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Venturi/Vortex Scrubber Technology for Controlling/Recycling Chromium Electroplating Emissions

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Chromium electroplating is an essential DOD process. Chromium has a combination of qualities that are very difficult to substitute, however, the process itself is inefficient, resulting in the production of byproduct gases that rise and create a mist of chromic acid (strongly regulated as an air pollutant) above the plating tank. Venturi/Vortex Scrubber Technology (VVST) was designed to control chromium electroplating emissions by collecting the gas bubbles before they burst at the solution surface.

This project demonstrated the Venturi/Vortex Scrubber Technology at the Marine Corps Logistics Base (MCLB) in Albany, GA. This study concluded that the PLRS was able to reduce the flow rate of the current conventional ventilation system at the one tank chromium electroplating facility at MCLB Albany by 63 percent. If new ventilation and control equipment were to be installed at MCLB Albany, this system would offer a 25 percent reduction in capital costs and a 48 percent reduction in annual costs, representing 36 percent in life-cycle cost savings. This study also presented a strong case for the use of Spark-Induced Breakdown Spectroscopy for monitoring real-time chromium emissions above a chromium electroplating tank.

Approved for public release; distribution is unlimited.

Foreword

This study was conducted for the Department of Defense (DOD), Environmental Security Technology Certification Program (ESTCP) under Project "Abatement of Hazardous Air Pollutant Emissions From Plating Operations"; Work Units E07 & E08. The technical monitor was Dr. Jeffrey Marqusee, Director, ESTCP.

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1 Introduction

Background

The Environmental Security Technology Certification Program (ESTCP) supports the demonstration and validation of environmental technologies that address priority Department of Defense (DOD) environmental requirements. The goal of the program is to quickly transition these technologies through the demonstration and validation phase to be fielded and commercialized. This final report summarizes the activities and results of the demonstration project titled "Venturi/Vortex Scrubber Technology for Controlling/Recycling Chromium Electroplating Emissions."

Chromium electroplating is an essential DOD process. Chromium has a combination of qualities that are very difficult to substitute such as hardness, high reflectance, high corrosion resistance, low coefficient of friction, high heat conductivity, and excellent wear resistance. Because of these combined properties, DOD facilities use the process to coat many military parts such as gun tubes, aircraft parts, artillery, and vehicle parts.

The process itself is inefficient, resulting in the production of byproduct gases (hydrogen and oxygen) that rise as bubbles to the plating solution surface and burst, creating a mist of chromic acid above the plating tank. Chromic acid is a known carcinogen and is strongly regulated as an air pollutant from the standpoints of both stack source and worker safety.

Recent regulations have forced DOD installations to install effective end-of-pipe control devices that incur large life-cycle costs. Conventional control technologies include packed bed scrubbers and composite mesh pad mist eliminators. There is a need for technologies that will reduce the cost of compliance for these DOD sites

The Venturi/Vortex Scrubber Technology (VVST) was designed to control chromium electroplating emissions by collecting the gas bubbles before they burst at the solution surface. A small amount of air is pulled from above the tank to help control any fugitive emissions. These streams are mixed to help collect particulates from the air and to aid coalescence of the bubbles. The liquid

stream returns to the tank while the gas stream is treated with a small filter/condenser unit. This technology was tested at the demonstration site and failed due to several key design flaws. A major redesign effort resulted in the Pushed Liquid Recirculation System (PLRS). This system simply controls the location in which bubbles pop so that the ventilation rate of a conventional system can be reduced. The expected benefits of this arrangement will be reductions in energy consumption and capital expenditures.

The most recent national emission standard for chromium electroplating was finalized in 1995 with an expected compliance date of February 1997. At the completion of this demonstration, it is estimated that all DOD electroplating sites are compliant with these requirements using conventional technology. However, chromic acid is highly corrosive resulting in a realistic equipment lifetime of approximately 10 years. In addition, more stringent regulatory standards may be considered by year 2002. The cost benefits of the PLRS can be realized with the replacement of the control/ventilation system at the time a replacement is needed.

Regulatory Issues

Two Federal regulations are relevant to the application of this technology: the Chromium Electroplating and Anodizing National Emissions Standard for Hazardous Air Pollutants (NESHAP, 60FR4948) and the Occupational Safety and Health Agency (OSHA) standard for worker breathing zone chromium concentrations (29CFR1910.94). With the change in design, the OSHA regulation is of primary concern since the effectiveness of the associated pollution control device is not reduced. The current standard is to maintain the chromic acid concentration in the worker breathing zone below 100 micrograms per cubic meter of air (52 $\mu g/m^3$ for chromium). There are no monitoring and reporting requirements associated with this regulation.

Previous Testing of the Technology

The original VVST was tested at Benet Laboratory, NY during March 1996. Testing participants are listed in Appendix A. The results were quite promising in that the mass flow of chromium from the VVST stack was below the strict California standard, which is usually considered more stringent than the NESHAP. It was also estimated that at least 76 percent of emissions were prevented. Ambient concentration measurements indicated that OSHA requirements were met, although sometimes marginally. The concerns that arose from this testing include: the sensitivity of the system to the liquid level, the user acceptance of the tank lid, and the actual ability of the system to

contain fugitive emissions considering the extremely low air flow rate. This demonstration project began under the presumption that solutions to these problems would be integrated into the VVST before implementation at MCLB Albany. More detailed information regarding this pilot demonstration can be found in Appendix B to this report, and in Hay et al. (1997, 1998).

Objectives

The original goal of this project was to demonstrate the Venturi/Vortex Scrubber Technology at the Marine Corps Logistics Base (MCLB) in Albany, GA and at Hill Air Force Base in Ogden, UT. The primary objective was to demonstrate that, as a replacement for conventional technology, this device could meet applicable air emission regulations and operate more economically than its conventional counterpart.

Approach

1. The VVST design went through two initial design changes before demonstration activities began:
   a. The original design, invented and tested in Santa Clara, CA and further tested a Benet Laboratory, Watervliet, NY, was tested and found to reduce stack emissions below the California standard.
   b. A second design incorporated two major design modifications to the original to correct system instability and to improve gas/liquid separation.
   c. A third design was developed to stabilize system operation and increase the gas-to-liquid flow rate.
2. The VVST was installed and tested at the Marine Corps Logistics Base in Albany, GA.
3. Because the VVST performed unsatisfactory in its trial run, the design was significantly altered. The original mechanism was changed by eliminating the venturi gas injector and gas/liquid separator, and creating a push-pull surface flow to control the bubbles. The new system is referred to as the Pushed Liquid Recirculation System (PLRS). The conventional ventilation system is required with this system, but at a reduced ventilation flow rate and with only one side of the hood. The demonstration objective changed to demonstrating a reduction in the ventilation requirements while maintaining compliance with applicable hygiene regulations.

4. The PLRS was installed and tested at the Marine Corps Logistics Base in Albany, GA (the second demonstration at Hill AFB was cancelled).
5. The PLRS performance was measured and analyzed.
6. A cost analysis was done to compare the installation, operation, and life-cycle costs of the PLRS to other ventilation reducing systems.

Mode of Technology Transfer

The control technology to effectively and economically control hazardous air emissions from chromium electroplating and anodizing operations developed as part of this research will be transferred to the Army industrial user community, and other military and private sector operations where the technology is applicable. It was selected for demonstration and validation as part of the Department of Defense (DOD) Environmental Security Technology Certification Program (ESTCP). The demonstration documented in this report took place at the Marine Corps Logistics Base in Albany, GA

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 cu ft	=	0.028 m^3
1 sq ft	=	0.093 m^2
1 gal	=	3.78 L
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32

2 Description of Technology

Description

The technology that was demonstrated underwent many design changes during the demonstration. The design phases and reasoning behind each modification are listed below. Hay et al. (1998) provides detailed descriptions of the three design phases of the VVST.

VVST Phase I

Robert Castle of Castle Hone and Lap, Santa Clara, CA invented the original Venturi/Vortex Scrubber Technology (Castle 1992). He tested the original unit on a very small chromium electroplating tank (15.5 gal) and showed promising results of reducing stack emissions below the strict California standard of 0.006 mg/amp-hr.

The Phase I VVST consisted of one or more drains with a cone-shaped funnel placed near the surface of the plating solution. Plating solution, containing bubbles that are generated in the electroplating process, is drawn down the drains by gravity, creating a vortex. Air above the solution is pulled down the drains and mixed with the solution by flowing through several curved sections in the drain tube. Most of the particulates contact the plating solution and are recycled during this mixing stage. The gas/liquid mixture then flows into a separation vessel. From the separation vessel, the liquid is pumped back into the plating tank and the gases are purged through a filter-condenser unit. This unit is loosely packed with polypropylene fiber-fill to collect the remaining particulates. The condensate is collected to be recycled and the gases are vented to the atmosphere. Figure 1 shows the Phase I VVST.

The VVST was further tested at Benet Laboratory, Watervliet, NY in 1996 using a 1230-gal chromium electroplating tank. The VVST unit tested had six drains and the separation chamber was placed inside the tank. The results again indicated that stack emissions could be reduced below the California standard.

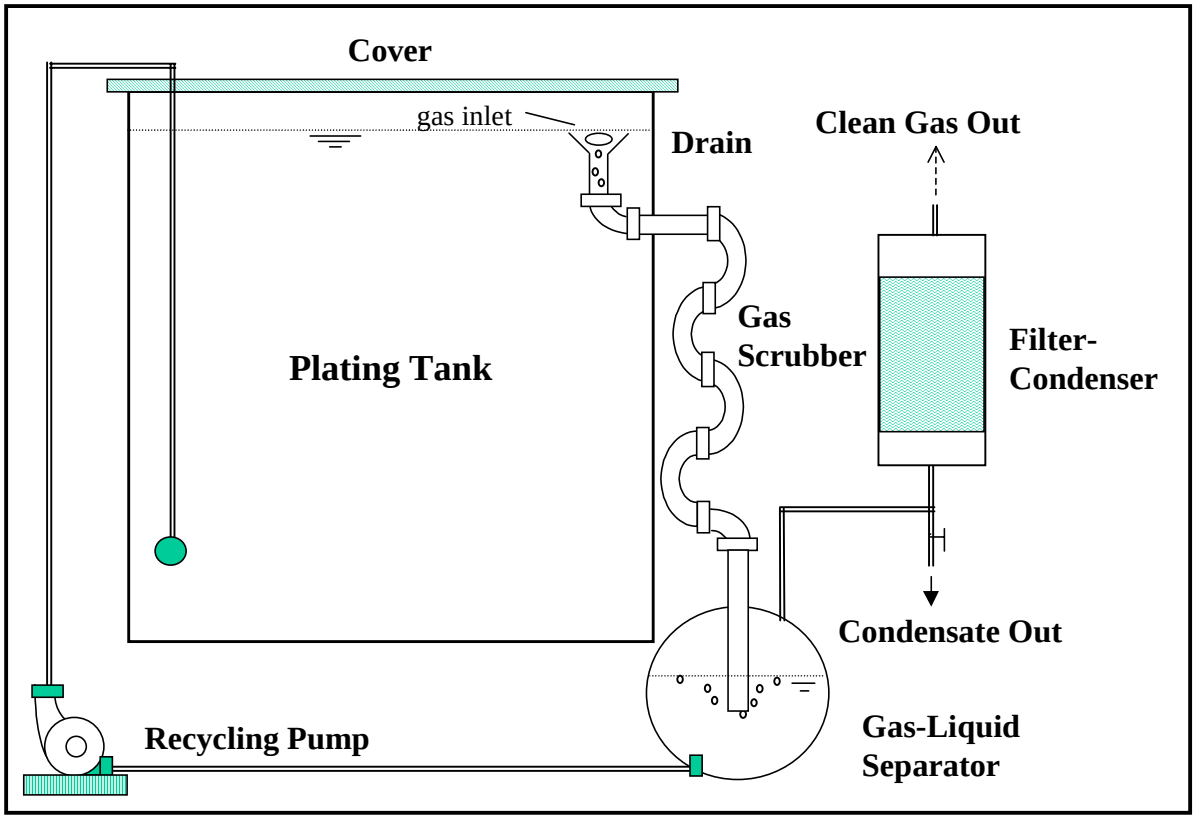


Figure 1. Phase I VVST.

Some hygiene measurements were taken that suggest that, while ambient concentrations were greater with the unit compared to the conventional system (especially without the lid), the chromium concentration was kept below OSHA standards. Considering the extremely low gas intake of the VVST unit (0.08 to 0.3 scfm) and observations suggesting that there was not complete control of the bubbles, these measurements remain suspect. However, it was estimated that at least 76 percent of the emissions were controlled.

The primary concern with this design is that the venturi drains are very dependent on the liquid height. A very small change (of a few millimeters) in the liquid height can cause instability in the drains to the point of failure. Another large concern is the low gas flow rate and the necessity of the lid.

VVST Phase II

The Phase II design incorporated two major design modifications made by Robert Castle. He attempted to correct the problem of system instability by replacing the venturi tubes with siphon tubes. Also, he employed centrifugal ejectors in the separation chamber to aid in the gas/liquid separation. With this design, the gas is pulled into the siphon tubes through small holes near the

surface of the solution. The siphoned gas/liquid flows into the separation chamber where it is separated. The rest of the system is identical to the Phase I design. This design would also require a loose fitting tank lid. Figure 2 shows the Phase II system.

This system was tested at the U.S. Army Construction Engineering Research Laboratory (CERL) with air and water. The results showed that the system was still quite unstable, however, the gas to liquid flow rate ratio was increased by one order of magnitude. Unfortunately, no tests were performed to verify the ability of the siphon tubes to control bubbles at the liquid surface.

VVST Phase III

The Phase III was developed solely by CERL to stabilize the operation of the system and increase the gas-to-liquid flow rate ratio. The solution was to introduce the gas to the liquid after the pump through a gas injector.

In this design, the liquid drawn from near the plating solution surface is pumped through a venturi throat where air from above the tank is injected into the liquid stream to coalesce the gas bubbles and scrub the particulates from the injected air. Pulling air from above the tank serves as a secondary control to help capture fugitive emissions to be recycled. The liquid/gas mixture passes through a centrifugal separator positioned in the plating tank. The plating solution exits the separator at the bottom and returns back to the tank. The gas leaves the top of the separator and enters a filter/condenser unit. This unit contains composite mesh pads to remove particulates in the gas stream. The unit is at a lower temperature than the plating solution (about 130 °F) so condensation further aids in the removal of the contaminant by increasing the particle sizes and providing wetted surfaces for the particles to adhere. Clean gas then leaves the plating building via a small stack. Figure 3 shows a basic system diagram.

