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Paint Spray Booth Design Using Recirculation/Partitioning Ventilation

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Many spray painting facility operators have been attempting to reduce the discharge of volatile organic compounds (VOCs) from paint spray booths to the atmosphere. Some have been able to convert to lower VOC containing paints and coatings such as powder coating, waterborne coating, and radiation cured coatings. However, because of the functional requirements of some painted surfaces, acceptable low polluting paints may not be available. Thus, these operations must continue to use higher polluting paint formulations.

The control of emissions from paint booths has been considered not economically viable due to the cost of treating the high volume of polluted air exhausted from these sources. However, studies conducted by EPA with various Department of Defense (DoD) services have demonstrated that the cost of typical spray booth control can be significantly reduced through the use of spray booth recirculation. Reductions of exhaust flow rates of up to 90 percent, when using recirculation, have been achieved in properly designed and operated booths without concern for the industrial hygiene or fire safety issues often mentioned when discussing recirculating booths. This paper presents the results of the design and demonstration program for a full scale recirculating spray paint booth installed and operated at the U. S. Marine Corps (USMC), Marine Corps Logistics Bases (MCLB) facility at Barstow, CA. It also summarizes the regulatory and safety design issues of recirculation spray booths.

BACKGROUND

The recirculating spray paint booth concept operates by venting a portion of the exhaust, via a bleed-off stream to a control system. The remaining exhaust air is returned to the booth after mixing with fresh air equal to the bleed-off stream volume. Figure 1 is a schematic of a recirculation ventilation spray booth exhaust scheme. In 1981, the John Deere Company patented a spray booth concept using recirculation [1]. That recirculating design discharged the exhaust stream to hot water heater burners to be used as combustion air, thus destroying the VOC content of the exhausted gases.

The use of air recirculation in spray booths has two major benefits. First, by reducing the exhaust volume significant savings in energy needed for conditioning (heating and cooling) the booth and in some cases facility air, can be realized. Second, both the capital and operating cost of the emissions control technology used to control the booth emissions can be reduced. Unfortunately, even with these known benefits, recirculation has not been widely accepted as a booth design option due to misinterpretation of Occupational Safety and Health Administration (OSHA) regulations and the pre-1985 National Fire Protection Association (NFPA) code prohibiting recirculation of air from a paint spray booth [2,3].

In 1988, a series of studies were initiated by the U.S. Air Force (USAF) and EPA to characterize the booth environment and emissions. The objectives of the studies were to dispel the safety concerns on the use of recirculation. The studies were conducted at Hill Air Force Base (AFB), UT, and Travis AFB, CA. Using multiple sampling systems, the booth environments were sampled along their lengths, heights, and widths to define the average concentrations in the various regions of the booths during operation. The conclusions from those studies indicated that recirculation can be employed as a method to reduce exhaust flow rates from spray booths without exceeding the exposure limits as defined by OSHA [4,5,6]. In addition, the studies also suggested a unique phenomenon in the exhaust flow patterns within and from the spray booths. A concentration gradient at the exhaust face was formed as the pollutant flowed from the booth with the concentration relatively high at the lower region of the booths and decreasing toward the ceiling.

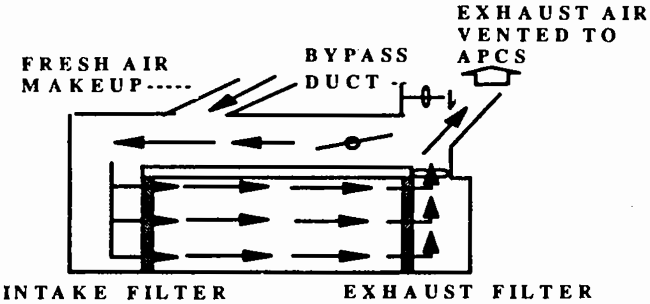

Figure 1. Exhaust Recirculation Spray Booth Ventilation

The evaporated solvents typically used in paints include: toluene, m,p,o-xylene, methyl isobutyl ketone, n-butyl alcohol, ethyl benzene, and butyl acetate. Common paint solvents have specific gravities greater than air which results in a tendency to settle to the floor of the booth. In addition, the average flow rate through a spray booth to comply with OSHA will be at least 1.8 km/h for conventional spray booths and 1.08 km/h for booths using electrostatic painting equipment [7]. The chemical and physical properties of the pollutants in the exhaust and the relatively slow air movement in the booth result in the formation of a region of high pollutant concentration in the lower levels of the booth. Thus, by taking advantage of this phenomenon, it was speculated that the basic spray booth recirculation design (Figure 1) could be further enhanced by partitioning (dividing) the exhaust into two streams and allowing the removal of a large percentage of the total pollutant volume in a smaller exhaust stream from the lower region of the booth. Figure 2 is a conceptual schematic of the recirculating/partitioned paint spray booth defined from the results of those studies.

