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Cost Effective VOC Emission Control Strategies for Military, Aerospace, and Industrial Paint Spray Booth Operations: Combining Improved Ventilation Systems with Innovative, Low Cost Emission Control Technologies

Jacqueline Ayer
AIR QUALITY SPECIALISTS
2280 University Drive
Newport Beach, CA 92660

Charles H. Darvin
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park NC 27711

INTRODUCTION

Controlling volatile organic compound (VOC) emissions from spray coating operations has historically been cost prohibitive, due to the high exhaust flow rates coupled with low VOC concentrations. Preliminary studies conducted by the EPA and Air Force indicate that significant emission control cost reductions can be achieved by reducing booth exhaust flow rates. These studies demonstrated that recirculation combined with exhaust flow partitioning can safely achieve a greater than 50% reduction in exhaust flow rates. In a separate study conducted by Pennsylvania State University and the Marine Corps demonstrated that the ultraviolet (UV)/ozone oxidation technology can be adapted to successfully control VOC emissions from paint spray operations. UV/ozone control technology operates at ambient temperature, and achieves very high destruction efficiencies (>95%). Due to the ambient temperature operation, the UV/ozone emission control system has very low associated operating costs and negligible secondary pollutants.

With funding made available through the DOD Strategic Environmental Research and Development Program (SERDP), the EPA's Air and Energy Engineering Research Laboratory (AEERL) and the U.S. Marine Corps Logistics Command launched a full scale split-flow/recirculation and UV/ozone technology demonstration program. The objective of the Demonstration Program is to confirm the viability of coupling split-flow/recirculation ventilation with UV/ozone oxidation to achieve relatively low cost VOC emission control. Under the Program, the exhaust flow rates from three paint booths will be reduced through split-flow/recirculation modification, and vented to a UV/Ozone based VOC emission control system. The Demonstration Program is being conducted at the Marine Corps Logistics Base located in Barstow, CA. Due to the innovative aspects of both the flow reduction strategy and the emission control system, this program has a relatively high profile within the environmental R&D branches of the EPA and the DOD.

This Demonstration Program entails several innovative elements, thus a 3 phase approach was developed and is now being implemented:

- <u>Phase I: Baseline Study</u> - involves full characterization of booth operating conditions, including a VOC/hazardous air pollutant (HAP) emission profile and in-booth hazardous constituent concentration measurements.

- <u>Phase II: Booth Ventilation System Modification and Control System Installation</u> - includes construction of the paint booth split-flow/recirculation ventilation systems, safety interlock controls, booth operating equipment, and the UV/ozone VOC emission control system.

- <u>Phase III: System Validation Study</u> - demonstrates split-flow/recirculation system operation, and adequate VOC destruction efficiency by the UV/ozone emission control system.

The Phase I Baseline Study efforts were completed in March, 1994. Phase II Booth Ventilation System Modifications are scheduled for completion in July, 1995. **The Phase I results indicate that the booth exhaust flow rates will be safely reduced by 60% from 114,000 cfm to less than 44,000 cfm through split-flow/ recirculation ventilation.** The Phase III demonstration will be completed in the Fall of 1995.

This paper discusses general flow reduction strategies and recirculation system enhancements achieved through split-flow/recirculation system optimization. This discussion is followed by a description of the Baseline (Phase I) field study results and a summary of the key engineering and safety issues that were addressed in the booth modification/construction designs to ensure safe operation of the split-flow/recirculation ventilation system. The paper further presents and discusses the UV/ozone oxidation technology, and its adaptation to controlling air stream emissions of VOCs. Finally, a discussion of the viability of adopting split-flow/recirculation in many industrial, aerospace, and military coating operations is also presented.

SPLIT-FLOW/RECIRCULATION VENTILATION - WHAT IS IT?

General Discussion of Exhaust Flow Reduction Via Recirculation

Most paint booths currently in use operate in a "single-pass" mode in which the ventilation air passes through the booth and is exhausted to the atmosphere or to a downstream air pollution control system (APCS). The single-pass mode of operation generates high exhaust air flow rates containing very low solvent concentrations; under these conditions, controlling VOC emissions is generally cost prohibitive. By implementing a flow reduction strategy that is appropriate to the particular operation of the booth, emission control costs are significantly reduced. This is because a typical APCS is sized based on the volumetric flow rate that must be processed; by reducing the flow rate, the control system size is reduced accordingly. This in turn reduces both the APCS capital and operating costs.

