measured concentrations, the geometric means are relatively consistent. The geometric mean level of lead for the staurolite generic abrasive category of 7.7 $\mu g/m^3$ is nearly 3 times higher than silica sand's geometric mean level of 2.74 $\mu g/m^3$.

The copper slag with dust suppressant (CPDS-1A/B) had a range and geometric mean slightly higher than its corresponding untreated counterpart (CP-2A/B). The reported range was 0.82 to 15.07 $\mu g/m^3$ with a geometric mean of 5.11 $\mu g/m^3$. The range for CP-2A/B was from below the limit of detection to 9.75 $\mu g/m^3$. The geometric mean was 2.25 $\mu g/m^3$. The geometric mean level of lead for the copper slag with dust suppressant category of 5.11 $\mu g/m^3$ is just under 2 times higher than silica sand's geometric mean level of 2.74 $\mu g/m^3$.

The nickel slag generic category of abrasive had 6 out of 8 samples with results above the limit of detection for lead. The range and geometric mean levels were widely variable within the generic abrasive category. Nickel slag N-01 had measured levels of lead ranging from below the limit of detection to 2.28 $\mu g/m^3$, with a geometric mean of 1.3 $\mu g/m^3$. Nickel slag N-02 had levels of lead ranging from 5.11 to 50 $\mu g/m^3$, with a geometric mean of 14.9 $\mu g/m^3$. The geometric mean level of lead for nickel slag generic category of 4.4 $\mu g/m^3$ is approximately 1.6 times higher than silica sand's geometric mean level of 2.74 $\mu g/m^3$.

The coal slag with dust suppressant had 6 out of 8 airborne samples with results above the limit of detection for lead. The range of reported concentrations varied, however, the geometric mean levels were relatively consistent between the individual abrasives within this generic category and their untreated counterpart. Coal slag with dust suppressant CSDS-01 had levels of lead ranging from below the limit of detection to 12.7 $\mu g/m^3$, and a geometric mean of 3.18 $\mu g/m^3$. In comparison, the paired, untreated coal slag (CS-06) had levels of lead ranging from below the limit of detection to 4.35 $\mu g/m^3$, and a geometric mean of 2.14 $\mu g/m^3$. Coal slag with dust suppressant CSDS-02 had levels of lead ranging from below the limit of detection to 88.9 $\mu g/m^3$, and a geometric mean of 5.14 $\mu g/m^3$. This corresponds with the untreated version of this coal slag (CS-01) which had a range of 2.27 to 10.5 $\mu g/m^3$, and a geometric mean of 4.76 $\mu g/m^3$. The geometric mean level of lead for the coal slag with dust suppressant abrasive category of 4.0 $\mu g/m^3$ is approximately 1.5 times higher than silica sand's geometric mean level of 2.74 $\mu g/m^3$.

The coal slag generic category of abrasives had 18 out of 28 airborne samples with results above the limit of detection for lead. While there was some variability in both the reported ranges and the geometric mean concentrations for the individual abrasives, the data within the generic category is relatively consistent. The geometric mean level of lead for the coal slag generic abrasive category of 3.89 $\mu g/m^3$ is approximately 1.4 times higher than silica sand's geometric mean level of 2.74 $\mu g/m^3$.

For the remaining abrasives, including: steel grit, garnet, olivine, and silica sand with dust suppressant, the reported ranges and geometric mean levels of lead are all similar or below that of the silica sand generic category abrasives. The notable exception is within the steel grit generic category of abrasives, where steel grit SG-1A/B had all results below the limit of detection, while steel grit SG-2A/B had a reported range of concentrations from 0.39 to 45.88 $\mu g/m^3$ and a geometric mean of 6.07 $\mu g/m^3$.

Manganese

Figure 8 illustrates the range and geometric mean for the airborne levels of manganese for each of the 40 abrasive products and the associated generic category of abrasive. All of the generic category of abrasives had at least 1 airborne sample result above the limit of detection for manganese, and in order of the highest to lowest geometric mean level include: copper slag with dust suppressant, steel grit, garnet, copper slag, olivine, nickel slag, coal slag, coal slag with dust suppressant, staurolite, specular hematite, crushed glass, silica sand with dust suppressant, and silica sand. The variability of results for individual abrasives within a generic category must also be considered in addition to comparison of the combined data for an entire generic category.

The silica sand generic category had 28 out of 28 airborne samples with results above the limit of detection. The results ranged from 4.61 to 356 $\mu g/m^3$. While the range of concentrations fluctuated, the geometric mean values for all of the individual silica sand abrasives, except silica sand SS-04, were relatively consistent. Silica sand SS-04 had the highest range for manganese, from 37.5 to 356 $\mu g/m^3$, and a geometric mean of

177 $\mu g/m^3$. The geometric mean level of manganese for the silica sand generic abrasive category is 45.7 $\mu g/m^3$. This will be used as the standard of comparison.

The copper slag with dust suppressant generic category of abrasives had 8 out of 8 airborne sample results above the limit of detection for manganese. The measured range for CPDS-1A/B of 932 to 11,357 $\mu g/m^3$, and a geometric mean of 2,718 $\mu g/m^3$can be compared to the untreated counterpart, copper slag CP-2A/B with a reported range of 701 $\mu g/m^3$ to 12,650 $\mu g/m^3$, and a geometric mean of 2,346 $\mu g/m^3$. The geometric mean level of manganese for the copper slag with dust suppressant category of 2,718 $\mu g/m^3$ is about 60 times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

The steel grit generic category of abrasives had 16 out of 16 airborne samples with results above the limit of detection for manganese. Once again, there was considerable variation between the individual abrasives. Steel grit SG-1A/B had results that ranged from 14.6 to 3,920 $\mu g/m^3$, with a geometric mean of 458 $\mu g/m^3$. Steel grit SG-2A/B had manganese levels ranging from 1,639 to 41,710 $\mu g/m^3$, with a geometric mean of 7,203 $\mu g/m^3$. The geometric mean level of manganese for the combined steel grit generic abrasive category of 1,815 $\mu g/m^3$ is about 40 times higher than silica sands geometric mean level of 45.7 $\mu g/m^3$.

The garnet generic abrasive category had 52 out of 52 airborne samples with results above the limit of detection for manganese. The reported ranges are highly variable. Garnet G-1A/B had the lowest reported range, from 58 to 954 $\mu g/m^3$. Garnet G-4A/B had the highest reported range, from 579 to 17,670 $\mu g/m^3$. The geometric mean level of manganese for the garnet generic abrasive category of 829 $\mu g/m^3$ is about 18 times higher than the silica sand geometric mean level of 45.7 $\mu g/m^3$.

The copper slag generic category of abrasive had 32 out of 32 airborne samples with results above the limit of detection for manganese. Once again, there was considerable variability within the data. Copper slag CP-1A/B had the lowest reported range from 35 to 447 $\mu g/m^3$. Copper slag CP-2A/B had the highest reported range from 701 to 12,650 $\mu g/m^3$. The geometric mean level of manganese for the copper slag generic abrasive category of 653 $\mu g/m^3$ is about 14 times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

Olivine had 4 out of 4 airborne samples with results above the limit of detection for manganese. The results ranged from 247 to 1,377 $\mu g/m^3$. The geometric mean level of manganese for olivine of 500 $\mu g/m^3$ is just about 11 times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

The nickel slag generic category of abrasive had 8 out of 8 airborne samples with results above the limit of detection. The range and geometric means for the individual abrasives were fairly consistent. The geometric mean level of manganese for the nickel slag generic abrasive category of 459 $\mu g/m^3$ is about ten times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

The coal slag generic abrasive category had 28 out of 28 airborne samples with results above the limit of detection for manganese. The range of concentrations for the individual abrasives within this category were fairly consistent, from 27 to 874 $\mu g/m^3$. The geometric mean level of manganese for the coal slag generic abrasive category of 149 $\mu g/m^3$ is a little over three times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

The coal slag with dust suppressant abrasive category had 8 out of 8 airborne samples with results above the limit of detection for manganese. There was little variation in the range or geometric mean between the individual abrasives within this category. In addition, the range and geometric means of the treated and untreated version of the same products were similar. The geometric mean level of manganese for the coal slag with dust suppressant generic abrasive category of 133 $\mu g/m^3$ is just under 3 times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

The staurolite generic category of abrasives had 8 out of 8 air samples with the results above the limit of detection for manganese. There were considerable differences in the range of reported concentrations. Staurolite S-01 had a broader range, from 19.5 to 522 $\mu g/m^3$. Staurolite S-02 had a narrower range from 52 to 271 $\mu g/m^3$. The geometric mean level of manganese for the staurolite generic abrasive category of 121 $\mu g/m^3$ is just over 2.5 times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

The specular hematite abrasive had a reported range of 16 to 249 $\mu g/m^3$ for manganese. The geometric mean level of 61 $\mu g/m^3$ is approximately 1.3 times higher than silica sand's geometric mean level of 45.7 $\mu g/m^3$.

The crushed glass abrasive had a reported range from 13 to 101 $\mu g/m^3$ for manganese. The geometric mean level of 57 $\mu g/m^3$ is slightly higher than the geometric mean level of silica sand of 45.7 $\mu g/m^3$.

The reported ranges and geometric means for the silica sands with dust suppressant were very similar with their untreated counterpart.

Nickel

Figure 9 illustrates the range and geometric mean for the airborne levels of nickel for each of the 40 abrasive products and the associated generic category of abrasive. The following generic category of abrasives had all airborne results below the limit of detection for nickel: crushed glass, staurolite, specular hematite, and silica sand with dust suppressant.

The following generic abrasive categories had at least one airborne sample with results above the limit of detection for nickel, and in order from the highest to the lowest geometric mean level include: olivine, nickel slag, steel grit, copper slag with dust suppressant, coal slag, coal slag with dust suppressant, copper slag, garnet, and silica sand. The variability of results for individual abrasives within a generic category must also be considered in addition to comparisons of combined data for an entire generic category.

The silica sand generic abrasive category had 4 out of 28 airborne samples with results above the limit of detection. The nickel level in these samples ranged from 5.02 to 16.3 $\mu g/m^3$. The geometric mean level of nickel for the silica sand generic abrasive category was 5.99 $\mu g/m^3$. This will be used as the standard for comparison.

The olivine abrasive had 4 out 4 airborne samples with results above the limit of detection for nickel. The results ranged from 865 to 4520 $\mu g/m^3$. The geometric mean level of 1,628 $\mu g/m^3$ is 270 times higher than silica sand's geometric mean level of 5.99 $\mu g/m^3$.

The nickel slag generic abrasive category had 8 out of 8 airborne samples with results above the limit of detection for nickel. The range in geometric mean levels of nickel varied considerably for the specific nickel slag abrasive. Nickel slag N-01 had a reported range from 89 to 2,897 $\mu g/m^3$ and a geometric mean of 606 $\mu g/m^3$. Nickel slag N-02 had a reported range from 613 to 6,040 $\mu g/m^3$ and a geometric mean of 1609 $\mu g/m^3$. The geometric mean level of nickel for the nickel slag generic abrasive category of 987 $\mu g/m^3$ is approximately 165 times higher than silica sand's geometric mean level of 5.99 $\mu g/m^3$.

The steel grit generic abrasive category had 14 out of 16 airborne samples with results above the limit of detection for nickel. The range and geometric mean was highly variable for the individual abrasives within this generic category. Steel grit SG-1A/B had a reported range from below the limit of detection to 724 $\mu g/m^3$, with a geometric mean of 52 $\mu g/m^3$. The reported range for steel grit SG-2A/B was from 162 to 4,380 $\mu g/m^3$, with a geometric mean of 733 $\mu g/m^3$. The geometric mean level of nickel for the steel grit generic abrasive category of 196 is approximately 33 times higher than silica sand's geometric mean level of 5.99 $\mu g/m^3$.

The copper slag with dust suppressant generic abrasive category had 6 out of 8 airborne samples with results above the limit of detection for nickel. The reported range of 5 to 116 $\mu g/m^3$ for CPDS-1A/B closely parallels the results for its untreated counterpart, copper slag CP-2A/B (5.2 to 127 $\mu g/m^3$). The geometric mean level for the copper slag with dust suppressant of 30.2 $\mu g/m^3$ is approximately five times higher than silica sand's geometric mean level of 5.99 $\mu g/m^3$.

The coal slag generic category had 23 out of 28 airborne samples with results above the limit of detection for nickel. The range of reported concentrations varied considerably among the individual abrasives within this category. Coal slag CS-04 had the lowest reported range, from below the limit of detection to 23 $\mu g/m^3$. Coal slag CS-07 had the highest reported range from 17.5 to 354 $\mu g/m^3$. The geometric mean level of nickel for the coal slag generic abrasive category of 28 μg/m^3 is approximately 4.5 times higher than silica sand's geometric mean level of 5.99 μg/m^3.

