REPORT OF A FEASIBILITY STUDY
OF
AUTOMATED ABRASIVE BLASTING EQUIPMENT FOR USE ON STEEL STRUCTURES

REPORT WRITTEN BY:
Alan Echt, M.P.H., C.I.H., NIOSH
Kevin H. Dunn, M.S.E.E., NIOSH
R. Leroy Mickelsen, M.S., P.E., NIOSH

REPORT DATE:
February, 2000

REPORT NO:
ECTB 183-23

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Division of Physical Sciences and Engineering
Engineering Control Technology Branch
4676 Columbia Parkway, Mail Stop R-5
Cincinnati, Ohio 45226-1998

SIC CODE: 3569

SURVEY DATES: 1997

SURVEYS CONDUCTED BY:
Alan Echt, NIOSH
Kevin Dunn, NIOSH
James D. McGlothlin, NIOSH

MANUFACTURERS/DESIGNERS CONTACTED:

U.S. Filter/Blastrac
San Diego, California

Flow International Corporation
Kent, Washington

En-vac Robotic Blasting Systems
Portland, Oregon

Pentek Inc.
Coraopolis, Pennsylvania

Construction Automation and Robotics Lab
North Carolina State University
Raleigh, North Carolina

Coke Steel Erection
Grand Rapids, Michigan

Department of Civil Engineering
University of Texas
Austin, Texas

Carderock Division
Naval Surface Warfare Center
West Bethesda, Maryland

PVBS, Inc.
Burlington, Ontario, Canada

MANUSCRIPT PREPARED BY: Diana R.Flaherty

DISCLAIMER

Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention.

ABSTRACT

This is the report of a project to determine the feasibility of using automated paint-removal technology on steel structures (ships, bridges, storage tanks, etc.). The major goal of the project was to determine the current status of the technology. This involved determining the number of prototypes currently available, the development stage of each prototype, and determining on which steel structures each prototype can be used. Observation of prototype systems in operation was a critical component of this project.

Nine prototype automated abrasive blasting devices were identified. Five site visits were conducted where observational data were collected. Devices were boom-mounted, suspended by cables, or self-propelled while held against the surface with a vacuum. Abrasive media varied from high-pressure water to silica sand. Availability ranged from developmental designs in university laboratories to marketed systems. Many of these prototypes will reduce employee exposures to lead (and silica), although determining the extent of the exposure reduction awaits more in-depth study. More capital investment must be made into these emerging technologies to bring them into full scale production and use, so that their potential for reducing employee exposures can be realized. Since the end of the data collection phase of this study in September 1997, several new automated abrasive blasting systems have entered the market. These are not included in this report.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is located in the Centers for Disease Control and Prevention (CDC), under the Department of Health and Human Services (DHHS). NIOSH was established in 1970 by the Occupational Safety and Health Act, at the same time that the Occupational Safety and Health Administration (OSHA) was established in the Department of Labor (DOL). The OSHAct legislation mandated NIOSH to conduct research and education programs separate from the standard-setting and enforcement functions conducted by OSHA. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards.

The Engineering Control Technology Branch (ECTB) of the Division of Physical Sciences and Engineering (DPSE) has been given the lead within NIOSH to study and develop engineering controls and assess their impact on reducing occupational illness. Since 1976, ECTB has conducted a large number of studies to evaluate engineering control technology based upon industry, process, or control technique. The objective of each of these studies has been to evaluate and document control techniques and to determine the effectiveness of the control techniques in reducing potential health hazards in an industry or for a specific process.

This is the report of a project to determine the feasibility of using automated paint-removal technology on steel structures (ships, bridges, storage tanks, etc.). The major goal of the project was to determine the current status of the technology. This involved determining the number of prototypes currently available, the development stage of each prototype, and determining on which steel structures each prototype can be used. Observation of prototype systems in operation was a critical component of this project.

A second goal of the project was to document the degree to which the automated technology reduces occupational exposures to lead. This involved air sampling to determine employee exposures to lead while they operated or observed the operation of the automated equipment.

OCCUPATIONAL EXPOSURE TO LEAD

Exposure to lead occurs via inhalation of dust and fume, and ingestion through contact with lead-contaminated hands, food, cigarettes, and clothing. Absorbed lead accumulates in the body in the soft tissues and bones. Lead is stored in bones for decades, and may cause health effects long after exposure as it is slowly released in the body.