The simplest method for reducing paint booth exhaust flow rates is to install a return air system which recirculates a portion of the exhaust air back into the booth (Figure 1). The portion that is not recirculated is vented to an emission control system. Prior to re-entering the booth, the recirculated stream is mixed with fresh make-up air that is required to replace the exhaust stream vented to the control device. The hazardous constituent concentration present in the recirculated stream is dictated by the percent recirculation that is employed, and the material release rate in the booth during painting. The flow reduction that is achieved by recirculation depends directly on the percent recirculated.

In 1990, the Federal Occupational Safety and Health Administration (OSHA) determined that paint booth recirculation was a viable alternative for reducing paint booth exhaust flow rates, provided that hazardous constituent concentrations in the booth intake stream remain below established safety limits. The key, therefore, to designing a safe and effective recirculation stream is to maximize the percent recirculation while ensuring that constituent concentrations remain below acceptable levels.

Enhancing Recirculation by Split-Flow Optimization

In simple recirculation, the hazardous constituent concentrations present in the controlled and recirculated exhaust streams are the same. Recirculation can be further enhanced by designing the ventilation system such that the hazardous constituent concentration in the controlled stream is greater than in the recirculated stream. Under these conditions, the recirculation rate can be further increased, and the exhaust flow rate vented to an APCS is proportionally reduced. EPA research conducted in 1990 suggests that a concentration gradient occurs at the exhaust face of typical paint booths. An optimal flow reduction strategy takes advantage of this stratification to cause a higher constituent concentration in the controlled stream. This is accomplished by "splitting" the exhaust flow into two streams at the booth exhaust face (Figure 2). By recirculating only exhaust air drawn from booth zone(s) containing relatively low constituent concentrations, the flow reduction percentage can be increased beyond that achieved with simple recirculation. Correspondingly, the volume flow rate of the controlled stream is reduced by drawing air only from booth zone(s) having relatively high concentrations.

Split-Flow Recirculation System Design Considerations

The location of the partition, or split, dictates the volumetric flow rate of the partitioned streams, and therefore determines the actual recirculation rate. The split location is derived iteratively from a mass balance equation developed based on a number of factors, including booth configuration, coating components and usage rates, and OSHA hazardous constituent exposure levels. For a booth with a flow partition oriented horizontally, the mass balance equation reduces to:

$$C_i = \frac{M_i \times X_i}{Q_b \times (\frac{a}{H})} \qquad \text{Equation } \mathbf{(1)}$$

Where

C_i = Concentration of compound *I* in the recirculated stream as it exits the booth downstream of the particulate filtration system.
M_i = Mass release rate of compound *I*
X_i = Percent of total mass of compound *I* located above the partition height
Q_b = Booth volumetric flow rate
a = Partition height
H = Booth exhaust face height

When employing this equation, it must be recognized that the particulate filtration efficiency should be applied to the variable M_i for solid phase constituents such as chromium. Furthermore, the parameter X_i is derived from an understanding of the concentration profile of compound *I* at the exhaust face immediately upstream of the split partition. To establish this parameter accurately, it must be recognized that paint overspray is composed of both solid and vapor phase components, and that these components react to gravity accordingly. Solid phase components are found at a lower elevation than vapor phase components; therefore, the parameter X_{isolid} may differ significantly from X_{ivapor}.

The significant design criteria for a safe and efficient recirculation system are based on understanding that the total hazardous constituent concentration in the recirculated stream must remain below safe exposure limits. Moreover, OSHA has established that, for flows containing a mixture of hazardous compounds (such as occurs in paint booth recirculation streams), the additive health effects of each compound must be considered. Under these conditions, the governing equation is:

$$\sum \frac{C_i}{PEL_i} \leq 1 \qquad \text{Equation (2)}$$

Where:

C_i = Concentration of compound I in the recirculated stream
PEL_i = OSHA established 8-hour time weighted average Permissible Exposure Level for compound I

The optimal split height may be determined iteratively by considering both Equations 1 and 2. The concentration value of each constituent that is derived from Equation 1 is input into Equation 2 to determine if the split height assumed in Equation 1 will yield sufficiently low concentrations to ensure compliance with OSHA regulations. This analytical procedure was employed to derive the Phase I results, and incorporated into the Phase II Design.