The VVST was installed at MCLB Albany and preliminary tests were conducted. Unfortunately, satisfactory operation of the unit was never achieved. The preliminary tests indicated that bubbles generated by the electroplating activity were not effectively controlled nor captured by the liquid recirculation. No bubbles were observed entering the liquid intake pipe. In addition, air emissions exiting the VVST stack were noticeably discolored with chromium. It is believed that the violent mixing of gas into the plating solution at the venturi throat caused excessive foaming, which gradually entered the air treatment system. Although this concept worked well in the laboratory using an air-water system, it did not translate well to the actual chromic acid operation. These problems presented major design flaws that led to the development of the PLRS.

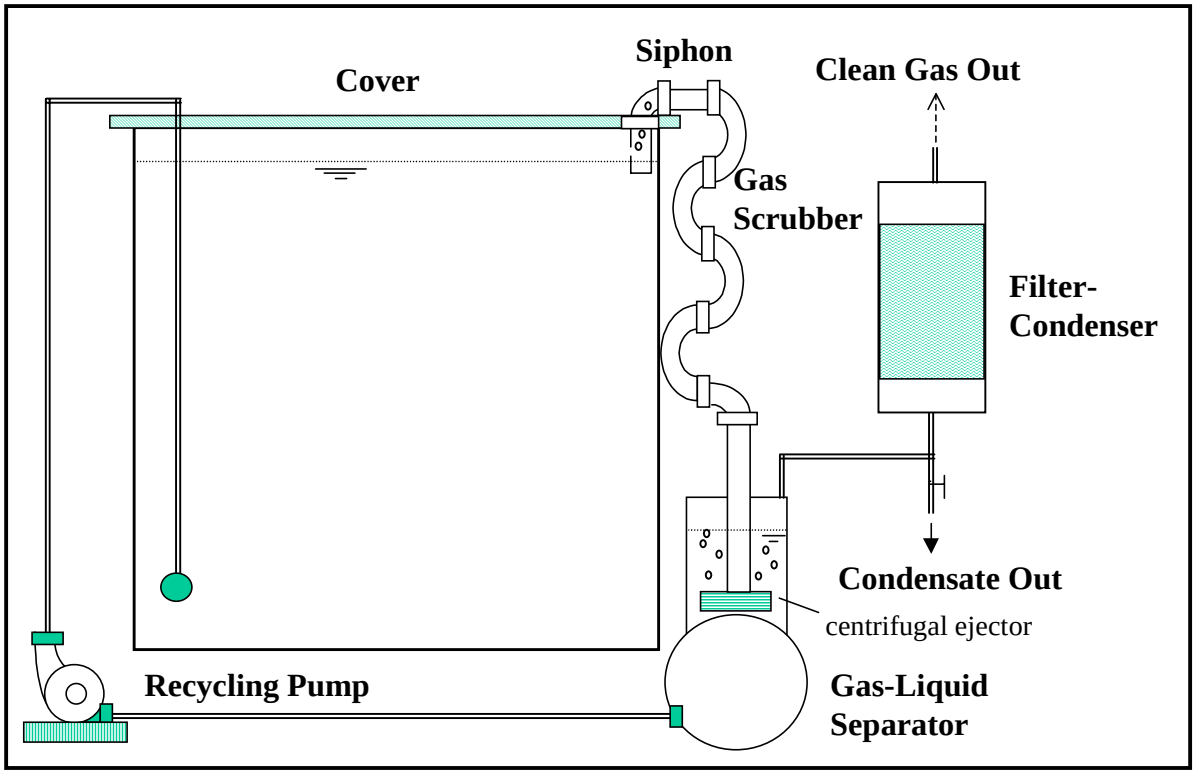


Figure 2. Phase II VVST.

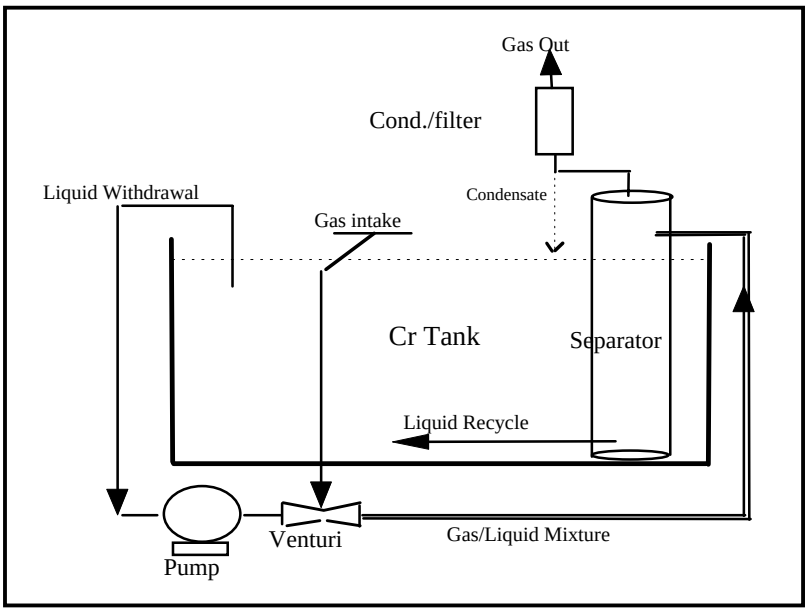


Figure 3. Phase III VVST.

PLRS

The ideas that led to the abandonment of the VVST concept and the development of the PLRS include:

1. Bubbles at the solution surface are not easily pulled across the tank and drawn into a liquid intake pipe without pulling an air/gas mixture directly at the surface. The original VVST drain did this well near the siphons, but was extremely unstable. This point was mistakenly ignored through the development of Phases II and III of the VVST. In contrast, pushing the liquid surface is a very effective method of moving bubbles at or near the surface.
1. The air flow rate associated with all three phases of the VVST is now believed to be completely inadequate. Observations of the chromium electroplating bath at MCLB Albany suggest that small bubbles are continuously rising and popping over the entire solution surface whether or not electroplating is active. The ventilation must be at least adequate to control the small fugitive particulates (minimum flow approximately 50 to 70 cu ft per minute per sq ft of tank surface area [cfm/sf]) if a complete tank lid is not used.
2. Mixing the liquid and gas streams tended to increase emission creation.
3. With an increased ventilation rate, conventional particulate emission controls will be most practical.

The change involved eliminating the venturi gas injector and the gas/liquid separator, recirculating the plating solution by a push-pull surface flow, and using a conventional ventilation system, but with a significantly reduced flow rate at the tank and pull from one side. The elimination of the venturi and vortex portions of the technology prompted the change in name to the PLRS.

With the PLRS, the liquid flow is achieved by pumping liquid from one side of the tank through jets and collecting the liquid near the liquid surface and at the far wall of the tank. The system pushes the plating bubbles to the far wall where they collect and burst. (The bubbles are not recirculated.) The large amount of bubbles created during active plating generates the majority of emissions. The fact that these bubbles pop at the tank wall instead of at the center of the tank near the plating activity, creates a lower ventilation flow requirement. This reduction could ultimately represent cost savings in energy for any control system and in capital costs for new systems.

In comparison to the VVST concept, the PLRS does not include the added benefit of recycling chromium air emissions directly back into the solution. However,

newer control devices most often allow for a closed loop scrubber rinsewater system. There is usually a first stage pad near the plating tank that collects the majority of captured chromium emissions. The pad is periodically rinsed with deionized water, which is then drained back into the electroplating tank. The addition of scrubber rinsewater is usually overcompensated by the evaporated losses from the hot electroplating tank.

In the demonstration, the liquid was pulled from the plating tank (T-60) through a 2-in. diameter chlorinated polyvinyl chloride (CPVC) horizontal distribution pipe placed approximately 6 in. below the surface on the southwest side of the tank. There were 3/8-in. holes (3-in. spacing) in this distribution pipe facing the southwest tank wall (rear wall) pointed 45 degrees upward. The liquid was pumped through 2-in. diameter CPVC piping by a 7.5 horsepower centrifugal pump. The flow passed through a throttle valve and an inline flow meter so that the flow rate could be controlled and monitored. The liquid was pumped back into the tank through two horizontal distribution pipes with ¼-in. diameter holes placed at approximately 1.5 in. below the tank liquid surface. The holes were evenly spaced (1.5 in.) across the front of the pipes and directed towards the opposite tank wall at a slight upward angle (15 degrees).

Bubbles were collected at the southwest wall of the tank under the modified ventilation hood. This modification consisted of a CPVC sheet with a 90-degree angle placed at the air inlet that extended the effective air intake farther out into the tank and closer to the surface. This way, the bubbles popped under the extension minimizing their ability to escape. The modification extended 3 in. outward and allowed an approximate 12-in. gap to the liquid surface. Figures 4 and 5 show the positioning of the PLRS in T-60 at MCLB Albany.

Observations made during the demonstration led to these design improvements:

1. The pump used for the PLRS demonstration was the same 7.5 horsepower pump originally supplied with the VVST. Since liquid only needs to recirculate from one side of the tank to the other, a vertical pump with its head piped and submerged in the plating solution would be more cost effective. Savings would include the capital costs of piping, pump and installation labor, pump maintenance (no seals to replace), and energy costs (lower horsepower required). This would also contain the electroplating solution within the tank.

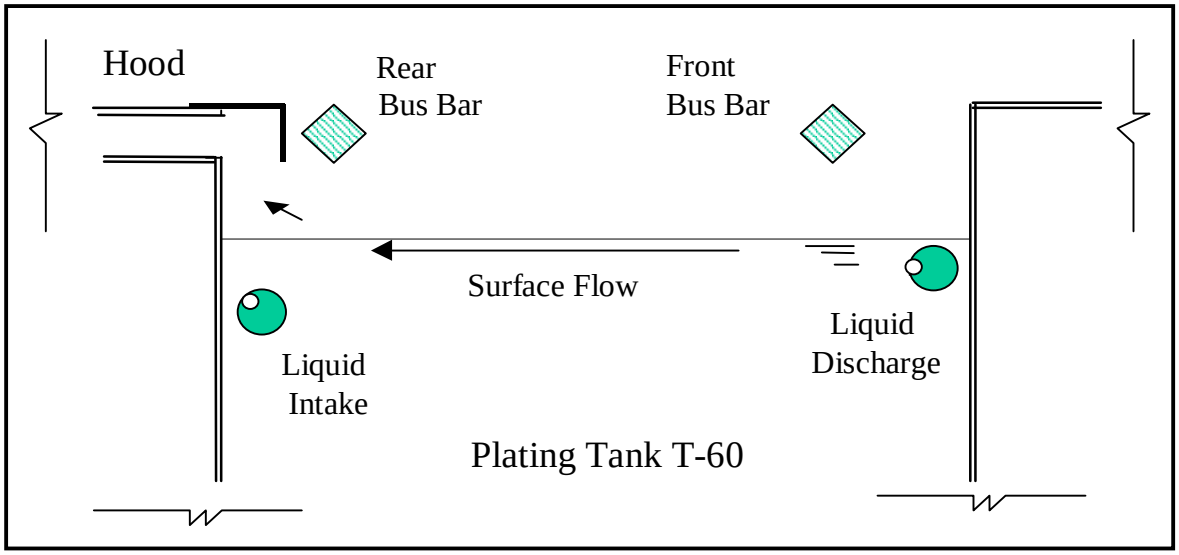


Figure 4. Cross-sectional view of PLRS placed in T-60 (not to scale).

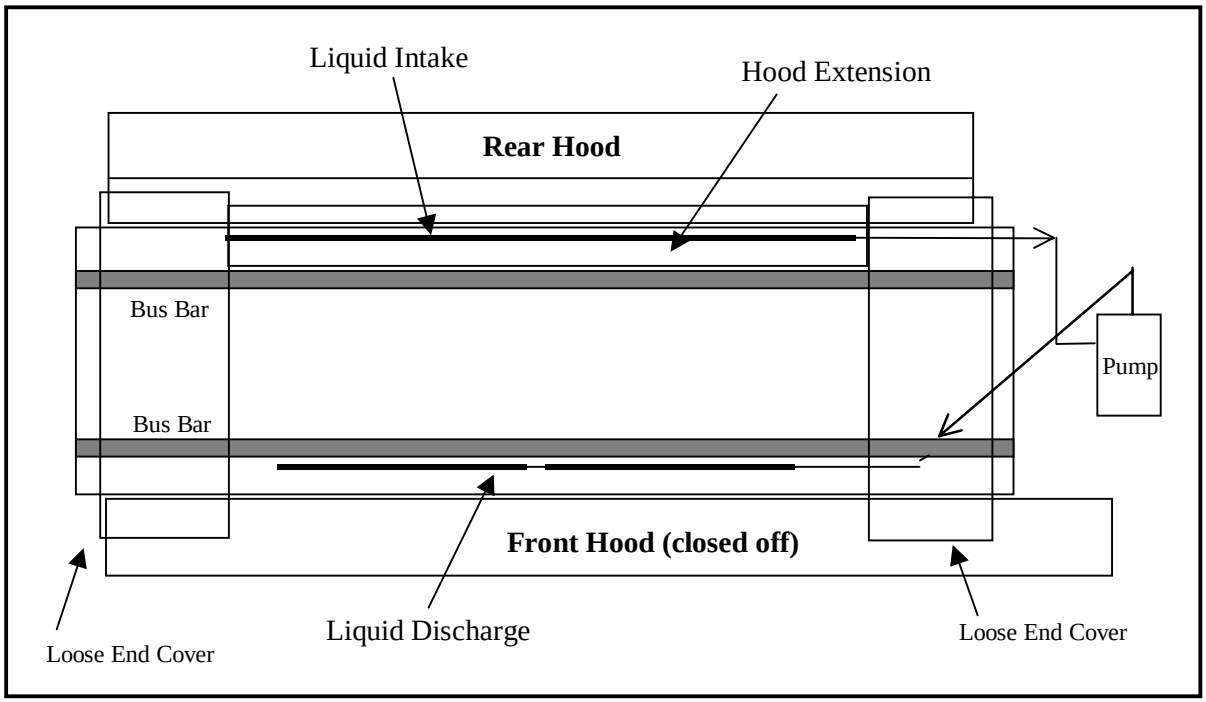


Figure 5. Top view of PLRS located in T-60 (not to scale).

2. The modified hood design should expand the entire side of the tank so that the side tank walls can be used as barriers to contain any fugitive emissions. This would also eliminate the need for partial tank lids.