Symptoms of lead exposure include weakness, excessive tiredness, irritability, constipation, anorexia, abdominal discomfort (colic), fine tremors, and "wrist drop."[1-3] Overexposure to lead may also result in damage to the kidneys, anemia, high blood pressure, infertility and reduced sex drive in both sexes, and impotence. An individual's blood lead level (BLL) is a good indication of recent exposure to, and current absorption of lead.[4] The frequency and severity of symptoms associated with lead exposure generally increase with the BLL.

The American Conference of Governmental Industrial Hygienists (ACGIH®) has proposed a Threshold Limit Value (TLV®) for lead of 50 $\mu g/m^3$ (8-hour TWA), with worker BLLs to be controlled to at or below 20 μg/dL, and designation of lead as an animal carcinogen.[5] The U.S. Public Health Service has established a goal, by the year 2000, to eliminate all occupational exposures that result in BLLs greater than 25 μg/dL.[6]

In homes with a family member occupationally exposed to lead, care must be taken to prevent "take home" of lead, that is, lead carried into the home on clothing, skin, and hair, and in vehicles. High BLLs in resident children, and elevated concentrations of lead in the house dust, have been found in the homes of workers employed in industries associated with high lead exposure.[7] Particular effort should be made to ensure that children of persons who work in areas of high lead exposure receive a BLL test. Fetal exposure to lead is associated with reduced gestational age, birthweight, and early mental development with maternal BLLs as low as 10 to 15 μg/dL.[8] Men and women who are planning on having children should limit their exposure to lead.

METHODS

Prototype automated abrasive blasting systems were identified through a literature review and a review of trade magazines and buyers' guides, through attendance at trade shows or conferences, by Internet search, and through contacts in the abrasive blasting industry. Once a prototype was identified, arrangements were made to attend projects where the product was in use, or to attend product demonstrations. At a minimum, the manufacturer's product literature or published peer-reviewed literature was obtained for each prototype.

RESULTS
DESCRIPTIONS OF AUTOMATED ABRASIVE BLASTING DEVICES

Coke Steel Erection/The Auto Blaster

The Auto Blaster was designed for removing paint from flanged-beam structures such as bridges and highway overpasses. This automated blasting system consists of a 40-ft by 2-ft working platform suspended from either end by drive wheel assemblies which propel the Auto Blaster as it travels the length of the bridge. Three-inch drive and guide wheels allow the system to pass under diaphragm stiffeners welded to the web of the beam. One of the drive assemblies floats, to allow the device to be adjusted to accommodate different structural widths, and the drive assemblies adjust to allow its use on beams of various flange widths. Eight articulating arms, each bearing a blasting nozzle, move vertically and horizontally to allow for simultaneous abrasive blasting of both sides of two I-beams. The machine can be operated in an automatic or manual mode, using a wireless hand-held controller. The blasting speed of the machine is adjustable from two to seventy-five feet per minute. Micro switches with small extension rods are positioned to stop the platform when it encounters an obstruction, such as a bridge pier or diaphragm. The motors and electronics are totally enclosed to prevent contamination with abrasive or debris. The platform can be used for touch-up blasting (the nozzles can be quickly disconnected from the articulation mechanisms) and painting.

The advantage of the Auto Blaster over conventional abrasive blasting is in its ability to operate automatically or via remote control from outside the containment, allowing the operator to work outside of the containment. Air sampling performed by a NIOSH investigator during a demonstration on a bridge mock-up inside a 50-ft by 50-ft by 15-ft high containment with 10,000 cfm nominal exhaust revealed that lead concentrations inside the containment ranged from 2800 to 10,300 $\mu g/m^3$ during two seven-minute tests. Samples collected outside the entrance to the containment and at the blast equipment contained 2 $\mu g/m^3$ and 5 $\mu g/m^3$, respectively. According to the manufacturer, the equipment is capable of blasting up to 4000 ft^2 of beam in about 50 minutes.

