ERDC/CERL TR-05-7

Construction Engineering Research Laboratory

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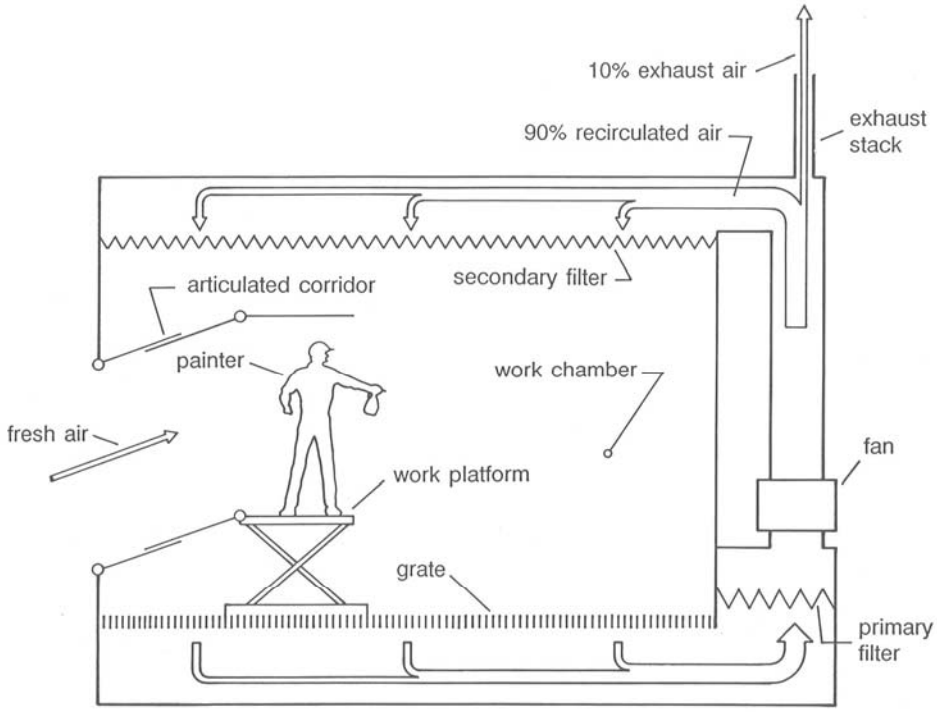
Engineer Research and Development Center

Mobile Zone Spray Booth Recirculation System

K. James Hay, Joyce Baird,
Clyde Smith, and Don Schiller

March 2005



Mobile Zone Spray Booth

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Final Report

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ABSTRACT: Army painting operations emit a large quantity of Hazardous Air Pollutants n the form of Volatile Organic Compounds (VOCs). Increasing regulatory pressure is beginning to impact these operations, which is resulting in the consideration of installing air pollution control devices. Controlling the ventilation of once-through paint booths is extremely costly. The Mobile Zone Spray Booth Recirculation System recirculates the air in the paint booth and exhausts less than 90 percent of conventional once-through systems, which is much less costly to treat. The system uses a mobile cab that moves with up to four degrees of freedom and provides the worker with fresh climatized air. Design studies for the Mobile Zone Spray Booth Recirculation System were conducted at four Army installations to demonstrate its applicability and cost effectiveness. The system was installed at Fort Hood, Texas with a recuperative catalytic oxidizer as the control device. Testing of the VOC control conducted in 2002 showed control efficiencies of 93 and 96 percent for two different paint applications. The system has undergone modifications and corrections since the testing. The system has met seven of the eight objective criteria related to performance and cost but has yet to meet the three subjective criteria related to usability and acceptance.

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Conversion Factors

Non-SI* units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees Fahrenheit	(5/9) x (°F – 32)	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
pounds	0.4535924	kilograms

*_Système International d'Unités_ ("International System of Measurement"), commonly known as the "metric system."

Preface

This study was conducted for Headquarters, Department of the Army under 6.3 Basic Research, "Environmental Compliance Technology." The CERL technical reviewer was Gary W. Schanche, CVT.

The work was performed by the Environmental Processes Branch (CN-E) of the Installations Division (CN), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Dr. K. James Hay. Part of this work was done by Mobile Zone Associates under contracts DACA88-98-M-0203, DACA42-00-P-0182, DACA42-00-P-0402, and DACA42-02-P-0078 and by MSE Technology Applications, Inc. under contracts DACA42-00-F-1122 and DACA42-01-F-0018. The technical editor was Linda L. Wheatley, Information Technology Laboratory—Champaign. Dr. Kirankumar V. Topudurti is Chief, CN-E, and Dr. John T. Bandy is Chief, CN. The associated Technical Director is Gary Schanche. The Director of CERL is Dr. Alan W. Moore.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL James R. Rowan, EN, and the Director of ERDC is Dr. James R. Houston.

1 Introduction

Background

Army painting operations emit a large quantity of hazardous organic vapors each year that are or will be subjected to National Emission Standards for Hazardous Air Pollutants (NESHAPs) implemented by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act Amendments (CAAA) of 1990. Primary sources of these emissions are spray booths where paints and coatings are applied to Army vehicles, armament, and equipment. Twenty-six major Army sites plus Army Reserve and National Guard facilities are affected. The primary NESHAP that will eventually affect these sites is the Defense Land Systems and Miscellaneous Equipment (DLSME) Surface Coating NESHAP (http://aec.army.mil/usaec/publicaffairs/update/win04/win0412.html). Under this proposed NESHAP and possibly stricter State regulations, many of the Army sites with spray booths may be required to change the Volatile Organic Compound (VOC) content of the coatings or install air pollution control equipment (PCE). Upcoming Urban HAP or Area Source rules may also affect nonmajor HAP sites that conduct painting.

Painting is an integral part of maintenance work throughout the Army for equipment and vehicles that have either a decorative or a protective coating, most of which are applied as "paint" by means of a spray gun. The primary function of all spray guns is to produce microscopic droplets from liquid paint, which is a mixture of resins and solvents. These droplets exit the spray gun nozzle and strike the workpiece. As the droplets land on the surface of the workpiece, they coalesce into a viscous liquid film, which begins to polymerize as the solvent evaporates. Once the solvent evaporates, it has no further use and becomes waste. Solvent typically makes up from 30 to 70 percent of the paint volume. Overspray, which is spray that does not land on the work surface to become part of the surface coating, is in a fine liquid particulate form. Overspray is also a waste and may account for 10 to 60 percent of the paint that is sprayed.

Painting usually takes place in a spray booth, which is a ventilated workroom. Functionally, it supports the painting process by removing the overspray and evaporated solvent wastes through its ventilating air exhaust system. Because Army spray booths are typically large to accommodate large vehicles and equipment, the total ventilation rate can be 70,000 cubic feet per minute (cfm) or more.

Fortunately, particulate filters installed in the exhaust system can easily and inexpensively capture overspray. The evaporated solvent, however, is an invisible gas that is difficult and expensive to capture because it is mixed in with large volumes of ventilation exhaust air. Typical control devices for organic solvents are carbon adsorbers and thermal incinerators. Both are prohibitively expensive for treating the full exhaust rate of a typical Army paint booth. With the increasing regulatory pressure, there is a need to reduce this cost of treatment so that Army paints and coatings containing high VOC concentrations can still be used, especially in cases where an acceptable substitute is not available. The most likely alternatives are water-reducible coatings, which in general are not as good as typical solvent paints because they cost more, require a more thorough surface cleaning to achieve the same adhesion (achieving a clean surface for maintenance painting is already a problem), and they take longer to dry, thereby slowing production.