The coal slag with dust suppressant generic category of abrasives had 6 out of 8 airborne samples with results above the limit of detection for nickel. The reported concentrations, ranging from 5.15 to 83.1 μg/cm^3, closely paralleled the corresponding untreated coal slag abrasive. The geometric mean level of nickel for the coal slag with dust suppressant generic abrasive category of 25.2 μg/m^3 is just over 4 times higher than silica sand's geometric mean level of 5.99 μg/m^3.

The copper slag generic abrasive category had 21 out of 32 airborne samples with results above the limit of detection for nickel. There was wide variability among the individual abrasives within the generic category. Copper slag CP-1A/B had the lowest reported range, from below the limit of detection to 21.2 μg/m^3. Copper slag CP-4A/B had the highest reported range, from 14 to 306 μg/m^3. The geometric mean level of nickel for the copper slag generic abrasive category of 19.2 μg/m^3 is just over 3 times higher than the silica sands geometric mean level of 5.99 μg/m^3.

The garnet generic abrasive category had 14 out of 52 airborne samples with results above the limit of detection for nickel. Three of the abrasives had results that were below the limit of detection on all samples collected. The remaining four abrasives had varying ranges of concentration, from 5 to 56 μg/m^3. The geometric mean level of nickel for the garnet generic abrasive category of 7.4 μg/m^3 is slightly higher than silica sand's geometric mean level of 5.99 μg/m^3.

Respirable Quartz

Figure 10 illustrates the range and geometric mean for the airborne levels of respirable quartz for each of the 40 abrasive products and the associated generic category of abrasive. Caution must be used when considering quartz data from the samples described on the first page of the Respirable Quartz Section in Appendix B, since these samples were evaluated by primary or secondary peak height measurement, due to problematical integration data caused by interferences. The following generic categories of abrasives had all airborne results below the limit of detection for respirable quartz: crushed glass, coal slag, coal slag with dust suppressant, nickel slag, olivine, specular hematite, copper slag with dust suppressant, and steel grit. NIOSH did not detect cristobalite in any of the airborne or bulk samples.

The following generic abrasive categories had at least 1 airborne sample with results above the limit of detection for respirable quartz, and in order of the highest to lowest geometric mean level, include: silica sand, silica sand with dust suppressant, garnet, copper slag, and staurolite. The variability of results for individual abrasives within a generic category must also be considered in addition to comparisons of combined data for an entire generic category.

The silica sand generic abrasive category had 27 out of 28 airborne samples with results above the limit of detection for respirable quartz. Silica sand SS-04 had a reported range from below the limit of detection to 13.0 mg/m^3. The remaining abrasives within this generic category resulted in a range of respirable quartz from 2.43 mg/m^3 to 43.2 mg/m^3. The geometric mean level of respirable quartz for the silica sand generic abrasive category was 8.83 mg/m^3. This will be used as the standard for comparison.

The silica sand with dust suppressant generic abrasive category had 9 out of 12 airborne samples with results above the limit of detection for respirable quartz. The range of concentrations varied widely between individual abrasives, with SSDS-03 having the lowest range (from below the limit of detection to 2.1 mg/m^3), and SSDS-01 having the highest reported range (from 5.61 to 30.6 mg/m^3). The geometric mean level of respirable quartz for the silica sand with dust suppressant generic abrasive category of 2,875 is 70% lower than silica sand's geometric mean level of 8.828 mg/m^3. However, the geometric mean concentrations for the corresponding pairs of treated and untreated abrasives (SSDS-01 and SS-01; SSDS-02 and SS-04; and SSDS-03 and SS-03) show relatively consistent geometric mean levels for two of the three individual paired sets.

The garnet generic abrasive category had 17 out of 52 airborne samples with results above the limit of detection for respirable quartz. Caution must be used when considering quartz data from the garnet samples described on the first page of the Respirable Quartz Section in Appendix B, since these samples were evaluated by primary or secondary peak height measurement, due to problematical integration data caused be interferences. Three of the seven specific abrasives within this generic category had no results above the limit of detection for respirable quartz. Of the remaining four, there is considerable variability with garnet G-6A/B showing a range from below the limit of detection to 0.24 mg/m^3 and garnet G-3A showing a range from below the limit of detection to 6.8 mg/m^3. The geometric mean level of respirable quartz for the garnet generic abrasive category of 0.23 mg/m^3 is nearly 98% lower than the geometric mean level of 8.83 mg/m^3 for silica sand.

The copper slag generic category of abrasive had 3 out of 32 sample results above the limit of detection for respirable quartz. Only one of the four individual abrasives within the generic category had considerable range of concentrations. Copper slag CP-4A/B had a reported range from below the limit of detection to 0.74 mg/m^3. The geometric mean level of respirable quartz for the copper slag generic abrasive category of 0.15 mg/m^3 is over sixty times lower than silica sand's geometric mean level of 8.83 mg/m^3.

Staurolite abrasive had 1 out of 8 samples with results above the limit of detection. The single sample concentration of 0.49 mg/m^3 resulted in a geometric mean of 0.15 mg/m^3, which is nearly 60 times lower than the geometric mean of 8.83 mg/m^3 for silica sand.

Silver

Figure 11 illustrates the range and geometric mean for the airborne levels of silver for each of the 40 abrasive products and the associated generic category of abrasive. The following generic categories of abrasives had all airborne results below the limit of detection for silver: crushed glass, nickel slag, olivine, staurolite, specular hematite, and silica sand.

The following generic abrasive categories had at least one airborne sample with results above the limit of detection for silver, and in order from the highest to lowest geometric mean level include: copper slag, copper slag with dust suppressant, steel grit, coal slag with dust suppressant, coal slag, silica sand with dust suppressant, and garnet. The variability of results for individual abrasives within a generic category must also be considered in addition to comparisons of the combined data for the entire generic category.

The silica sand generic abrasive category had no measured results above the limit of detection. The geometric mean for the silica sand generic abrasive category equals the limit of detection for each abrasive divided by two, which is 0.84 $\mu g/m^3$. This will be used as the standard for comparison.

The copper slag generic category of abrasive had 20 out of 32 airborne samples with results above the limit of detection for silver. The range was somewhat variable, with a high of 13.79 $\mu g/m^3$ for copper slag CP-2A/B and a high of 77.5 $\mu g/m^3$ for CP-4A/B. Copper slag CP-1A/B had no results above the limit of detection for silver. The geometric mean level of silver for the copper slag generic abrasive category of 3.46 $\mu g/m^3$ is approximately 4 times higher than silica sand's geometric mean level of 0.83 $\mu g/m^3$.

The copper slag with dust suppressant generic category of abrasive resulted in 5 out of 8 airborne samples with results in excess of limit of detection. The results ranged from 0.81 to 9.42 $\mu g/m^3$, which closely parallel the range for the untreated counterpart (copper slag, CP-2A/B) with a range from below the limit of detection to 13.7 $\mu g/m^3$. The geometric mean level for the copper slag with dust suppressant of 2.1 $\mu g/m^3$ is approximately 2.5 times higher than silica sand's geometric mean level of 0.83 $\mu g/m^3$.

The steel grit generic category of abrasive had 1 out of 16 airborne samples with results above the limit of detection. This sample was associated with abrasive SG-1A/B and had a concentration of 15.24 $\mu g/m^3$. The geometric mean level of silver for the steel grit generic abrasive category of 1.64 $\mu g/m^3$ is nearly two times higher than silica sand's geometric mean level of 0.83 $\mu g/m^3$.

The coal slag with dust suppressant generic abrasive category had 2 out of 8 airborne samples with results above the limit of detection for silver. These results were higher than the corresponding untreated coal slag abrasive. For CSDS-01, the maximum concentration of 20.62 $\mu g/m^3$ can be compared to the untreated counterpart coal slag CS-

06's maximum concentration of 1.94 $\mu g/m^3$. Similarly, the maximum concentration for CSDS-02 of 1.95 $\mu g/m^3$ can be compared to the non-detectable results for the untreated counterpart CS-01. The resulting geometric mean level of silver for the coal slag with dust suppressant generic category of 1.38$\mu g/m^3$ is approximately 1.6 times higher than silica sand's geometric mean level of 0.83 $\mu g/m^3$.

For the remaining generic categories of abrasives, including coal slag, silica sand with dust suppressant, and garnet, each had only one airborne result above the limit of detection for silver. The corresponding geometric mean levels of silver in the coal slag, silica sand with dust suppressant and garnet were slightly above (1.94, 1.88, and 3.11 $\mu g/m^3$, respectively) the geometric mean level of silver in silica sand (0.83 $\mu g/m^3$).

Titanium

Figure 12 illustrates the range and geometric mean for the airborne levels of titanium for each of the 40 abrasive products and the associated generic category of abrasive. All of the generic abrasive categories had airborne samples with results above the limit of detection for titanium, and in order of the highest to the lowest geometric mean level include: copper slag with dust suppressant, coal slag with dust suppressant, staurolite, coal slag, copper slag, nickel slag, garnet, silica sand, silica sand with dust suppressant, specular hematite, steel grit, olivine, and crushed glass. The variability of results for individual abrasives within a generic category must also be considered when making comparisons using combined data for an entire generic category.

The silica sand generic category of abrasive had 28 out of 28 samples with results above the limit of detection for titanium. The results were highly variable, and ranged from 4.58 to 565 $\mu g/m^3$. The geometric mean level of titanium for the silica sand generic abrasive category was 48.8 $\mu g/m^3$. This will be used as the standard for comparison.

The copper slag with dust suppressant resulted in a range from 790 to 8,879 $\mu g/m^3$, and a geometric mean concentration of titanium of 2,078 $\mu g/m^3$, which is over 40 times higher than silica sand's geometric mean level of 48.8 $\mu g/m^3$. This measured range and geometric mean concentration is essentially identical to the untreated counterpart (copper slag CP-2A/B) with a range from 578 $\mu g/m^3$ to 9,747 $\mu g/m^3$ and a geometric mean level of 1826 $\mu g/m^3$.

The coal slag with dust suppressant generic category of abrasives had 8 out of 8 airborne samples with results above the limit of detection for titanium. The range of reported concentrations of 332 to 5,589 $\mu g/m^3$ is consistent for one set of paired data (CSDS-02 and CS-01). However, the range for CSDS-01 of 332 to 4,568 $\mu g/m^3$ is far broader than the corresponding matched pair of CS-06 with a range of 813 to 2,010 $\mu g/m^3$. The geometric mean level of titanium for the coal slag with dust suppressant generic category of abrasive of 1581 $\mu g/m^3$ is over 30 times higher than silica sand's geometric mean level of 48.8 $\mu g/m^3$.

The staurolite generic category of abrasive had 8 out of 8 airborne samples with results above the limit of detection for titanium. The range of concentrations from 228 to 3,769 $\mu g/m^3$ were somewhat variable, but the maximum concentrations for either of the individual abrasives were roughly equivalent. The geometric mean level of titanium for the staurolite abrasive category of 1,565 $\mu g/m^3$ is over 30 times higher than silica sand's geometric mean level of 48.8 $\mu g/m^3$.

The coal slag generic abrasive category had 28 out of 28 airborne samples with results in excess of the limits of detection for titanium. The range was somewhat variable between the individual abrasives, with coal slag CS-03 resulting in the highest range of 722 to 10,576 $\mu g/m^3$ and geometric mean of 2,830 μg/m3, and CS-05 resulting in the lowest range of 173 to 1,423 $\mu g/m^3$ and geometric mean of 599 $\mu g/m^3$. The geometric mean level of titanium for the coal slag generic abrasive category of 1,545 $\mu g/m^3$ was about 30 times higher than silica sand's geometric mean level of 48.8 $\mu g/m^3$.

The copper slag generic abrasive category had 32 out of 32 airborne samples with results above the limit of detection for titanium. The total reported range of concentrations from 146 to 9,747 $\mu g/m^3$ was fairly broad and variable between the individual abrasives. The geometric mean level of titanium for the copper slag generic abrasive category of 1,240 $\mu g/m^3$ was about 25 times higher than silica sand's geometric mean level of 48.8 $\mu g/m^3$.

The nickel slag generic abrasive category had 8 out of 8 airborne samples with results above the limit of detection for titanium. The range of measured concentrations was widely variable between the two individual abrasives. Nickel slag N-01 had a reported range of 18 to 290 $\mu g/m^3$ and a geometric mean of 93.6 $\mu g/m^3$. Nickel slag N-02 had a reported range from 347 to 2,708 $\mu g/m^3$ and a geometric mean of 763 $\mu g/m^3$. The geometric mean level of titanium for the nickel slag generic abrasive category of 267 $\mu g/m^3$ is approximately 5.5 times higher than silica sand's geometric mean level of 48.8 $\mu g/m^3$.

