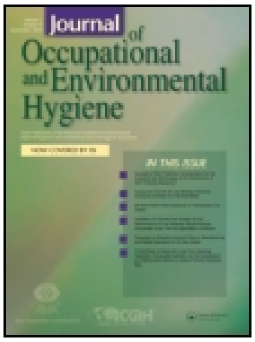

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A Review of Engineering Control Technology for Exposures Generated During Abrasive Blasting Operations

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This literature review presents information on measures for controlling worker exposure to toxic airborne contaminants generated during abrasive blasting operations occurring primarily in the construction industry. The exposures of concern include respirable crystalline silica, lead, chromates, and other toxic metals. Unfortunately, silica sand continues to be widely used in the United States as an abrasive blasting medium, resulting in high exposures to operators and surrounding personnel. Recently, several alternative abrasives have emerged as potential substitutes for sand, but they seem to be underused. Some of these abrasives may pose additional metal exposure hazards. In addition, several new and improved technologies offer promise for reducing or eliminating exposures; these include wet abrasive blasting, high-pressure water jetting, vacuum blasting, and automated/robotic systems. More research, particularly field studies, is needed to evaluate control interventions in this important and hazardous operation.

Keywords abrasive blasting, engineering controls, exposures, silica

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Abrasive blasting is a common method for removing surface coatings prior to repainting or other treatments. It is employed to remove lead-based paints from highway bridges and overpasses; to remove various coatings from ships, storage tanks, and other structures; and to expose aggregate material in concrete for decorative purposes. Since passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991, public funding for bridge and highway restoration has increased. In June 1998, Congress enacted the Transportation Equity Act for the 21st Century (TEA-21), described as the largest public works bill in U.S. history.(1) Massive investment in infrastructure repair has greatly increased the number of construction workers currently engaged in abrasive blasting operations, making exposures associated with this task an important occupational health problem.

The construction work force is made up of over 7 million workers employed in a large number of specialized trades.(2) A number of trades may engage in abrasive blasting operations. The most significant exposure risks are to painters who perform blasting, and to laborers and masonry workers. Proportionate mortality ratios (PMRs) for silicosis in these trades are among the highest in the industry.(3) These trades make up approximately 20% of the construction work force. Because much of the abrasive blasting work currently under way involves removal of hazardous paint within containment structures, painters may be at the greatest risk. The most common abrasive blasting method uses high-pressure air to propel abrasive media against treated surfaces at extremely high velocities, which generates large amounts of toxic, inhalable dust. The toxicity of this dust is primarily a function of the material used as the abrasive, the nature of the coating being removed, the underlying substrate, and the history of the abrasive, (e.g., contamination due to recycling).

In general, interventions designed to reduce worker exposure can be categorized as: (1) engineering, (2) administrative, (3) personal protective equipment (PPE), or (4) work-practice controls. These terms have specific legal definitions but also more general connotations within the occupational and environmental hygiene community. Violation of an OSHA permissible exposure limit (PEL) will result in an employer citation for the overexposure and the failure to use engineering and/or administrative controls. An interim abatement period is specified where PPE is permissible to reduce exposures below the PEL, and in some cases the PPE may be part of a permanent solution.

Preference for engineering controls has a deep-rooted history in hygiene; they are designed to provide reliable protection without the responsibility for its success falling to the employee. Additional benefits accrue in the form of reduced bystander exposures due to control at the source. Administrative controls that permit rotation of employees into and out of exposure regions to reduce the time-weighted average concentration have generally been frowned on by occupational hygiene professionals, perhaps due to the great uncertainty involved in actually specifying a "safe" exposure level. The very high concentrations of toxic materials that occur during blasting operations make administrative controls infeasible.

Over the years there has been a greater appreciation of the role that worker training, education, and supervision play in achieving successful control solutions. These work-practice controls are an essential part of any strategy to reduce exposure and are most effective when used in conjunction with sound engineering controls and, if necessary, PPE. Engineering controls can be further classified into substitution, automation, ventilation, isolation, and elimination subcategories. These categories are used here to explore the various interventions designed to reduce worker exposures in abrasive blasting operations.