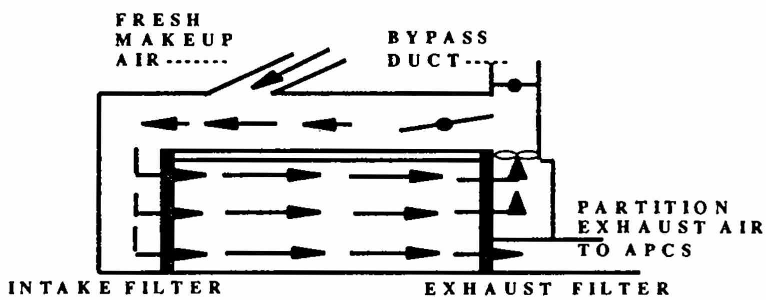

Figure 2. Recirculation/Partitioned Spray Booth Ventilation

The Impact of Codes and Regulations On Spray Booth Design

The design and operation of paint spray booths is governed by codes and regulations established by consensus organizations and the various State and Federal regulatory agencies. They include OSHA, NFPA, and the American Conference of Governmental Industrial Hygienists (ACGIH). The pre-1985 NFPA 33 Standard for Spray Painting Using Flammable and Combustible Materials prohibited the use of recirculation in paint spray booths [3]. This prohibition was incorporated into the OSHA regulation and applied to industrial hygiene safety. However, the original intention of the code was to prevent the formation of concentrations approaching the explosive level of VOCs and was due primarily to the lack of reliable and accurate monitoring equipment to ensure that VOC concentrations in the booth and exhaust did not exceed the 25 percent lower explosive limit (LEL) for the volatile constituents. In 1985, the NFPA code was revised to permit recirculation and includes strict provisions for monitoring and controlling air movement in the booth.

The volatile concentration needed to support combustion, however, is several orders of magnitude higher than the concentration found in typical spray booths even when operating in a recirculating mode. Thus, the deciding factor and the most important design criterion for a manned recirculating booth atmosphere is not whether the booth will reach 25 percent LEL, but will the booth atmosphere approach the established personnel exposure limits (PELs) as defined in OSHA 29 CFR Part 1910, subpart z Toxics and Hazardous Substances [8]. Similar limits are also recommended by ACGIH guidelines. In

1989, OSHA issued a policy directive accepting the use of recirculation in spray booths when operated under the established PEL [9]. In 1992, ACGIH concurred on the use of recirculation in spray booths when designed and used properly. The procudure is presented in the ACGIH Manual of Recommended Practice [10].

Recirculating/Partitioned Booths Demonstration at USMC Facility, Barstow, CA

In 1993, a joint demonstration project sponsored by the Strategic Environmental Research and Development Program (SERDP) was initiated by the EPA and the USMC. The objectives of the program were to define the degree of exhaust flow reduction that can be achieved by dividing a booth's exhaust stream into two flows, or partitioning the booth: one stream a rich pollutant stream, and the other a lean stream, recirculated back to the booth. The study of the recirculation/partitioning design would permit an evaluation of the impact of the design on industrial hygiene safety within the booth. The demonstration included three modified booths, and an end-of-pipe control system processing exhaust from all three booths. Each booth used the partitioned design concept shown in Figure 3 which allowed for the removal of the greatest volume of pollutant in the least volume of air exhausted. Table 1 presents each demonstration booth's dimensions.

Table 1. Demonstration spray booth dimensions

Booth No.	Depth, m	Width, m	Height, m	Partition Height, m
1	18.2	6.1	5.5	2.7
2	6.1	9.1	3.0	2.0
3	3.0	6.7	3.0	2.0

Booth Design

Operator safety is the paramount consideration in the design and operation of a manual recirculating spray booth. The pollutant concentration limits that drive the spray booth design are codified in OSHA 29 CFR 1910.1000 and OSHA 29 CFR 1910.107 which govern booth ventilation and worker exposure requirements [8,2]. The ACGIH threshold limit values (TLVs) can also be used since they are typically more conservative than OSHA PELs. The demonstration booths at the Barstow facility used the TLV limits which resulted in a somewhat higher exhaust flow rate than would be used if the PELs are used for each compound. Based on the PEL or TLV values which limit the allowable toxic pollutant concentraion in the recirculating stream, the booth design and partition heights were determined.