The garnet generic category of abrasives had all 52 samples with results above the limit of detection for titanium. The results were highly variable with garnet G-2A/B resulting in the lowest range from 10 to 114 $\mu g/m^3$ and garnet G-7A/B resulted in the highest range from 160 to 1,252 $\mu g/m^3$. The geometric mean level of titanium for the garnet generic abrasive category of 187 $\mu g/m^3$ is nearly 4 times higher than silica sand's geometric mean level of 48.8 $\mu g/m^3$.

The silica sand with dust suppressant generic abrasive category had 11 out of 12 airborne samples with results in excess of limit of detection for titanium. The recorded range of concentrations, from 2 to 598 $\mu g/m^3$ is similar to the generic category of silica sand of 5 to 565 $\mu g/m^3$. In addition, there is reasonably consistent data between two of the three-paired sets of data (i.e. SSDS-01 with SS-01; and SSDS-02 with SS-04). However, silica sand with dust suppressant SSDS-03 is somewhat lower than its corresponding untreated counterpart silica sand SS-03. As a result, the geometric mean level of titanium for the silica sand with dust suppressant generic category of abrasive of 30.6 μg/m^3 is 40% lower than the silica sand geometric mean level of 48.8 μg/cm^3.

The remaining abrasives including specular hematite, steel grit, olivine, and crushed glass all had reported ranges and geometric mean levels below silica sand.

Vanadium

Figure 13 illustrates the range and geometric mean for the airborne levels of vanadium for each of the 40 abrasive products and the associated generic category of abrasive. The crushed glass category of abrasive did not result in any measurements above the limit of detection for vanadium.

The following generic abrasive categories had at least one airborne sample with results above the limit of detection for vanadium, and in order from the highest to the lowest geometric mean level include: copper slag with dust suppressant, coal slag, coal slag with dust suppressant, copper slag, steel grit, nickel slag, garnet, staurolite, silica sand with dust suppressant, silica sand, olivine, and specular hematite. The variability of results for individual abrasives within in a generic category must also be considered in addition to comparisons of combined data for an entire generic category.

The silica sand generic abrasive category had 18 out of 28 airborne samples with results above the limit of detection for vanadium. There is considerable variability in results with silica sands SS-01, SS-02, SS-03, SS-06, and SS-07 ranging from below the limit of detection to the maximum value of 7.52 μg/m^3, while silica sands SS-04 and SS-05 range from a low of 3.56 to a high of 35.34 μg/m^3. The geometric mean for the silica sand generic abrasive category was 3.16 μg/m^3. This will be used as the standard for comparison.

The copper slag with dust suppressant generic abrasive had 8 out of 8 airborne samples with results above the limit of detection for vanadium. The range of concentrations was from 40 to 454 μg/m^3. This is similar to the corresponding untreated copper slag CP-2A/B which ranged from 31 to 518 μg/m^3. The geometric mean level of vanadium for the copper slag with dust suppressant of 108 μg/m^3 is nearly 35 times higher than the silica sand's geometric mean level of 3.16 μg/m^3.

The coal slag generic category of abrasive had all 28 airborne samples with results above the limit of detection for vanadium. While there was variability within the ranges, the geometric mean concentrations are relatively consistent. The total range of reported concentrations were from 9.46 to 666 μg/m^3. The range of geometric means was 38.6 to 173 μg/m^3. The geometric mean level of vanadium for the coal slag generic abrasive category of 70 μg/m^3 is 22 times higher than silica sand's geometric mean level of 3.16 μg/m^3.

The coal slag with dust suppressant generic category of abrasive had 8 airborne samples with results above the limit of detection for vanadium. The range of concentrations was much smaller for one pair of untreated and treated coal slags (CS-06 and CSDS-01) and very similar for the second pair (CS-01 and CSDS-02). The geometric mean levels of the two-paired sets were nearly identical. The geometric mean level of vanadium for the coal slag with dust suppressant of 54 $\mu g/m^3$ is just under 20 times higher than silica sand's geometric mean level of 3.16 $\mu g/m^3$.

The copper slag generic category of abrasive had all 32 airborne samples with results above the limit of detection for vanadium. With the exception of copper slag CP-1A/B with a range of 3 to 59 $\mu g/m^3$, the remaining three copper slag abrasives were all within a range from 11.33 to 519 $\mu g/m^3$. The geometric mean level of vanadium for the copper slag generic category of abrasives of 45.3 $\mu g/m^3$ is nearly 15 times higher than silica sand's geometric mean level of 3.16 $\mu g/m^3$.

The steel grit generic abrasive category had 15 out of 16 airborne samples with results above the limit of detection for vanadium. There was considerable variability between the two abrasives within the category. Steel grit SG-1A/B had a reported range from 3.31 to 142 $\mu g/m^3$ and a geometric mean of 12.1 $\mu g/m^3$. Steel grit SG-2A/B ranged from 15 to 480 $\mu g/m^3$ and a geometric mean of 80.5 $\mu g/m^3$. The geometric mean level of vanadium for the steel grit generic abrasive category of 31.2 $\mu g/m^3$ is about 10 times higher than silica sand's geometric mean level of 3.16 $\mu g/m^3$.

The nickel slag generic abrasive category had all 8 airborne samples with results above the limit of detection for vanadium. The results were somewhat different between the two specific abrasives within the category. The geometric mean level of vanadium for the generic category of 29.1 $\mu g/m^3$ is approximately 6.5 times higher than silica sand's geometric mean level of 3.16 $\mu g/m^3$.

The garnet generic category of abrasives had 50 out of 52 airborne samples with results above the limit of detection for vanadium. The results were highly variable among the individual abrasives with garnet G-2A/B resulting in a maximum reported concentration of 6.43 $\mu g/m^3$ and a geometric mean of 2.82 $\mu g/m^3$, and garnet G-6A/B resulting in a maximum concentration of 121 $\mu g/m^3$ and a geometric mean of 29.3 $\mu g/m^3$. The geometric mean level of vanadium for the garnet generic abrasive category of 10.8 $\mu g/m^3$ is nearly 3.5 times higher than silica sands geometric mean level of 3.16 $\mu g/m^3$.

The staurolite generic category of abrasives had all 8 airborne samples with results above the limit of detection for vanadium. The range of concentration and geometric mean for the individual abrasives within the category were relatively consistent and ranged from 2.28 to 22.96 $\mu g/m^3$. The geometric mean level of vanadium for the staurolite generic abrasive category of 7.3 $\mu g/m^3$ was just over 2 times higher than silica sand's geometric mean level of 3.16 $\mu g/m^3$.

The silica sand with dust suppressant generic category of abrasives had 7 out of 12 sample results above the limit of detection for vanadium. The results within the individual abrasives within this category were highly variable. Silica sand with dust suppressants SSDS-01 and SSDS-03 had similar ranges, from below the limit of detection to 3.71 $\mu g/m^3$. Silica sand with dust suppressant SSDS-02 had a range from below the limit of detection to 2,043 $\mu g/m^3$. The results for SSDS-02 did not compare with the paired untreated silica sand (SS-04) either. The geometric mean level of vanadium for the silica sand with dust suppressant category of 3.29 $\mu g/m^3$ is slightly higher than silica sand's geometric mean level of 3.16 $\mu g/m^3$.

The remaining abrasives including olivine and specular hematite have measured ranges and geometric mean levels below that for silica sand.

FIGURE 3 – ARSENIC AIR SAMPLE RESULTS

FIGURE 4 – BERYLLIUM AIR SAMPLE RESULTS

FIGURE 5 – CADMIUM AIR SAMPLE RESULTS

FIGURE 6 – CHROMIUM AIR SAMPLE RESULTS

FIGURE 7 – LEAD AIR SAMPLE RESULTS

FIGURE 8 – MANGANESE AIR SAMPLE RESULTS

FIGURE 9 – NICKEL AIR SAMPLE RESULTS

FIGURE 10 – RESPIRABLE QUARTZ AIR SAMPLE RESULTS

FIGURE 11 – SILVER AIR SAMPLE RESULTS

FIGURE 12 – TITANIUM AIR SAMPLE RESULTS

FIGURE 13 – VANADIUM AIR SAMPLE RESULTS

Industrial Hygiene Discussion

Ten generic types of abrasives, plus three generic types treated with dust suppressant, were evaluated for 28 metals/elements, and respirable quartz and cristobalite, through the analysis of airborne dust and bulk materials. For comparison purposes, NIOSH selected twelve health-related agents for comparative analysis, including: arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, respirable quartz, silver, titanium, vanadium, and radium-226. Table 11, found at the end of this discussion on page 120, summarizes the airborne monitoring results for each of these health-related agents except radium-226, which is discussed elsewhere, 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 as illustrated previously in the Industrial Hygiene Results section of this report. The following is a discussion of key observations concerning this data. It is summarized by generic type of abrasive.

Crushed Glass

Three of the 4 airborne samples of crushed glass had a measured concentration above the limit of detection (LOD) for beryllium. Crushed glass has a geometric mean concentration of beryllium (0.08 $\mu g/m^3$), which is similar (14% less) to that of silica sand (0.09 $\mu g/m^3$).

Three of the 4 airborne samples of crushed glass had a measured concentration above the LOD for chromium. The geometric mean concentration of 12.5 $\mu g/m^3$ is similar (1.8 times greater) to that of silica sand at 7.1 $\mu g/m^3$.

All 4 airborne samples of crushed glass had a concentration above the LOD for lead. The geometric mean concentration of 12.2 $\mu g/m^3$ was 4.4 times greater than that of silica sand at 2.7 $\mu g/m^3$.

All 4 airborne samples of crushed glass had a measured concentration above the LOD for manganese. The geometric mean concentration of 56.9 $\mu g/m^3$ was similar (1.2 times greater) to that of silica sand at 45.7 $\mu g/m^3$.

Three of the 4 airborne samples of crushed glass had a measured concentration above the LOD for titanium. Silica sand's geometric mean airborne titanium concentration (48.8 $\mu g/m^3$) was 7.6 times greater than that of crushed glass (6.4 $\mu g/m^3$).

Arsenic, cadmium, nickel, respirable quartz, silver, and vanadium were not detected above the LOD in any of the crushed glass airborne samples. Crushed glass also has a lower geometric mean concentration than silica sand for beryllium and titanium. Crushed glass had a greater geometric mean concentration than silica sand for only chromium, lead, and manganese; but is only 1.8, 4.4, and 1.2 times greater, respectively.

Based on the industrial hygiene results in the laboratory study, substituting crushed glass for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. The airborne concentrations for the other health-related agents should also be reduced, with the exception of chromium, lead, and manganese which were slightly higher for crushed glass. Only 1 abrasive was tested for crushed glass, but only 3 major producers currently process and market recycled crushed glass for the abrasive blasting industry. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Coal Slag

Nine of the 28 airborne samples of coal slag had a measured concentration above the LOD for arsenic. The geometric mean concentration of 2.9 $\mu g/m^3$ for the coal slag generic abrasive category was similar (1.4 times higher) to that of silica sand at 2.0 $\mu g/m^3$. Coal slag has the fifth highest geometric mean concentration of arsenic; copper slag and copper slag with dust suppressant, steel grit, and nickel slag were higher.

All 28 airborne samples of coal slag had a measured concentration above the LOD for beryllium. The geometric mean concentration of 2.04 $\mu g/m^3$ for the coal slag generic abrasive category was 23 times higher than that of silica sand at 0.09 $\mu g/m^3$. Coal slag had the second highest geometric mean concentration of beryllium, next to coal slag with dust suppressant. The geometric mean concentration of beryllium for coal slag was 2.6 times higher than the next highest generic abrasive category (copper slag).

Ten of the 28 airborne samples of coal slag had a measured concentration above the LOD for cadmium. The geometric mean concentration of 0.13 $\mu g/m^3$ for the coal slag generic abrasive category was similar (1.6 times greater) to that of silica sand at .08 $\mu g/m^3$. Coal slag had the third highest geometric mean concentration of cadmium; behind copper slag and nickel slag.

Twenty-six of the 28 airborne samples of coal slag had a measured concentration above the LOD for chromium. The geometric mean concentration of 38.7 $\mu g/m^3$ for the coal slag generic abrasive category was 5.4 times higher than that of silica sand at 7.1 $\mu g/m^3$. Coal slag has 6 abrasive categories with higher geometric mean concentrations of chromium, and 6 with lower geometric mean concentrations of chromium.