3. The liquid discharge pipes should be secured and level. Also, the piping arrangement should provide even flow to each discharge pipe.

4. A horizontal CPVC sheet should be placed above the jets to protect from blockage and spray being diverted upwards.

A typical design air flow rate used for standard pull-pull ventilation systems for chromium electroplating is 250 cfm/sf of tank surface area. It is expected that this technology could allow for a reduction to approximately 60 cfm/sf if implemented properly (i.e., with improvements listed above). It is interesting to note that the State of Georgia has a minimum guideline of 100 cfm/sf. The liquid flow should be adequate to push the liquid surface across the short side of the tank within 2 seconds. A general design liquid flow rate is 3 gal/minute/sq ft of tank surface area.

Strengths, Advantages, and Weaknesses

The primary strength of the PLRS is that, by reducing the required ventilation rate, a lower life-cycle cost can be realized. The advantages of this technology over conventional end-of-pipe control technologies include:

1. Lower capital cost (smaller ventilation system needed)
2. Reduced scrubber wastewater (less water needed for washing down smaller system)
3. Minimized space requirements for treatment device and ventilation ducts
4. Replaces conventional air circulation for the plating tank (conventional air circulation contributes to emission generation)
5. Lower energy costs
6. Removes less climatized air from plating shop (additional energy savings).

Disadvantages associated with this technology include:

1. Uses some space in plating tank — approximately several inches near long sides of tank for liquid piping (this space requirement may be problematic for crowded tanks)
2. Higher chromium loading in ventilation air
3. The cost savings will be less significant for facilities running 24 hours per day, due to the liquid pump.

There are also other competing ideas available for reducing ventilation requirements, such as sealed tank covers, automated tank covers, push-pull air systems, and mist suppressants. The idea of tank covers is not well accepted by plating shops in DOD. Covers do not allow for convenient placement and withdrawal of parts, particularly when multiple parts are processed simultaneously.

Push-pull air systems allow for a decrease in ventilation by pushing the emitted particulates with an air jet across the top of the tank towards the ventilation hood. This is a very similar concept to that of the PLRS, except the PLRS pushes the liquid and suppresses the generation of the emissions until they are below the hood. Push-pull air systems can be effective if designed properly. However, achieving the proper design can be difficult and obstacles in the air path can easily disturb a push-pull system's effectiveness. The expected ventilation reduction (for a well designed system) can be almost as large as that of the PLRS.

The potential benefits of mist suppressants could be impressive. As part of the NESHAP, decorative chromium electroplating and chromic acid anodizing shops can meet compliance by using only fume suppressants (no control device). This incurs approximately only $600 per year per tank in material costs with potentially no capital costs. Mist suppressants typically contain fluorinated agents that reduce the surface tension of the bath so that gas bubbles do not burst with the energy necessary to propel liquid particulates into the air above the tank. Ferguson suggests that the concentration of chromium directly above the tank can be reduced by 98 percent (Ferguson 1998). Ferguson conducted experiments on a tank already using a push-pull air system ventilating at a rate of 82 cfm/sf of tank surface area. (It should be noted that this flow is an already reduced rate similar to that expected with the PLRS). The ventilation rate was further reduced to 50 cfm/sf per sq ft of tank surface area with a mist suppressant. Unfortunately, mist suppressants chemically alter the plating solution chemistry and have been accused of adversely affecting plating quality. This is particularly the case for hard chromium electroplating where the plate is very thick. Since all DOD facilities perform hard chromium electroplating for durability, strength, reliability, and wear, the use of mist suppressants is completely avoided.

Factors Influencing Cost and Performance

The primary design criteria of the PLRS are the ventilation rate and liquid flow rate. Factors that can affect the design include the tank dimensions, the plating arrangements, and obstacles within the tank (Table 1).

Table 1. Factors influencing cost and performance of the PLRS.

Design Factors	Operation Factors	Energy/Maintenance Factors
Tank dimensions	Liquid height fluctuations	Hours of operation
Fixed obstacles	Temporary obstacles	Pump type
Plating arrangement	Room drafts	Pump/blower size ratio

Given the results of this demonstration, the design ventilation rate would be 75 scfm/sq ft of tank surface area. Obstacles in the tank, including the plating arrangements, may inhibit the correct positioning of the discharge pipes. This may necessitate either a unique piping design or a larger ventilation rate.

The performance of the unit is measured in its ability to lower the ventilation requirements without risking the workers safety by allowing an increase in the ambient chromium concentration. Factors that could affect the performance during operation include the positioning of the liquid discharge pipes under the liquid surface, large obstacles (parts, anodes, shields) that significantly interrupt the cross-flow pattern of the solution, and large room air drafts. The holes in the liquid discharge pipes should be positioned no more than 2.5 in. below the surface to ensure adequate surface flow. The surface velocity will begin to quickly decrease as the holes in the pipes descend below 3 in. and splashing can occur if the jets in the pipes are at the surface or above. This mandates the use of a liquid level controller in a tank using the PLRS. If not controlled, the liquid height can deviate more than this 2.5 in. range due to evaporation, overfilling, or part displacement. Large obstacles can block the surface flow and allow bubbles to pop away from the ventilation hood. Room drafts, if large enough, can disrupt the ventilation pattern at the tank and push emissions into the worker's breathing zone.

The PLRS energy savings are affected by the hours of operation. The more hours a facility operates during the day, the less the energy savings. This is because the liquid pump only operates during electroplating and the ventilation blower operates continuously. During pump operation, some of the energy reduction achieved through the lower ventilation rate will be offset.

The maintenance for ventilation system using the PLRS is comparable to that of a similar but larger control system without the PLRS. Due to its smaller size, the costs for replacing filters should be less. However, the additional piping and liquid pump will probably compensate for the reduction. Using a vertical pump (no seals) will minimize the maintenance requirements for the pump.

3 Site/Facility Description

Background

The VVST and PLRS were installed and tested at the Marine Corps Logistic Base in Albany, GA. This government owned/operated facility performs vehicle rework on military vehicles. The electroplating shop possesses one chromium electroplating tank where they generally resurface small vehicle parts. Like all other chromium electroplating facilities, the hexavalent chromium emissions generated by the process must be controlled to levels dictated by applicable air regulations.

The original appeal of performing a demonstration at MCLB Albany was the possibility of achieving complete facility compliance by applying this technology to the only plating tank. Most DOD facilities with chromium electroplating have multiple tanks. An additional benefit was that the ambient chromium concentration is solely due to the single tank (i.e., no contributions from nearby tanks). This turned out to be the most important advantage for testing the PLRS at MCLB Albany, because of the importance of hygiene sampling.

The existing control system at MCLB Albany was tested and determined to be compliant with Georgia State regulations (and the NESHAP) in 1995.

Site/Facility Characteristics

MCLB Albany has one chromium electroplating tank located in building 2200. The tank is 11 ft long by 3 ft wide by 8 ft deep, and holds approximately 2000 gal of plating solution. The facility generally plates small military vehicle parts such as camshafts and hydraulic shafts. The largest part plated is about 3 ft long by 1 ft in diameter. The parts are plated in batch mode controlled manually. Typically only one large part or a basket containing several small parts are plated for several hours.

The chromium electroplating facility has a rectifier with a capacity of 8,000 amps. The engineering firm that performed the stack test of the existing control equipment in October 1995 estimated a Maximum Cumulative Potential

Rectifier Capacity (MCRC) for the unit as 47 million ampere-hours per year (ESE, 31 October 1995). This assumes 8,400 hours of operation a year with 70 percent usage of rectifier at maximum amperage. This qualifies the operation as a small hard chromium electroplating facility under the NESHAP. The actual usage of the unit is much less. Typically, the unit is operated one shift per day, 5 days per week. In addition, the unit can only be operated at a maximum amperage of 1200 amps without arcing and is usually operated near 400 amps to achieve high quality plating.

The existing air pollution control system includes a horizontal composite mesh pad, a horizontal fiber bed mist eliminator, and a vertical chevron mist eliminator in-series respectively. The device includes a 15 horsepower blower motor run continuously at a rate of approximately 6750 cfm (originally rated at 8250 cfm, or 250 cfm/sf). The large composite mesh pad and fiber bed require periodic maintenance and replacement. The electroplating tank had an air circulation system prior to this demonstration. There is no treated scrubber wastewater at this facility, because there is a closed loop rinsewater system.

If implemented, the cost benefits at this location would primarily be a reduction in power requirements and maintenance costs. Because there is an existing device meeting current regulatory requirements, no immediate capital benefit would be realized. In fact, the capital costs for retrofitting the system would not quickly be offset by operational savings. However, when the time comes for installing new ventilation equipment and control device, integrating the PLRS into the control scheme could save capital.

Figures 6 and 7 show the location of the demonstration at MCLB Albany, GA.

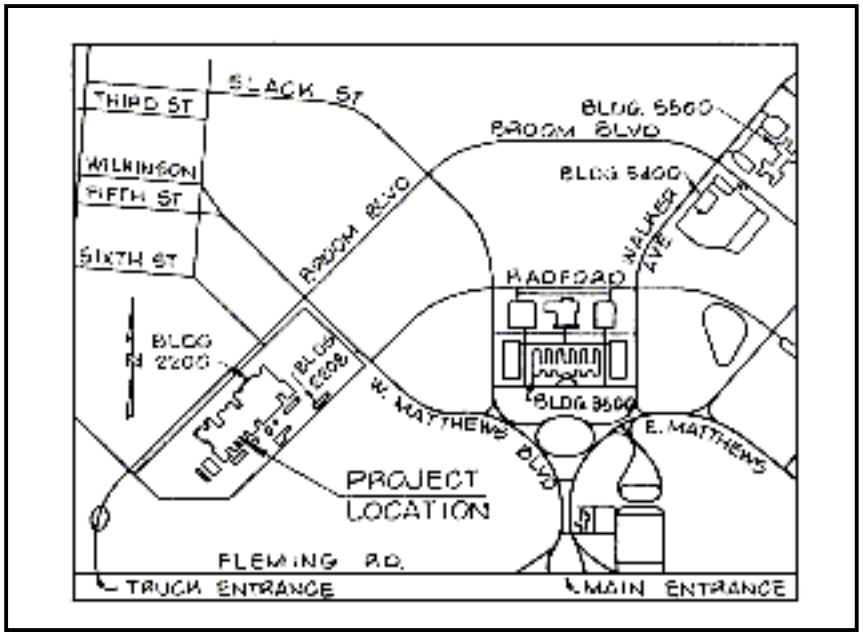


Figure 6. Project location at MCLB Albany.

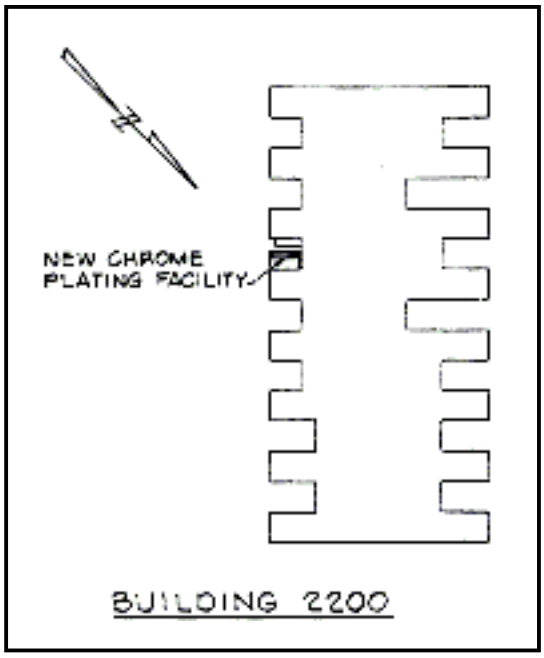


Figure 7. Building 2200.

4 Demonstration Approach

Performance Objectives

The objective of this demonstration was to evaluate the ability of the PLRS to control chromium electroplating air emissions below applicable regulatory standards in an economically advantageous manner by reducing ventilation requirements. The standard to be met is the OSHA requirement of 0.05 milligrams per cubic meter chromium air concentration in the work space. It is also expected that this technology will reduce the costs of conventional technology without disrupting standard plating operations and plating quality control. This must be demonstrated through a life-cycle cost comparison with conventional technology.

There has been discussion of a more stringent OSHA standard, possibly two orders of magnitude less than the current standard (0.5 micrograms per cubic meter on a 8 hour time-weighted average [Altmayer 1996]). If adopted, this would be a difficult standard to meet. Although not necessary for compliance, this possible standard serves as a benchmark for this demonstration.

Physical Setup and Operation

A detailed description of the positioning of the PLRS at MCLB Albany is given in Figures 4 and 5 (p 17). All piping was schedule 80 CPVC, the majority of which was 2-in. diameter. A technician from Benet Laboratory performed construction of the PLRS onsite. He was assisted by a representatives from the Naval Facilities Engineering Service Center (NFESC), Port Hueneme, CA and CERL. Construction involved all piping, the ventilation hood extension, and partial lid fabrication. Installation was performed between 30 March and 6 April 1998. Two days were dedicated to removing the VVST, 3 days for construction and testing, and 2 additional days for fixing construction errors and retesting.

The pump was installed during the VVST portion of the demonstration and was located in the containment pit near the tank bottom. The pump required a three-phase 208V power hookup. MCLB electricians made the appropriate connections and installed a control panel for the pump near the rectifier. A

manually operated power switch in the control panel controlled the pump. A separate control panel housed the power supply and readout for the inline flow meter. The inline flow meter and control valve were also installed during the previous VVST installation. Installation of this equipment took approximately 2 days. The pump installation was difficult due to its location in the containment pit.

The contractor who installed the original ventilation and control system (KCH) modified the existing ventilation system to allow for bypass and control of the ventilation rate at the tank. This was done to demonstrate a reduction in the ventilation rate. The following modifications (Figure 8) were made in less than 1 day by a skilled KCH technician:

1. A bypass damper tee was installed in the main duct to divert outside air into the ventilation system (3).
2. The non-operational damper located upstream of the front tank hood was replaced (1).
3. Profile plates were placed in the inline mist eliminator (2).

Adjusting the three dampers controlled the flow rate. Profile plates were necessary to maintain an adequate air velocity through the inline mist eliminator so its performance was not compromised.