BACKGROUND

Historically, abrasive blasting has produced some of the more serious dust exposures in industrial operations(4) and unfortunately this situation continues today.(5) Difficulty in controlling these exposures is attested to by the fact that respiratory protection, i.e., the type CE supplied-air blasting helmet, shown in Figure 1, is often the required and default control measure, despite legal and professional preference for engineering controls. There is historical(6) and recent(5) documentation suggesting the inadequacy of respiratory protection programs for abrasive blasting operations. In 1997 an IARC Working Group classified quartz as an IARC group 1 carcinogen indicating sufficient evidence of human carcinogenicity.(7) The American Conference of Governmental Industrial Hygienists(8) has established a threshold limit value (TLV®) for respirable quartz of 50 μg/m^3 with an "A2" designation indicating a suspect human carcinogen and NIOSH(9) has also adopted a recommended exposure limit (REL) of 50 μg/m^3. The OSHA PEL for respirable quartz in CFR 1910.1000 Table Z-3 gives a specific standard for each dust based on its silica content.(10)

Ironically, it appears there have been relatively few exposure studies conducted for abrasive blasting operations and fewer still that provide any definitive information on control efficiency. The majority of studies that do exist seem motivated primarily by concern over lead exposure. One study(11) presented personal exposures for workers performing abrasive blasting operations at U.S. Air Force facilities. Various substrates including aluminum, steel, and advanced composite materials were involved. The abrasives varied but included glass beads, aluminum oxide, plastic, and walnut shells. Button aerosol