The Mobile Zone Spray Booth Recirculation System was developed to reduce the exhaust ventilation rate so that a much smaller and less expensive control device could treat the solvent vapors in the ventilation air. Implementation of the Mobile Zone System will allow the Army to use any type of paint, in any quantity, in any geographic location without environmental restriction. The paint can be chosen based on cost and performance rather than its environmental characteristics, and the painting operations become essentially pollution free.

The Mobile Zone concept was primarily developed through a U.S. EPA Small Business Innovative Research grant (1989-1990), which resulted in the U.S. Patent #4,926,746 issued 22 May 1990 (Smith 1990). The development continued under a Department of Energy, Energy Related Inventions grant (1991-1994). Mobile Zone Associates carried out the research for both grants, where they designed and constructed a prototype. The prototype was tested at River Steel Co. in Nashville, TN. ERDC/CERL began exploring the Mobile Zone System as an option for minimizing the cost of controlling HAP emissions from Army paint booths in 1998 as part of the ERDC/CERL HAP project.

Objectives

The objective of the ERDC/CERL HAP project is to develop and demonstrate cost-effective technologies to help the Army meet current and future demands of HAP regulations. The primary objective of this study was to determine the suitability of the Mobile Zone System for Army spray booths. This involved determining whether typical Army spray booths can be retrofitted with the Mobile Zone System and at what cost. Another objective was to install and test the Mobile Zone System at an Army facility. This technology is expected to meet the exit criteria set by the HAP

Project, which is a minimum control efficiency of 81 percent when used in conjunction with an air pollution control device and a 20 percent reduction in cost over conventional VOC treatment. Additional objectives for the installation of the Mobile Zone at an Army facility are as follows:

- A minimum 90 percent reduction in the spray booth exhaust rate in the Mobile Zone recirculation mode
- No negative impact on production rates or quality
- No negative impact on worker safety
- The booth shall retain its existing flow ventilation pattern, nominally, a laminar ventilation pattern
- The booth shall retain its existing multi-stage dry filtration
- The booth's modifications shall meet current National Fire Protection Association (NFPA) 33 standards (NFPA 1988) and Occupational Safety and Health Administration (OSHA) regulations (29 CFR 1910.94) without a variance
- The equipment shall be designed for longevity, reliability, and maintainability including, wherever possible, stock materials and components
- The equipment will be intuitive to use, requiring little training
- The equipment will be convenient to use so that it will be the first choice of the painter, assuring a high utilization rate.

Approach

Studies were performed at four Army installations to develop designs for installing the Mobile Zone System on one paint booth at each site. The initial study was conducted at Watervliet Arsenal (WVA) in 1998, and subsequent studies at McAlester Army Ammunition Plant (AAP), Fort Riley, and Fort Hood were performed in 2000. An appropriate booth was selected at each site for a design analysis. After consideration of various factors, one of the four booths was selected for the complete installation of the Mobile Zone System. The Mobile Zone System was then installed in the booth and tested for control of VOCs emitted during the painting process.

Mode of Technology Transfer

This technology was permanently installed (full-scale) and tested at a paint booth at Fort Hood. This report documents those activities and will be available on the CERL web page. The CERL web site address is: http://www.cecer.army.mil/

The HAP Project is part of the Army Environmental Quality Technology (EQT) Program. This technology was tested through the ERDC/CERL HAP Project, which

uses 6.3 advanced development and field-testing funds. As part of the EQT process, a technology transfer plan is being developed by the U.S. Army Environmental Center (AEC) for this technology as well as other qualified HAP Project technologies. The support and endorsement of major Army commands (MACOMs) will be sought to increase the possibility of future implementation to other Army paint booths.

2 Characteristics of the Mobile Zone System

General Spray Booth Design

A spray booth is a ventilated work chamber for containing emissions from the spray application of a surface coating onto a workpiece. The ventilating air is frequently heated or cooled and then drawn across the entire cross section of the booth as uniformly and free of turbulence as possible at a velocity at least equal to the applicable OSHA minimum (60, 100, or 150 feet per minute [fpm]; 29 CFR 1910.94). The ventilating air entrains the overspray and solvent vapors, carries them through the ventilation system, and exhausts out the stack to the atmosphere. Several benefits result from this arrangement: the removal of overspray greatly improves the quality of the finish because, if it settles on the workpiece, the appearance of the finish will be unacceptably rough; the harmful overspray and toxic solvent vapor are greatly reduced from the worker's breathing zone; and the concentration of solvent vapor is kept low by the dilution effect of the ventilating air thereby reducing the risk of fire and explosion.

The two types of spray booths are sidedraft and downdraft. The Army uses both types. In a sidedraft booth, the fresh ventilating air enters through one side of the booth, traverses the spray booth work area and exits as exhaust air through the opposing side of the booth. In a downdraft booth, the fresh ventilating air enters through the ceiling, traverses the spray booth work area, and exits through grates that form the floor. In either type of booth, a diffuser grill or filter section is often used to uniformly distribute the ventilating air across the booth to establish laminar flow. The downdraft booth has the advantage of working with gravity to remove VOCs and overspray from the booth. The sidedraft booth gets little assistance from gravity. The disadvantage to the downdraft booth is increased expense in fabrication and installation. Typically, the downdraft booth is used for large workpieces such as vehicles and aircraft, especially when a fine finish is required. The sidedraft booth is typically used for smaller pieces such as furniture, parts, and components of larger products. The size of the booth is determined by the size of the largest workpiece plus space for the worker to maneuver while applying the spray paint. The volume of ventilating air required is proportional to the size of the booth. The

painted workpiece may be left in the booth to air dry or moved to a curing oven to force dry.

Figure 1 shows a diagram of a typical paint booth and its downdraft ventilation system (Smith and Brown 1993). The ventilation system is designed for the air to make only one pass through the booth. The primary filter controls particulates generated in the spray booth, while the secondary filter distributes the makeup air and controls particulates that could otherwise settle on the painted surface.