PHASE I RESULTS

Test Results and Projected Volumetric Flow Reduction

The paint booths targeted for this Program employ standard military specification chemically resistant coatings such as wash primers (DOD-P-15328), epoxy primers (MIL-P-53030), and topcoats (MIL-C-53039). Some of the components contained in these coatings are classified as potentially hazardous by OSHA; therefore, the Baseline Study focussed particularly on these compounds. A detailed field study was conducted to obtain the information necessary to derive the optimal split location for each of the three paint booths included in this study. Key data collected include:

- Coating usage rates.

- Concentration profiles of hazardous constituents at the exhaust face upstream of the particulate filtration system; profiles for both solid phase (metals and solid phase isocyanates) and vapor phase (VOC) constituents were developed. These data provided information pertaining to constituent stratification at the booth exhaust face.

- Organic and inorganic (i.e., chromium and other metals) hazardous constituent concentrations downstream of the particulate filtration system.

- Filtration efficiency test results to identify the particulate filtration system with the highest collection efficiency for the coatings and spray equipment particular to the booths studied.

These data were combined to derive the optimal split height, and therefore the volumetric exhaust flow rate to the emission control system for each of the three booths included in the study. Table 1 summarizes the projected flow rate reductions achieved for each booth. To accommodate the workpiece throughput requirements at the Barstow Marine Corps Logistics Base, it was decided that Booths 2 and 3 would operate sequentially; i.e., Booths 2 and 3 would never operate simultaneously. This further reduces the volumetric flow rate vented to the APCS. From the results summarized in Table 1, it is clear that a significant reduction in exhaust flow rates will be achieved for all three booths through the implementation of split-flow/ recirculation. The total volumetric flow rate from all three booths dropped from 114,000 cfm of uncontrolled exhaust to less than 44,000 cfm of controlled exhaust.

Booth Modification Design Criteria and Considerations

Designs for the booth modifications combine several elements that are critical to ensuring safe and continuous operation of the split-flow/recirculation paint spray booths. These include:

- A safety interlock system employing a continuous monitor in the recirculation stream to ensure that constituent concentrations present in the booth intake air remain below defined safety levels.

- Variable frequency drives on the fans coupled with flow monitors to ensure that the flow rate through the booth remains constant, even if the particulate filtration system is at capacity.

- Other interlocks to ensure that the booths are not used unless the APCS is on-line and fully operational.

- The use of high efficiency particulate filters to ensure maximum removal of paint overspray particulate, especially hexavalent chromium containing particulate generated from the use of military specification wash primers.

- Provisions for a time delay in booth fan start-up and shut-down procedures to ensure that the exhaust flow rate from each booth matches the APCS fan operation as booth fans are turned on and off throughout the day. This ensures complete coordination between the booths and the APCS.

- Variability in the split-height to allow for optimization of this parameter during the System Validation (Phase III) activities. After Phase III is completed, the split-heights will be locked into place.

These and other design considerations were incorporated in the final booth modification specifications so that simple and safe operation are ensured. In addition, the operating requirements for each booth were developed in concert with staff from the Barstow Marine Corps Logistics Base so that booth operators would have a thorough understanding of booth modifications and operating procedures.

UV/OZONE BASED AIR POLLUTION CONTROL SYSTEMS

The UV/ozone technology relies on the use of ultraviolet (UV) light in combination with ozone to completely oxidize organic contaminants present in process streams. The organic compounds are oxidized either through direct photolysis (absorption of the UV light), or through excitation and decomposition via contact with ozone and hydroxyl radicals that are generated from UV/ozone interaction. UV/ozone oxidation is commonly used in the waste water treatment industry to eliminate most organic and even some inorganic compounds in waste water effluent. It is also frequently employed in drinking water purification systems to remove contamination. In the latter half of the 1980's a new application for UV/ozone oxidation was pioneered with the development of the first ambient temperature oxidative APCS. Pilot-scale and full-scale systems successfully demonstrate destruction efficiencies of up to 95%, even under conditions of low VOC concentrations coupled with high flow rates.