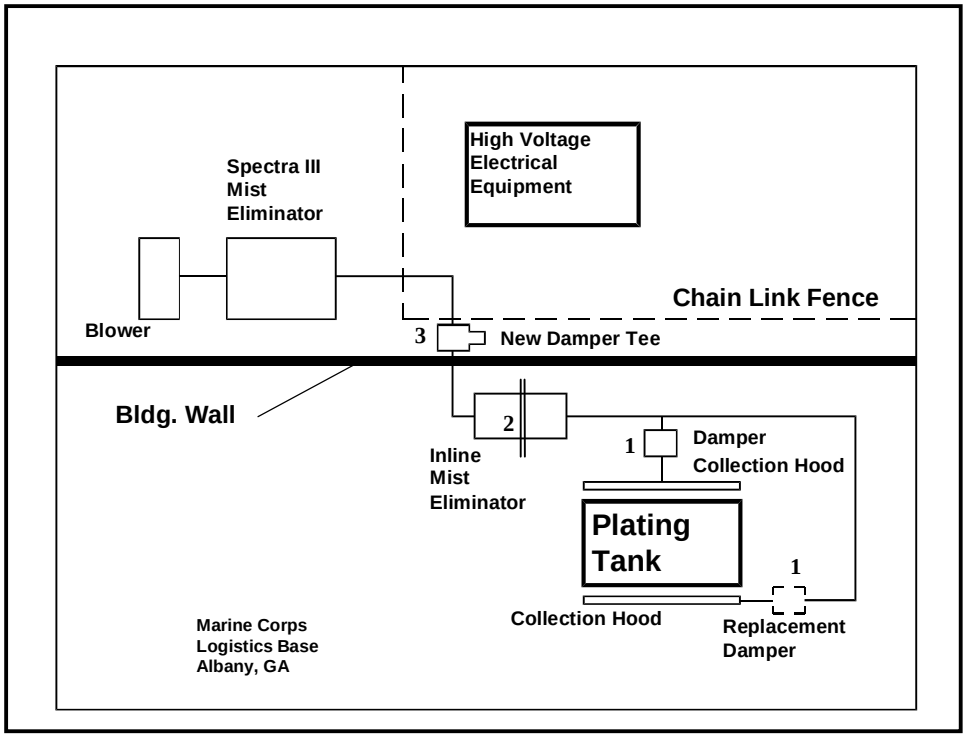


Figure 8. Modifications to the existing ventilation system.

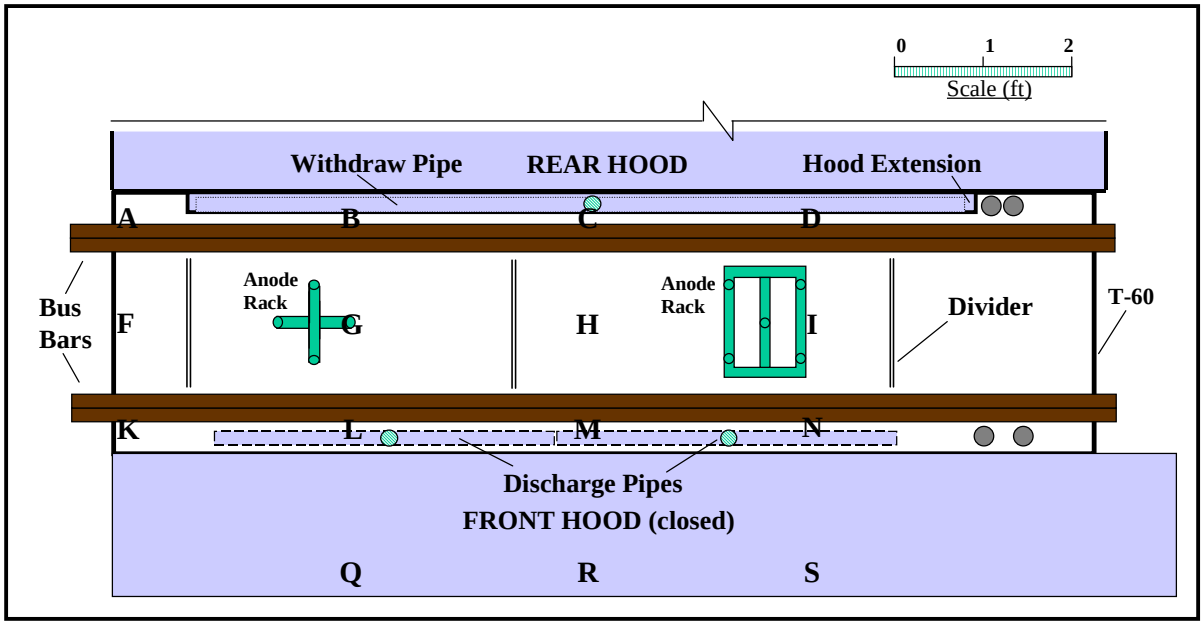


Figure 9. Plating arrangement and sampling locations (top view).

During the testing, the tank operated under conditions to maximize HAP emission creation. Two large hydraulic shafts were plated at 800-1100 amps. This high amperage is greater than normally used at MCLB Albany (400 Amps). Each hydraulic shaft was suspended separately in the plating tank connected to a rack with four surrounding anodes. The shafts are 21 in. long and cylindrical. The section that is plated on the shafts is 7.5 in. long with a diameter of 2.25 in. Figure 9 shows the plating arrangement in electroplating tank T-60 to scale. The bath temperature was approximately 140 °C.

Under standard operation, the PLRS would run continuously while plating is performed. At all other times, the PLRS pump would be shut down and only the ventilation system would operate. In an actual implementation, the pump power switch should be linked to the rectifier, so that when the rectifier was on, the PLRS would operate. During the 4-day demonstration, the PLRS was operated manually.

Sampling Procedures.

The demonstration sampling activities were performed 14-17 April 1998. Sampling included ventilation air flow rate measurements and industrial hygiene monitoring. Industrial hygiene sampling involved two types of measurements: conventional stationary time averaged sampling, and Spark-Induced Breakdown Spectroscopy (SIBS) for real-time measurements. SIBS is a relatively new technology that has recently been verified through several field

tests (Hunter et al., 1998; Fraser et al., 1998a). The SIBS unit draws a continuous air flow rate into a spark chamber where a high voltage spark excites the chromium to visible wavelengths. Optical detection of this excitation gives the amount of total chromium present in the sample. Calibrating the sample volume gives the concentration of chromium in the air stream. Physical Sciences, Inc. (PSI) of Andover, MA operated SIBS. U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM) performed the stationary time-averaged sampling according to OSHA Method ID-215 (OSHA 1998).

During the experiments, the ventilation rate was changed within a range from full flow rate of 6830 scfm to a low rate of 1200 scfm (207 to 36 cfm/sf). During these tests, the PLRS was operational except for when the ventilation was at full rate. Hygiene measurements at this rate were used for a base comparison. The ventilation air flow rate was measured with a pitot tube traversing the ventilation duct according to USEPA Method 2, "Determination of Stack Gas Velocity and Volumetric Flow Rate" (40CFR60A). The measurement was made in the main duct following the inline mist eliminator. A measurement was taken each time the dampers were adjusted to change the ventilation rate at the tank. Before sampling would occur, the chromium concentration in the worker breathing zone was monitored using Draeger® colorimetric tubes to determine whether conditions were safe for experimental personnel (see Appendix C).

The SIBS monitor was suspended above the tank using a crane (Figure 10). At each ventilation rate, a series of SIBS measurements were taken that scanned most of the space above the electroplating tank. Figure 9 shows the sampling locations. Positions A through N were at 20 in. above the plating solution surface and positions Q through S were located 48 in. above the surface. Positions Q through S represent the worker breathing zone. Positions E, J, O, and T are not shown in Figure 9 because of piping obstacles that prevented measurements at these locations. These obstacles also prevented plating activity near the northwest end of the tank. The SIBS monitor would remain over each location for approximately 3 minutes. Real-time measurements taken every second and averaged every 5 seconds were averaged to give a concentration measurement for that location.

Fraser et al. (1998b) give details of this procedure. As part of the SIBS technique, air that passes through the monitor also passes through a glass microfiber filter to collect 99.98 percent of particulates. These filters were analyzed for total chromium by an independent laboratory. Integration of the SIBS results compared to the filter analyses provides a means for evaluating the accuracy of the SIBS data.

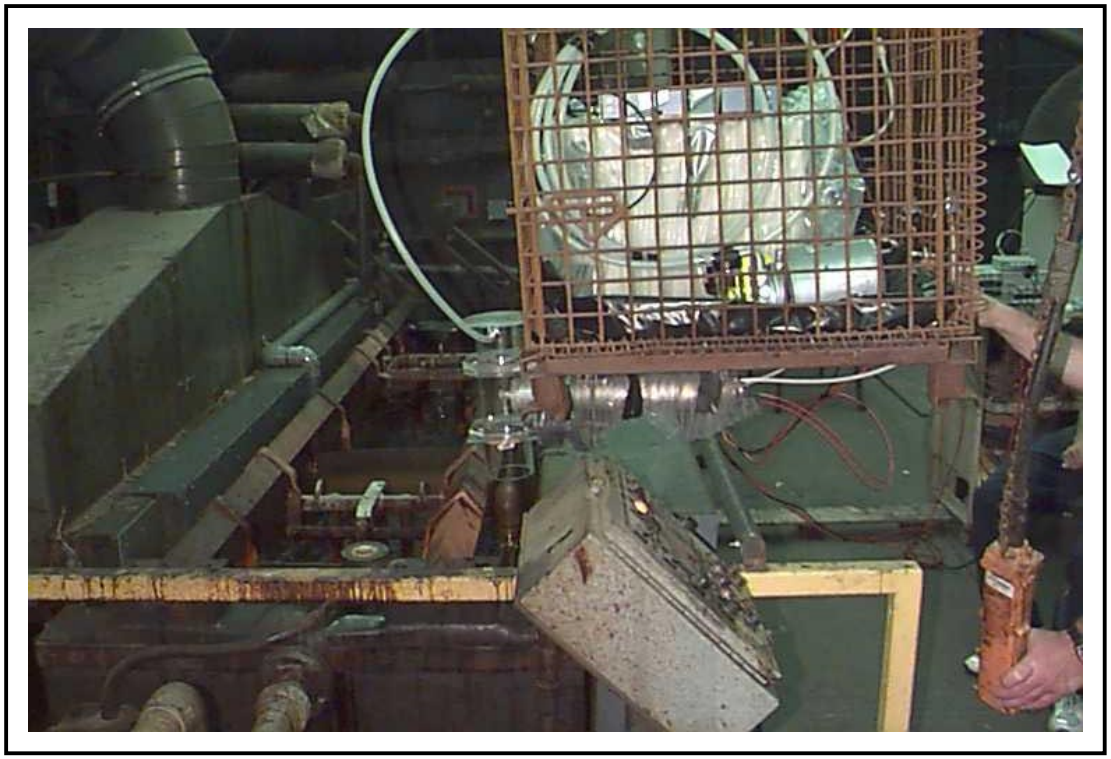


Figure 10. SIBS monitor suspended above plating tank.

The stationary sampling was performed using four ventilation rates (6830, 3263, 2249, and 1493 scfm). Samplers were placed at positions H, Q, R, and S. Sample duration was 50 to 75 minutes. They were collected through 37 mm diameter, 5-micron pore mixed cellulose ester filters at a flow rate of 4L per minute. Three samples were taken at each location for each flow rate except for at 3263 scfm where only one sample was taken at each location.

To evaluate the effectiveness of the PLRS, another test was performed with the SIBS monitor positioned at fixed positions and the PLRS pump was turned on and off. This test was performed three times, one at a ventilation rate of 3263 scfm and two at 1845 scfm.

The liquid flow recirculated through the PLRS was measured with an inline acid resistant PVDF rotor flow sensor. An approximate average flow rate throughout the tests was 100 gal/minute.

Analytical Procedures.

Stationary time-averaged hygiene samples were analyzed for hexavalent chromium offsite at the USACHPPM. The analysis method used is described as part of OSHA method ID215 (OSHA 1998). The analytical instrument used for

the quantification of hexavalent chromium was an ion chromatograph with a post-column reactor. The Demonstration Plan discusses this (cf. Appendix B).

Real-time measurements were analyzed onsite using the SIBS technology. For an account of the analytic procedure and performance of SIBS during this demonstration, see Fraser et al. (1998b). The SIBS instrument measures for total chromium. It is assumed that the chromium emitted from the plating tank is predominantly in the hexavalent state so that comparisons between the OSHA Method ID-215 and SIBS measurements are reasonable.

5 Performance Assessment

Performance Data

Figure 11 shows a sample of raw data from the SIBS monitor. The plot in Figure 11 includes data from two sampling locations, presented on a 5-second time scale. For each location, the data is converted to concentrations and averaged. The SIBS monitor responds to particulates or groups of particulates that pass through its spark gap. As can be seen from this figure, there is large deviation due to the nonhomogeneous nature of the sample. For example, the standard deviation for the sample at 20 in. above the surface in Figure 11 is 70 percent.

Table 2 summarizes the SIBS concentration data for the tank surveys. The first entry in each cell is the average concentration and the second entry, if present, is a corresponding OSHA Method ID-215 result. Table 2 also gives standard deviations. The accepted detection limit of the SIBS instrument is 10mg/m^3 so that data measured below this level are reported as <10mg/m^3. Empty cells indicate that either no measurements were taken or that data were not valid. It is important to note that the SIBS measurements were averaged over approximately 3 minutes at each sampling location while the OSHA Method ID-215 samples were taken for about 1 hour each. Appendix C gives the analysis of the OSHA Method ID-215 samples.

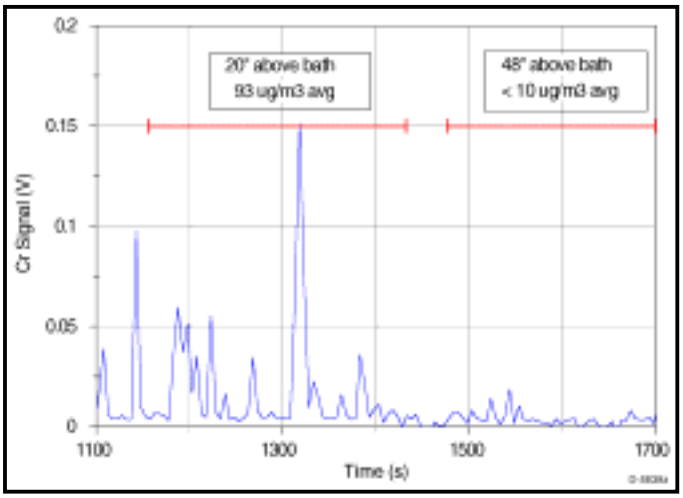


Figure 11. SIBS sample data.

Table 2. Tank survey chromium concentrations.