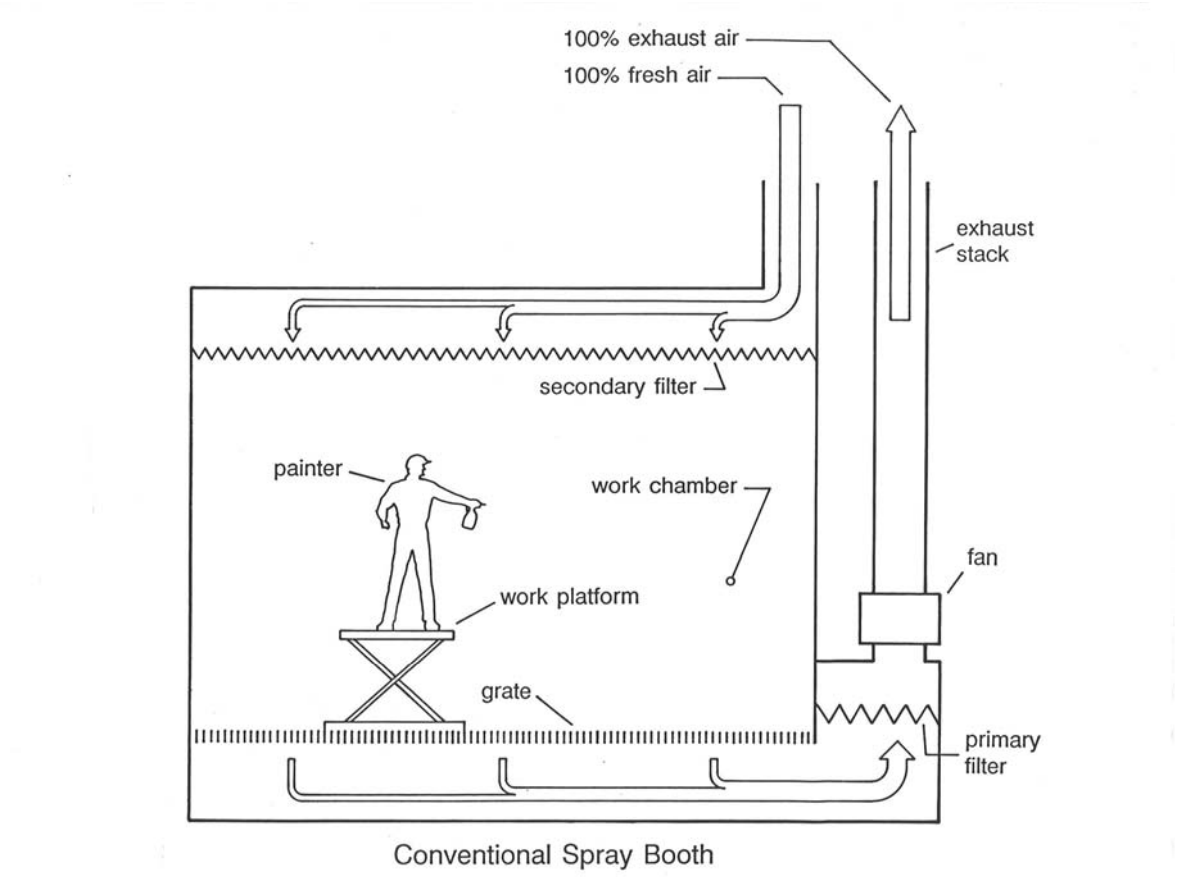


Figure 1. Typical paint booth with downdraft ventilation.

Mobile Zone System

The Mobile Zone System reduces the exhaust ventilation rate so that the solvent vapors can be treated in a more economical manner. The concept is that the ventilation rate in the booth remains the same and passes through the particulate filters, but is then recycled back through the booth. A much smaller portion of this airflow is routed to a control device for treatment and exhaust. This concentrates the solvent vapors in the paint booth so that the workers need additional protection, which is provided by passing the make-up ventilation air at a velocity of 100 fpm through

a mostly enclosed mobile work platform cab, from which the worker paints. The typical design calls for 2,000 cfm air flow rate through the cab and out the exhaust, which is independent of the recycled air flow rate. By design, the Mobile Zone System is for application only on manned paint spray booths. It can be incorporated into a new paint spray booth or retrofitted into an existing booth.

Figure 2 is a diagram of a spray booth with the Mobile Zone System (Smith and Brown 1993). To change a booth from a typical setup (Figure 1) to the Mobile Zone, the following changes need to be made: (1) the intake and exhaust stacks are joined to form a loop, and (2) the original make-up intake is removed (or bypassed) and a smaller one is added (done because less heat is required for the recirculated air so that the existing heater will be too large), (3) the work platform is installed within the booth workspace, (4) the particulate filtration system is converted to dry filters if it is a water wash system; otherwise, humidity from water evaporation would rise to an unacceptable level, (5) air conditioning and heating are added to the fresh air supply for the work platform cab (optional but very desirable), (6) air PCE is added to the exhaust stack.

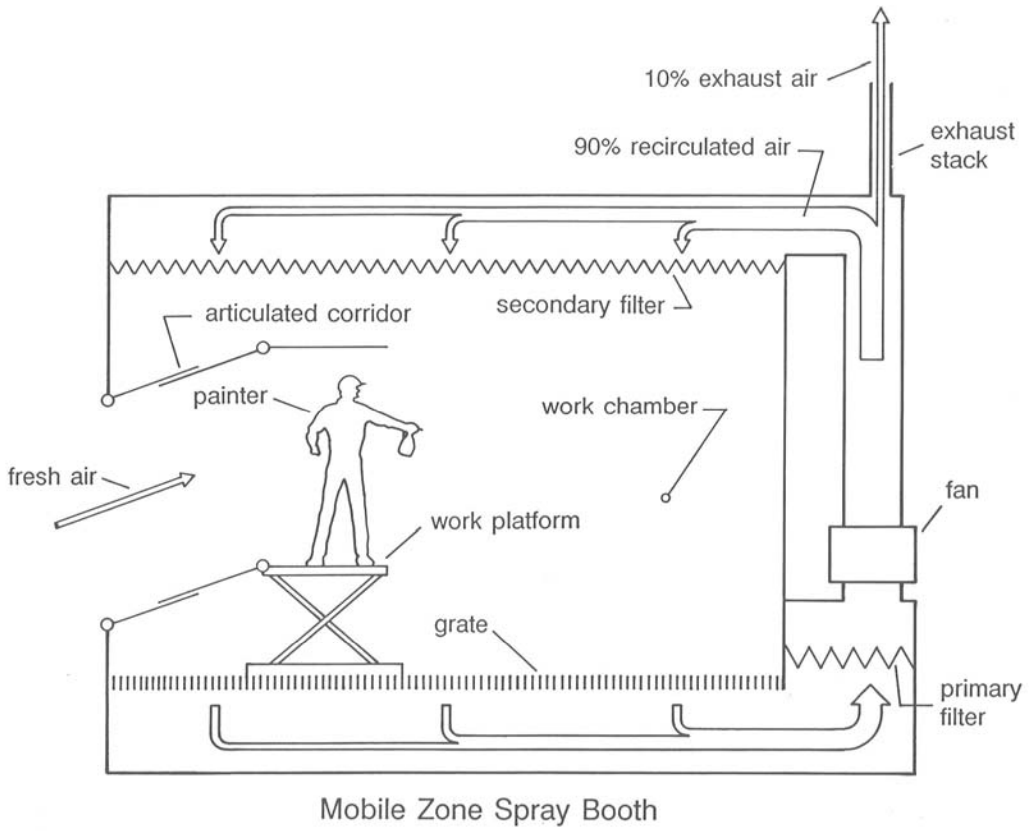


Figure 2. Paint booth with Mobile Zone System.

Recycling air through a spray booth is not new. Some companies, primarily those that use robotic or automatic spray equipment, began to recirculate ventilating air to reduce volume, increase concentration and allow the purchase of smaller control equipment. When recycling is attempted on manned spray booths, the workers may be subject to unreasonable danger within the recirculated zone. OSHA regulations (29 CFR 1910.94) discourage this approach and many government facilities and companies have determined the concept unacceptable, even if the workers are isolated by means of ventilated suits, from increased concentration of pollutants within the recirculated zone. High ratios of recirculated air to fresh air mean, in the event of a fire, that smoke and heat will build up rapidly, possibly seconds. The smoke will blind the worker and potential rescuers so that injury or death may occur. A key feature of the Mobile Zone System that differentiates it from other recirculation proposals is that the worker is always located in a fresh air zone rather than a recirculated zone. This feature allows high rates of recirculation without compromising the worker's safety.

A prominent feature of the Mobile Zone System is the mobile work platform. Mobile work platforms are often used in commercial painting operations to increase productivity and worker safety. Figure 3 shows a typical commercial application. In addition to the fresh climate-conditioned make-up air, the Mobile Zone work platform offers compressed air for the paint gun, electricity for task lighting, and class D breathing air to the painter's full face respirator if needed. Powered by compressed air, the platform can have up to four degrees of movement (up/down, side to side, front to back, and rotate). For the case of four degrees, the cab can be designed to access any location in the booth. In a simple application, such as a small side-draft booth with a conveyor system, the booth could be stationary or have just one degree of movement (side to side).