Flow International Corporation/ HydroCat™

A waterjet system developed by Flow International Corporation is designed to remove coatings from structures with possible applications to marine as well as non-marine industries. The HydroCat™ can be used to strip the coatings from overhead surfaces (such as the bottom of ship hulls), vertical surfaces (tanks, ship hulls), as well as flat decks (non-skid decking etc.). The unit uses a rotating head assembly with 8 Hornet™ nozzles which deliver water at a nominal pressure of 40,000 psi and a flowrate of 6.5 gallons per minute (gpm). The HydroCat™ unit measures 27 inches by 30 inches overall with the 12 inch rotating waterjet and weighs approximately 160 pounds. The rotating waterjet head assembly is contained in a vacuum shroud which seals against the surface which is being cleaned and contains the effluent water and debris removed from the ship surface. This high level of vacuum is also used to attach the unit to the ship when operations require a vertical or overhead traverse path along a ship hull. Two motors mounted on the HydroCat™ chassis drive the four wheels and provide the motive force to move the unit along the surface. The speed of the unit can be adjusted to provide cleaning rates ranging from 100-1000 ft^2/hr based on the coating type, thickness, and surface finish requirements. The operation of the unit is supported by two 10 foot skids, one containing the Husky water pump assembly and the second containing the FlowVac vacuum system. A water filtration unit with a one cubic yard filter bag is also provided to remove solids from the effluent water.

A small control unit (15 x 8 inches) is used to startup/shutdown the water pump and vacuum system, control the direction and speed of the unit, and to control the winches which are used during vertical surface cleaning operations. A joy stick is used to allow the operator to manually steer the unit and an autosteer switch allows the semi-autonomous operation of the unit after it has been properly aligned. Two winches are used during vertical operations to prevent the unit from swinging away from the ship surface in the event of loss of power/loss of vacuum. This feature is strictly incorporated for safety reasons to prevent injury to personnel or damage to ship. The controller can be placed on a table or can be worn over the shoulder for convenient operations.

A NIOSH researcher observed the HydroCat™ while it cleaned an inside deck of a cargo ship while stationed at a pier on August 25, 1997. The unit removed an estimated 30 mil paint coating at a rate of 480-500 ft^2/hr during the demonstration. The surface was stripped down to bare metal and the area directly behind the unit was completely dry to the touch. There were no visible emissions and no water mist was observed in the immediate vicinity of the unit. The operation required the use of one person to control the unit with an additional person to occasionally provide visual alignment and to move cables and hoses. The unit has previously been used to clean a vertical surface (underwater hull) with minimal interferences from vacuum hoses and electrical cables. The unit cleaned the surface within 4-6 inches of obstructions. The A-3000 handheld pneumatic waterjet can be used to remove coatings from areas inaccessible to the HydroCat™.

U.S. Navy/ High Pressure Water Jet Paint Removal and Recovery System

This is a spin-off of a National Aeronautics and Space Administration/United Technologies project to develop an advanced stripping system based on high-pressure waterjet cleaning. The Navy's system, the Hull Jet 60, was developed by the Naval Surface Warfare Center (Carderock Division) and United Technologies Pratt and Whitney Waterjet Systems (the Air Force developed the Large Aircraft Robotic Paint Stripping system). The system is designed for use on large ships, barges, floating drydocks and other vessels. The system is made up of a modified high-reach with the manipulator frame mounted in place of the bucket, a 20-foot CONEX box housing a diesel-powered high pressure pump, a 40-foot CONEX box housing water purification equipment, a generator, and an air compressor; and a remote operator's console. The system is controlled from the remote console. The tool consists of a 6-inch long belt-driven rotating bar (the high-pressure water-blast nozzle) with 22 orifices which discharge 40,000 psi water at 10 gallons per minute. The blast nozzle is housed in a shroud equipped with two vacuum hoses. Two concentric rings of nylon bristles form the seal between the shroud and the surface. This assembly is mounted on a frame approximately 8 feet by 8 feet, which it traverses. The system is capable of fully automatic or manual operation. NIOSH investigators observed the system removing the freeboard paint from the hull of an aircraft carrier. The coating was removed to bare metal in the 30ft^2 operating window in approximately five minutes. Use of the system eliminates the need for expensive containments and allows other trades to work adjacent to the paint-removal operation. It is capable of removing one layer of coating at a time, or complete removal. It is suited to large, flat areas, such as ships' hulls and flight decks. A seventeen-pound "hand-held" version of the tool is being developed, as is a version capable of traveling beneath the vessel's hull in drydock.

The Navy claims that the system can reduce the waste generated from the hull of one aircraft carrier from 6,000,000 pounds generated by dry abrasive blasting to 100,000 pounds. The system also reduces cost by eliminating the need for containment construction and cleanup ($1.4 million for a recent amphibious assault ship [LHA]). The Navy points to other savings as well, through eliminating the need for personal protective equipment (PPE), reduced waste disposal costs, producing a cleaner surface, allowing other maintenance activities to take place near the operation, reducing time in drydock, and reducing man-hour requirements. In four demonstration projects, the average removal rate for coating ranging from flight-deck nonskid to removing a five-coat system from the underwater hull of an aircraft carrier in drydock was 178 $ft^2/hour$.