To determine the most efficient booth partition height, a mass balance is developed around Figure 2. The equations assume steady state booth operation, which will result in the most conservative (worst case) results. The mass balance is defined by:

$$q_r c_r + q_m c_m = q_b c_b \tag{1}$$

where:

q_r = volume flow rate of recirculated air
c_r = hazardous constituent concentration in recirculated air
q_m = volume flow rate of fresh makeup air
c_m = hazardous constituent concentration in fresh makeup air
q_b = volume flow rate through paint booth
c_b = hazardous constituent concentrations in air upstream of painter location

Since it can be assumed that the booth makeup air is free of hazardous constituents, Equation (1) at the booth inlet becomes:

$$q_r c_r = q_b c_b \tag{2}$$

The mass balance equation at the booth exhaust face is defined as:

$$q_b c_b + m_g = q_r c_r + q_e c_e \tag{3}$$

where :

m_g = hazardous constituent mass generation rate from paint application process
q_e = volume flow rate of exhaust air vented to the air pollutant control system (APCS)
c_e = hazardous constituent concentrations in exhaust air vented to the APCS

The left side of Equation (3) represents the mass flow rate at the booth intake face plus the mass of pollutant generated by the spray gun in the booth during painting. The right side of Equation (3) defines the mass flow rate exiting the booth into the recirculation duct and the exhaust duct, respectively. Based on previous studies of spray booth exhaust characteristics, the exhaust concentration profile is not uniform across the exhaust face, and forms a non-linear decreasing concentration gradient from the bottom to the top of the exhaust filter face [5,6]. Figure 3 shows the general concentration profile at the exhaust face. The shaded area of Figure 3 represents the pollutant mass that enters the exhaust duct at the exhaust face below the partition height s.

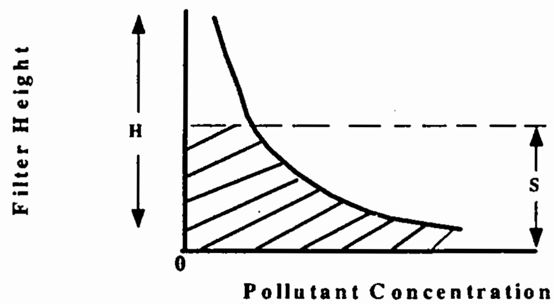

Figure 3. Total VOC Concentration Profile at the Exhaust Face

It is possible; therefore, to take advantage of this profile by strategically locating the exhaust duct to the APCS. The location of the flow partition is determined experimentally by testing and developing a concentration profile of the exhaust face of the booth. Thus, an additional element is added to Equation (3) that defines the impact of the partitioning of the booth flow to the recirculation and exhaust ducts. When incorporated into Equation (3), it locates the exhaust duct and correlates the pollutant mass flow rate to the exhaust stream at the exhaust face. That relationship is defined by:

$$q_e c_e = m_g(1 - X) + c_b q_b(s/H) \quad (4)$$

where:

X = percent of hazardous constituents generation in the booth exiting above height s.
s = partition height
H = exhaust filter height

Substituting Equation (4) into Equation (3) yields:

$$q_r\, c_r = q_b\, c_b\, (1 - s/H) + m_g\, X \quad (5)$$

The $q_b\ c_b(1 - s/H)$ term in Equation (5) represents the hazardous constituent mass flow rate in the recirculation stream that is reintroduced at the intake face. The third term in Equation (4) represents the mass of pollutant that is introduced into the recirculation duct by the painting operation. The mathematical expression that defines the relationship between the constituent concentrations in the recirculation stream and the partition height therefore becomes:

$$c_r = (m_g\ X) / q_r\ (s/H) \quad (6)$$

The partition height and corresponding recirculation rate that yield acceptable hazardous constituent concentrations in the booth intake stream may then be derived iteratively from Equation (6).