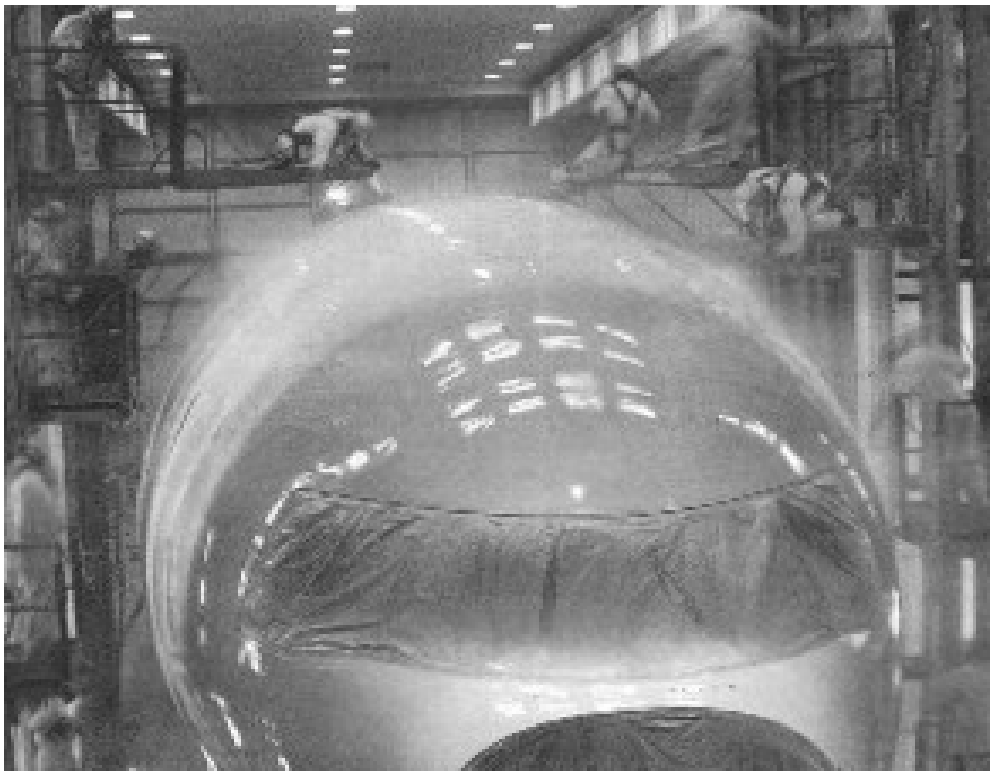


Figure 3. Typical commercial painting application of work platforms.

The VOC concentration is different in two ways between the standard spray booth and the Mobile Zone booth. In the standard spray booth, the VOC concentration will build up and decay in close relation to the operation of the spray gun. Considering that a typical spray booth will be swept clean of VOCs in about 30 seconds, it is apparent that spray gun operation and VOC concentration are highly correlated. The concentrations typically range between 10 and 200 parts per million (ppm). When a large object is coated with fresh paint, then the VOC concentration will take longer to decay because the wet paint is also a VOC source. In the Mobile Zone booth, the VOCs will build up to much higher levels and decay much more gradually. This is beneficial to the operation of the VOC control equipment in three ways: (1) lower air flow rate to treat results in smaller VOC control equipment, (2) higher concentration of VOC results in a greater fuel value for incinerators or greater removal efficiency for carbon absorbers, and (3) a more uniform concentration through the production cycle is easier to control.

Benefits and Limitations of Mobile Zone System

A paint booth equipped with the Mobile Zone will exhaust approximately 2,000 cfm. This means a reduction of more than 90 percent for a booth with a conventional flow rate of more than 20,000 cfm. The reduced exhaust requires correspondingly smaller VOC control equipment and heating and/or air-conditioning equipment. This results in significant reductions in capital and operating costs for the booth if air pollution control is required.

The efficient containment and control of the VOCs in the booth makes the painting operation almost pollution free and, therefore, much less restricted by Federal, state, and local regulations. This substantially increases the possibility of being able to use any paint in any quantity.

The Mobile Zone System not only supplies fresh make-up air to the painter at 100 fpm, but it also heats and/or cools that air for the painter's comfort while painting. In addition, the use of a motorized work platform increases productivity. For example, some Army booths require two workers, one to paint and the other to assist by dragging the paint hose line and moving the ladder. With the Mobile Zone System, the second worker is not required because the platform is mechanically controlled and carries the hose along with it.

The Mobile Zone System takes up some space in the booth. If there is limited space due to the workpiece or surrounding equipment, then it is very difficult if not impossible to retrofit the booth with the Mobile Zone System. The system design is flexible, however, so this is not an issue in most cases.

Learning to use the cab requires some training. The controls are relatively intuitive; however, compared to walking and climbing a ladder, it is more difficult to operate. An initial reduction of productivity and uneasiness in the workers can occur until they become accustomed to the system. Because the mobile cab is solidly constructed, if misused, it could damage vehicles or equipment in the booth despite the installed bumpers and low-impact force. Aircraft skin, for example, could be damaged by a collision, which could result in workers' unwillingness to use the cab.

3 Design Studies

Usually, a production coating operation paints workpieces that are similar if not the same for the entire day or longer. A maintenance coating operation paints workpieces that differ in size and shape on a sporadic as-needed basis. It appears that Mobile Zone technology could be easily retrofitted to production booths. However, not all maintenance paint booths are large enough to retrofit a Mobile Zone System because of the more demanding access requirements of the sometimes widely varying workpiece shapes and sizes. A paint booth with the Mobile Zone System designed in from the start would be best for maintenance operations.

Design studies were conducted on paint booths from four different Army installations: WVA, McAlester AAP, Fort Riley, and Fort Hood. The chosen booths at WVA and McAlester AAP are used for production type activities, while the booths at Forts Riley and Hood are used for maintenance work. The two different types of booths were chosen to show the applicability of retrofitting existing Army paint booths with the Mobile Zone technology. The following design studies include discussions of the existing operation, the proposed Mobile Zone design retrofits, and rough cost estimates to implement the retrofit with a VOC air pollution control device.

Watervliet Arsenal

A design study for the Mobile Zone System was conducted at WVA on a large downdraft paint spray booth used in 1998 for painting cannon barrels. The drawings in Figures 4 and 5 show the top and side views of the existing spray booth, respectively. Figures 6, 7, and 8 are photographs of the booth.

At the time of the study, the configuration of the booth provided for a large volume of air to be drawn in from the outside and introduced into the booth through filters in the ceiling. A make-up air heater heated this air during the winter. An equal volume was exhausted through gratings located in the floor. The contaminated air was exhausted to the atmosphere by means of an exhaust fan located above the spray booth. The OSHA standards (29 CFR 1910.94) for this type of paint operation require ventilating air at a velocity of 100 fpm across the ventilated cross section. The flow rate through the booth should be 70,000 cfm because the ventilated cross section is 700 ft^2 (20 by 35 ft).

