Paint Spray Booth Design Using Recirculation/Partitioning Ventilation

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Many spray painting facility operators have been under pressure to reduce the discharge of volatile organic compounds (VOC) emissions to the atmosphere. Some operators have been able to convert their operations to lower VOC containing paints and coatings such as waterborne coatings, radiation cured coatings. However, because of the functional requirements for some painted surfaces, acceptable paints with low VOC content may not be available. Consequently, these manufacturers may require the continued use of the higher VOC content 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. Studies conducted by EPA with various Department of Defense (DoD) services, however, have demonstrated that the cost associated with typical spray booth control system can be significantly reduced through the use of spray booth recirculation. Reductions of exhaust flow rates of up to 90 percent may be possible when using recirculation 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 of full scale recirculating spray paint booths installed and operated at the U.S. Marine Corps (USMC), Marine Corp Logistics Base (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 only 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 shows 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 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 system used to control the booth emissions can be reduced. Unfortunately, even with these known benefits, recirculation was not 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 the EPA to characterize the booth environment and emissions. The objectives of the studies were to develop safety con-
cerns regarding 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 painting operations. 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 toxic compound 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. It was found that 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.

The evaporated solvents typically used in paints include: toluene, m,p-xylene, MEK, n-butyl alcohol, ethyl benzene, and butyl acetate. It was speculated that common paint solvents each have specific gravities greater than air which results in a tendency for them to settle to the floor of the booth. In addition, the average flow rate through a typical spray booth to comply with OSHA will be at least 1.58 cubic feet per minute (CFM) for conventional spray booths and 0.98 CFM for booths using electrostatic painting equipment [7]. Thus, combining the chemical and physical properties of the pollutants in the exhaust and the relatively slow air movement in the booth results in the formation of a region of high pollutant concentration in the lower levels of the booth. By taking advantage of this phenomenon, it was further 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. This could result in a relatively lower average pollutant concentration in the recirculated stream and a correspondingly higher concentration in the smaller exhaust stream. Thus, more pollutant can be removed from the booth in the exhaust stream in a smaller exhaust volume. Figure 2 presents a conceptual schematic of the recirculating/partitioned paint spray booth designed from the results of those studies.

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 35 Spray Painting Using Flammable or Combustible Materials prohibited the use of recirculation in paint spray booths [5]. 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 combustible solvent concentrations approaching the explosive level of the contained VOCs. It 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 LEL for the volatile constituents. In 1985, the NFPA code was revised to permit recirculation and included strict provisions for exhaust monitoring and control of air movement in the booth.

The volatile concentration needed to support combustion 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 recirculated rebooth atmosphere is not whether the booth will reach 25 percent LEL, but will the booth atmosphere approach the established permissible exposure limits (PELs) as defined in OSHA 29 CFR Part 1910 Subpart Z Toxic and Hazardous Substances [8]. Similar limits are also recommended by ACGIH guidelines. In 1989, OSHA issued a policy directive sanctioning 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 and 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 by partitioning the booth into 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 by further lowering the pollutant concentration in the recirculated stream. 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 2 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.

Booth Design

Operative 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 [2,8]. The ACGIH threshold limit values (TLV) can also be used to develop booth design and operating limits since they are typically more conservative than OSHA PELs. The demonstration booths at the

![Figure 2. Recirculating/Partitioned Spray Booth Ventilation.](image-url)
Table 1. Demonstration spray booth dimensions

<table>
<thead>
<tr>
<th>Booth No.</th>
<th>Depth, m</th>
<th>Width, m</th>
<th>Height, m</th>
<th>Partition Height, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.2</td>
<td>6.1</td>
<td>5.5</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>6.1</td>
<td>9.1</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>3.6</td>
<td>6.7</td>
<td>3.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Barsow 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 most restrictive PEL or TLV values which limit the allowable toxic pollutant concentration 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:

$$q_c c_r + q_m c_m = q_b c_b$$  \(1\)

where:
- $q_c$ = 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 paint location

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

$$q_c c_r = q_b c_b$$  \(2\)

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

$$q_b c_b + m_g = q_c c_r + q_c c_r$$  \(3\)

where:
- $m_g$ = hazardous constituent mass generation rate from paint application process
- $q_b$ = volume flow rate of exhaust air vented to the air pollutant control system (APCS)
- $c_r$ = 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 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. The exhaust profiles remain the same for both conventional and recirculated booth operation. The additional element that defines the impact of the partitioning on the booth flow to the recirculation and exhaust ducts is added to Equation (3). 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:

$$q_c c_r = m_g (1 - X) + c_b q_b (s / H)$$  \(4\)

where:
- $X$ = percent of hazardous constituents generation in the booth exiting above height $a$
- $s$ = partition height
- $H$ = exhaust filter height

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

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

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 in Figure 2. 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:

$$c_r = (m_g X) / q_b x (s / H)$$  \(6\)

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

Continuous monitoring and discrete testing of the booth operation and exhaust were conducted over a one month period to confirm that the predicted recirculation and exhaust stream concentration levels were achieved. The spray booth installations at the Barrow facility met all operating and safety design requirements projected at the beginning of the program.

First, the pollutant concentrations within each booth was 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 the pollutant concentration gradient as found in previous studies. For example, Figures 4 and 5 show the characteristic particle solids and organic VOC pollutant distributions, respectively, at the exhaust face for booth 1. As shown, pollutant masses are primarily concentrated at the lower region of the booth. The presence of the concentration gradient in the booths, allows the partition design to minimize the amount of pollutant exiting the booth in the exhaust stream to the APCS, thus achieving the flow reduction capability of the design. Simultaneously, the pollutant discharged from the booth to the recirculating stream is minimized and maintained at an acceptable level.

In Figures 4 and 5, over 70 percent of the generated pollutant exits the booth at or below the 2.7 meter level of the 5.5 meter high exhaust filter. Table 2 presents a summary of the flow reductions achieved with the new or modified booths.

LITERATURE CITED