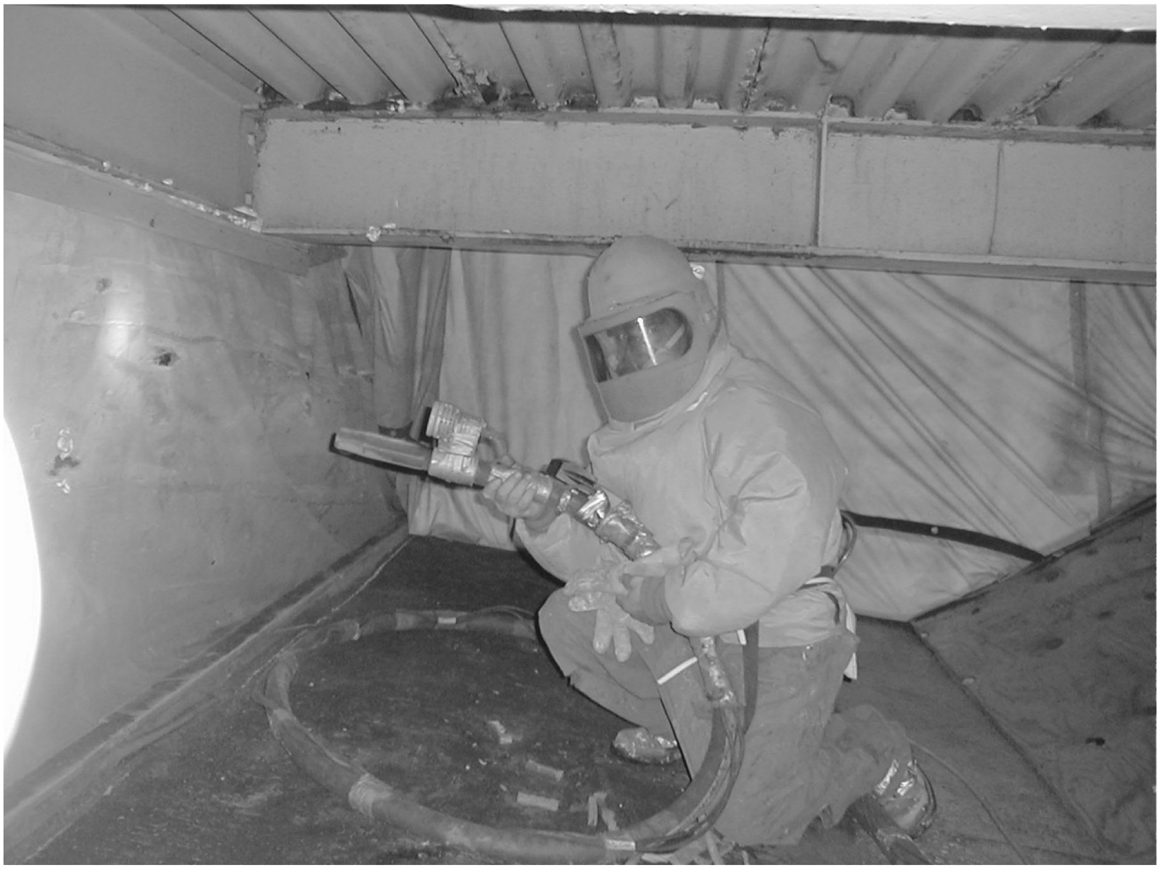

FIGURE 1. Abrasive blaster wearing Type CE supplied-air respirator in containment area (Photo by Norman Zuckerman)

samplers were used to measure inhalable aerosols containing 25 metals. The 8-hour time-weighted average (TWA) concentrations were up to 250, 6, and 5 times higher than the PELs for cadmium, lead, and hexavalent chromium, respectively.

In a study(12) of abrasive blasting operations carried out by the North Carolina Department of Environmental Health, respirable silica exposures were measured inside supplied-air respirators. TWA levels ranged from nondetected to 0.2 mg/m^3 for tasks ranging from 62–211 min. The authors found respirable silica levels of 0.04–0.53 mg/m^3 for nearby traffic controllers and similar levels for hopper loaders in the area. Concern was raised over inadequate respiratory protective practices, and a suggestion was made for a substitute abrasive to replace the silica sand.

In another study(13) of abrasive blasting on a steel bridge to remove paint prior to repainting, exposures to lead, cadmium, and chromium were measured in containment areas. Steel shot was used as the abrasive. Airborne lead concentrations were measured near the workers' breathing zones. Lead and cadmium levels in the containment exceeded the OSHA PEL by factors of 219 and 3.1, respectively. The authors noted that the use of supplied-air blasting helmets would not effectively reduce lead exposure to the PEL at these airborne levels.

Despite the fact that several countries have banned silica sand as an acceptable abrasive for blasting operations,(14,15) this has not been adopted in the United States. NIOSH(16,17) has recommended against the use of sand containing more than 1% crystalline silica for such operations, and the ANSI(18) voluntary consensus standard (ANSI/AIHA Z9.4-1997 Abrasive-Blasting Operations — Ventilation and Safe Practices for Fixed Location Enclosures) calls for the elimination of silica in abrasive blasting. Recent economic pressures generated by environmental regulations during the removal of lead-based paints on bridges and other steel structures appear to have had important consequences. The use of containment structures to minimize lead discharge to the environment, and the need to minimize costly hazardous waste, may have acted to increase worker exposures. This in turn seems to have motivated some new technological solutions including the use of recyclable abrasives without careful consideration of the new hazards introduced by these materials. Studies by NIOSH also provide some important new documentation regarding substitute abrasives and controls. This and other information is summarized below.

Engineering Controls

The different types of engineering controls identified above are described in this section. Often, combinations of these controls are present and are somewhat arbitrarily assigned to one category or another.

Substitution

The term "substitution" can apply to both the processes and/or the material used in the operation. One extensive study(19) funded by NIOSH, was conducted in three distinct phases. The first included a laboratory evaluation, the second part was a controlled field study, and the third phase was a comparison between the first two. Phase 1 involved the evaluation of 13 generic abrasives: 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 hematitie, staurolite, and steel grit. One to seven individual products from within each of these 13 generic categories (a total of 40) was tested for 7 performance related characteristics: cleaning rate, consumption rate, surface profile, breakdown rate, abrasive embedment, micro-hardness, and conductivity. During use, the products were evaluated for generating airborne exposures to over 30 contaminants but in particular: arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, silver, titanium, vanadium, and quartz.

The report concluded, "Most of the alternative abrasives evaluated have performance characteristics that are equivalent to or better than silica sand."(19,p.4) With regard to exposures to the 11 agents identified above the study concluded, "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."(19,p.4) The study noted that broad variability within product type limited their ability to make general recommendations regarding health-related exposures.