North Carolina State University Construction Automation & Robotics Laboratory/ Robotic Bridge Maintenance System

This prototype was developed by NCSU's Construction Automation & Robotics Laboratory with help from the Federal Highway Administration and the North Carolina Department of Transportation. NIOSH researchers observed its operation at a bridge test facility. The system consists of a four degree-of-freedom robotic arm and containment system mounted on a gantry table attached to the end of a modified truck-mounted peeper crane. A gripper mounted on the robot's wrist grips a universal attachment which allows it to hold a selection of tools. The system is capable of remote inspection, spray washing, depainting, and painting of bridge I-beams and bridge bearings. The system can be deployed autonomously using a CAD drawing of the bridge and an overlay algorithm and information from encoders mounted on the crane's joints. Alternatively, the system can be teleoperated using two cameras which are part of the system, one mounted on the arm of the robot (this camera is also used for inspection tasks) and the other placed on the bridge. Sonars mounted on the boom, robot, and containment system are used to position the robot once deployed under the bridge.

The system has gone through several test and demonstration phases on an experimental bridge structure. Several of the components, such as the robot manipulator, the vision system, or the modified crane boom have performed very well. Other elements, such as the containment system for the sand blasting operation, still need further improvements. One test included the use of the CO_2 (dry ice) system, called Cryoblaster, developed by Oak Ridge National Laboratory. In that experiment the Cryoblaster was operated by the robot manipulator and removed the paint from the steel surface without creating the large amount of contaminated debris created by sandblasting.

PVBS Inc./Vacuum Abrasive Steel Cleaning and Reclamation System

NIOSH researchers observed the operation of this system, which incorporates the PVBS Vacuum Abrasive Steel Cleaning and Reclamation System, during the overhaul of a research vessel. Observations and air sampling data indicate that the PVBS automated blasting tool effectively removed and contained lead-based paint during the demonstration. The system observed included the blast head, a trailer housing the cleaning and reclamation system, an electric winch, and a hand-held controller. The PVBS marine vacuum blast head demonstrated on a ship's superstructure during a NIOSH site visit consisted of two conventional abrasive blasting nozzles connected via blast hoses to the blast pot. The nozzles, located 18 inches apart, traveled inside the blast head on a slide mechanism which moved back and forth driven by an air cylinder. Reed switches which sensed the magnetic piston inside the air cylinder controlled the stroke of the nozzles. The blast head rode over the surface of the hull on rubber skirts. The head was held in intimate contact with the hull surface by the force of the vacuum, however, some leakage of abrasive and debris was noted during the demonstration. A newer model, which incorporated three blast nozzles and an improved seal was scheduled to be delivered after the demonstration. The top and bottom skirts rode on skis to allow them to travel over obstructions. Blast media, rust, and paint were contained within the tool and immediately vacuumed to the cleaning and reclamation system. A variable speed electric winch allowed the blast head to travel up and down the hull at the rate required to achieve the desired finish. A single pass cleaned the tested portions of the superstructure to a white metal finish.

The cleaning and recycling system includes a 7-ft diameter displacement chamber which allows heavy particles to leave the airstream for separation and recycling. Smaller particles move with the airstream to the filtration system. The filtration system is an on/off line independent system housed in two tanks, each of which holds five cartridge filters. The cartridge filters have a computer-controlled pulse jet reverse air wash cleaning system. When one filter loads, it goes off-line and enters the cleaning cycle, while the other unit comes on-line. As each cartridge is cleaned, a group of valves which connect the filter unit to the main vacuum in the displacement chamber via the paint dust filter open simultaneously. The self-cleaning paint dust filter deposits the fine dusts into a drum for disposal.

Abrasive is recycled from within the main vacuum unit by transporting spent abrasive from the displacement chamber via a vibratory conveyor. A two-tier separation process takes place during transport. One screen allows all of the fine material, such as spent abrasive, to be separated. A second screen separates larger waste products, such as rust. The material remaining in the vibratory conveyor is recyclable abrasive, which is fed to the blast pot via a vacuum line. Patented compensation valve technology allows the use of one vacuum system to perform several tasks. All equipment in the PVBS unit is computer controlled with operator input via a touch screen display.