Eighteen of the 28 airborne samples of coal slag had a measured concentration above the LOD for lead. The geometric mean concentration of 3.9 $\mu g/m^3$ for the coal slag generic abrasive category is similar (1.4 times higher) to that of silica sand at 2.7 $\mu g/m^3$. Coal slag had 6 generic abrasive categories with higher geometric mean concentrations of lead, and 6 with lower geometric mean concentrations of lead.

All 28 airborne samples of coal slag had a measured concentration above the LOD for manganese. The geometric mean concentration of 148.7 $\mu g/m^3$ for the coal slag generic abrasive category was 3.2 times higher than that of silica sand at 45.7 $\mu g/m^3$.

Coal slag had 6 generic abrasive categories with higher geometric mean concentrations of manganese, and 6 with lower geometric mean concentrations of manganese.

Twenty-three of 28 airborne samples of coal slag had a measured concentration above the LOD for nickel. The geometric mean concentration of 28.3 $\mu g/m^3$ for the coal slag generic abrasive category was 4.7 times higher than that of silica sand at 6.0 $\mu g/m^3$. Coal slag had the fifth highest geometric mean concentration of nickel; olivine, nickel slag, steel grit, and copper slag with dust suppressant were higher.

Coal slag has only 1 of 28 airborne samples with a concentration (2.6 $\mu g/m^3$) above the LOD for silver. All of silica sand's airborne samples were less than the LOD for silver. Coal slag had the fifth highest geometric mean concentration of silver; copper slag and copper slag with dust suppressant, steel grit, and coal slag with dust suppressant were higher.

All 28 airborne samples of coal slag had a measured concentration above the LOD for titanium. Coal slag's geometric mean concentration of 1545 $\mu g/m^3$ was about 32 times higher than that of silica sand at 48.8 $\mu g/m^3$. Coal slag had the fourth highest geometric mean concentration of titanium; copper slag with dust suppressant, staurolite, and coal slag with dust suppressant were higher.

All 28 airborne samples of coal slag had a measured concentration above the LOD for vanadium. Coal slag's geometric mean concentration of 70.0 $\mu g/m^3$ was about 22 times higher than that of silica sand at 3.1 $\mu g/m^3$. Coal slag had the second highest geometric mean concentration of vanadium; only copper slag with dust suppressant was higher.

All of coal slag's airborne samples were less than the LOD for respirable quartz. Based on the industrial hygiene results in the laboratory study, substituting coal slag for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. However, the coal slag generic abrasive category is not without potential hazardous health-related agent concerns.

Coal slag, as a generic category of abrasives, has a greater geometric mean airborne concentration than that of silica sand for all of the remaining ten hazardous health-related agents, but the coal slag geometric mean of arsenic (1.4x), cadmium (1.6x), lead (1.4x), manganese (3.2x), and silver (1.1x) are only 1.1 to 3.2 times greater than that of silica sand. Out of the thirteen generic abrasive categories, untreated and treated coal slag have the two highest geometric mean airborne concentrations of beryllium, being 23 times greater than that of silica sand and 2.6 times greater than the next highest generic abrasive category (copper slag). All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Coal Slag with Dust Suppressant

One out of 8 airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for arsenic. The geometric mean concentration of 2.3 $\mu g/m^3$ was similar (1.15 times higher) to that of silica sand at 2.0 $\mu g/m^3$. Coal slag with dust suppressant had the sixth highest geometric mean concentration for arsenic; copper slag, copper slag with dust suppressant, steel grit, nickel slag, and coal slag were higher.

All eight airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for beryllium. The geometric mean concentration of 2.2 $\mu g/m^3$ was over 25 times higher than that of silica sand at 0.09 $\mu g/m^3$. Coal slag with dust suppressant had the highest geometric mean concentration of beryllium, followed closely by coal slag.

One of eight airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for cadmium. The geometric mean concentration of 0.08 $\mu g/m^3$ was the same as silica sand at 0.08 $\mu g/m^3$. Only copper slag with dust suppressant, crushed glass, and olivine had lower geometric mean concentrations of cadmium.

Seven of 8 airborne samples of coal slag with dust suppressant had a measured concentration above the limit of detection for chromium. The geometric mean concentration of 39.5 $\mu g/m^3$ was about 5.5 times higher than that of silica sand at 7.1 $\mu g/m^3$. Coal slag with dust suppressant had the sixth highest geometric mean concentration of chromium; nickel slag, steel grit, olivine, copper slag, and copper slag with dust suppressant were higher.

Six of 8 airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for lead. The geometric mean concentration of 4.0 $\mu g/m^3$ is about 1.5 times higher than that of silica sand at 2.7 $\mu g/m^3$. Coal slag with dust suppressant had the sixth highest geometric mean concentration of lead; copper slag, crushed glass, staurolite, copper slag with dust suppressant, and nickel slag were higher.

All 8 airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for manganese. The geometric mean concentration of 132.6 $\mu g/m^3$ was nearly 3 times greater than silica sand at 45.7 $\mu g/m^3$. Coal slag with dust suppressant is the eighth highest geometric mean concentration for manganese; staurolite, specular hematite, crushed glass, silica sand with dust suppressant, and silica sand were lower.

Six of 8 airborne samples of coal slag with dust suppressant had a measured concentration above the limit of detection for nickel. The geometric mean concentration of 25.2 $\mu g/m^3$ was 4.2 times higher than silica sand at 6.0 $\mu g/m^3$. Coal slag with dust suppressant had the sixth highest geometric mean concentration for nickel; olivine, nickel slag, steel grit, copper slag with dust suppressant, and coal slag were higher.

Two of 8 airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for silver. The geometric mean concentration was 1.4 $\mu g/m^3$. There were no measured concentrations of silver above the limit of detection for silica sand abrasives. Coal slag with dust suppressant had the fourth highest geometric mean concentration of 7 abrasive categories with measurable results. Copper slag, copper slag with dust suppressant, and steel grit had higher geometric mean concentrations. Coal slag, silica sand with dust suppressant, and garnet had lower geometric mean concentrations. There was no detectable silver in crushed glass, olivine, staurolite, specular hematite, or silica sand.

Eight of 8 airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for titanium. The geometric mean concentration of 1581 $\mu g/m^3$ was 32 times higher than that of silica sand at 48.8 $\mu g/m^3$. Coal slag with dust suppressant had the second highest geometric mean concentration. Only copper slag with dust suppressant was higher.

Eight out of 8 airborne samples of coal slag with dust suppressant had a measured concentration above the LOD for vanadium. The geometric mean concentration of 54.1 $\mu g/m^3$ was 16.9 times higher than that of silica sand at 3.2 $\mu g/m^3$. Coal slag with dust suppressant had the third highest geometric mean concentration of vanadium; copper slag with dust suppressant and coal slag were higher.

All of coal slag's airborne samples were less than the LOD for respirable quartz. Based on the industrial hygiene results and the laboratory study, substituting coal slag for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. However, the coal slag generic abrasive category is not without potential hazardous health-related agent concerns.

Coal slag with dust suppressant as a generic category of abrasive has a higher geometric mean airborne concentration than that of silica sand for all but one of the remaining ten hazardous health-related agents. The geometric mean concentration of chromium was essentially identical for coal slag with dust suppressant and that of silica sand. Out of the 13 generic abrasive categories, coal slag with dust suppressant had the highest geometric mean concentration of beryllium, second highest geometric mean for titanium, and third highest geometric mean for vanadium. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Nickel Slag

Four of the 8 airborne samples of nickel slag had a measured concentration above the LOD for arsenic. The geometric mean concentration of 9.7 $\mu g/m^3$ was 4.8 times higher than that of silica sand at 2.0 $\mu g/m^3$. The geometric mean concentration of nickel slag was the fourth highest; copper slag, copper slag with dust suppressant, and steel grit were higher.

Five out of 8 airborne samples of nickel slag had measured concentrations of beryllium above the LOD. The geometric mean concentration of 0.14 $\mu g/m^3$ was similar (1.5 times higher) than that of silica sand at 0.09 $\mu g/m^3$. Nickel slag had the fifth highest geometric mean concentration of beryllium; coal slag with dust suppressant, coal slag, copper slag, and copper slag with dust suppressant were higher.

Four out of 8 airborne samples of nickel slag had measured concentrations above the LOD for cadmium. The geometric mean concentration of 0.25 $\mu g/m^3$ is about 3 times higher than silica sand at 0.08 $\mu g/m^3$. Nickel slag had the second highest geometric mean concentration of cadmium; copper slag was higher.

All 8 airborne samples of nickel slag had measured concentrations above the LOD for chromium. The geometric mean concentration of 811.8 is nearly 115 times higher than that of silica sand at 7.1 $\mu g/m^3$. Nickel slag had the highest geometric mean concentration of chromium, and 3.5 times higher than the next highest generic category of steel grit.

Six airborne samples of nickel slag had measured concentrations of lead above the LOD for lead. The geometric mean concentration of 4.4 $\mu g/m^3$ was 1.6 times higher than silica sand at 2.7 $\mu g/m^3$. Nickel slag had the fifth highest geometric mean concentration of lead; copper slag, crushed glass, staurolite, and copper slag with dust suppressant were higher.

All 8 airborne samples of nickel slag had measured concentrations above the LOD for manganese. The geometric mean concentration of 459 $\mu g/m^3$ was nearly 10 times higher than silica sand at 45.7 $\mu g/m^3$. Nickel slag had the sixth highest geometric mean concentration for manganese; copper slag with dust suppressant, steel grit, garnet, copper slag, and olivine were higher.

All 8 of the airborne samples of nickel slag had measured concentrations above the LOD for nickel. The geometric mean concentration of 987 $\mu g/m^3$ was nearly 165 times higher than silica sand at 6.0 $\mu g/m^3$. Nickel slag had the second highest geometric mean concentration of nickel; olivine was higher.

All 8 airborne samples of nickel slag had a measured concentration above the LOD for titanium. The geometric mean concentration of 267.3 $\mu g/m^3$ was nearly 5.5 times higher than silica sand at 48.8 $\mu g/m^3$. Nickel slag had the sixth highest geometric mean concentration of titanium; copper slag with dust suppressant, coal slag with dust suppressant, staurolite, coal slag, and copper slag were higher.

All 8 airborne samples of nickel slag had measured concentrations above the LOD for vanadium. The geometric mean concentration of 29.1 $\mu g/m^3$ was 9 times higher than silica sand at 3.2 μg/m^3. Nickel slag had the sixth highest geometric mean concentration of vanadium; copper slag with dust suppressant, coal slag, coal slag with dust suppressant, copper slag, and steel grit were higher.

Respirable quartz and silver were not detected above the LOD in any of the nickel slag airborne samples. Based on the industrial hygiene results in the laboratory study, substituting nickel slag for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. However, the nickel slag generic abrasive category is not without potential hazardous health-related agent concerns.

Nickel slag as a generic category of abrasives had the highest geometric mean concentration of chromium, and second highest concentrations of cadmium and nickel. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Olivine

Two of the 4 airborne samples of olivine had a measured concentration above the LOD for beryllium. The geometric mean concentration of 0.03 μg/m^3 was approximately 1/3 that of silica sand at 0.09 μg/m^3. Olivine had the lowest geometric mean concentration of beryllium for all 13 generic categories of abrasives.

All 4 airborne samples of olivine had measured concentrations above the LOD for chromium. The geometric mean of 116.8 μg/m^3 was nearly 116.5 times higher than silica sand at 7.1 μg/m^3. Olivine had the third highest geometric mean concentration of chromium; nickel slag and steel grit were higher.

One of the 4 airborne samples of olivine had a measured concentration above the LOD for lead. The geometric mean concentration of 1.6 μg/m^3 was approximately 60% of the silica sand at 2.7 μg/m^3. Olivine had the next to the lowest geometric mean concentration of lead for all of the 13 generic categories of abrasives; silica sand with dust suppressant was lower.

All 4 airborne samples of olivine had measured concentrations above the LOD for manganese. The geometric mean concentration of 500 μg/m^3 was nearly 11 times higher than that of silica sand at 45.7 μg/m^3. Olivine had the fifth highest geometric mean for manganese; copper slag with dust suppressant, steel grit, garnet, and copper slag were higher.

All 4 airborne samples of olivine had measured concentrations above the LOD for nickel. The geometric mean concentration of 1628.5 μg/m^3 was 271 times that of silica sand at 6.0 μg/m^3. Olivine had the highest geometric mean concentration of nickel and was nearly 1.7 times higher than the next highest, nickel slag.

Three out of 4 airborne samples of olivine had a measured concentration above the LOD for titanium. The geometric mean concentration of 7.4 $\mu g/m^3$ was only about 15% that of silica sand at 48.8 $\mu g/m^3$. Olivine had the second lowest geometric mean concentration of titanium, only crushed glass was lower.