In Phase 2 of the project, a field site was selected and more realistic working conditions were involved. A portable containment facility was used around the exterior hull of a coal barge. The hull was not painted but had significant rust and pitting. However, only a small subset of the original abrasives were used. Unfortunately, specular hematitie and glass beads were not among those evaluated. Personal and area samples were collected for several agents including respirable quartz. There was one personal sample and three area samples available per abrasive per agent. Table I shows a summary of the abrasives used and some of the contaminants evaluated. In general, the highest measurements in each contaminant category were associated with the highest contaminant concentration in the bulk abrasive prior to blasting.(14) Although the data set is limited, concentrations above current TLV levels are observed for respirable quartz, cadmium, arsenic, chromium, and beryllium.

A separate study(20) suggested that dolomite may be a good alternate abrasive for silica. The authors noted that it is nontoxic, cleans surfaces well, has a relatively low breakdown rate, and inhibits flash rusting. Dolomite is a calcium magnesium carbonate and if uncontaminated it should be classified as a nuisance dust.

Several studies examined the toxicity of various abrasives with mixed results. In one study,(21) six abrasives (sand, sand treated with dust suppressant, garnet, coal slag, specular hematite, and staurolite) were examined for in vitro toxicity by exposing rat alveolar macrophages to various concentrations of the blasting material. Only treated sand showed a lower

TABLE I. Measured Airborne Concentrations of Selected Contaminants for the Abrasives Used in Phase 2 of Study in Reference 19

	Arsenic (μg/m^3)	Respirable Quartz (mg/m^3)	Cadmium (μg/m^3)	Beryllium (μg/m^3)	Chromium (μg/m^3)	Lead (μg/m^3)
Coal slag	8.59	0.148	0.496	3.334	111.4	11.33
	7.77	ND^A	0.525	4.83	121.84	11.76
Nickel slag	4.306	ND^A	0.344	0.15	3513.1	6.88
	4.772	ND^A	0.596	0.17	4038.2	7.16
Staurolite	1.229	2.301	0.248	0.577	74.08	42.82
	ND^A	2.06	0.205	0.53	63.6	34.9
Silica sand	4.225	27.6	0.185	0.792	36.08	6.052
	4.411	37.6	0.191	4.83	94.53	7.56
Silica sand with dust suppressant	6.190	19.04	0.216	0.94	33.52	8.563
	7.335	24.2	0.511	0.14	42.9	11.24
Copper slag	21.82	ND^A	0.448	0.766	73.7	6.785
	33.126	ND^A	3.727	1.24	101.45	10.14
Garnet	9.292	2.6	1.105	0.505	94.37	8.558
	11.076	1.84	1.292	0.62	108.7	10.26
Steel grit	22.654	ND^A	0.426	ND^A	1025.0	7.173
	185.8		12.253	ND^A	8576.3	24.5
2003 TLVs	10.0	0.05	10.0	2.0	500.0	50.0

Note: The first value is the geometric mean of all samples above the detection limit, ($N \leq 4$) the second value is the operator breathing zone value.
^{A}ND = none detected.

toxicity index than sand. In a follow-up study,$^{(22)}$ the authors indicated that specular hematite had lower in vivo toxicity than any of the other five agents. Coal slag showed elevated toxicity compared with the other agents. Other in vivo work$^{(23)}$ indicated increased pulmonary fibrosis in animals receiving coal slag exposure (intralobar installation) but not with slags from copper smelters; however, both showed granulomas. An in vivo study$^{(24)}$ of the fibrogenic potential of quartz (Minusil) and coal slags using rats indicated that while a progressive interstitial fibrosis was evident for the coal slags, it was considerably less than that observed for the quartz exposures.