The manufacturer's literature claims a production rate of 600 ft^2/hour per tool to a white metal finish. Savings in operating costs are realized by the ability for other trades to work alongside the unit, no need for containment or PPE, the ability of the equipment to run continuously, and conservation of abrasive through separation and reuse. In addition to the automated unit described, hand-held tools are available for use with the PVBS unit. Air sampling for metals and particulates conducted by NIOSH investigators during the use of the hand-held tools yielded results below applicable occupational exposure criteria.

MHI Marine Engineering, Ltd. (a subsidiary of Mitsubishi Heavy Industries, Ltd.)/En-vac

The En-vac is a joystick-steered, rate controlled abrasive-blasting robot. The system consists of the robot, recycling unit, filter unit, and vacuum unit. The robot works 100 ft vertically and 300 ft horizontally from support. The four-wheel (each independently motor- driven) robot head is held to the work surface by a vacuum which also serves to contain emissions. The seal is maintained by a rubber blast shield. The recycling unit collects, separates and classifies residues, and recycles abrasives. Blast residues are stored for packaging and disposal. The filter unit is self cleaning by air pulse. The electric vacuum unit houses the system's controls, which are extended to the operator's joystick case. The unit requires an operator and part-time attendant. The unit can accommodate a range of abrasives, but the manufacturer claims that the best results are achieved with SAE G50 steel grit, which can be recycled at least ten times.

Cost savings are realized over conventional open blasting because of the elimination of the need for containments, PPE, and scaffolding. The manufacturer quotes production rates of 500 ft^2/hr for removing mill scale from steel, 300 ft^2/hr for removing tar epoxy coating from steel, and 90 ft^2/hr for removing glass-flake coating from steel, all to an SSPC-SP 10-SSA 2.5 finish, at a cost of $\$0.34/ft^2$, $\$0.56/ft^2$, and $\$1.86/ft^2$, respectively. The unit is suitable for steel and concrete structures, including storage tanks and spheres, ships, tank interiors, and process equipment. Specialized robots are available for structures with inside corners, outside corners and small radii, such as bridge and roadway piers.

University of Texas/Automated Surface Finishing System for Large Diameter Storage Tanks[9]

This automated system consists of a motion module which rolls along the tank's surface. The motion module is attached to the tank's wind girt using two steel cables. The rate at which cable is fed through two hoists at the rear of the module controls the placement and movement of the module over the tank surface. Excess cable is contained in two assemblies mounted beneath the module. The system can be configured for either blasting or painting by changing the process module attached to the motion module. An over spray unit mounts to the back of the system for use in painting operations. A closed loop system using a PC-based control program operates the system via an axis controller using feedback from a motor-mounted encoder.

A demonstration project in 1992 found that use of the unit resulted in satisfactory blasting and painting of a tank at the test site. A vertical speed of 3.8 cm/sec was used to produce an SSPC SP-6 finish on the test surface. The authors of the report of the demonstration project estimated that daily productivity of the system would be 220 m^2/day, assuming a 90% duty cycle and a two-person crew, primarily responsible for set-up and monitoring tasks.

U.S. Filter/European Blast Cleaning Equipment (EBE)

There are eleven models of machines ranging from hand-held vacuum blasters and small spot blasting machines to large vertical machines for steel and concrete, as well as a machine for the underside of ships. All EBE machines are electrically driven, some have their own integral hydraulic drive system which allows the machine to traverse the surface being cleaned at a continuous, controlled speed. Abrasive is thrown at the surface to be cleaned by centrifugal force imparted by feeding the abrasive radially onto paddle-like blades attached to high-speed rotating wheel. Abrasive rebounding from the cleaned surface is recovered for reuse. This process is assisted by airflow created by two exhaust fans (one on the dust collector, one on the machine). Air enters the machine through a brush screen at the rear, travels across the work surface, up the reclaim duct, through the separator, dust collector, and fan to atmospheric discharge. The company claims that total abrasive is recycled at a rate of six times per minute. The abrasive is cleaned during recycling and separated debris are passed to a remote dust collector for automatic drumming or bagging. Containment is achieved by resilient urethane seals at the front, a brush screen across the air intake at the rear, and spring-loaded manganese seals at each side.