Two of 4 airborne samples of olivine had a measured concentration above the LOD for vanadium. The geometric mean concentration of 1.6 $\mu g/m^3$ was approximately half that of silica sand at 3.2 $\mu g/m^3$. Olivine had the third lowest geometric mean concentration of vanadium, only staurolite and crushed glass were lower.

Arsenic, cadmium, respirable quartz, and silver were not detected above the LOD in any of the olivine airborne samples. Olivine had a lower geometric mean concentration than silica sand for arsenic, beryllium, cadmium, lead, respirable quartz, titanium, and vanadium. Olivine had an equivalent geometric mean concentration of silver. Olivine had a greater geometric mean concentration than silica sand for chromium, manganese, and nickel.

Based on the industrial hygiene results in the laboratory study, substituting olivine for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. The airborne concentrations for the other health-related agents should also be reduced, with the exceptions of chromium, manganese, and nickel. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Staurolite

Three of the 8 airborne samples of staurolite had a measured concentration above the LOD for beryllium. The geometric mean concentration of 0.06 $\mu g/m^3$ was approximately 66% that of silica sand at 0.09 $\mu g/m^3$. Olivine had the fourth lowest geometric mean concentration of beryllium; silica sand with dust suppressant, steel grit, and olivine were lower.

One of 4 airborne samples of staurolite had a measured concentration above the LOD for cadmium. The geometric mean concentration of 0.09 $\mu g/m^3$ was essentially identical to silica sand at 0.08 $\mu g/m^3$. There were 6 generic abrasive categories with geometric mean concentrations of cadmium higher than staurolite, and six categories with geometric mean concentrations lower than staurolite.

Three of 8 airborne samples of staurolite had a measured concentration above the LOD for chromium. The geometric mean concentration of 8.6 $\mu g/m^3$ was similar (1.2 times higher) to that of silica sand at 7.1 $\mu g/m^3$. Staurolite was the fourth lowest geometric mean for chromium; silica sand, silica sand with dust suppressant, and specular hematite were lower.

Seven of the 8 airborne results of staurolite had measured concentrations above the LOD for lead. The geometric mean concentration of 7.7 $\mu g/m^3$ was 2.8 times higher than silica sand at 2.7 $\mu g/m^3$. Staurolite had the third highest geometric mean concentration of lead; copper slag and crushed glass were higher.

All 8 of the airborne sample results for staurolite had measured concentrations above the LOD for manganese. The geometric mean concentration of 121 $\mu g/m^3$ was 2.6 times higher than silica sand at 45.7 $\mu g/m^3$. Staurolite had the ninth highest geometric mean concentration for manganese; specular hematite, crushed glass, silica sand with dust suppressant, and silica sand were lower.

One of the 8 airborne samples of staurolite had a measured concentration above the LOD for respirable quartz. The geometric mean concentration of 0.14 mg/m^3 was less than 2% of that of silica sand at 8.8 mg/m^3. Of the 5 generic categories of abrasives with detectable concentrations of respirable quartz (silica sand, silica sand with dust suppressant, garnet, and copper slag), staurolite had the lowest concentration.

All 8 of the airborne sample results of staurolite had a measured concentration above the LOD for titanium. The geometric mean concentration of 1564 $\mu g/m^3$ was 32 times higher than that of silica sand at 48.8 $\mu g/m^3$. Staurolite had the third highest geometric mean concentration of titanium; copper slag with dust suppressant, and coal slag with dust suppressant were higher.

All 8 airborne samples of staurolite had measured concentrations above the LOD for vanadium. The geometric mean concentration of 7.3 $\mu g/m^3$ was about 2.3 times higher than silica sand at 3.2 $\mu g/m^3$.

Arsenic, nickel, and silver were not detected above the LOD in any of the staurolite airborne samples. Staurolite had a lower geometric mean concentration than silica sand for beryllium, nickel, and respirable quartz. Based on the industrial hygiene results in the laboratory study, substituting staurolite for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. The airborne concentrations for the other health-related agents should also be reduced, except for lead and titanium where staurolite had the third highest geometric mean concentrations. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Specular Hematite

Only 1 of the 4 airborne samples of specular hematite had a measured concentration above the LOD for beryllium. The geometric mean concentration of 0.06 $\mu g/m^3$ was similar (about 31% less) to that of silica sand at 0.09 $\mu g/m^3$.

Only 1 of the 4 airborne samples of specular hematite had a measured concentration above the LOD for cadmium. The geometric mean concentration of 0.1 $\mu g/m^3$ was similar (about 1.3 times greater) to that of silica sand at 0.08 $\mu g/m^3$.

All 4 airborne samples of specular hematite had measured concentrations above the LOD for manganese. The geometric mean concentration of 61.0 $\mu g/m^3$ was similar (about 1.3 times greater) to that of silica sand at 45.7 $\mu g/m^3$.

All 4 airborne samples of specular hematite had a measured concentration above the LOD for titanium. Silica sand's geometric mean concentration of titanium at 48.8 $\mu g/m^3$ was 3.2 times greater than specular hematite at 15.1 $\mu g/m^3$.

Only 1 of the 4 airborne samples of specular hematite had a measured concentration above the LOD for vanadium. Silica sand's geometric mean concentration of vanadium at 3.2 $\mu g/m^3$ was 2.2 times greater than specular hematite at 1.4 $\mu g/m^3$.

Arsenic, chromium, lead, nickel, respirable quartz, and silver were not detected above the LOD in any of the specular hematite airborne samples. Specular hematite had a lower geometric mean concentration than silica sand for beryllium, titanium, and vanadium. Specular hematite had a greater geometric mean concentration than silica sand for cadmium and manganese, but was only 1.3 times greater.

Based on the industrial hygiene results in the laboratory study, substituting specular hematite for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. The airborne concentrations for the other health-related agents should also be reduced, with the exception of cadmium and manganese (which are slightly higher for specular hematite). Only one abrasive was tested for specular hematite, but only one major producer mines specular hematite and markets this product for the abrasive blasting industry. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Silica Sand

Two out of 28 airborne samples of silica sand had measured concentrations above the LOD for arsenic. The geometric mean concentration was 2.0 $\mu g/m^3$, which placed silica sand third lowest within the 13 generic abrasive categories. Garnet and olivine were lower.

Seventeen of 28 airborne samples of silica sand had measured concentrations above the LOD for beryllium. The geometric mean concentration was 0.087 $\mu g/m^3$. This placed silica sand seventh highest out of the 13 generic abrasive categories, with 6 abrasives having higher geometric mean concentrations and 6 abrasive categories having lower geometric mean concentrations.

Seven out of 28 airborne results of silica sand had measured concentrations above the LOD for cadmium. The geometric mean concentration was 0.08 $\mu g/m^3$. This placed silica sand as fifth lowest geometric mean concentration of cadmium within the 13 generic abrasives. Coal slag with dust suppressant, copper slag with dust suppressant, crushed glass, and olivine had lower concentrations.

Eight out of 28 airborne samples of silica sand had measured concentrations above the LOD for chromium. The geometric mean concentration was 7.1 $\mu g/m^3$. This places silica sand third lowest among the 13 generic abrasives. Silica sand with dust suppressant and specular hematite had lower geometric mean concentrations.

Seventeen out of 28 airborne samples of silica sand had measured concentrations above the LOD for lead. The geometric mean concentration was 2.7 $\mu g/m^3$. This placed silica sand eighth out of 13 generic abrasives. Steel grit, specular hematite, garnet, olivine, and silica sand with dust suppressant, had lower geometric mean concentrations of lead.

All 28 airborne samples of silica sand had measured concentrations above the LOD for manganese. The geometric mean concentration was 45.7 $\mu g/m^3$. This was the lowest geometric mean concentration for manganese out of the 13 generic abrasives.

Four out of 28 airborne sample results had a measured concentration above the LOD for nickel. The geometric mean concentration was 6.0 $\mu g/m^3$. This placed silica sand ninth out of 13 generic abrasives. Staurolite, specular hematite, crushed glass, and silica sand with dust suppressant had lower geometric mean concentrations of nickel.

Twenty-seven out of 28 airborne samples of silica sand had measured concentrations above the LOD for respirable quartz. The geometric mean concentration was 8.8 mg/m^3. Silica sand had the highest geometric mean concentration of respirable quartz of all the generic categories of abrasives.

All 28 airborne samples of silica sand had measured concentrations above the LOD for titanium. The geometric mean concentration was 48.8 $\mu g/m^3$. This placed silica sand eighth out of 13 generic abrasives. Silica sand with dust suppressant, specular hematite, steel grit, olivine, and crushed glass had lower geometric mean concentrations of titanium.

Eighteen out of 28 airborne samples had a measured concentration above the LOD for vanadium. The geometric mean concentration for silica sand was 3.2 $\mu g/m^3$. This placed silica sand tenth out of 13 generic abrasives. Olivine, specular hematite, and crushed glass had lower geometric mean concentrations of vanadium.

Silica Sand with Dust Suppressant

Four out of 12 airborne results of silica sand with dust suppressant had measured concentrations above the LOD for beryllium. The geometric mean concentration of 0.06 $\mu g/m^3$ was about 66% of silica sand at 0.9 $\mu g/m^3$. Silica sand with dust suppressant had the third lowest geometric mean concentration of beryllium; steel grit and olivine were lower.

Two out of 12 airborne samples of silica sand with dust suppressant had a measured concentration above the LOD for cadmium. The geometric mean concentration of 0.1 $\mu g/m^3$ was similar to silica sand (1.25 times higher) at 0.08 $\mu g/m^3$. Silica sand with dust suppressant had the seventh highest geometric mean concentration of cadmium; copper slag, nickel slag, coal slag, garnet, specular hematite, and staurolite were higher.

Two of 12 airborne samples of silica sand with dust suppressant had measured concentrations above the LOD for chromium. The geometric mean concentration of 6.0 $\mu g/m^3$ was approximately 85% of silica sand at 7.1 $\mu g/m^3$. Silica sand with dust suppressant had the second lowest geometric mean concentration for chromium; specular hematite was lower.

Four out of 12 airborne samples of silica sand with dust suppressant had measured concentrations above the LOD for lead. The geometric mean concentration of 1.3 $\mu g/m^3$ was approximately 1/2 that of silica sand at 2.7 $\mu g/m^3$. Silica sand with dust suppressant had the lowest geometric mean concentration of lead of all 13 generic abrasive types.

All 12 airborne sample results for silica sand with dust suppressant had measured concentrations above the limit of detection for manganese. The geometric mean concentration of 54.4 $\mu g/m^3$ was similar to (1.2 times higher) silica sand at 45 $\mu g/m^3$. Silica sand with dust suppressant was the second lowest geometric mean concentration of manganese; only silica sand was lower.

Nine out of 12 airborne samp les of silica sand with dust suppressant had measured concentrations above the LOD for respirable quartz. The geometric mean of 2.6 mg/m^3 was approximately 1/3 that of silica sand at 8.8 mg/m^3. The silica sand with dust suppressant abrasive category had the second highest geometric mean concentration of respirable quartz of all 13 generic abrasive types.

Only one of 12 airborne samples of silica sand with dust suppressant had measured concentration above the LOD for silver. The geometric mean of 0.9 $\mu g/m^3$ is essentially identical to that of silica sand at 0.8 $\mu g/m^3$. Silica sand with dust suppressant had the second lowest geometric mean concentration of silver out of the 7 abrasives with detectable concentrations; garnet was lower.

Eleven of 12 airborne samples of silica sand with dust suppressant had measured concentrations above the LOD for titanium. The geometric mean concentration of 30.6 $\mu g/m^3$ was about 62% of silica sand at 48.8 $\mu g/m^3$. Silica sand with dust suppressant had the fifth lowest geometric mean concentration of titanium; specular hematite, steel grit, olivine, and crushed glass were lower.

Seven out of 12 airborne samples of silica sand with dust suppressant had measurable concentrations above the LOD for vanadium. The geometric mean concentration of 3.3 $\mu g/m^3$ was essentially identical to silica sand at 3.2 $\mu g/m^3$. Olivine, specular hematite, and crushed glass had lower geometric mean of concentrations of vanadium.

Copper Slag

All 32 airborne samples of copper slag had a measured concentration above the LOD for arsenic. The geometric mean concentration of 89.1 $\mu g/m^3$ for the copper slag generic abrasive category was 44 times higher than that of silica sand at 2.0 $\mu g/m^3$. Copper slag had the highest geometric mean concentration of arsenic, being six, eight, and nine times higher than the next three highest generic abrasive categories (copper slag with dust suppressant, steel grit, and nickel slag, respectively). Copper slag was the only generic abrasive category which had all (32 of 32) of its airborne samples above the LOD for arsenic.