Ventilation Flow Rate, scfm	PLRS on/off	Measured Concentration (µg/m³)														
		A	B	C	D	F	G	H	I	K	L	M	N	Q	R	S
6830	off.	<10	<10	<10	<10	<10	<10	<10 0.072±0.018	<10	<10	<10	<10	<10	<10 0.054±0.038	<10 0.031±0.015	<10 0.033±0.042
4827	on					<10	<10	<10	<10							
3263	on	<10	<10	<10	<10	<10	<10	<10 0.12±0.02	<10	<10	<10	<10	<10	<10 0.045±0.017	<10 0.036±0.016	<10
2249	on	<10	25±16	<10	<10	<10	<10	10±14	<10	<10	<10	13±14	<10	<10 0.25±0.15	<10 0.28±0.14	<10 0.31±0.12
1845	on	<10	<10	11±20	72±55	<10	<10	13±10	186±50	18±12	<10	15±14	27±22	15±13	<10	13±10
1704	on	<10	<10	<10	57±37	93±70	47±41	<10	85±57	27±9	<10	36±34	69±64	14±10	11±3	16±8
1493	on	32±32	481±163	125±35	259±114	116±80	384±101	152±74 228±158	448±110	144±77	89±74	138±74	190±93	<10 4.6±0.4	17±4 4.2±1.1	16±24 5.2±1.0
1200	on											880±302				

* Where there are multiple entries, the first is SIBS data and the second is OSHA Draft Method ID-215 data.

Table 3. SIBS data for three conditions at which PLRS was turned on.

Ventilation Rate (scfm)	Sampling Position	Avg. Conc. (µg/m^3) PLRS on	Avg. Conc (µg/m^3) PLRS off
3263	G	58±24	121±27
1845	I	165±123	259±102
1845	G (low)	576±397	1223±291

Table 3 lists the SIBS data for the three conditions at which the PLRS was turned on and off. The position G (low) is located at G but only 12 in. above the liquid surface.

Data Assessment

The test at full ventilation (6830 scfm) without the PLRS showed that the existing system was more than adequate at controlling fugitive emissions. At all sampling locations, the chromium concentration was below the SIBS detection limit. The ID-215 results were very low, even directly above the tank at position H. SIBS measurements do not indicate chromium concentrations above 10 µg/m^3 until the ventilation rate is reduced to 2249 scfm. At this rate, only two locations, B and M, had measurements above the detection limit. As the ventilation rate decreases, more locations have measurements above 10 µg/m^3 and the concentrations mostly increase. This is particularly noticeable between the two ventilation rates of 1845 scfm and 1493 scfm. During the test at 1200 scfm, a Draeger® colorimetric tube test indicated a chromium concentration above the OSHA PEL in the worker breathing zone. A very high concentration is also shown by the only SIBS measurement taken at this rate. For safety reasons, a full SIBS scan was not taken.

Figure 12 shows the tank survey data in Table 2 averaged for each ventilation rate (not including positions Q, R, and S). Values less than the detection limit are averaged as 10 microns per cubic meter, which provides an overestimated value for ambient concentrations. However, this figure gives a good indication of the effect of lowering the ventilation rate on the capture of fugitive emissions. The average ambient concentration above the tank increases at a ventilation rate of 2300 scfm. The first data points above the OSHA PEL are observed at 1845 scfm. Based on this plot, it appears a minimum design ventilation rate for this system is approximately 2500 scfm. This represents a 63 percent reduction in the current ventilation rate and a 70 percent reduction from the original design rate of 8250 scfm.

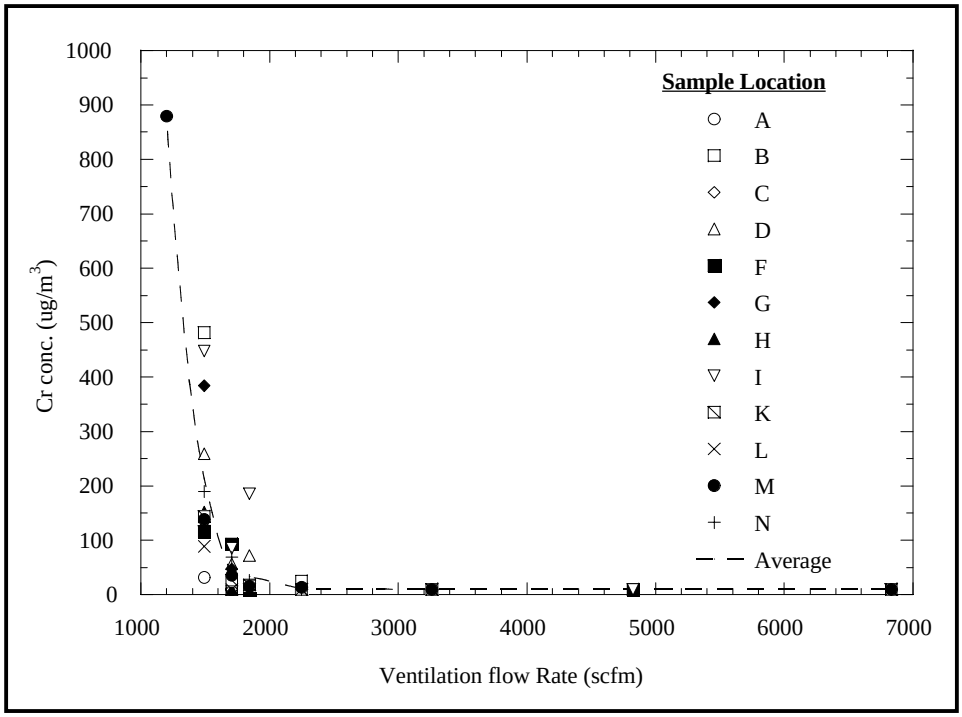


Figure 12. Concentration above tank vs. ventilation rate.

Figure 12 also shows the individual concentrations at each sampling location. Position I appears to be a large contributor to fugitive emissions. This is expected due to its proximity to one of the plating sources. It is also interesting that positions K, L, M, and N, which are the farthest positions from the operating hood, are below the average concentration at each flow rate. This indicates that the bubbles are bursting away from these positions as is intended with the PLRS.

Figure 13 shows the internal SIBS filter results during this demonstration plotted against the corresponding SIBS integrations. Figure 13, which covers over two orders of magnitude of chromium mass, shows an excellent correlation. Four of the five measurements are within 20 percent of the filter measurements. Fraser et al. (1998) gives details of the SIBS evaluation. The SIBS measurements appear to be consistent with the ID-215 method measurements. This is evident at position H. Measurements at 6830 and 3263 scfm were well below the SIBS detection limit. At 2249 scfm the ID-215 measurement is within SIBS detection. Unfortunately, a SIBS measurement was not taken at this position. However, the other measurements A through N are consistent. At 1493, the SIBS measurement of 152±74 is within range of the ID-215 measurement of 228±158. The helps to verify the accuracy of the SIBS measurements. Most SIBS measurements taken in the worker breathing zone are below the detection limit. At 1493 scfm, the SIBS measurements above the detection limit compare well to the ID-215 measurements.

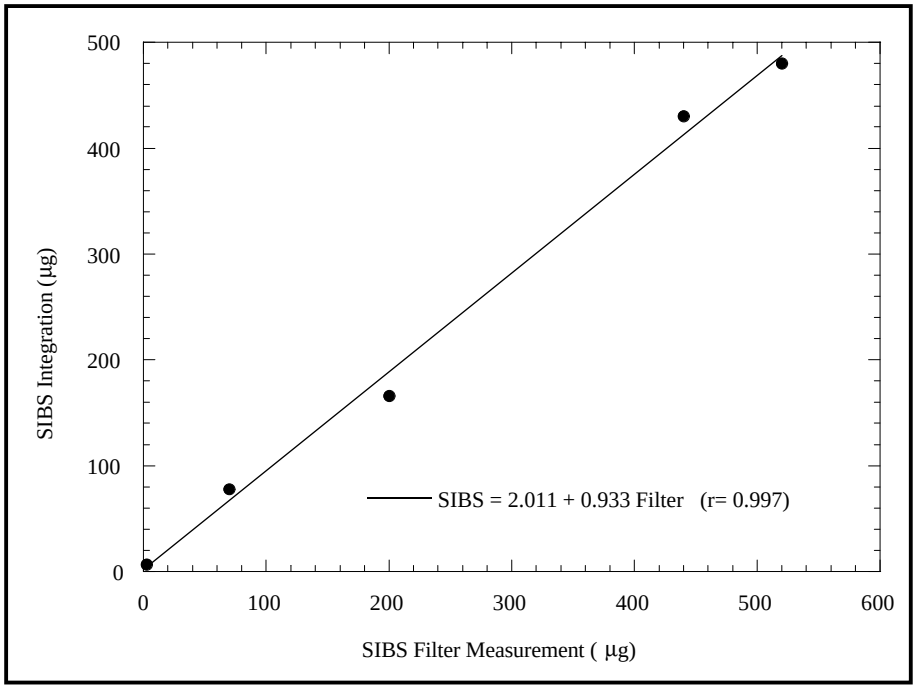


Figure 13. SIBS filter results compared with SIBS integrations.

ID-215 measurements show that the chromium concentration in the worker breathing zone stayed below the current and proposed OSHA limits for the ventilation rates of 2249 scfm and greater. However, the average ID-215 concentration increased almost one order of magnitude from 0.039 to 0.28 µg/m^3 as the ventilation rate decreased from 6830 to 2249 scfm. An increase of more than one order magnitude is seen as the rate decreases to 1493 scfm (4.7 µg/m^3).

Figure 14 shows the relationship of worker breathing zone concentration to the ventilation rate. It should be noted that the ID-215 measurement at 3263 scfm was based on limited data. Only one sample was taken at positions Q and R each and no samples were taken at position S. This figure confirms a design ventilation rate of approximately 2500 scfm (~75 cfm/sf).

Table 3 lists some data to assess whether the PLRS is actually providing a benefit, and whether the lower ventilation rate was effective in controlling the emissions without the PLRS. The data indicate an average 47 percent reduction in emissions at the three sampling points with the PLRS operating. This is not conclusive due to limited data. Observations support the measurements. During one of these experiments, the SIBS monitor became covered with chromic acid and the detector was saturated only during the portion in which the PLRS was off. Figure 15 shows the result of this occurrence. The PLRS clearly reduced the mist above the tank while operating. Figure 16a and 16b show how bubbles from the plating activity are controlled and pushed toward the ventilation hood by the PLRS.

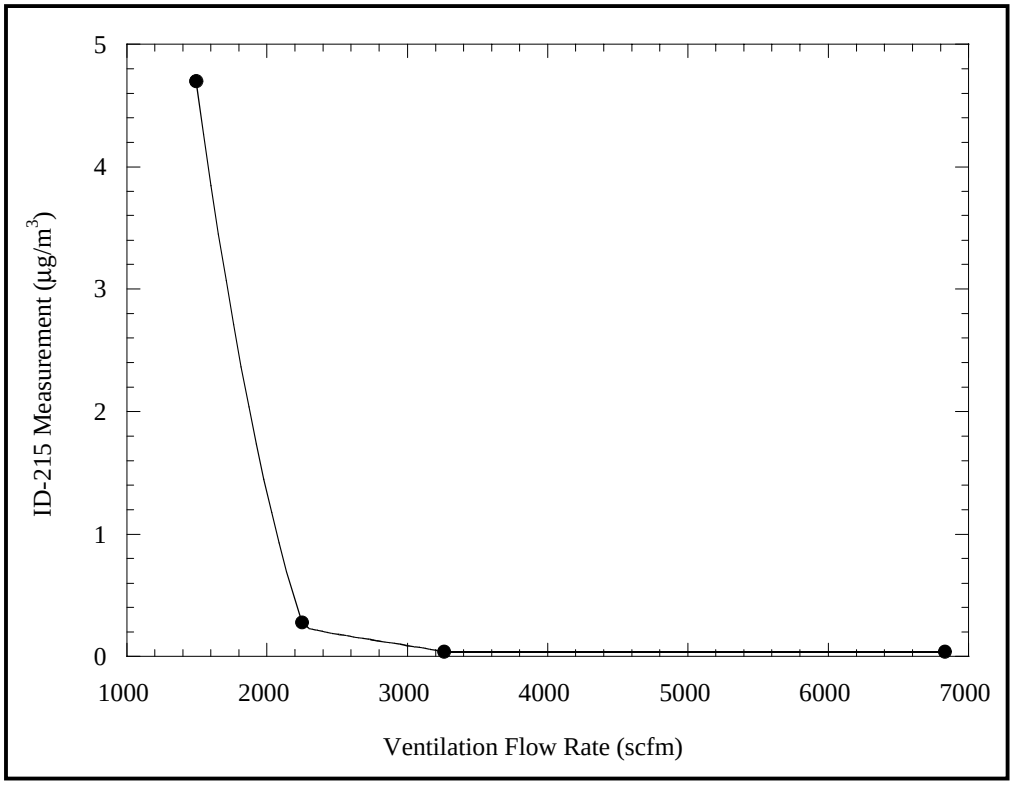


Figure 14. ID-215 Measurements vs. ventilation rate.