As noted above, the substitution principle may also be applied to the process itself, and alternative techniques exist that appear to have significant potential to reduce exposures associated with the abrasive. In these instances, exposures to the surface material being removed still remain, however. Perhaps the most promising method is ultrahigh-pressure (UHP) water jetting. A report$^{(25)}$ noted successful application of UHP water jetting (25,000 psi or greater) by the U.S. Navy to replace grit blasting. This system allowed complete containment of water and stripped coatings, and the water could be cleaned and reused on site for further jetting. A second study$^{(26)}$ reviewed ultrahigh-pressure (>35,000 psi) water jetting and notes its superiority relative to abrasive blasting for salt removal from the surface. However, in some cases the water jet may not profile the steel surface in a way that an abrasive medium might. This has implications for the bond strength between the surface and the subsequent coating and may limit the use of water jetting in some cases. The high water pressures pose a risk of amputation if not used carefully.

Wet abrasive blast cleaning methods should be distinguished from high-pressure water blasting since the former can obtain the same anchor profiles as dry blasting. However, dust is suppressed by the use of water, which is the primary agent used for removing coatings and residue from surfaces. Abrasive is injected into the water stream to create the desired surface profile.

Another technique involved the use of needle guns and/or mechanical scrapers either with or without chemical strippers. These methods have some promise but may be of limited value on larger jobs due to productivity concerns. In addition, it may also be necessary to use abrasive blasting to profile the surface for subsequent painting as observed in a NIOSH investigation$^{(27)}$ of dust exposures during the chemical stripping of lead-based paint from an overpass.

In one of the more detailed studies on abrasive blasting exposure control available,$^{(27)}$ investigators examined a wet abrasive blasting operation that involved removal of concrete on the exterior surfaces of parking garages to expose underlying aggregate material for decorative purposes. The wet abrasive blasting system employed a mixture of 80% sand and 20% water, which was transported to the hand-held nozzle by air pressure. Personal samples were collected for total and respirable dust and silica. Video exposure monitoring was also employed to obtain information on specific task exposures. This involved synchronizing output from a real-time aerosol photometer (worn by the worker) and the video record of the task. Three water application rates were examined, ranging from none to 3 L/min, and tasks were segregated into blasting at ground level, blasting on an elevated platform, and helpers.

TABLE II. Wet Abrasive Blasting Summary Exposures

Worker Activity	No. of Samples	Respirable Dust Geometric Mean and (Range) mg/m^3	Respirable Quartz Geometric Mean and (Range) mg/m^3
Blasting at ground level	7	0.93 (0.34–2.85)	0.22 (0.12–0.43)
Blasting on elevated platform	9	0.60 (0.18–1.06)	0.13 (0.04–0.41)
Helper	8	0.34 (0.15–0.6)	0.06 (ND[A]–0.1)

[A] ND = none detected.

Analysis of variance and multiple comparison tests were used to analyze the data. The results indicated that worker tasks were the only statistically significant factor in explaining exposure. Workers who were blasting at ground level had significantly higher exposures than the helpers. Table II presents some summary data. Although the water rate was not statistically significant, the author notes "water application rates may have reduced respirable dust concentrations by a factor of 2–2.5 for the workers performing abrasive blasting."(28,p.6) Despite this possible reduction, however, the geometric mean exposure for all tasks was above the NIOSH REL. Based on analysis of the blasting sand and the concrete surface being removed, the author concluded that the likely source of most of the crystalline silica exposure was the concrete being removed.

Recently, the use of solid carbon dioxide (dry ice) pellets as an abrasive blasting medium has been reported.(29) This process propels the pellets with compressed air (80–100 psi and 120–150 cfm) at supersonic speeds at the surface being cleaned. The pellets eventually sublime, leaving only the contaminant for disposal. Adequate ventilation must be supplied in enclosed areas to prevent buildup of carbon dioxide and displacement of oxygen. Gloves are recommended because of the cold temperature of the dry ice.

Remotely Operated Automated Devices

Fully or partially automated abrasive blasting machines of various types are available that, in some cases, permit remote operation and thus successful control through isolation as well. Two related reports(30,31) examined the feasibility of using automated abrasive blasting equipment for paint removal on steel structures. Nine automated devices were identified and five were observed (the Auto Blaster, HydroCat, U.S. Navy High Pressure Water Jet, NCSU Robotic Bridge Maintenance System, and the Pittman Vacuum Blasting System). Observational data were collected during site visits to evaluate the current status of the technology. Air sampling during use of the Pittman Vacuum Blasting System (PVBS) was used to document the degree to which such technology reduces occupational exposure to lead. The studies concluded that "the PVBS system effectively removed and contained lead during a demonstration,"(30,p.720) but further research is needed to evaluate the effectiveness of the waste separation and concentration process during shot recycling.