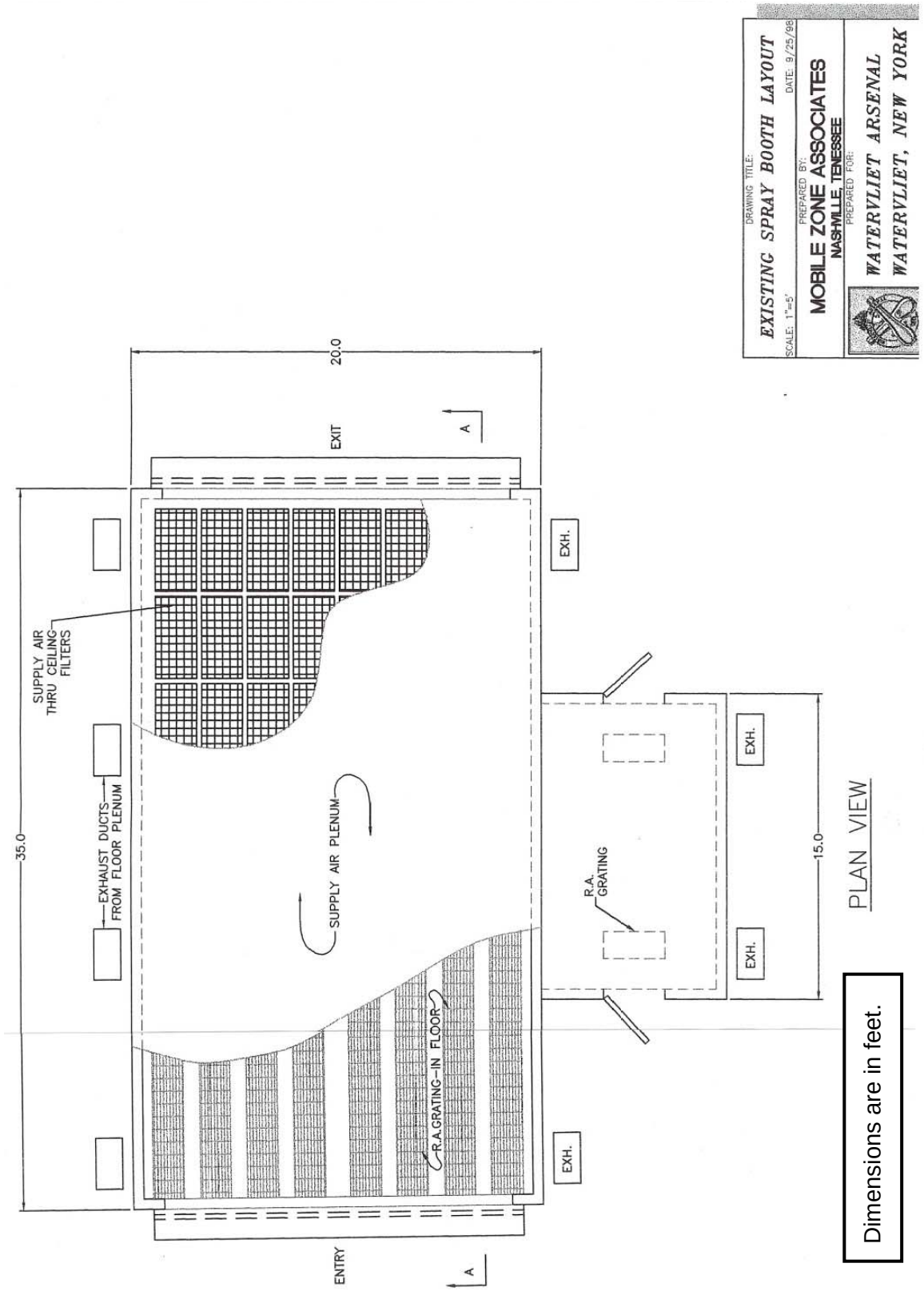
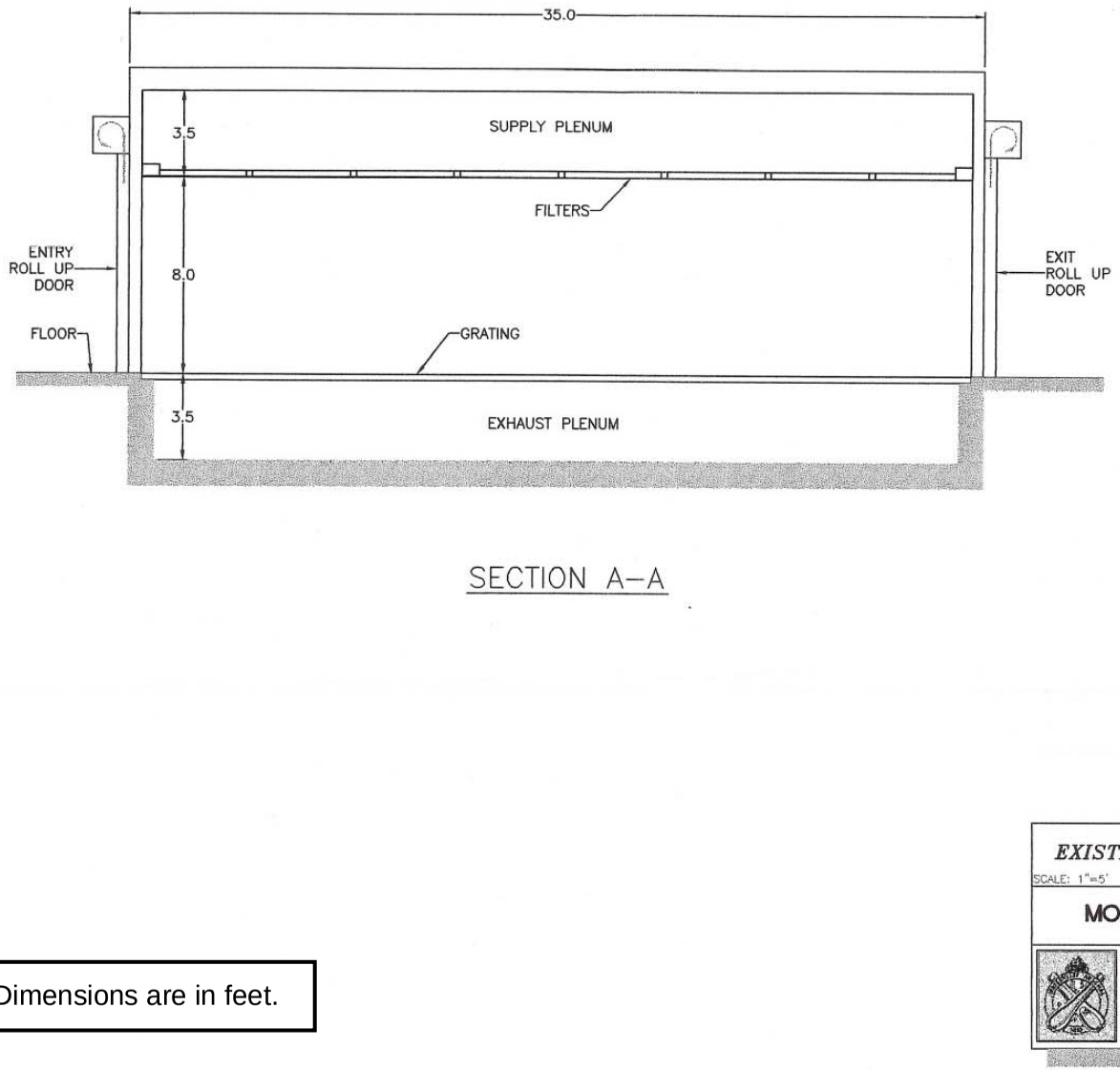


Figure 4. Existing WVA spray booth layout (top view).