Thirty-one out of 32 samples of copper slag had a measured concentration above the LOD for beryllium. The geometric mean concentration of 0.8 $\mu g/m^3$ for the copper slag generic abrasive category was 9 times higher than that of silica sand at 0.09 $\mu g/m^3$. Copper slag had the third highest geometric mean concentration of beryllium; only coal slag and coal slag with dust suppressant were higher.

Twenty-seven of 32 airborne samples of copper slag had a measured concentration above the LOD for cadmium. The geometric mean concentration of 1.0 $\mu g/m^3$ for the copper slag generic abrasive category was about 12 times higher than that of silica sand at 0.08 $\mu g/m^3$. Copper slag had the highest geometric mean concentration of cadmium, which was about four times higher than the next highest generic abrasive category (nickel slag).

All 32 airborne samples of copper slag had a measured concentration above the LOD for chromium. The geometric mean concentration of 82.2 $\mu g/m^3$ for the copper slag generic abrasive category was about 12 times higher than that of silica sand at 7.1 $\mu g/m^3$. Copper slag had the fourth highest geometric mean concentration of chromium; nickel slag, steel grit, and olivine were higher.

Twenty-nine of 32 airborne samples of copper slag had a measured concentration above the LOD for lead. The geometric mean concentration of 92.0 $\mu g/m^3$ for the copper slag generic abrasive category was about 34 times higher than that of silica sand at 2.7 $\mu g/m^3$. The geometric mean concentration of lead was the highest for the copper slag generic abrasive category, being seven times higher than the next highest generic abrasive category (crushed glass).

All 32 airborne samples of copper slag had a measured concentration above the LOD for manganese. The geometric mean concentration of 652.7 $\mu g/m^3$ for the copper slag generic abrasive category was about 14 times higher than that of sand at 45.7 $\mu g/m^3$. Copper slag had the fourth highest geometric mean concentration of manganese; copper slag with dust suppressant, steel grit, and garnet were higher.

Twenty-one of 32 airborne samples of copper slag had a measured concentration above the LOD for nickel. The geometric mean concentration of 19.2 $\mu g/m^3$ for the copper slag generic abrasive category was about 3 times higher than that of silica sand at 6.0 $\mu g/m^3$. Copper slag has the seventh highest geometric mean concentration of nickel; olivine, nickel slag, steel grit, treated copper slag, coal slag, and treated coal slag were higher.

Copper slag was one of five generic abrasive categories with airborne concentrations of respirable quartz above the LOD. However, only one copper slag abrasive (CP-04) had respirable quartz concentrations above the LOD. Silica sand's geometric mean airborne respirable quartz concentration at 8.83 mg/m^3 was about 59 times higher than copper slag's at 0.14 mg/m^3.

Twenty of 32 airborne samples of copper slag had a measured concentration above the LOD for silver. Copper slag had the greatest geometric mean concentration of silver (3.5 $\mu g/m^3$) and is about twice that of the next two highest generic abrasive categories, treated copper slag and steel grit. All of silica sand's airborne samples were less than the LOD for silver.

All 32 airborne samples of copper slag had a measured concentration above the LOD for titanium. Copper slag's geometric mean concentration of 1240 $\mu g/m^3$ was about 25 times higher than that of silica sand at 48.8 $\mu g/m^3$. Copper slag had the fifth highest geometric mean concentration of titanium; copper slag with dust suppressant, staurolite, coal slag with dust suppressant, and coal slag were higher.

All 32 airborne samples of copper slag had a measured concentration above the LOD for vanadium. Copper slag's geometric mean concentration of 45.3 $\mu g/m^3$ was about 14 times higher than that of silica sand at 3.1 $\mu g/m^3$. Copper slag had the fourth highest geometric mean concentration of vanadium; copper slag with dust suppressant, coal slag, and coal slag with dust suppressant were higher.

Based on the industrial hygiene results in the laboratory study, substituting copper slag for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. However, the copper slag generic abrasive category is not without potentially hazardous health-related agent concerns. Copper slag has greater geometric mean airborne concentrations than silica sand for all of the remaining 10 hazardous health-related agents. Out of the 13 generic abrasive categories, copper slag has the highest geometric mean airborne concentrations of arsenic, cadmium, lead, and silver. Copper slag has the highest geometric mean concentrations of beryllium, titanium, and vanadium, with the exception of untreated/treated coal slag and treated copper slag. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Copper Slag with Dust Suppressant

Seven out of 8 airborne samples of copper slag with dust suppressant had a measured concentration above the limit of detection for arsenic. The geometric mean of 14.9 $\mu g/m^3$ was approximately 7.5 times higher than silica sand at 2.0 $\mu g/m^3$. Copper slag with dust suppressant had the second highest geometric mean concentration for arsenic; copper slag was higher.

All 8 airborne samples of copper slag with dust suppressant had a measured concentration above the LOD for beryllium. The geometric mean concentration of 0.6 $\mu g/m^3$ was 6.7 times higher than silica sand at 0.09 $\mu g/m^3$. Copper slag with dust suppressant had the fourth highest geometric mean concentration of beryllium; coal slag with dust suppressant, coal slag, and copper slag were higher.

Two of the 8 airborne samples had a measured concentration above the LOD for cadmium. The geometric mean 0.08 $\mu g/m^3$ was essentially identical to silica sand at 0.08 $\mu g/m^3$. Copper slag with dust suppressant had the third lowest concentration of cadmium; crushed glass and olivine were lower.

All 8 airborne samples of copper slag with dust suppressant had measured concentrations above the LOD for chromium. The geometric mean concentration 66.8 $\mu g/m^3$ was about 9.4 times higher than silica sand at 7.1 $\mu g/m^3$. Copper slag with dust suppressant had the fifth highest geometric mean concentration of chromium; nickel slag, steel grit, olivine, and copper slag were higher.

Five of the 8 airborne samples of copper slag with dust suppressant had a measured concentration above the LOD for lead. The geometric mean concentration of 5.1 $\mu g/m^3$ was approximately 1.9 times higher than silica sand at 2.7 $\mu g/m^3$. Copper slag with dust suppressant had the fourth highest geometric mean concentration for lead; copper slag, crushed glass, and staurolite were higher.

All 8 of the airborne samples for copper slag with dust suppressant had a measured concentration above the LOD for manganese. The geometric mean concentration of 2718 $\mu g/m^3$ was nearly 60 times higher than silica sand at 45.7 $\mu g/m^3$. Copper slag with dust suppressant had the highest geometric mean concentration of manganese.

Six of the 8 airborne samples for copper slag with dust suppressant had a measured concentration above the LOD for nickel. The geometric mean of 30.2 $\mu g/m^3$ was approximately 5 times higher than silica sand at 6.0 $\mu g/m^3$. Copper slag with dust suppressant had the fourth highest geometric mean concentration of nickel; olivine, nickel slag, and steel grit were higher.

Five of 8 airborne samples of copper slag with dust suppressant had a measured concentration above the LOD for silver. The geometric mean concentration of 2.1 $\mu g/m^3$ was about 2.6 times higher than silica sand at 0.8 $\mu g/m^3$. Copper slag with dust suppressant had the second highest geometric mean concentration of silver; copper slag was higher.

All 8 of the airborne samples of copper slag with dust suppressant had measured concentrations above the LOD for titanium. The geometric mean of 2078 $\mu g/m^3$ was about 42 times higher than silica sand at 48.8 $\mu g/m^3$. Copper slag with dust suppressant had the highest geometric mean concentration of titanium.

All 8 air samples of copper slag with dust suppressant had measured concentrations above the LOD for vanadium. The geometric mean concentration of 108 $\mu g/m^3$ was about 34 times higher than silica sand at 3.2 $\mu g/m^3$. Copper slag with dust suppressant had the highest geometric mean concentration of vanadium.

All of the copper slag with dust suppressant airborne samples were less than the LOD for respirable quartz. Based on the industrial hygiene results in the laboratory study, substituting copper slag with dust suppressant for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. However, the copper slag with dust suppressant generic abrasive category is not without potential hazardous health-related agent concerns.

Copper slag with dust suppressant as a generic category of abrasives had the highest geometric mean concentrations of manganese, titanium, and vanadium, and the second highest geometric mean concentrations for arsenic and silver. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Garnet

Only one of 52 airborne samples of garnet had a measured concentration above the LOD for arsenic. The geometric mean concentration of 2.0 $\mu g/m^3$ was essentially identical to silica sand at 2.0 μg/m^3. Garnet had the lowest geometric mean concentration of arsenic of all the 8 generic abrasives which had any samples greater than the limit of detection for arsenic.

Thirty of 52 airborne samples had measured concentrations above the LOD for beryllium. The geometric mean concentrations of 0.1 μg/m^3 was essentially identical (1.1 times higher) to silica sand at 0.09 μg/m^3. Garnet had the sixth highest geometric mean concentration of beryllium; coal slag with dust suppressant, coal slag, copper slag, copper slag with dust suppressant, and nickel slag were higher.

Twenty-five of 52 airborne samples of garnet had measured concentration above the LOD for cadmium. The geometric mean concentration of 0.13 μg/m^3 was about 1.6 times higher than silica sand at 0.08 μg/m^3. Garnet had the fourth highest geometric mean concentration of cadmium; copper slag, nickel slag, and coal slag were higher.

Thirty-seven of 52 airborne samples of garnet had measured concentrations above the LOD for chromium. The geometric mean concentration of 18.2 μg/m^3 was approximately 2.6 times higher than silica sand at 7.1 μg/m^3. Garnet had the sixth lowest geometric mean concentration of chromium; crushed glass, specular hematite, staurolite, silica sand, and silica sand with dust suppressant were lower.

Twenty-four of 52 air borne samples of garnet had measured concentrations above the LOD for lead. The geometric mean concentration of 1.84 μg/m^3 was approximately 68% of silica sand at 2.74 μg/m^3. Garnet had the third lowest geometric mean concentration of lead; olivine and silica sand with dust suppressant were lower.

All 52 airborne samples of garnet had measured concentrations above the LOD for manganese. The geometric mean of 829 μg/m^3 was approximately 18 times higher than silica sand at 45.7 μg/m^3. Garnet had the third highest geometric mean concentration of manganese; copper slag with dust suppressant and steel grit were higher.

Fourteen of 52 airborne samples of garnet had a measured concentration above the LOD for nickel. The geometric mean concentration of 7.4 μg/m^3 was similar (1.2 times higher) to silica at 6.0 μg/m^3. Garnet had the sixth lowest geometric mean concentration of nickel; silica sand, specular hematite, staurolite, crushed glass, and silica sand with dust suppressant were lower.

Seventeen of 52 airborne samples of garnet had measured concentrations above the LOD for respirable quartz. The geometric mean concentration of 0.2 mg/m^3 was about 2% that of silica sand at 8.8 mg/m^3. Of the five generic abrasives with detectable concentrations of respirable quartz, garnet had the third highest measured concentration; silica sand and silica sand with dust suppressant were higher. Caution must be used when considering quartz data from the samples described on the first page of the Respirable Quartz Section in Appendix B, since these samples were evaluated by primary or secondary peak height measurement, due to problematical integration data caused by interferences.

Only 1 of 52 airborne samples of garnet had a measured concentration above the LOD for silver. The geometric mean concentration of 0.85 $\mu g/m^3$ was essentially identical to silica sand at 0.83 $\mu g/m^3$. Of the 7 generic categories of abrasives with measured concentrations of silver, garnet had the lowest geometric mean concentration.

All 52 airborne samples of garnet had measured concentrations above the LOD for titanium. The geometric mean concentration of 187 $\mu g/m^3$ was about 3.8 times higher than silica sand at 48.8 $\mu g/m^3$. Six abrasives had higher geometric mean concentrations while 6 other generic categories had lower geometric mean concentrations of titanium.

Fifty of the 52 airborne samples of garnet had measured concentrations above the LOD for vanadium. The geometric mean of 10.8 $\mu g/m^3$ was about 3.4 times higher than silica sand at 3.2 $\mu g/m^3$. An equal number of generic abrasive categories had geometric mean concentrations of vanadium above that of garnet while 6 generic categories of abrasives had geometric mean concentrations below that of garnet.

Based on the industrial hygiene results in the laboratory study, substituting garnet in abrasive blasting should reduce airborne respirable quartz concentrations. However, the garnet generic abrasive category is not without potential hazardous health-related agent concerns.