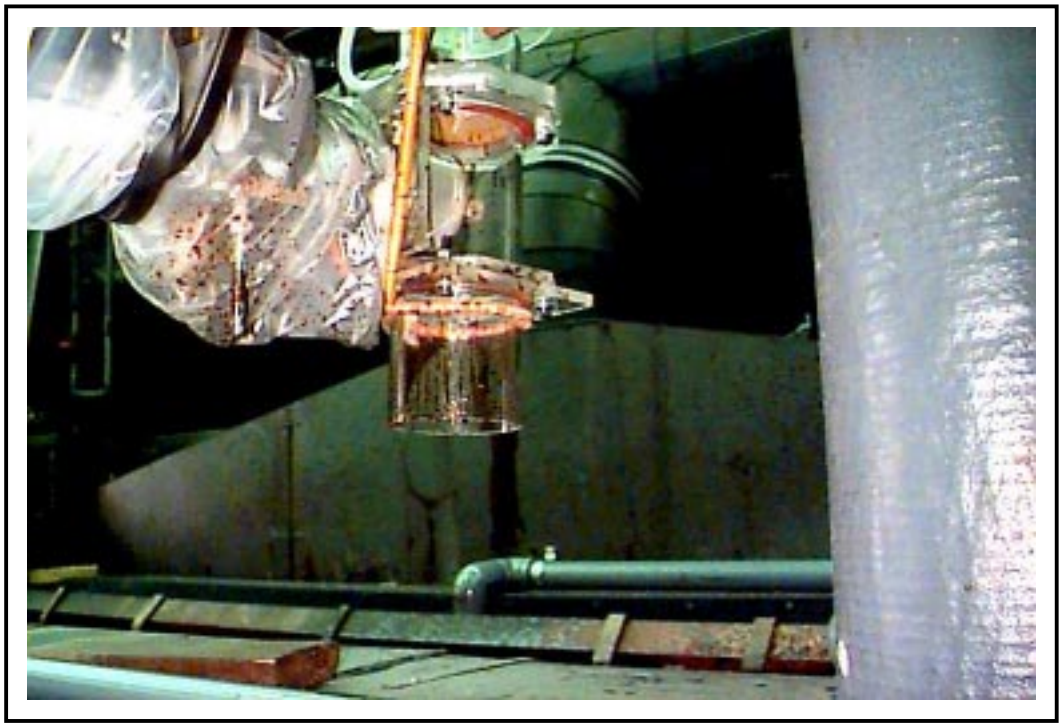
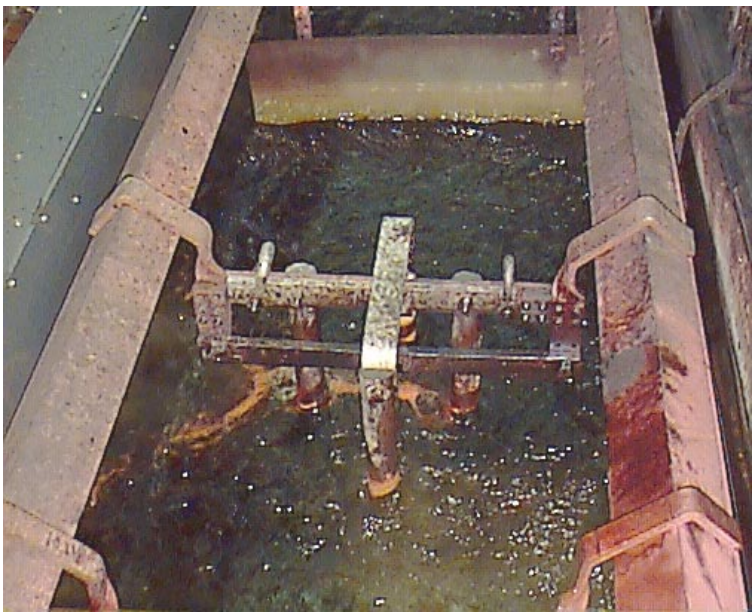


Figure 15. SIBS monitor splashed with chromic acid.

a. PLRS off; left anode rack



b. PLRS on; left anode rack

Figure 16. Effect of PLRS on surface bubbles (a. PLRS off, b. PLRS on).

Figure 17 shows a schematic of the observed bubble pattern on the plating surface with the PLRS operating. Appendix D contains additional images of the demonstration. The cross-flow was more effective for the right plating activity than the left. The data did not indicate the high population of bubbles drifting out from the wall as shown because no sampling locations were positioned directly above (near F and G). However, data did indicate a higher measurement at locations B and D where bubbles were present.

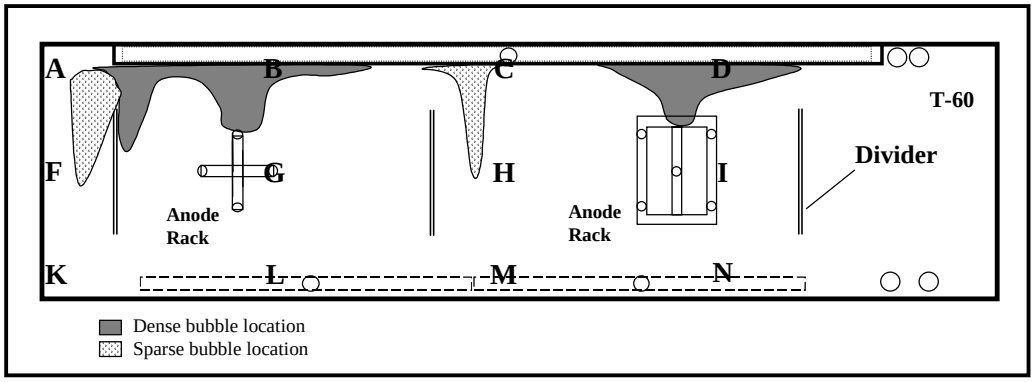


Figure 17. Bubble flow pattern with PLRS operating.

Overall, the results of the demonstration clearly show that the ventilation rate can be safely lowered using the PLRS. The results indicate, but do not prove, that the PLRS lowers emission release above the center of tank, plating activities are not affected by the liquid cross flow, and that the SIBS technique is a useful tool for measuring chromium concentrations above an active electroplating tank. What was not shown conclusively was whether it was possible to significantly reduce the ventilation rate without the PLRS. An experiment that would have helped determine this would have been to perform an additional tank survey at each ventilation rate without the PLRS operating. This experiment was not conducted due to time restrictions during the demonstration.

Some issues that may provide some variability to the data include the placement of the partial cover on the northwest (right) end of the tank. The cover was positioned just after the test at 1845 scfm and before the test at 1704 scfm. Figure 12 shows the effect of the cover at positions D and I. The concentrations at these positions decreased as the flow rate decreased from 1845 scfm to 1704 scfm. The also brings up the point that there were no samples drawn from this end where the cover was placed. However, it appeared that the emissions and bubbles were well confined by the last divider. A more significant variant was the applied current. For most of the experiments, the current varied between 800 and 1100 amps. This was controlled manually and, consequently was not consistent. The current would drift over the course of the experiments. An attempt was made to correct this during the last few tests at lower ventilation rates. During these tests the current was maintained between 1000 and 1100 amps. This probably contributed slightly to higher ambient concentrations.

Technology Comparison

As discussed in Chapter 2 (p 18), there are several competing technologies. Table 4 lists ventilation rate, maintenance requirements, ease of use and other comments for each of these technologies. Maintenance required for a conventional pull-pull ventilation system and control device is listed as normal. Since the other technologies still use a conventional ventilation system, the table lists the additional equipment or activities that will require maintenance exceeding normal.

The ventilation rates listed are approximations. The automated lid system only provides a ventilation reduction if multiple tanks are on the same ventilation system. The value listed is from an example given by Hankinson et al. (1998) for a 10-tank shop. The fewer the tanks, the higher the average ventilation rate.

The easiest technology to operate and maintain is the conventional system. To benefit from the cost savings of a ventilation reduction technology, the operator will be saddled with additional responsibilities. In the case of mist suppressants and automated tank lids, this extra work could be problematic. However, it is possible that the mist suppressant could eliminate the requirement for an end of pipe control device. In this case, the substantial extra savings and elimination of control device maintenance would seem to justify the operator's burden.

Table 4. Characteristics of competing emission control technologies.

Technology	Vent. Rate (scfm/sf)	Maintenance	Ease of Use (1=easy, 5=hard)	Comments
Conventional Pull-Pull Vent. System	250	Normal	1	
Push-Pull Ventilation System	90	Push air pipes and pump	2	Obstacles affect performance
Automated Tank lids	100	Tank lid mechanisms	5	Undesirable tank covers
Mist Suppressant	50	Adding chemicals, monitoring surface tension	4	Potential effect on plating quality, could eliminate need for control device.
PLRS	75	Liquid recirculation pipes and pump	2	

6 Cost Assessment

Table 5 provides estimated cost figures for implementing conventional technology, the PLRS, and two other competing technologies (the Push/Pull ventilation system and the surface tension modifier, otherwise known as a Wetting Agent Fume Suppressant [WAFS]). The example given is for installing new systems at MCLB Albany. Because this is a one tank facility, an automated tank cover system (as discussed in Chapter 5, p 38) would not be practical. The example given is for installing new systems at MCLB Albany. Due to low energy costs and a warm climate, this example represents a conservative cost savings when applying ventilation-reducing technologies.

Table 5. Cost comparisons for ventilation-reducing technologies at MCLB Albany.

	Conventional Pull System	PLRS	Push/Pull System	WAFS
Specifications & Capital Costs:				
Ventilation System Flow Rate	8250 CFM	2500CFM	3000CFM	1650CFM
Ventilation Blower Size	20 BHP	7.5 BHP	7.5 BHP	5.0 BHP
Auxiliary Pump/Blower Size	N/A	5BHP	1.5BHP	N/A
Blower, Ducts, Control	$37,761	$17,680	$17,680	$7,123
Installation of Ventilation	$7,158	$6,060	$6,060	$4,060
Delivery of Ventilation	$2,900	$2,900	$2,900	$2,900
Startup of Ventilation System	$1,850	$1,850	$1,850	$1,850
Auxiliary Equipment	N/A	$4,000	$4,000	N/A
Installation of Auxillary Equipment	N/A	$2,000	$2,000	N/A
Design & Start-up of				
Auxillary Equipment	N/A	$2,800	$2,800	N/A
Total Capital Costs	**$49,669**	**$37,290**	**$37,290**	**$15,933**
Annual Operating Costs:				
Required Ventilation Blower BHP	14.58	5.25	6.3	3.5
Ventilation Blower Electrical Efficiency	86%	84%	84%	84%
AuxillaryPump/Blower Efficiency	—	85%	84%	—
Ventilation Blower Operating Hours	8700	8700	8700	8700
Auxillary Equipment Operating Hours	none	1500	8700	none
Electricity Cost $/kWh	$0.050	$0.050	$0.050	$0.0
Ventilation Blower Electricity	$5,496	$2,026	$2,431	$1,351
Auxillary Equipment Costs	N/A	$329	$386	N/A
Materials Costs	$200	$100	$100	$1,200
Operating Labor Costs	N/A	N/A	N/A	$2,000

	Conventional Pull System	PLRS	Push/Pull System	WAFS
Maintenance Labor Costs	$1,000	$1,000	$1,000	$500
Total Annual Operational Cost:	**$6,696**	**$3,455**	**$3,917**	**$5,051**
Operational Costs in Present Worth	**$41,142**	**$21,230**	**$24,069**	**$31,034**
(10 yr., 10% interest factor is 6.1446)				
Total Costs in Present Worth	**$90,811**	**$58,520**	**$61,359**	**$46,967**
(10 yr., 10% interest factor is 6.1446)				

Assumptions and notes used to create Table 5 are:

1. The cost and size of the mist eliminator, blower, ventilation ducting systems, ventilation system installation, and delivery, and also the startup costs are based on a quote from the original equipment supplier. The conventional system here includes a preliminary mesh pad unit, a horizontal composite mesh pad unit, the blower, a chevron blade mist eliminator, ductwork, and hoods.

2. The exhaust blower power requirements for the conventional and PLRS systems are based on information supplied by the blower manufacturer. The costs for the push/pull system and WAFS are estimated.

3. The auxiliary system installation costs for the PLRS and push/pull system are estimated at 40 hours at $50.00 per hour.

4. Auxiliary system design and startup is estimated at 40 hours at $70.00 per hour.

5. Electricity rate is based on the current annual average electricity cost at MCLB Albany, GA.

6. A 10-year life expectancy is based on the experience of MCLB Albany.

7. The annual cost dollar value will remain constant for 10 years.

8. Using WAFS would eliminate the need for a control device.

Some annual costs are not included in Table 5. These include permitting, stack monitoring and testing, and chromic acid recovery. It is assumed that these costs remain similar for all technologies listed in Table 5.

Table 6. Cost savings percentages for competing technologies over conventional.

Cost	PLRS	Push/Pull System	WAFS
Capital	25	25	68
Annual	48	42	25
Life Cycle	36	32	48

Based on the evaluation in Table 5, Table 6 lists the expected savings percentage over the conventional technology. It appears that the Push/Pull system and the PLRS offer competitive savings. Although the WAFS provides additional savings, the degradation of the plating bath due to the chemical addition is an unknown factor. If the WAFS requires a more frequent changing of chromic acid solution, the cost savings would quickly dissipate. In addition, as discussed in Chapter 2 (p 21), fume suppressants are not recommended for use in hard chromium electroplating processes.

At other locations with more expensive energy, the annual savings of a ventilation-reducing technology over conventional technology would be larger. In addition, reducing the ventilation in colder climates translates to less heating of indoor air during colder months. Hankinson et al. (1998) point out that these savings can be greater than the energy savings through the reduction in the main blower size. Their estimate translates to an approximate $1 in heating bill savings per cubic foot per minute reduction in the ventilation rate. If the example in Table 5 were in a cold climate, the PLRS would allow for an additional $5750 in savings; the push-pull system for an additional $5250; and the mist suppressant for an additional $6600.

The cost estimates in Table 5 can be reasonably translated to a multiple tank facility. The important considerations are that each tank will require auxiliary equipment or chemicals and the ventilation system will need to be large enough to support ventilation at all tanks.

7 Regulatory and Technology Transfer Issues

Approach to Regulatory Compliance and Acceptance

The primary regulatory issue for this technology is the worker breathing zone chromium concentration (29CFR1910.94). Although no OSHA paperwork or permits are necessary to operate an alternative technology, it is important that this technology can maintain the ambient concentration within specifications for worker safety. This standard can be enforced if violations are reported and substantiated.

The Chromium Electroplating and Anodizing National Emission Standard for Hazardous Air Pollutants (60FR4948) sets a standard based on Maximum Achievable Control Technology (MACT), which, for this case, are end of pipe technologies such as packed bed scrubbers and composite mesh pad units. These technologies process a large flow rate of air pulled from above the tanks. As a result, the standard is based on a specified chromium concentration exiting the stack. The standards are 0.015 mg/dscm (milligrams per dry standard cubic meter) for large facilities, and 0.03 mg/dscm for small facilities. An alternate technology to MACT may be used if the emitted chromium concentration meets the MACT standard or if it is officially recognized by USEPA to reduce the chromium mass emissions below the level of MACT.

A ventilation system using the PLRS will have an air flow rate approximately one-third that of a recommended standard (250 cfm/sf of tank surface area). However, the mass of chromium that must be controlled may be similar so that the control device must be able to handle approximately three times greater chromium loading and still meet the NESHAP exhaust concentration. According to the USEPA (1993), MACT will exhaust a constant concentration regardless of the inlet concentration. At MCLB Albany, this was not tested because the existing ventilation system would have required a complete retrofit and the stepwise reduction of the ventilation rate during the experiments would not have been possible. However, it is a good assumption that currently available technologies (including MACT) can satisfactorily control a heavier loading.