Dimensions are in feet.

Figure 5. Existing WVA spray booth layout (side view).

Figure 6. View of WVA booth from outside of booth.

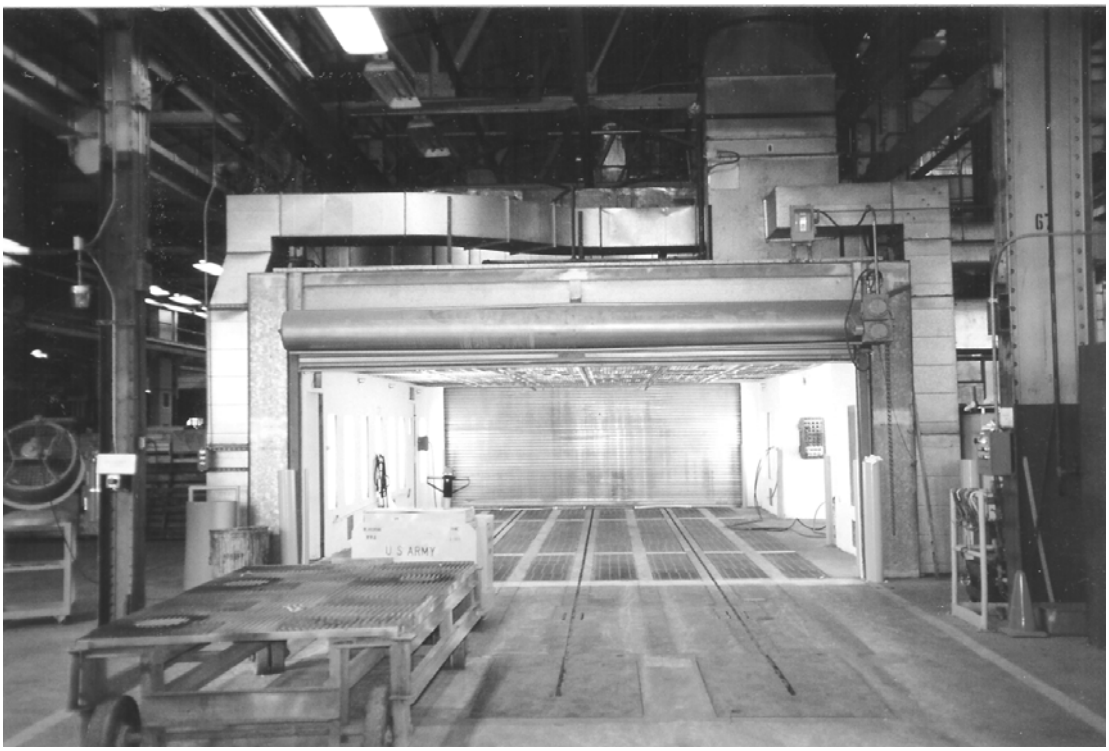


Figure 7. View of WVA booth through entrance.

Figure 8. Paint mixing area in WVA booth.

Overhead doors on each end of the booth provided entry and exit for moving parts in and out of the booth. When painting was in progress, the overhead doors were closed. A vestibule located at the side of the booth was used for paint mixing and walk-in access to the booth.

The painting equipment consisted of a Binks 64 cup gun and Binks Mach 1 spray gun. Although the coating specifications vary between the different types of cannon barrels, the most commonly used coating specification called for a primer wash pretreatment. Application of the coating would be less than 4 gallons per hour (one painter) at the maximum specification.

Two cannon barrels were placed side by side on a dolly that was towed into the spray booth. The areas of the dolly that support the barrels were not accessible to the painter. Therefore, after the barrels were painted and dried, the painting sequence was repeated to coat the unpainted areas. Taking the barrels through the painting process twice added substantially to the processing time. It was also difficult to paint the underside of the gun barrels, which required the painter to stoop down with poor lighting and spray paint in the opposite direction of the spray booth ventilating air. Other parts painted in the booth on a nonroutine basis included some breech parts and ship propeller shafts.

With the Mobile Zone System, 97 percent of the ventilating air would recirculate. Ventilating air would be drawn from the work chamber of the paint booth through the filter panels into the exhaust plenum. The filters will remove most of the particulates but not the solvent vapors. The exhaust plenum would be connected to a fan that is connected to the supply plenum. The fan would move the recirculated ventilating air from the exhaust plenum to the supply plenum, where it would blow through another set of particulate filters down into the work chamber, completing the recirculation circuit.

Two thousand cfm would be drawn from the exhaust plenum through a fan and into VOC control equipment. With the VOC destroyed by the control equipment, the spent air would be exhausted to the atmosphere through a stack. Openings would be left in the booth to allow 2,000 cfm of fresh make-up air to enter the booth. The openings would be two doors with filter panels. The fresh air would enter through the filter panels (which remove any dust) then pass through the opening created in the Mobile Zone cabin and finally into the work chamber.

The existing paint booth make-up and air heaters would be abandoned, as they would no longer be needed. The two 7,000 cfm heaters, one gas-fired and the other a steam coil, did not operate simultaneously. Considering the large building volume and low exhaust rate with the Mobile Zone System (2,000 cfm), fresh air would be drawn from the building interior making the system reliant on the building heaters. Figure 9 shows the proposed ventilation with the Mobile Zone System.

With the Mobile Zone System installed, the positioning of the parts to be painted would be changed. A new cannon barrel dolly would, as before, carry two barrels into the booth. The new dolly, however, would carry the barrels one above the other and rotate the barrels for painting access. The new dolly would support the barrels by engaging the bore surfaces that are not painted. The top barrel would be painted first while the bottom barrel is draped. After a coat of paint is applied to the top barrel, the drape would be removed and the bottom barrel would get a coat of paint. The dolly with barrels could be left in the booth for the coat to dry or removed to make room for another dolly with barrels. With this arrangement, the practice of touch-up coating of the support areas would be eliminated and productivity improved. Also, the painter would have the best possible access to the surfaces being painted allowing better control of the paint gun and paint buildup on the surface. The painter would not have to paint the poorly illuminated bottom of the barrel in a direction opposite to the ventilating air direction.