Garnet had the third highest geometric mean concentration of respirable quartz and manganese, and the fourth highest geometric mean concentration of cadmium. All of the airborne data from the laboratory must be viewed as indicative only relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

Steel Grit

Twelve of 16 airborne samples of steel grit had measured concentrations above the LOD for arsenic. The geometric mean concentration of 10.7 $\mu g/m^3$ was over 5 times higher than silica sand at 2.0 $\mu g/m^3$. Steel grit had the third highest geometric mean concentration of arsenic; copper slag and copper slag with dust suppressant were higher.

Three of 16 airborne samples of steel grit had measured concentrations above the LOD for beryllium. The geometric mean concentration of 0.05 $\mu g/m^3$ was approximately 55% that of silica sand at 0.09 $\mu g/m^3$. Beryllium had the second to the lowest geometric mean concentration of beryllium; olivine was lower.

Two of 16 samples of steel grit had measured concentrations above the LOD for cadmium. The geometric mean concentration of 0.08 $\mu g/m^3$ was essentially identical to silica sand at 0.08 $\mu g/m^3$. Coal slag with dust suppressant, copper slag with dust suppressant, crushed glass, and olivine had lower geometric mean concentrations of cadmium.

Fourteen of 16 airborne samples of steel grit had measured concentrations above the LOD for chromium. The geometric mean concentration of 231 $\mu g/m^3$ was over 32 times that of silica sand at 7.1 $\mu g/m^3$. Steel grit had the second highest geometric mean concentration of chromium; nickel slag was higher.

Eight of 16 airborne samples of steel grit had measured concentrations above the LOD for lead. The geometric mean concentration of 2.6 $\mu g/m^3$ was slightly less than silica sand at 2.7 $\mu g/m^3$. Steel grit had the fifth lowest geometric mean concentration of lead; specular hematite, garnet, olivine, and silica sand with dust suppressant were lower.

All 16 airborne samples of steel grit had measured concentrations above the LOD for manganese. The geometric mean concentration of 1815 $\mu g/m^3$ was nearly 40 times higher than silica sand at 45.7 $\mu g/m^3$. Steel grit has the second highest geometric mean concentration of manganese; copper slag with dust suppressant was higher.

Fourteen of 16 airborne samples of steel grit had measured concentrations above the LOD for nickel. The geometric mean concentration of 196 $\mu g/m^3$ was nearly 33 times higher than silica sand at 6.0 $\mu g/m^3$. Steel grit had the third highest geometric mean concentration of nickel; olivine and nickel slag were higher.

Only one of 16 airborne samples of steel grit had a measured concentration above the LOD for silver. The geometric mean concentration of 1.6 $\mu g/m^3$ was nearly double that of silica sand at 0.8 $\mu g/m^3$. Of the 7 generic categories of abrasives with measured concentrations of silver, steel grit was third highest; copper slag and copper slag with dust suppressant were higher.

Thirteen of 16 airborne samples of steel grit had measured concentrations above the LOD for titanium. The geometric mean concentration of 13.9 $\mu g/m^3$ was approximately 28% that of silica sand at 48.8 $\mu g/m^3$. Steel grit had the third lowest geometric mean of titanium; olivine and crushed glass were lower.

Fifteen of 16 airborne samples of steel grit had a measured concentration above the LOD for vanadium. The geometric mean concentration of 31.2 $\mu g/m^3$ was nearly 10 times higher than silica sand at 3.2 $\mu g/m^3$. Steel grit had the fifth highest geometric mean concentration of vanadium; copper slag with dust suppressant, coal slag, coal slag with dust suppressant, and copper slag were higher.

All of steel grit's airborne samples were less than the LOD for respirable quartz. Based upon the industrial hygiene results in the laboratory study, substituting steel grit for silica sand in abrasive blasting should reduce airborne respirable quartz concentrations. However, the steel grit generic abrasive category is not without potential health-related agent concerns.

Steel grit as a generic category of abrasives had the second highest geometric mean concentrations of chromium and manganese, and the third highest geometric mean concentrations of arsenic, nickel, and silver. All of the airborne data from the laboratory must be viewed as indicative only of the relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of work site conditions. In addition, variability between individual abrasives within a generic category must also be considered prior to drawing any broad health-based conclusions.

TABLE 11

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

Treated Versus Untreated Abrasives

Two coal slags, three silica sands, and one copper slag abrasive were treated with dust suppressant. Table 12 and Figure 14 present a comparison of the measured airborne concentrations of 11 health-related agents for paired sets (i.e. treated and untreated variables of the same products), of six abrasive trials, of the 66 sets of paired data:

- 32 paired sets of data (48.5%) are essentially identical (i.e. within ± 15%)
- 20 paired sets of data (30.3%) show a decrease in measured concentrations (i.e. greater than 15%) with the treated abrasive
- 14 paired sets of data (21.2%) show an increase in measured concentrations (i.e. greater than 15%) with the treated abrasive

Combined, nearly 70% of the paired data sets indicate measured concentrations of health-related agents either remained the same (i.e. ± 15%) or actually increased (i.e. greater than 15%) for the abrasive treated with dust suppressant over the paired untreated abrasive.

TABLE 12

COMPARISON OF GEOMETRIC MEAN CONCENTRATIONS OF HEALTH-RELATED AGENTS FOR PAIRED UNTREATED AND DUST SUPPRESSANT TREATED ABRASIVES

FIGURE 14 – PAIRED ABRASIVES - EFFECT OF TREATING ABRASIVES WITH DUST SUPPRESSANTS CHARTS

Bulk Sample Results

Figures 15 to 25 on pages 125 to 135 show the range of measured and geometric means of concentrations for the virgin bulk levels of eleven hazardous health-related agents for each of the 40 abrasive products and the associated generic category of abrasives tested. These are the same eleven hazardous health-related agents that were used for comparative analysis of the airborne concentrations. The recyclable abrasives include the samples collected from both the initial blast run (indicated by the letter A - i.e. Garnet-07A represents the initial blast run conducted for Garnet abrasive #7) and the blast run that was conducted after tests for the recycling capability of the abrasive was completed (indicated by the letter B - i.e. Garnet-07B represents the final blast run conducted for Garnet abrasive #7 after the recycling tests were completed). The range and geometric mean are indicated by a bar chart and a small square, respectively. The shaded bars indicate the range and geometric mean of the entire generic category of abrasive.

Any abrasive product or generic category of abrasive with all bulk samples having results below the limit of detection (LOD) for the given health-related agent are represented by only a small square (these abrasives will have no bar since there is no range to display). For abrasives having any samples below the limit of detection for the given health-related agent, the geometric mean was calculated by using LOD/2, which is the method used to estimate the average concentration in the presence of non-detectable values described by Hornung and Reed.[18]

One virgin and one used bulk sample was collected for each abrasive blast trial. Only one individual abrasive was used for the crushed glass, specular hematite, and olivine generic categories. However, specular hematite has one major source to supply the abrasive blasting market and crushed glass was relatively new to the abrasive blasting market when this study commenced. These three abrasive categories will have no range to report since only one virgin bulk sample was analyzed for the eleven health-related agents. The small square for these three abrasive categories will represent the single virgin bulk sample concentration.

Table 13 summarizes the virgin bulk concentrations for each of these health-related agents by generic category of abrasive. These Figures 15 to 25 and Table 13 provide some indication of the source of the airborne concentrations described previously in the industrial hygiene results and discussion sections, along with the iron (97.3%), manganese (.96%), copper (0.01%), chromium (0.01%), phosphorous (0.006%), molybdenum (0.004%), and vanadium (0.004%) content in the steel plates which were blasted.

Caution must be used when considering quartz data from the bulk samples described on the first page of the Respirable Quartz Section in Appendix B, since these samples were evaluated by secondary peak height measurement, long range qualitative scan, or microscopic analysis. These samples were analyzed by these alternative measurements due to problematical integration data caused by interferences.

FIGURE 15 – ARSENIC BULK SAMPLE RESULTS

FIGURE 16 – BERYLLIUM BULK SAMPLE RESULTS

FIGURE 17 – CADMIUM BULK SAMPLE RESULTS

FIGURE 18 – CHROMIUM BULK SAMPLE RESULTS

FIGURE 19 – LEAD BULK SAMPLE RESULTS

FIGURE 20 – MANGANESE BULK SAMPLE RESULTS

FIGURE 21 – NICKEL BULK SAMPLE RESULTS

FIGURE 22 – QUARTZ BULK SAMPLE RESULTS

FIGURE 23 – SILVER BULK SAMPLE RESULTS

FIGURE 24 – TITANIUM BULK SAMPLE RESULTS

FIGURE 25 – VANADIUM BULK SAMPLE RESULTS

TABLE 13 – SUMMARY OF BULK SAMPLE RESULTS OF HEALTH-RELATED ELEMENTS BY GENERIC CATEGORY OF ABRASIVE

Radiation

Alpha spectrometry measurements have been performed using respirable airborne samples of abrasive blasting materials to determine the content of radium-226 (^{226}Ra). These measurements were analyzed by following the NIOSH contract laboratory Standard Operating Procedure (SOP) WN-IN-314 "The Determination of Radium-226 in Solids by Alpha Spectrometry." [12]

Gamma spectrometry measurements have been performed using virgin and used bulk samples of abrasive blasting materials to determine the content of several gamma-emitting isotopes. These measurements were analyzed by following the NIOSH contract laboratory (SOP) WR-EP-325 "Determination of Gamma Emitting Isotopes." [13]

Alpha and gamma spectrometry methods are usually adequate to evaluate the content of the long-lived radionuclides ^{238}U, ^{232}Th, and ^{40}K as well as their progeny. In fact, the detection of ^{238}U and ^{232}Th using gamma spectrometry is only possible by detection of their photon emitting progeny since the parent radionuclides emit only alpha particles.

Since the concentrations of these radionuclides is typically very low, it is necessary to measure bulk samples having masses of at least a few hundred grams, except for radiochemical analysis of ^{226}Ra, which is usually restricted to analysis of less than 1 gram. Unfortunately, several bulk sample results reported for this study phase were based upon gamma spectrometry measurements of samples having relatively small mass so their results are somewhat uncertain.

Three criteria were adopted to identify positive results:

(1) The reported result for a sample must exceed the range of detection limits for all samples reported in a batch.
(2) The reported result for a sample must exceed three times the reported uncertainty.
(3) If the reported nuclide is a member of a chain, its parent must also be present, especially if the progeny has a short half-life.

In many cases, results were reported without levels of uncertainty, so that the only criteria remaining to determine significance was the detection limits.

^{226}Ra by Radiochemical Separation and Alpha Spectrometry:

Thirteen respirable airborne samples were submitted for specific analysis of ^{226}Ra, representing copper slag CP-1A, copper slag CP-1B , coal slag PC-03 (Black Beauty 2040 coal slag used for the third operator process check), crushed glass CG-01, garnet G-4A, garnet G-4B, olivine O-1, specular hematite SH-01, silica sand with dust suppressant SSDS-02, nickel slag N-01, steel grit SG-1A, and silica sand SS-05. Total dust samples were also submitted for specific analysis of ^{226}Ra for specular hematite SH-01, silica sand with dust suppressant SSDS-02, and nickel slag N-01 since the respirable samples collected did not have sufficient mass for analysis. Unfortunately, the total airborne sample of specular hematite SH-01 also had insufficient mass to perform the analysis. Respirable and total dust samples were also submitted for analysis of ^{226}Ra for staurolite S-02, but gamma spectrometry analysis for different isotopes was inadvertently conducted.

The respirable airborne samples of nickel slag N-01, copper slag CP-1A, copper slag CP-1B, coal slag PC-03, garnet G-4B, and silica sand SS-05 exceeded the limit of detection (LOD). One sample, copper slag CP-1A, was considerably in excess of the usual concentration of ^{226}Ra. Unfortunately, uncertainty was not reported for these results so it is not possible to determine the reliability of these results.

Radium-226 is part of the 238U chain and is found naturally in all soils at a concentration of approximately 1 pCi g-1. The variability of the concentration is quite large and can range from non-detectable to nearly 5 pCi g^{-1} depending upon local geology. In areas contaminated by naturally occurring barium-radium sludge from crude oil recovery operations, it is not uncommon to find ^{226}Ra concentrations equal to approximately 20 - 50 pCi g^{-1}.

Gamma Spectrometry Analysis:

Airborne Samples

A respirable and a total dust sample of staurolite S-02 was submitted for analysis of several gamma-emitting isotopes. Two filters were dissolved, diluted to 100 g, and counted for approximately 2 hr. The total dust sample was positive for ^{60}Co and ^{137}Cs, indicating the presence of technologically-enhanced radioactive material. Although uncertainty was not reported with these results, the magnitude of the results for ^{60}Co and ^{137}Cs is substantially in excess of the reported detection limits. Other naturally occurring radionuclides are not present, although the counting time is much less than desirable.