Many new technologies are being developed to remove surface coatings more economically and with potential benefits in terms of exposure reductions. A web report(32) indicated that NASA's Jet Propulsion Lab in Pasadena, Calif., has developed a robotic paint removal system combining ultrasound with water jetting. The ultrasound loosens the paint with localized heating and mechanical stresses. The water jet follows up to remove the blistered paint. Another web report(33) identified work by the DOE related to surface removal processes. The DOE's interest is with removal of radioactive concrete surfaces, but the technology is applicable to other, more general removal processes as well.

In the report, *Evaluation of Coating Removal and Aggressive Surface Removal Technologies Applied to Concrete Walls, Brick Walls, and Concrete Ceilings*, the following technologies were examined: the Pentek WallWalker (a robotic concrete scabbler); the NELCO Porta Shot Blast JHJ-2000 (a centrifugal shot blaster); the LTC PTC-6 (a concrete scabbler); and the Advance Recyclable Media System (a sponge blast system). In the sponge blast system, the abrasive medium is held trapped in small "sponge-like" foam packets. Dust sampling was conducted near the operator and results are reported in Table III. Three of the four technologies evaluated still resulted in personal dust exposures to the equipment operator at levels in excess of legal and recommended limits. The WallWalker operator exposure levels were at the nondetectable level.

Another technology(34) showing promise for removing paint from bridges and overpasses is the Electrostrip process. This technique employs an electrochemical, cathodic reaction to remove the paint. A direct current is applied to the steel structure, which serves as the cathode. The anode is an absorbent pad with imbedded screen and electrolyte. In a field trial(33) of this method, area and personal exposures for lead were reported for work at two sites. Area samples ranged from 4.4 to 13.7 μg/m^3 while personal results ranged from 5.1 to 223.7 μg/m^3. The higher personal exposures were associated with power tool work, but insufficient information was provided to conclude anything about the method's ability to reduce lead exposures. The elimination of the abrasive and the subsequent exposures is, however, appealing. The authors concluded further studies are needed to increase the productivity and efficiency of the process.

Ventilation

Although ventilation is often used in abrasive blasting rooms and containment areas, it is primarily to maintain visibility or limit emissions, not to control worker exposure, which

TABLE III. Dust Levels for Various Surface Removal Technologies

Technology	Dust Level (mg/m^3)	Description
WallWalker	64.9, 46.7, 106.5; none detected	At scabbler head; at worker location
Porta Shot Blast	15.2, 16.6	Personal samples on operators
PTC-6	28.6, 30.82	Personal samples on operators
Advance Recyclable Media System (ARMS)	2729.8	Shoveling blasting media
	232.6	Operating blasting nozzle

is generally done with respiratory protection. For blasting done outside containment areas, the high air pressures and abrasive velocities make ventilation difficult. However, one study(35) indicated that vacuum blasting may be a viable solution. Vacuum blasting was conducted on a bridge with lead paint (average lead content of paint 17% by mass). Steel shot abrasive was used, cleaned on site, and reused. The blasting machine operated at 100 psi, delivered a nominal 81 cfm of air and the localized vacuum suction removed 130 cfm.

Worker exposure measurements for lead (outside the respirator) were 27–76 μg/m^3 during the blasting period. Area samples in adjacent locations indicated 8-hr TWA airborne Pb concentrations from 1–10 μg/m^3. The authors noted that the vacuum blasting approach compared favorably with open blasting in regard to personal lead exposures, with geometric means of 55 μg/m^3 vs. 4200 μg/m^3, respectively. They observed that the worker must keep the vacuum blasting head close to the surface (a brush encloses the vacuum) to prevent dust from escaping. The vacuum-blasting head is heavier than a conventional nozzle, thus raising some ergonomic concerns. The paint removal rate was estimated at approximately one tenth the rate of open blasting, based strictly on paint removal not including cleanup or containment.