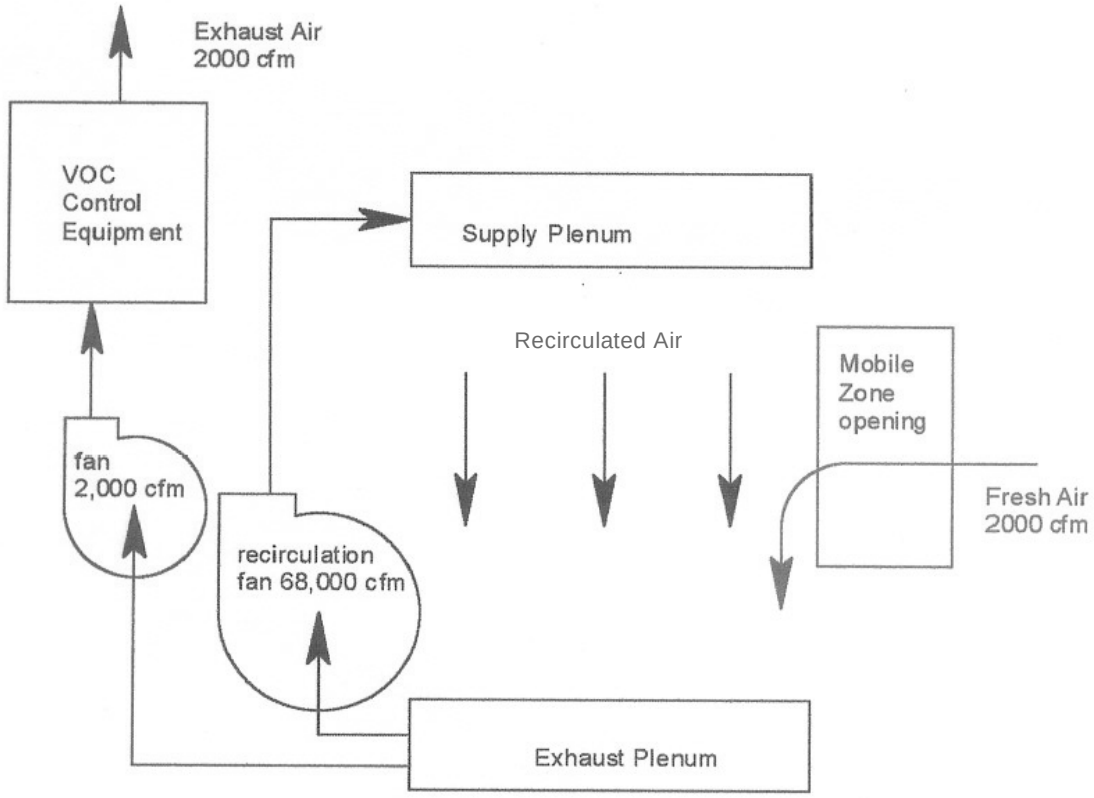


Figure 9. Proposed ventilation in the WVA booth with the Mobile Zone System.

The way the painter accesses the parts would also be changed. Instead of walking around the part, he/she would ride in a Mobile Zone cab. Fresh air would enter through the filter panels in the doors of the vestibule and travel through the Mobile Zone cab across the painter. He/she would control movement of the cab by a foot-operated valve that gives bi-directional and proportional speed control over the air motor that powers the rotation. Air motors are well suited to these applications because they are safe (nonsparking), compact, and reliable. This cab would move with one degree of freedom, side to side. Figures 10–12 show the proposed booth configuration with the Mobile Zone System.

Equipping the spray booth with a cab with one degree of movement would not halt the painting of the occasional or unusual part. Some parts could be rotated by means of a turntable. A motorized turntable is recommended for extremely heavy parts. For other parts, the simplest way is to paint one side, turn it around, and paint the other side.

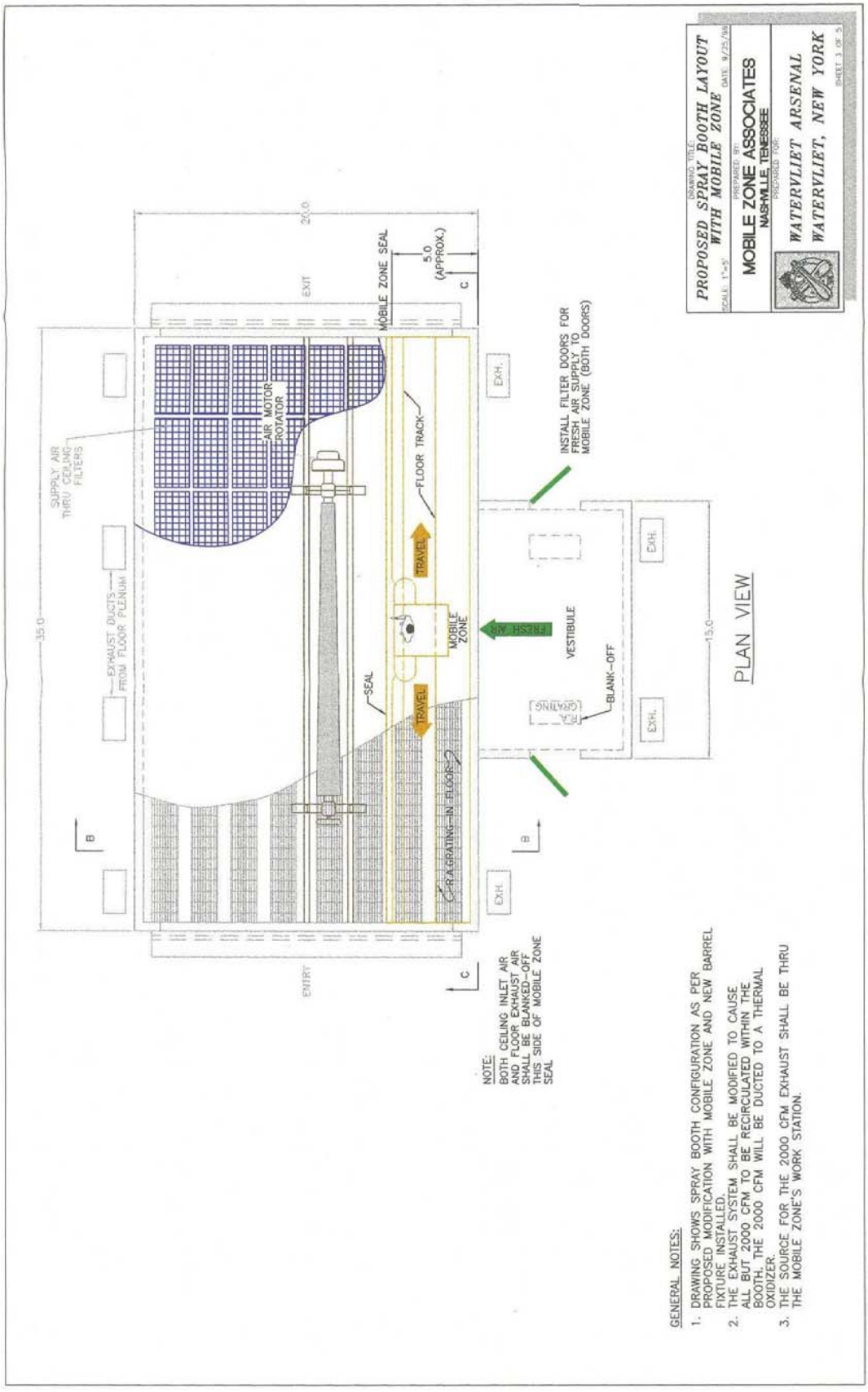


Figure 10. Proposed WVA spray booth layout with Mobile Zone (top view).