The company lists five areas where their system saves money compared with conventional abrasive blasting. These include reduced labor costs due to a reduced need for personnel, reduced abrasive consumption (0.5 kg/m^2 vs. 50 kg/m^2 for conventional blasting), labor and material savings due to elimination of containments and scaffolding (and PPE), reduced energy costs, and reduced down-time for the cleaned structure because other trades can work alongside the blast cleaning equipment.

Pentek, Inc./WallWalker

The WallWalker is an automated blasting and painting system designed for use on tanks, ships, stacks, and buildings. Up to three standard blast nozzles can be mounted on a four-wheel shrouded work head providing production comparable to three experienced blasting operators. The WallWalker work head is vacuum sealed to the surface and attached by a once-fed-through cable system to two pivoting automated cable feed motors mounted in the upper left and right parameters of the work area. The user enters the height, width, and speed into a computer controller according to the job's requirements. The command controller adjusts cable lengths via the cable feed motors to move the blasting and painting work head across the surface. The WallWalker provides automated precision control to within 1 inch over a 100 by 100 foot area. The WallWalker provides surface coverage up to 24 inches per pass. A VAC-PAC vacuum system reportedly captures 99.5 percent of abrasives, paint, dust, and debris without the use of external containment structures. The VAC-PAC provides two-stage HEPA filtration for hazardous materials with continuous reverse flow pulse jet cleaning to maximize filter life. The debris are deposited directly into a 55-gallon drum or recyclable systems for easy disposal.

The WallWalker was developed by Pentek, Inc. in cooperation with the Department of Energy to perform radioactive surface decontamination. The demonstration of the unit involved the surface removal of 1/8-inch of concrete on the walls of a waste storage vault. The WallWalker was configured with a scabbling module as well as an integral radiation detector for pre and post decontamination surveys during the demonstration. Optional work heads include ultra high pressure water jetting, scabbling, CO_2 blast, and inspection systems.

DISCUSSION AND CONCLUSIONS

Nine prototype automated abrasive blasting devices were identified. Five site visits were conducted where observational data were collected. Devices were boom-mounted, suspended by cables, or self-propelled while held against the surface with a vacuum. Abrasive media varied from high-pressure water to silica sand. Availability ranged from developmental designs in university laboratories to marketed systems. Many of these prototypes will reduce employee exposures to lead (and silica), although determining the extent of the exposure reduction awaits more in-depth study. Abrasive blasting, construction, demolition, and painting contractors should explore the economic trade-offs involved in acquiring and using this technology. For most prototypes, advantages include eliminating the need to construct large ventilated containment structures, the ability to perform other tasks, such as repainting, alongside the prototype, and reduced compliance costs. However, the original equipment costs may in some cases exceed the costs of traditional abrasive blasting devices. In addition, many of the prototypes described in this report are best suited to depainting large, flat, surfaces, such as storage tanks and ship hulls. More capital investment must be made into these emerging technologies to bring them into full scale production and use, so that their potential for reducing employee exposures can be realized.

REFERENCES

1. Hernberg S, et al [1988]. Lead and its compounds. In: Occupational medicine. 2nd ed. Chicago, IL: Year Book Medical Publishers.

2. Landrigan PJ, et al [1985]. Body lead burden: summary of epidemiological data on its relation to environmental sources and toxic effects. In: Dietary and environmental lead: human health effects. Amsterdam: Elsevier Science Publishers.

3. Proctor NH, Hughes JP, Fischman ML [1991]. Lead. In: Chemical hazards of the workplace. 3rd ed. Philadelphia, PA: J.B. Lippincott Company, Philadelphia, pp 353-357.

4. NIOSH [1978]. Occupational exposure to inorganic lead. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHEW (NIOSH) Publication No. 78-158.

5. ACGIH [1996]. 1996 threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists.

6. DHHS [1990]. Healthy people 2000: national health promotion and disease objectives. Washington, DC: U.S. Department of Health and Human Services, Public Health Service, DHHS Publication No. (PHS) 91-50212.

7. Grandjean P and Bach E [1986]. Indirect exposures: the significance of bystanders at work and at home. Am Ind Hyg Assoc J 47(12):819-824.

8. ATSDR [1990]. Toxicological profile for lead. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry. DHHS (ATSDR) Publication No. TP-88/17.

9. Dailey CM, Traver AE, Wesley GL, Haas CT, O'Connor, JT [1993]. Field testing of an automated surface finishing system for large diameter storage tanks. In: Automation and Robotics in Construction X, Watson GH, Tucker RL, Walters JK, eds. Amsterdam, NY, Elsevier Science Publishers, B.V.