RESULTS AND CONCLUSIONS

The spray booth installations at the Barstow facility met all operating and safety design requirements projected at the beginning of the program. Continuous monitoring and discrete testing of the booth operation and exhaust were conducted over a 1 month period to confirm that predicted recirculation and exhaust stream concentrations levels were achieved. First, the pollutant concentrations within each booth were not significantly increased with the use of recirculation. There was no apparent degradation in booth atmosphere compared to pre-modification levels. It was found that the resulting flow patterns in the modified booths improved the overall atmosphere of the booth. Second, test results for each booth validated the presence of a pollutant concentration gradient as found in previous studies. For example, Figures 4 and 5 below show the metal and organic mass distribution at the exhaust face. The pollutant mass is primarily concentrated at the lower region of the booth. The concentration gradient is important for maximizing the amount of pollutant exiting the booth in the partitioned stream to the APCS, thus achieving the flow reduction capability of the design. In figures 4 and 5, over 70 percent of the of the generated pollutant exits the booth at or below the 9 foot (2.7 meter) level of the 18 foot (5.5 meter) high exhaust filter. Table 2 presents a summary of the flow reductions achieved with the new or modified booths.

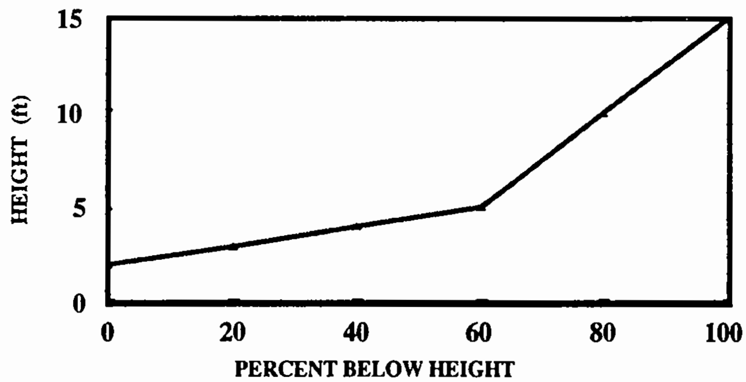

Figure 4. Cumulative Distribution of Metals at Various Heights in Booth 1.

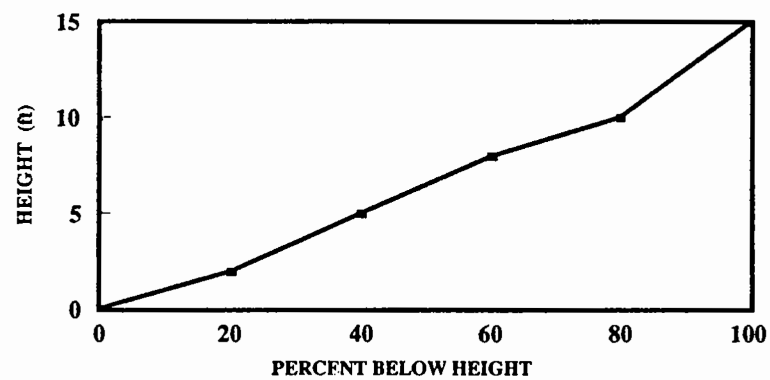

Figure 5. Cumulative Distribution of Organic Mass at Various Heights in Booth 1.

Table 2. Summary of volumetric flow rate reduction achieved at Marine Corps Logistics Bases paint booths.

Booth No.	Initial Exhaust Flow Rates m^3/min	Projected Exhaust Flow Rates m^3/min	Final Exhaust Flow Rates to APCS m^3/min	Percent Exhaust Flow Reduction to APCS
1	1,500	566	572	62
2	1,783	580	604	66
3	778	393	415	47
Total	4,061	1,539	1,591	61

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16. ABSTRACT The paper gives results of a design and demonstration program for a full-scale recirculating spray paint booth installed and operated at the U.S. Marine Corps, Marine Corps Logistics Bases facility at Barstow, CA. It also summarizes the regulatory and safety design issues of recirculation spray booths. The control of emissions from paint booths has been considered to be not economically viable due to the cost of treating the high volume of polluted air exhausted from these sources. However, studies conducted by EPA with various Department of Defense services have demonstrated that the cost of typical spray booth control can be reduced significantly through the use of spray booth recirculation. Reductions of exhaust flow rates of up to 90% when using recirculation have been achieved in properly designed and operated booths without the industrial hygiene and fire safety problems often mentioned when discussing recirculating booths.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Ventilation	Spray Booths	13A
Emission	Recirculation/Partition-ing	14G

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