Isolation

The concept of isolation generally involves enclosing either the process or the worker or both to reduce the spread of contaminant from its source. This strategy is often used in abrasive blasting operations on bridges and overpasses to reduce the spread of lead dust. It also helps in collecting spent abrasive for recycling and/or disposal. The abrasive blasting room and cabinet are examples of isolation. While isolation often helps prevent the spread of the exposures to other nearby personnel, it may not do much for the operator who still requires respiratory protection. However, isolation has been used in conjunction with automated/robotic blasting systems successfully to protect the operator.

DISCUSSION

Abrasive blasting is often used to remove surface coatings prior to repainting or other surface treatments. In this capacity an important benefit associated with the abrasive is the "profiling" of the underlying substrate, that is, the abrasive roughens the surface in a way that subsequently permits a good bond between it and the paint or coating. The ability of silica to provide this desirable profile has been noted in reports indicating the drawbacks of some alternative methods, for example, ultrahigh-pressure water jetting, however, other reports indicate this is not a serious drawback.

In a detailed study(19) reviewing substitute abrasives, the ability of alternate abrasives to provide suitable surface profiles was examined along with many other qualities. In the test, the investigators requested that abrasive manufacturers provide abrasive material designed to produce a surface profile of from 2–3 mils. In subsequent testing, many of the abrasives met this criterion along with silica sand, most notably specular hematite, which also proved superior when evaluated for toxicological effects and as competitive as silica when judged on cleaning rates.

There does not seem to be much exposure data on abrasive blasting in the field that would allow definitive conclusions on the effectiveness of controls, although in some cases this is moot. For example, substituting water jetting for abrasive blasting will obviously eliminate the abrasive exposure, but exposure to surface coating components like lead, cadmium, or other toxic metals may be unaffected. The available exposure data suggests that vacuum blasting and automated devices provide reduced exposures when used properly. Wet blasting may also provide some benefit relative to dry application, but further studies are needed.

There are many new technologies being developed that may have beneficial results on reducing exposures for abrasive blasting and other surface removal operations. However, these technologies may introduce new hazards, for example, lasers, microwaves, that will require their own control considerations. Of particular concern is the generation of combustible dusts, which may pose an explosion hazard at high concentrations. Organic dusts, such as sponge type blasting media, may fall under OSHA's requirement for enclosed systems when organic abrasives are used. Metal abrasives may also generate explosive dusts, such as aluminum, which may require equipment and grounding suitable for NFPA Class II locations. Further evaluation of these and other technologies with regard to exposure and safety hazards is needed.

CONCLUSIONS

Abrasive blasting operations continue to produce unacceptably high exposure to both the abrasive and the surface constituents being removed. These agents may include crystalline silica, lead, cadmium, arsenic, beryllium, chromates, and others. Evidence exists that in some cases respiratory protection will be inadequate due to the extreme levels of the toxic agents. There is information available that indicates viable substitute abrasive materials and blasting methods exist, and silica sand should be eliminated from this operation. Hazardous exposures to metals and other materials must still be considered, however, even if silica is eliminated.

The use of ultrahigh-pressure water jetting or wet blasting should be considered as a potential alternative to dry blasting, although profiling considerations may be an issue, particularly for water jetting. The potential exposure to surface constituents will still be an issue with water jetting, and it will be important to evaluate these exposures. Vacuum blasting should be considered as a control measure when abrasive blasting is employed; work practice controls will be needed, especially to ensure that the brush remains in contact with the surface being blasted. Enclosures and/or use of remotely operated removal systems should also be considered when feasible. Abrasive blasting with dry ice may also be a viable alternative in many cases.

There is a need for more field studies to evaluate the efficiency of various control interventions. In particular, exposure data and feasibility-of-use information on specular hematite and wet blasting methods are indicated. Exposure information on some of the newer technologies including the remotely operated automated devices is also needed. Although abrasive blasting continues to be an important unit operation of the economy and is likely to remain so in the future, the exposures associated with it are significant. Existing PPE solutions provide some interim protection; however, the need for implementation of improved engineering controls is pressing.

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