Advantages of UV/Ozone Based Air Pollution Control Systems Over Standard Technologies

There are a number of inherent advantages of a UV/ozone based emission control system over standard technologies such as thermal or catalytic oxidation and carbon adsorption. These advantages include:

- Ambient temperature operation; this eliminates losses incurred by thermal oxidation systems in heating up the entire exhaust flow to the requisite oxidation temperature.
- Virtually no start-up time; the system goes from "off" to fully operational in less than 5 minutes.
- A destruction efficiency in excess of 95%, even under conditions of high volumetric flow rate coupled with low VOC concentrations.
- No secondary pollutant emissions such as nitrogen oxides (NO_x), carbon monoxide (CO), and products of incomplete combustion (PICs) of natural gas
- Virtually no waste stream generation, unlike carbon adsorption or other adsorption based systems.
- Long equipment life cycles, due to ambient temperature operation.
- Complete oxidation of most organic constituents, including chlorinated and heavy (7+ carbon) organic compounds.
- Moderate installation costs, and extremely low operating costs.
- Remote terminal unit (RTU) operation, which offers full system monitoring and control capabilities.

These advantages make UV/ozone based systems an attractive alternative for VOC emission control, and were a driving factor in the decision made by the Marine Corps to pursue further research and technology development. The research focusses on optimizing various system design considerations such as lamp number and location. The research will also confirm the ability of the UV/Ozone technology to oxidize the entire spectrum of organic compounds present in military coatings.

UV/Ozone Air Pollution Control System Operation

A schematic diagram illustrating the UV/Ozone Air Pollution Control System is provided in Figure 3. The contaminated exhaust air is directed through a multistage filter to remove any solid pollutants that are present. The exhaust air stream is then vented to a wet scrubber, where the water soluble and miscible contaminants present in the air stream are collected and oxidized. In the scrubber module, the air stream is mixed with ozone saturated water to achieve oxidation. The scrubber water passes through an ozone contact tower to replenish the levels of ozone and hydroxyl radicals, and is then recirculated to the scrubber. The non-soluble components present in the air stream that are not removed by the scrubber are collected on a carbon adsorption module. Ozone is continuously injected into the carbon adsorption module for in-situ oxidation of the adsorbed organics.

The UV/ozone APCS is fully automated; therefore, facility operator maintenance and oversight is virtually eliminated. For this Demonstration Program, the UV/ozone APCS will be equipped with intake and exhaust stack organic monitoring systems that continuously monitor and record organic concentrations. The data are recorded in a convenient format to allow efficient downloading, storage, and transmittal via modem to interested parties. The monitoring data collection and download system is fully automated, thus operating and maintenance requirements are minimized. In addition, a remote terminal unit (RTU) is included to provide full access to current system data and booth operating information such as volumetric flow rates and exhaust concentrations. The data are accessed through user friendly menu driven programs to ensure simple operation.

The computer based processing unit that controls the UV/ozone APCS operation may also be programmed and fully integrated with the operation of the three paint booths modified for this Demonstration Program. The advantages of employing this central control option are many: it can interlock the ventilation system to ensure that the UV/ozone system start-up sequence is initiated the instant that any paint booth is turned on, as well as ensure that the booths are not operated without the APCS being on line.

ADAPTATION OF THE SPLIT-FLOW/RECIRCULATION TECHNOLOGY TO AEROSPACE AND OTHER INDUSTRIAL COATING OPERATIONS.

Most spray coating operations can be retrofit with split-flow/recirculation ventilation to reduce the cost of controlling VOC emissions, whether vented to a conventional or more advanced APCS. Because split-flow/recirculation is a ventilation technology that operates separately from the APCS, it is compatible with all emission control systems. The degree of flow reduction that can be achieved is a function of many parameters, as described previously. For example, the flow rate reduction that may be achieved for large hangar operations in which two or three paint stations are used and from which 250,000 cfm is exhausted could be 80% or more. The flow reduction that may be realized by smaller operations may not be quite so dramatic, but even a 20% reduction in exhaust flow rates will translate to significant savings when installing an APCS. In general, the cost of installing the split-flow/recirculation system is a fraction of the incremental cost savings realized on the APCS.

It should also be recognized that the decision to convert to split-flow/recirculation operation is not necessarily driven by concerns relating to environmental regulations. Employing split-flow/recirculation can eliminate a tremendous load on standard heating, ventilation, and air-conditioning (HVAC) systems by reducing the volume of air requiring conditioning prior to entering the booth. This may be a critical concern to facilities located in seasonally harsh environments such as Minnesota in the winter, or Arizona in the summer.

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Table 1. Summary of projected volumetric flow rate reductions for Barstow Marine Corps Logistics Base paint booths targeted by the Program[a].