Virgin and Used Bulk Samples

Virgin and used bulk samples of the same thirteen abrasives previously described in the Alpha Spectrometry Analysis Section were submitted for analysis of several gamma-emitting isotopes. The samples were directly counted for approximately 2 to 4 hours. The mass of each sample (160 grams) and the uncertainty for each result were only provided for garnet G-4A, steel grit SG-1A, and silica sand SS-05.

Both the virgin and used bulk samples of staurolite S-02 indicate the presence of ^{232}Th (from ^{228}Ac), ^{226}Ra, and the short-lived progeny of ^{226}Ra and ^{224}Ra. The counting time is much less than desirable. The virgin and used samples of garnet G-4A indicate the presence of ^{232}Th (from ^{228}Ac) and ^{212}Pb. However, the presence of ^{212}Pb in the garnet samples cannot be confirmed according to the protocol, because its immediate decay product, ^{212}Bi, was not positive. The bulk samples for the other abrasives were not positive.

Conclusions

Although several samples of abrasive blasting materials have been analyzed for natural and technologically-enhanced radioactive materials, the methods used to perform the analyses may not have been optimized to detect very low concentrations of activity expected to be present in these materials. Typical concentrations of naturally occurring radioactive materials in soil are expected to be approximately 1 - 2 pCi g^{-1}. The concentrations of activity reported for the majority of these samples suggest that each matrix is representative of natural materials with expected amounts of 232Th, 238U, and 40K. However, the small sample size and short counting times preclude a reliable, quantitative assessment of the true concentrations present in each sample.

On the other hand, although 137Cs was identified in a respirable and a total dust sample of staurolite S-02 , no other artificial (i.e., technologically-derived) radioactive contaminants were identified that would likely result in excess risk to workers using these substances.

Gamma spectrometry measurements were not sufficiently sensitive to produce reliable results. The minimum sample size for gamma spectrometry should be approximately 500 g and samples should be counted for at least eight hours each to achieve sufficient measurement sensitivity and reliability to determine the presence of low concentrations of activity expected to be found in these natural matrix materials. The only sample mass reported by the laboratory was only 160 grams and the counting times were either 2 or 4 hours, which made it very difficult to substantiate the validity of results that were reported in excess of the limit of detection.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Conclusions from the study are provided separately below for performance and industrial hygiene issues. The abrasives were evaluated for cleaning rate, consumption rate, surface profile, breakdown, hardness, embedment, and conductivity. The abrasives are grouped below based on similar performance characteristics relative to silica sand.

Abrasive Performance Issues

Coal slag and nickel slag exhibit performance characteristics (e.g. cleaning rates, consumption rates, breakdown, etc.) based on the study parameters that are comparable to silica sand with a few exceptions. They are considerably softer, and the amount of abrasive particulate embedded in the surface increases. The conductivity of the nickel slag and the coal slag treated with dust suppressant is also higher than silica sand.

Olivine and staurolite displayed increased cleaning rates and reduced consumption rates compared with silica sand. They are both softer than silica sand, with staurolite exhibiting less breakdown and olivine more embedment. The conductivity of the staurolite is also greater than silica sand.

Crushed glass and specular hematite exhibit performance characteristics similar to silica sand with a few exceptions. Both are softer materials and the consumption rate of specular hematite was lower. The conductivity of the crushed glass was slightly higher than silica sand.

The remaining products (copper slag, garnet, and steel grit) were tested as recyclable products. As a result, the ultimate consumption rates per square foot will be much less than silica sand. The copper slag and garnet also exhibited increased cleaning rates. All were softer than silica sand (with garnet being the hardest of the group) and with the exception of steel grit, displayed an increase in particle embedment. Steel grit also showed the lowest breakdown rate of the group. Conductivity of the copper slag and garnet was greater than silica sand.

Although the amount of data is limited, the use of dust suppressant on silica sand appears to have no consistent effect relative to its performance characteristics (e.g. cleaning rates, consumption rates, breakdown, etc.). For each attribute, at least one of the treated silica sand abrasives displayed improved performance relative to its untreated counterpart, and at least one showed reduced performance. For the coal slags, the same inconclusive results were produced with one exception. Based on the limited data, the dust suppressant appears to reduce embedment. Only one copper slag treated with dust suppressant was evaluated, and as a result, trends can not be determined. Based on the single sample, the dust suppressant reduced cleaning and consumption rates, reduced breakdown, and increased embedment.

Cost data was developed based on the preparation of steel plates in a laboratory blast room. The values are only valid for the specific conditions under which the data was collected (controlled metering valve setting, 100 psi nozzle pressure, 18 inch nozzle-to-workplace distance, #4 nozzle, and fixed blast cleaning angle). The results, both in an absolute and relative sense will have no applicability to field conditions. The cost analysis revealed a wide range in results between individual abrasives within a given generic type. For example, the cost of using the seven silica sand abrasives ranged from $1.37/square foot to $2.49/square foot. When averaging the costs for each abrasive type as a generic category, all abrasives with the exception of crushed glass and specular hematite were less costly to use than silica sand. In the case of crushed glass and specular hematite, only one abrasive from each type was evaluated, and in both cases, at least one of the silica sand abrasives was more expensive to use.

Industrial Hygiene-Related Issues

While the study analyzed 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. All of the airborne data from the laboratory must be viewed as indicative only of relative potential for the presence of health-related agents, since the laboratory conditions were not necessarily representative of worksite conditions. In addition, variability between individual abrasives within a generic abrasive category must also be considered prior to drawing any broad conclusions regarding airborne concentrations of hazardous health-related agents. The attributes of the specific abrasive, rather than the generic class of abrasive, must be considered when making any health based comparisons.

Based on the industrial hygiene results collected in the laboratory study, silica sand abrasives exhibited the highest levels of respirable quartz. The relative airborne concentrations of the other 10 health-related agents in silica sand varied, and were indirectly proportioned to the concentration of quartz in the virgin abrasive. However, since 1974, NIOSH has recommended that silica sand or other material containing greater than 1.0% crystalline silica (quartz) be prohibited as a media for abrasive blasting. Substituting any of the alternative abrasives for silica sand should considerably reduce airborne respirable quartz concentrations for abrasive blasting. This respirable quartz reduction could serve as a major step in preventing the occurrence of silicosis in abrasive blasting.

Substitution of crushed glass and specular hematite for silica sand in abrasive blasting should also reduce the airborne concentrations for most of the hazardous, health-related agents studied. However, crushed glass and specular hematite do not differ greatly from silica sand with respect to airborne cadmium, chromium, lead, and/or manganese concentrations. The remaining alternative abrasives had at least one hazardous health-related agent which resulted in a considerably higher geometric mean concentration of the agent than that of silica sand as described below.

Coal slag and coal slag with dust suppressant had greater geometric mean airborne concentrations than those of silica sand for the eleven hazardous health-related agents, except respirable quartz (all samples were below the LOD for respirable quartz). However, the treated/untreated coal slag geometric mean airborne concentrations of arsenic, cadmium, lead, manganese, and silver are only 1.1 to 3.2 times greater than that of silica sand. Out of the thirteen generic abrasive categories, untreated and treated coal slag have the two highest geometric mean airborne concentrations of beryllium, being 23 times greater than that of silica sand and 2.6 times greater than the next highest generic abrasive category (copper slag). These two categories of coal slag abrasives (i.e., untreated and treated) also had elevated levels of titanium and vanadium.

Nickel slag, as a generic abrasive category, had greater geometric mean airborne concentrations than that of silica sand for the eleven hazardous health-related agents, except respirable quartz (all samples were below the LOD for respirable quartz). Nickel slag had the highest geometric mean concentration of chromium, second highest geometric mean concentrations of cadmium and nickel, and fourth highest geometric mean concentrations of arsenic.

Olivine had lower or similar geometric mean concentrations of beryllium, lead, silver, titanium, and vanadium, than that of silica sand. Olivine had the third, fifth, and highest geometric mean concentrations of chromium, manganese, and nickel, respectively, all of which were greater than that of silica sand. Arsenic, cadmium, respirable quartz, and silver were not detected above the LOD in any of the olivine airborne samples.

Staurolite had lower or similar geometric mean concentrations of beryllium and cadmium, than that of silica sand. However, staurolite had the third highest geometric mean concentrations of lead and titanium; which were greater than that of silica sand. Arsenic, nickel, and silver were not detected above the LOD in any of the staurolite airborne samples.

The copper slag and copper slag with dust suppressant generic abrasive categories had considerably greater geometric mean airborne concentrations, compared to silica sand, for the eleven hazardous health-related agents, except cadmium and respirable quartz. Out of the thirteen generic abrasive categories, untreated/ treated copper slag had the two highest geometric mean airborne concentrations of arsenic and silver; and the highest geometric mean concentrations of beryllium, titanium, and vanadium, with the exception of untreated/ treated coal slag.

Garnet, as a generic abrasive category, had higher geometric mean concentrations, compared to silica sand, for the eleven hazardous health-related agents, except beryllium, lead, nickel, respirable quartz, and silver. Garnet had the third highest geometric mean concentrations of manganese and respirable quartz (the highest of the alternative abrasives), and the fourth highest geometric mean concentration of cadmium.

Steel grit, as a generic abrasive category, had higher geometric mean concentrations than that of silica sand for the eleven hazardous health-related agents, except beryllium, cadmium, lead, and respirable quartz (all samples were below the LOD for respirable quartz). Steel grit had the second highest geometric mean concentrations of arsenic, nickel, and silver.

When comparing the effect of a dust suppressant to reduce dust generations, nearly 70% of the paired data sets indicate measured concentrations of health-related agents either remained the same (i.e. ± 15%) or actually increased (i.e. greater than 15%) for the abrasive treated with dust suppressant over the paired untreated abrasive.

In summary, while no single abrasive category had reduced levels of all health-related agents, all the substitutes offer advantages over silica sand with regard to respirable quartz. All but two of the alternative abrasive categories (crushed glass and specular hematite) have substantially higher levels of some other health-related agents, as compared to silica sand. In addition, even within a given generic category, there was considerable variability between the individual abrasives.

These variations are likely the result of varying raw material sources (e.g. coal slags derived from different coal streams) and/or manufacturing process (e.g. variations in copper or nickel smelting processes). Unfortunately, the data on the concentration of these contaminants in the virgin abrasive (on a percent by weight basis) was insufficient to establish definitive thresholds for use in materials selection, as described below.

For 110 out of 998 measured airborne concentrations (of the eleven health-related agents) above the LOD, the contaminant in the virgin bulk abrasives was non-detectable (excludes data from final run of recycled abrasives). Other sources of contamination may be possible (e.g. blast substrate). Data in Appendix 4 suggest that iron (97.3%), manganese (.96%), copper (0.01%), chromium (0.01%), nickel (0.01%), phosphorous (0.006%), molybdenum (0.004%), and vanadium (0.004%) should be the only other sources of contaminants in the substrate that was blasted on. The analytical technique for the raw materials and the air samples are the same, but the limit of detection for the bulk samples is reported in different units (µg/gm) than those reported for the air samples µg/filter). Therefore, the results based on the limits of detection for the airborne samples do not necessarily correlate to the results based on the limits of detections for the bulk samples. For the bulk samples that were reported as non-detected for a given health-related agent and a corresponding airborne level was detected for the same agent; most of the airborne levels were below the limit of quantification or barely above the limit of quantification. Obviously, if a minimum threshold cannot be established, selection criteria based upon elemental analysis of virgin abrasives will be of limited benefit. Furthermore, a statistically valid correlation between the concentration of the contaminant and the corresponding airborne concentrations must first be demonstrated in order for a selection criteria to be developed. The data from this study is not sufficient to evaluate this correlation, but provides some indication that a correlation may exist.

Recommendations

Based upon the above conclusions, consideration should be given to the following recommendations:

1. In order to reduce the airborne concentrations of the eleven hazardous health-related agents, consider the use of crushed glass or specular hematite. In addition, staurolite and olivine might be considered as alternatives to silica sand to reduce airborne concentration to most of the eleven hazardous health-related agents.

2. When coal slag, nickel slag, copper slag, garnet and/or steel grit abrasives are used as alternatives to silica sand, select specific products from within the generic category which limit worker exposure to multiple toxic contaminants and which optimize desired performance characteristics. As indicated throughout this study, the attributes of the individual products within a generic classification varied widely.

3. 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.

4. 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, this study identified the need for additional research. The recommended studies should be used to:

5. 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.

6. Evaluate the potential for correlations between the concentration of health-related agents in all virgin abrasives and in particular coal slag, nickel slag, copper slag, garnet and steel grit, and the resulting airborne concentrations, for use as a selection criteria.

7. 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).

8. Further studies should be considered to 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.

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