It should be noted that during the setup of the Venturi/Vortex system, the NESHAP requirement was of great importance. Several regulatory personnel (listed in Appendix A) were notified of the demonstration. Ultimate regulatory permitting and enforcement at MCLB Albany is the duty of the State of Georgia. Technology descriptions and the sampling protocol were sent to the Georgia Department of Natural Resources. The permit process with the State of Georgia was started and ready for approval pending positive test results. With the negative test results of the Venturi/Vortex system, no further actions were taken. The current point of contact for MCLB Albany's chromium electroplating air permitting is Frank Neiderhand. (See Appendix A.)

DOD Need

An estimated 21 DOD sites currently operate chromium electroplating facilities (Table 7). The information listed was gathered by informal survey and may no longer be current. Blank entries indicate insufficient information.

Table 7. DOD chromium electroplating facilities.

Installation	Number of Tanks (Cr plating & anodizing)	Number of Treated Ventilation Streams
Air Force		
Hill AFB	17	3
Kelly AFB	17	3
McClellan AFB (BRAC)		
Robins AFB		
Tinker AFB	16	4
Army		
Anniston AD	6	2
Corpus Christi AD	6	1
Crane AAP	2	1
Lake City AAP	1	1
Letterkenny AD	6	2
Red River AD	3	2
Rock Island Arsenal	14	4
Watervliet Arsenal	10	5
Navy (Marine Corps)		
Cherry Point NAD	5	1
Jacksonville NAD	7	2
Kings Bay NSB	2	1
Louisville NOS	5	2
MCLB Albany	1	1
Norfolk NSY	4	1
North Island NAD	4	2
Puget Sound NSY	4	1

Most, if not all, sites are currently compliant with the NESHAP, which was promulgated in 1995. The compliance deadline was 25 January 1997. To meet compliance, many sites recently invested in expensive air pollution control systems. The USEPA will need to reassess the impact of the NESHAP within 7 years of promulgation (2002). They will perform a risk assessment and consider a more stringent standard based on the risk to the community. In addition to the NESHAP, several states are already beginning to consider risk-based rules. In most cases, MACT will not adequately meet a risk-based rule that requires a maximum one-in-a-million risk to the community. Installation of new equipment may be necessary. Since chromic acid is an extremely corrosive agent, the lifetime of conventional ventilation equipment is approximately 10 years. Consequently, some sites will soon be considering new systems, at which time this technology could offer potential savings.

Transition

The next step for this technology is further development. As mentioned in Chapter 2, observations made during the demonstration have led to design improvements. These modifications will be tested by CERL. The technology will then need further demonstration for validation. Another demonstration for the PLRS is tentatively planned for fiscal year 2002. It will be part of an Army-funded research program addressing hazardous air pollution problems. CERL will manage this second demonstration.

It is recommended that DOD users wait until the conclusion of the second demonstration before considering transfer. This is not expected to be a problem since there is currently no urgency to implement this new technology. Following a successful second demonstration, technology transfer should proceed accordingly. Meanwhile, documentation of this first demonstration will be sent to environmental points of contacts at DOD facilities with chromium electroplating.

Industry has not been involved in the development or demonstration of this technology thus far. A recent journal article (Fraser et al. 1998) submitted to Plating and Surface Finishing (a trade journal for electroplaters) summarized the use of the SIBS technology for monitoring the ambient chromium concentrations during this demonstration. Another article has been presented at the 20th AESF/EPA Conference for Environmental Excellence (Fraser et al. 1999). This paper and another in progress will discuss the technology and experimentation during the demonstration. These papers will help expose the PLRS to the chromium electroplating industry.

8 DOD Requirements and Lessons Learned

Official DOD Requirement Statements

The demonstration of this technology addresses the following DOD requirements:

- Army
  - 2.1.g Hazardous Air Pollutant (HAP) Emission Control (ranked #6, 1996)
  - 2.3.c Develop Recycle/Reuse Technologies (ranked #19, 1996)
- Air Force
  - 2.404 Emission Control Technology
  - 2.207 Treatment/Recycling Technologies
- Navy
  - 3.I.3.b Reuse/Recycle Waste Generated from Plating and Finishing

Processes.

With the exception of the Army requirements, the above list contains 1994 requirements.

How Requirements Were Addressed

Two primary requirements listed above are emission control technologies and recycling technologies. The Venturi/Vortex Scrubber Technology, if successful, would have met all requirements listed above for chromium electroplating. The VVST is an alternative control technology that was designed to reduce the cost of compliance while also reducing and recycling the emissions created by the electroplating process. On the other hand, the PLRS is not an alternative control technology, but rather a supplement to conventional systems. It does meet the emission control requirement by reducing the cost of compliance compared to conventional systems alone. The PLRS does not meet the recycling requirements because it does not contribute to recycling any more than currently available control technologies with closed loop rinsewater systems.

Lessons Learned

This demonstration was plagued with schedule delays. The first major delay was the result of some equipment lost in the warehouse of the demonstration site combined with the United Parcel Service strike of August 1997. The strike was unpredictable. However, allowing extra time for delivery may have alleviated this problem. It would have also been helpful to establish a delivery plan so that equipment would have been delivered directly to the POC at the demonstration site. This would have avoided misplacement in the warehouse.

An important lesson learned, from the standpoint of a Principal Investigator, is to allow the demonstrating technology to significantly mature before initiating a demonstration project under the ESTCP program. The VVST was a tested, but unproven, concept and the actual equipment to be tested was a major modification to the original idea. Laboratory work brought the new design (Phase III) to the point of testing but still required development for application to an actual chromic acid tank. When installed during the demonstration, the severity of the design flaws did not allow for onsite modifications, nor did the nature of the project lend itself well to ongoing developmental work.

Listed below are several lessons learned regarding the operation of the PLRS:

1. It is important to level the liquid return pipes during installation. When properly level, the jets will provide an even flow across the surface.

2. The design should incorporate the sides of the tanks as barriers so that bubbles near the sides will be contained within the surface flow.

3. A protective shield should be installed directly above the jets so that an accidental blockage will not cause spraying of plating solution upwards and out of the tank.

9 Conclusion

This project demonstrated the Venturi/Vortex Scrubber Technology at the Marine Corps Logistics base (MCLB) in Albany, GA. The initial testing of the VVST revealed significant design flaws. The VVST was replaced with the Pushed Liquid Recirculation System, which controls the bubbles with a surface flow. This system does not replace the conventional ventilation system as was intended with the VVST, but rather allows for a reduction in the ventilation flow rate. As a result, the original objective, which was to show that the VVST could meet applicable air emission regulations, was changed — to demonstrating a reduction in the ventilation requirements at MCLB Albany while maintaining compliance with applicable hygiene regulations.

This study concluded that the PLRS was able to reduce the flow rate of the current conventional ventilation system at the one tank chromium electroplating facility at MCLB Albany by 63 percent. If new ventilation and control equipment were to be installed at MCLB Albany, this system would offer a 25 percent reduction in capital costs and a 48 percent reduction in annual costs, representing 36 percent in life-cycle cost savings. This study also presented a strong case for the use of Spark-Induced Breakdown Spectroscopy for monitoring real-time chromium emissions above a chromium electroplating tank.

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Appendix A: Points of Contact

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Appendix B: Data Archiving and Demonstration Plan(s)

All data obtained during the demonstration will be grouped together and archived at CERL. Other information that will be archived includes financial records, background information, regulatory information, reports, and correspondence. The records will be kept in a permanent filing system with the Industrial Operations Division of the Utilities and Industrial Operations Laboratory at CERL. The phone number for this division is (217) 373-3497. The project manager for this project is Dr. K. James Hay (see Appendix A). By contacting the project manager or the division (in case of personnel changes), one can obtain copies of all information including the raw data, the demonstration plan, this final report, related CERL technical reports, and references for related technical articles. These numbers can also be reached by contacting the main switchboard of CERL at (217) 352-6511.

*Note: CERL has recently undergone a reorganization. Dr. K. James Hay is now with the Environmental Processes Branch, (217) 398-5531 (voice).

Appendix C: USACHPPM Industrial Hygiene Report

MCHB-TS-OFS (40)

FINAL REPORT

INDUSTRIAL HYGIENE SURVEY NO. 55-ML-6906-98

CHROMIUM ELECTROPLATING EMISSIONS TESTING

U.S. MARINE CORPS LOGISTICS BASE

ALBANY, GEORGIA

14-17 APRIL 1998

1. Background. The USACHPPM Industrial Hygiene Field Services Program performed sampling and smoke tests for the U.S. Army Construction Engineering Research Laboratories (CERL) to determine whether occupational exposures to airborne hexavalent chromium (chromium [VI]) during plating could potentially be controlled at a reduced exhaust ventilation rate by an experimental recirculation system. The work was performed at the Maintenance Shop, Building 2200, U.S. Marine Corps Logistics Base (USMCLB) Albany, GA during 14-17 April 1998.

2. Occupational Exposure Limits.

a. The OSHA Permissible Exposure Level (PEL) for airborne chromium [VI] in water-soluble compounds is a ceiling limit of 100 $\mu g/m^3$, measured as chromic acid (Reference 1). This is equivalent to a concentration of 52 $\mu g/m^3$ measured

as chromium. OSHA has initiated rulemaking to reduce the PEL to 0.5 $\mu g/m^3$ as an 8-hour time weighted average (TWA) exposure level (Reference 2). The American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value – Time Weighted Average (TLV-TWA®) is 50 $\mu g/m^3$ measured as chromium (Reference 3). This exposure limit is for an 8-hour TWA. The NIOSH Recommended Exposure Level (REL) is 1 $\mu g/m^3$ measured as chromium, based on a 10-hour TWA.

b. The International Agency for Research on Cancer (IARC) has determined that chromium [VI] is carcinogenic to humans (Reference 4). ACGIH classifies chromium [VI] compounds as confirmed human carcinogens (Reference 3). NIOSH lists chromic acid as a potential occupational carcinogen (Reference 1).

c. The Army is required to comply with the more stringent of OSHA and ACGIH exposure limits. It is good practice to comply with NIOSH RELs wherever feasible, and to minimize exposures to carcinogens to the maximum feasible extent.

3. Description of tank and experimental recirculation system.

a. The predominant source of chromium [VI] exposure during chrome-plating operations is the chromic acid mist from the bursting of gas bubbles that are generated around work pieces in the plating solution.

b. The chrome plating tank at Building 2200 is approximately 3 ft. wide and 12 ft. long. Exhaust ventilation slots along the front and back edges of the tank are designed to draw in air horizontally from the centerline. This is a standard ACGIH configuration, Fig. VS-70-02 (Reference 5). To be effective, the system must generate an adequate air velocity to capture the mist at the points where it is generated. The further that a slot is from these points, the more airflow is required to produce the needed velocity.

c. The CERL experimental recirculation system evaluated in this survey served two perforated pipe headers that ran the length of the tank just under the surface. The plating solution was drawn into the rear header and pumped out from the front header to create a steady flow of the top portion of the plating solution towards the back of the tank. The flow pushed the bubbles rising around the workpieces at the tank centerline close to the back slot before they burst. For this study, a shroud was also installed over the rear slot to induce the exhaust air to flow vertically upward before entering the slot.

4. Initial evaluation.

a. The exhaust system was evaluated at the full exhaust flow rate of 6830 standard cubic feet per minute (SCFM) with the recirculation system off, and at flow rates reduced in steps to a minimum of 1200 SCFM. The proportion of the flow drawn through the rear slot was increased to 100% at lower flow rates by blanking off the plenum serving the front slot. At lower flow rates, loose plates were placed over the right end of the tank to determine the effect on performance.

b. The purpose of the initial evaluation was to determine the range in which exhaust airflow became inadequate to control exposures in order to target further sampling, and to determine whether there was an immediate hazard to personnel connected with this survey.

c. A Bramec Miniax® KS No. 0117, 75-second smoke candle was passed above the entire open area of the tank, close above the liquid. The movement of the smoke was observed in order to evaluate the overall capture performance of the exhaust system, and to find particular locations where capture seemed to be weak.

d. A grid system indicating horizontal and vertical locations with respect to the tank was used. Locations Q, R, S, and T were at the front edge of the front plenum, approximately 16 in. horizontally from the edge of the liquid surface, and at 28, 64, 94, and 144 in. from the left edge of the liquid surface respectively. These points were respectively at approximately the ¼, ½, ¾ in. from the left end and at the right end of the tank. Location H was centered above the surface of the solution. Level 1 was at the top edge of the ventilation plenums, approximately 16.5 in. above the surface of the solution. Level 2 was 70 in. above floor level, approximately at breathing zone level, and 50.5 in. above the surface level.

e. Air samples lasting 400 seconds were collected in Draeger® “Chromic acid 0.1/a” colorimetric tubes, Part # 6728681, using a Draeger Accuro® hand pump, at grid points at or nearby locations occupied by the personnel connected with this survey. Sampling was performed from the center to the right end of the tank, in accordance with the escape patterns indicated by smoke testing. The tubes indicate chromic acid by a color change along the reading area that is roughly proportional in length to the airborne concentration. A scale is marked on each tube, running from 100 $\mu g/m^3$ measured as chromic acid (the OSHA ceiling limit) to 500 $\mu g/m^3$. The relative standard deviation is 50%, indicating a

high degree of variability. Minor color changes can be observed well below the lower end of the marked scale.

5. Air filter sampling and analysis.

a. Sampling was performed at the full exhaust flow rate of 6830 SCFM with the recirculation system off, and at the three reduced flow rates of 3263, 2289, and 1493 SCFM with recirculation on. The reduced flow rates were selected to span the range in which effective capture of the mist was expected to break down, based on the initial evaluations. Air samples were collected on 37mm diameter, 5-µm pore mixed cellulose ester (MCE) filters in closed-face cassettes, at a nominal flow rate of 4.0 L/min. Pumps were calibrated using a primary standard before and after each series of samples. The pump flow rate for each sampling run varied by less than the maximum acceptable 5% between calibrations.

b. General area samples were collected because no actual chrome plating work was being performed during the survey, and the operator was out of the room nearly all of the time. Samples were collected at grid points Q2, R2, S2, and H1. Points Q2, R2, and S2 appeared to be likely breathing zone locations for workers standing at the tank. Point H1 was selected as the worst possible case for a worker leaning over the tank.

c. Three air samples were collected consecutively at each of the four grid points at 6830, 2289, and 1493 SCFM. The duration was 75 minutes for each sample, except 50-55 minutes per sample for H1 at 1493 SCFM. Due to time limitations, only a single 75 minute sample could be collected at each point at 3263 SCFM setting. The nominal flow rate for each sample was 4 liters per minute. One blank, matched as to manufacturer's filter batch, was submitted for each set of air samples corresponding to an exhaust flow rate. The blank cassette was not unsealed, but was otherwise handled exactly like the sample cassettes.

d. Samples were analyzed by the USACHPPM-Main Laboratory using OSHA Draft Method ID-215, which has since been fully validated (Method 4). The draft method was selected because OSHA used it in preference to their older, fully-validated Method ID-103. The laboratory's quantitative detection limit was 0.040 µg/sample.