Booth	Initial exhaust flow rate (cfm)	Final exhaust flow rate vented to control device (cfm)	Flow reduction achieved (%)
1	55,000	23,000	58
2	59,000	21,000	64
3	22,000	14,500	34

[a] Booths 2 and 3 are never operated simultaneously, thus the highest flow rate processed through the control device is 23,000 + 21,000 = 44,000 cfm.

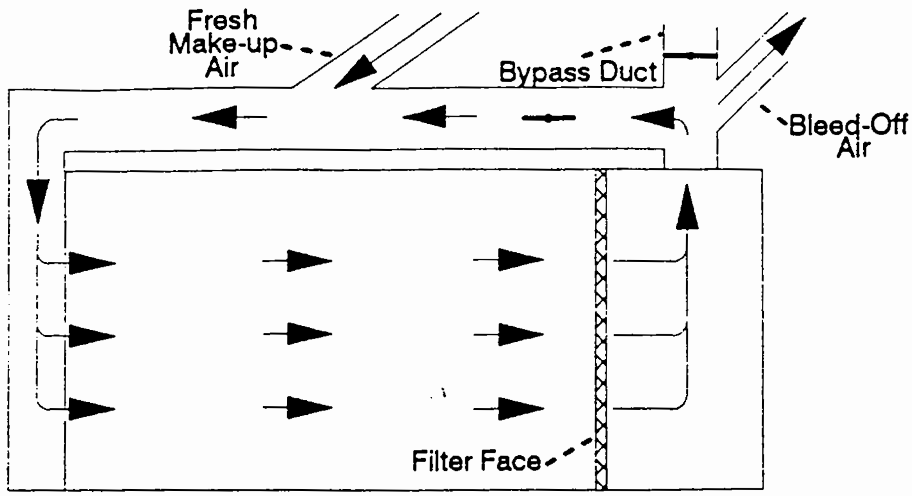

Figure 1. Schematic Diagram Illustrating Simple Recirculation Ventilation

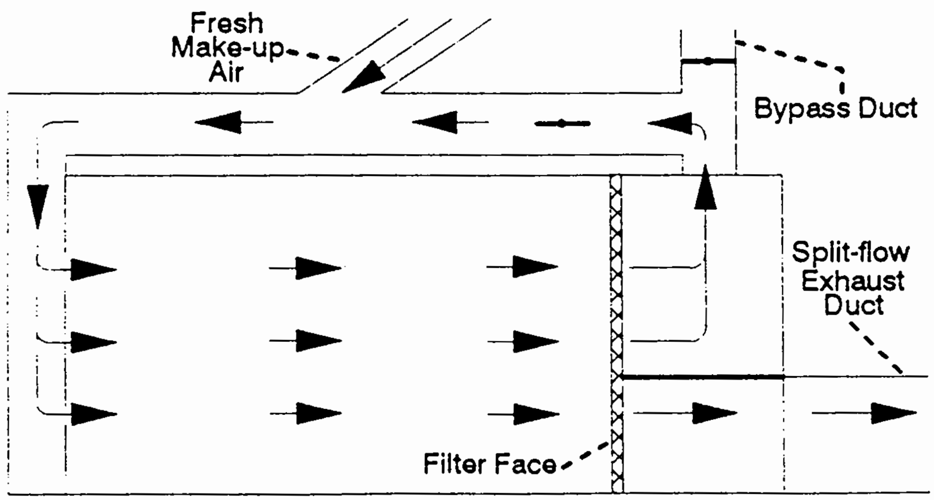

Figure 2. Schematic Diagram Illustrating Enhanced Recirculation Via Split-Flow Partitioning (Split-Flow Recirculation)

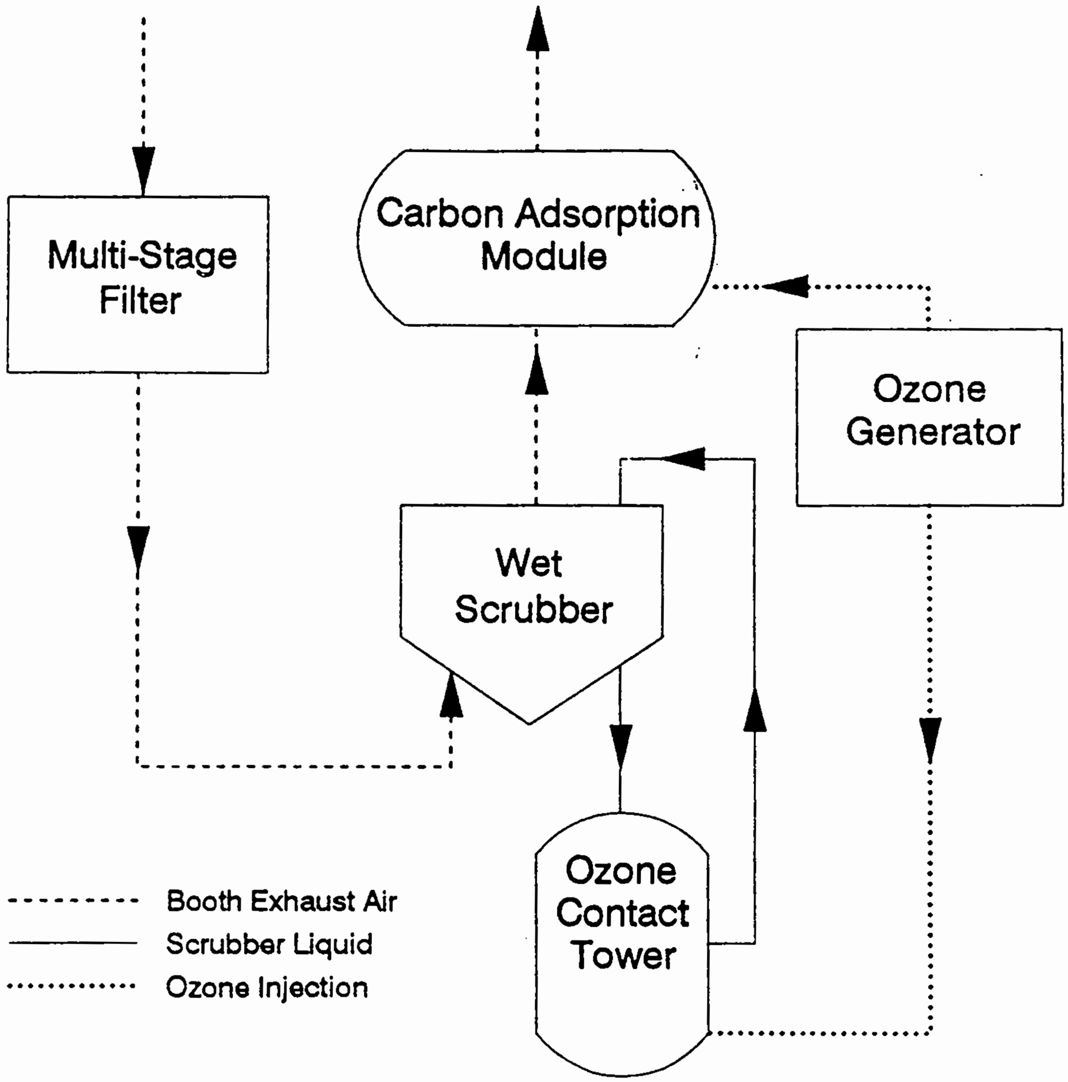

Figure 3. Schematic Diagram Illustrating UV/Ozone APCS Operation

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16. ABSTRACT The paper describes a full-scale demonstration program in which several paint booths were modified for recirculation ventilation; the booth exhaust streams are vented to an innovative volatile organic compound (VOC) emission control system having extremely low operating costs. (NOTE: Controlling emissions from spray coating operations has historically been cost prohibitive, due to high exhaust flow rates coupled with low VOC and hazardous air pollutant (HAP) concentrations. Preliminary studies indicate that significant emission control cost reductions are achievable by reducing booth exhaust flow rates; these studies demonstrated that recirculation combined with exhaust flow partitioning can safely acieve a >50% reduction in exhaust flow rates.) The booth exhaust flow rates were safely reduced from 114,000 to 44,000 cfm. The program involved: (1) a baseline study, involving full characterization of booth operating conditions including a VOC/HAP emission and in-booth constituent stratification profile, and operator hazardous exposure assessments for all booths; (2) booth ventilation system modification, including construction of recirculation/partition ventilation systems, safety interlock controls, booth operating equipment, and the VOC control system; and (3) a post-conversion study to demonstrate safe recirculation system operation and adequate destruction efficiency.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Toxicity	Pollution Control	13B	06T
Spray Painting		Stationary Sources	13H	
Emission		Paint Spray Booths	14G	
Ventilation		Volatile Organic Compounds (VOCs)	13A	
Organic Compounds			07C	
Volatility		Hazardous Air Pollutants (HAPs)	20M	

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