6. Results.

a. Observations during smoke and colorimetric tube testing are provided in Attachment 1. The smoke tests indicated a deterioration of exhaust system capture performance as the flow rate was reduced. At 2411 SCFM and below, the escape of smoke was clearly visible. Room air currents appeared to move the smoke towards the right end and then upward. Placing plates over the right end of the tank at an exhaust rate of 1845 SCFM appeared to improve capture overall; however, turbulence was observed under the plates themselves, which indicates a potential for release in itself.

b. Chromium [VI] concentrations at or below the OSHA ceiling limit of 100 $\mu g/m^3$ at S2 and T2 were indicated at 1845 SCFM and below. No definite color changes were noted at points 5 to 8 feet in front of the tank at low levels.

c. At 1493 SCFM, a faint brown spot, the color of the plating solution, directly below the air inlet of the cassette, was observed on the air sampling filters at Q2, R2, and S2. Filters at H1 had a much darker spot and each of the cassettes used at H1 had several visible droplets of plating solution dried on the outside.

d. The blank results were above the laboratory's quantitative detection limit in 3 of 4 cases. This is attributed to chrome contamination either in the filters used to collect the sample or from a source in the analytical procedure, because the filter cassettes had not been unsealed before being submitted to the laboratory.

e. The concentration reported for each air sample was corrected for the corresponding blank result, as required by ID-215. For each flow rate of 6830, 2249, and 1493 SCFM, the air concentration at each of grid point was estimated using the mean of the calculated concentrations from the 3 air samples taken at that grid point. The single calculated concentrations at Q2, R2, and H1 were used as estimates for the 3263 SCFM flow rate. The single S2 sample at 3263 SCFM was lost during analysis.

7. Statistical analysis.

a. Statistical methods are described in detail in Attachment 2.

b. A 95% confidence interval was determined for each estimated mean concentration. This interval is defined by calculating upper and lower confidence limits, and represents the range in which the true mean value of the exposure level during the measured interval falls with 95% probability. Estimates cannot

be determined to be significantly different unless their confidence intervals do not overlap.

c. The 95%, 95% upper tolerance level ($UTL_{95,95}$) was also calculated for each of these results. This is the level below which air concentrations would be expected to be for 95% of the time over the long term, determined with 95% confidence. This statistic is useful in determining compliance to occupational exposure limits based on a limited number of measurements.

d. A pooled estimate of the concentration at Q2, R2, and S2 was made from all 9 calculated concentrations at each exhaust flow rate of 6830, 2249, and 1493 SCFM. The larger number of calculated results allows more precise estimates. Pooling was considered appropriate because each grid point is a plausible location for a worker to stand, and because the confidence intervals for the calculated concentrations at each exhaust flow rate overlap to the extent that, by observation, they can be considered to be part of the same statistical population.

8. Air Filter Sampling [cf. Attachment 3].

a. At 6830 SCFM, representing the existing ventilation system, the UTLs for the 4 grid points and for the pooled Q2, R2, and S2 were below the NIOSH REL. There was no significant difference between the individual and the pooled Q2, R2, and S2 results at 6830 SCFM and those at 3263 and 2249 SCFM. There was a significant difference between the individual and the pooled Q2, R2, and S2 results at 2249 SCFM and those at 1493 SCFM. There was also a significant difference between the pooled Q2, R2, and S2 result at 6830 SCFM and the one at 2249 SCFM.

b. Because of the very high variability in H1 air sample results at reduced ventilation rates, attributed to the random collection of large mist droplets, no significant differences in H1 concentrations could be demonstrated. However, the individual calculated concentrations and the spots observed on the filters clearly indicate a very sharp rise in expected concentrations for the lower exhaust flow rates.

c. At 6830 SCFM, the individual and pooled UTLs for Q2, R2, and S2 were below both the NIOSH REL of 1 $\mu g/m^3$ and the possible future OSHA PEL of 0.5 $\mu g/m^3$. The same was true of UTLs for Q2 and R2 at 3263 SCFM. At 2249 SCFM, the individual and pooled UTLs for Q2, R2, and S2 exceeded the NIOSH REL slightly, and the corresponding UTLs at 1493 SCFM were considerably higher. None of the UTLs reached the ACGIH TLV-TWA® of 50 $\mu g/m^3$ (8-hour time-weighted average) or the current OSHA ceiling PEL of 100 $\mu g/m^3$.

9. Discussion.

a. Smoke testing indicated the possibility of mist escape at reduced ventilation levels and indicated that room air currents would convey uncaptured mist along the length of the tank towards the right end, and then upwards.

b. There are several factors that should be considered in interpreting sampling results in general. Different work pieces or higher plating currents are likely to affect the rate at which mist is produced and therefore the airborne concentrations of chromium [VI]. General area samples such as the ones collected are not always well correlated to worker breathing zone exposures.

c. Colorimetric tube results at or near the grid point T2 indicate the possibility of worker breathing zone exposures at levels up to the OSHA ceiling PEL at least at 1845 SCFM and below. It was not clear why colorimetric tube indications at S2 and T2 were higher at 1845 SCFM than at lower levels. Colorimetric tube results are highly variable, and all except one of the results in this survey were below the measurement scale. These results are also based on sampling durations that are much shorter than for air filter samples, which makes them more sensitive to short-term conditions.

d. Air filter sample results indicated much lower exposure levels at reduced exhaust flow rates than did colorimetric tube testing. The UTLs calculated in this survey may be underestimates because of limitations in statistical calculation methods, as explained in Attachment 1, but this is unlikely to account for the magnitude of the difference. The smoke and colorimetric tube results suggest that the air filter sampling locations, although the most likely locations for worker breathing zones, did not reflect the highest possible air concentrations around this tank. As exhaust flow rates are reduced, the efficiency of mist capture is expected to become more sensitive to flow disturbances from crossdrafts. Crossdrafts moving from the tank towards work stations, at the same tank or at adjacent operations, could produce much higher worker exposures than were indicated by air filter sampling in this survey.

10. Conclusions.

a. The results indicate that there is a potential for adequate control of chromium [VI] emissions from chrome plating tanks at a substantially reduced exhaust airflow rate using the CERL experimental recirculation system.

b. The results indicate that the potential effects of crossdrafts on worker exposures need to be carefully considered in future evaluations of the experimental system.

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Attachment 1. Observations During Smoke and Colorimetric Tube Testing.

Exhaust Flow Rate	Recirc. System	Other Conditions Or Notes	Smoke Tube Results		Colorimetric Tube Results	
SCFM	STATUS		Overall Capture Performance	Areas of Weak Capture	Sampling Location	Result
6830	On		Fair to good	Front left corner	S2	None
3263	On		Fair	Front left corner	S2	None
	Off		Fair	Front left corner	S2	None
2249	On		Poor; smoke billowed high	Right end, especially	Between T1 and T2	None
				front corner		
1845	On		Poor		T2	Less than 100 µg/m3
		8 min after initial tube			S2,	Less than 100 µg/m3
		15 min after initial tube			Near R2, 6 ft in front	None
		25 min after initial tube			Between S2 and T2	Possible slight color change
		35 min after initial tube			T2	100 µg/m3
	On	Loose plates placed over	Better capture, but turbulence		Various - S1, S2, T1	Less than 100 µg/m3
		right end of tank (near T2)	under plate		and T2, and over tank	
	Off	"			T2	None
		"			S2	None
1704	On	Loose plates placed over	Poor	Entire front edge	Near S2, 5 ft in front	None
		right end of tank (near T2)				
		5 min after initial tube			Near Q2, 8 ft in front	None
		45 min after initial tube			Near S2, 5 ft in front	None
1200	On	Loose plates placed over	Very poor – substantial escape	Both ends	T2	Less than 100 µg/m3
		right end of tank (near T2)	at right end			
1493	On	30 min after turndown			Near T2, 5 ft in front	Possible slight color change
		1 hr after turndown			Near S2, 5 ft in front	None
		2 hr after turndown			Near Q2 and R2,	None

Attachment 2. Statistical Analysis of Air Filter Sample Results.

1. Correction of reported air concentrations. The calculated sample result is the difference between the reported sample result and the corresponding blank result. The reported blank mass (µg) was converted to an equivalent mass per unit volume (µg/m^3) figure using the minimum of the air volumes that were collected for the corresponding samples. Blanks reported below a limit of detection were assumed to be at the limit of detection for calculation purposes.

2. Calculation of standard deviations for calculated air concentrations.

a. The variances associated with each of the reported concentration and the blank equivalent concentration contribute to the variance of their difference, the calculated concentration. If the sources of variation are assumed to be independent, the variance of a sum or difference of two statistics is equal to the sum of their individual variances (Reference 6). The standard deviation is the square root of this sum. The standard deviation for the calculated result, SD_c, is therefore:

$$SD_c = (v_r + v_b)^{0.5}, \text{ where}$$

v_r = the variance of the reported concentration

v_b = the variance of the blank equivalent concentration

The assumption of independent variances is conservative in this case because both blank and field results share common sources of variation in the analysis.

b. Because there is a single blank result for each set of samples, v_b could not be estimated from actual data. The coefficient of variation of 0.059 listed by OSHA for Draft Method ID-215, valid for the range of 0.12 to 0.42 µg/m^3, was used instead. It was assumed that the coefficient of variation remains constant over this range.

c. The coefficient of variation , CV_T, is defined as follows:

$CV_T = SD/y$, where y = the mean of a number of samples

Therefore v_b was estimated:

$$v_b = (y(CV_T))^2$$

Therefore:

$$SD = y(CV_T)$$

3. Calculation of confidence intervals and Upper Tolerance Limits.

a. To define 95% confidence intervals, two-sided upper and lower confidence limits (UCLs and LCLs) were calculated for each set of 3 calculated concentrations at each grid point, and for each set of 9 pooled Q2, R2, and S2 concentrations, using the Student's t variate. The formulas are (Reference 6):

$UCL = y + (t(SD_c)/n^{0.5})$ and $LCL = y - (t(SD_c)/n^{0.5})$, where

y = mean of sample

t for a sample size of 3 and 95% confidence, 2-sided = 3.182

t for a sample size of 9 and 95% confidence, 2-sided = 2.262

n = sample size

b. The one-sided 95%, 95% upper tolerance limit (UTL) was also calculated for each result. The formula is (Reference 7):

$UTL_{95,95} = x + K(SD_c)$, where

K for a sample size of 3, 95% level, 95% confidence = 7.655

K for a sample size of 9, 95% level, 95% confidence = 3.031

c. By observation, the ranges of results at Q2, R2, and S2 for each of the 6830, 2289, and 1493 SCFM ventilation rates overlap each other to the extent that they can be considered to belong to the same population. The three grid points each appear to be plausible locations for workers' breathing zones. The samples for the three grid points at each of the ventilation rates can therefore be pooled to create a sample of nine, which reduces statistical uncertainty.

d. The above calculations were based on the assumption that the sample results follow a normal distribution. Airborne chemical exposures are usually assumed to follow a log-normal distribution for statistical calculation purposes. However, no method for calculating the geometric standard deviation of the calculated sample results, which would be required in order to calculate log-normal UCL, LCL, and $UTL_{95,95}$ results, could be located. The UCL and $UTL_{95,95}$ may be underestimated as a result (Reference 8).

Attachment 3. Air Filter Sampling Results.

EXHAUST FLOW, SCFM	RECIRC. SYSTEM STATUS	RESULT	LOCATION				
			Q2	R2	S2	Q2-R2-S2 Pooled	H1
6830	Off	Estimated concentration, μg/m^3	0.054	0.031	0.033	0.039	0.072
		Estimated standard deviation	0.03736	0.01512	0.04156	0.03159	0.01810
		Upper bound, 95% confidence interval	0.147	0.069	0.136	0.063	0.117
		Lower bound, 95% confidence interval	-0.038	-0.006	-0.071	0.015	0.027
		(95%,95%) Upper Tolerance Limit	0.34	0.15	0.35	0.13	0.21
3263	On	Estimated concentration, μg/m^3	0.045	0.036	UK	NA	0.12
		Estimated standard deviation	0.01658	0.01610			0.01992
		Upper bound, 95% confidence interval	0.086	0.076	UK	NA	0.17
		Lower bound, 95% confidence interval	0.004	-0.004	UK	NA	0.07
		(95%,95%) Upper Tolerance Limit	0.17	0.16	UK	NA	0.27
2249	On	Estimated concentration, μg/m^3	0.25	0.28	0.31	0.28	10
		Estimated standard deviation	0.1518	0.1422	0.1221	0.1238	13.5596
		Upper bound, 95% confidence interval	0.62	0.63	0.62	0.38	44
		Lower bound, 95% confidence interval	-0.13	-0.07	0.01	0.18	-24
		(95%,95%) Upper Tolerance Limit	1.4	1.4	1.2	0.66	110
1493	On	Estimated concentration, μg/m^3	4.6	4.2	5.2	4.7	228
		Estimated standard deviation	0.3606	1.0970	1.0067	0.8903	158.1518
		Upper bound, 95% confidence interval	5.5	6.9	7.7	5.4	621
		Lower bound, 95% confidence interval	3.7	1.5	2.7	4.0	-165
		(95%,95%) Upper Tolerance Limit	7.3	13	13	7.4	1400

Appendix D: Additional Demonstration Images

Figure D1. Electroplating shop area at MCLB Albany.

Figure D2. Chromium electroplating tank (T-100) prior to demonstration.

Figure D3. First stage mesh pad control unit.

Figure D4. Horizontal composite mesh pad control unit.

Figure D5. Blower, Chevron blade unit, and stack at MCLB Albany.

Figure D6. 7.5 HP liquid pump prior to installation.

Figure D7. VVST installed in T-100.

Figure D8. VVST filter/condenser unit and control panels.

Figure D9. VVST gas injector (black piping) and flow control valve (red handle).

Figure D10. Plating arrangement during PLRS demonstration (right side).

Figure D11. ID-215 sampling (PLRS demonstration).

Figure D12. Smoke testing (PLRS demonstration).

Figure D13. Ventilation rate measurement (PLRS demonstration).

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