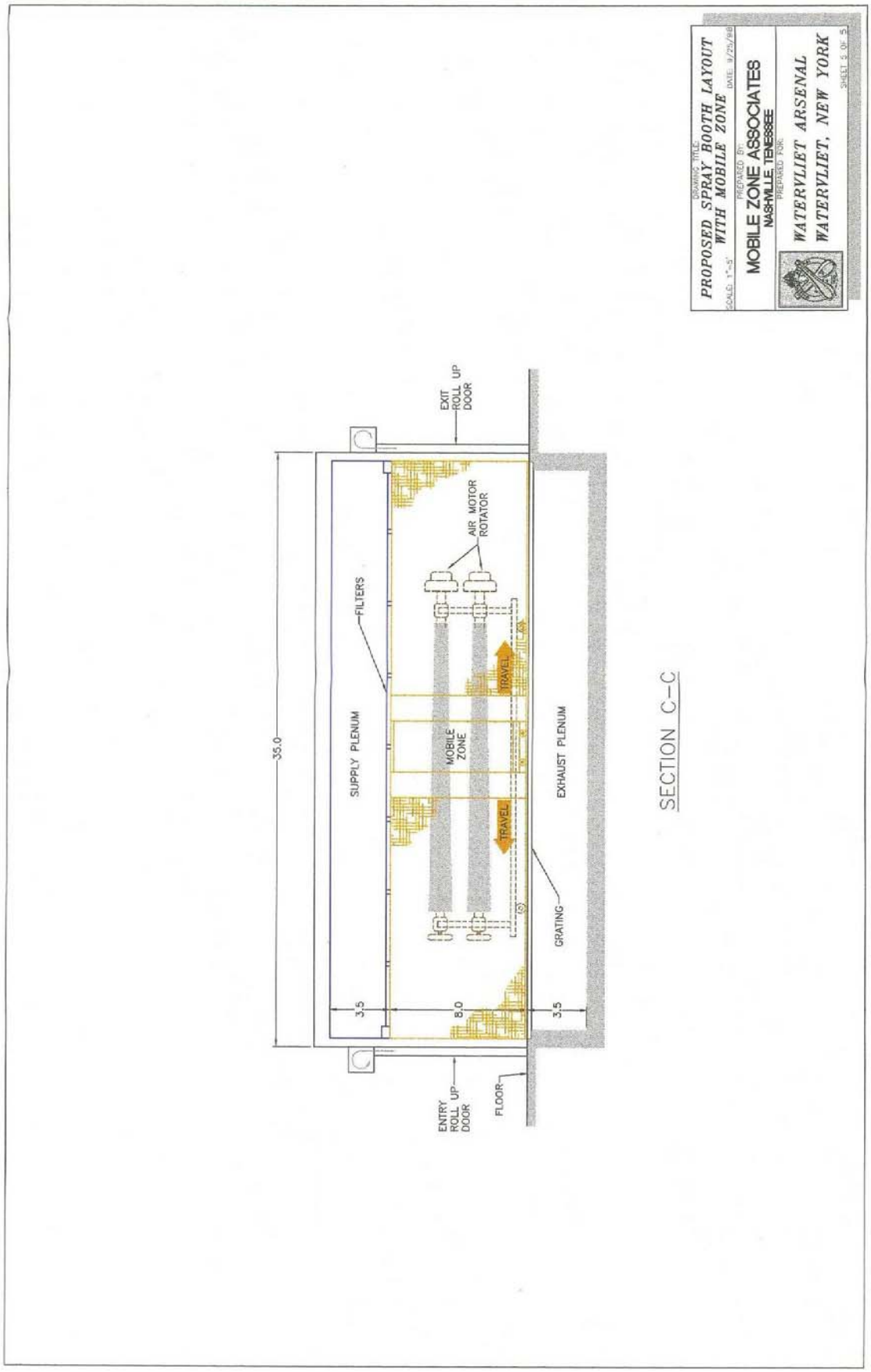


Figure 11. Proposed WVA spray booth layout with Mobile Zone (side view).

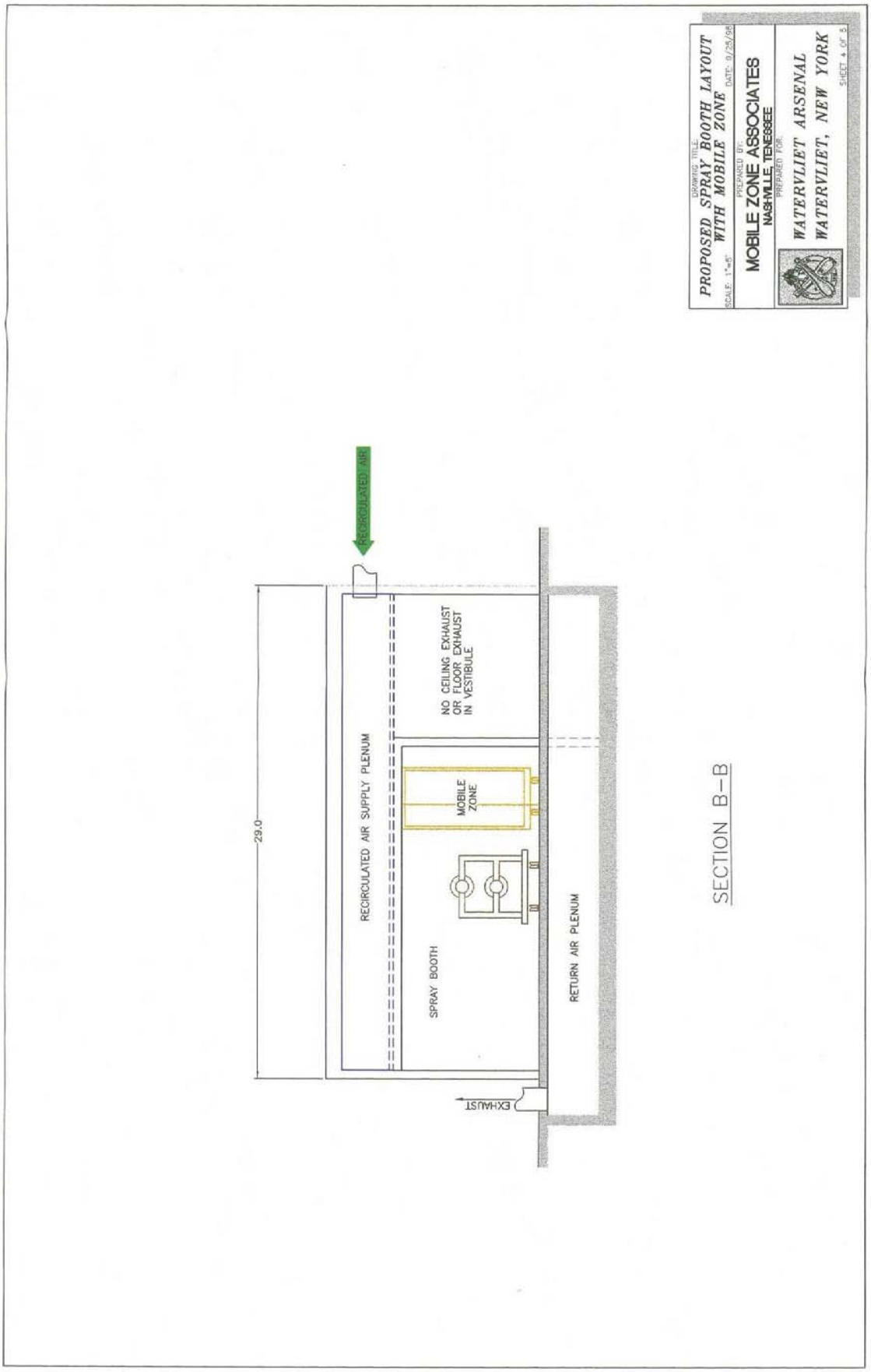


Figure 12. Proposed WVA spray booth layout with Mobile Zone (entry end view).

A ship propeller shaft is an example of an unusual part occasionally painted at WVA. The shaft is longer than the booth, so one end is painted, the shaft repositioned, and the other end painted. Since the shaft is longer than the booth, it protruded from the booth and the roll up door could not be closed. Containment is compromised under this procedure. However, the shaft could be painted in the same manner (by repositioning it) with the installed Mobile Zone System.

A recuperative incinerator (i.e., thermal recuperative oxidizer) is recommended for VOC control. This equipment is relatively compact and would fit above the transition area between the spray booth and oven. It can be turned on and off as needed and would be operated by a programmable logic controller (PLC) that can be interfaced with facility computers. Table 1 presents estimated operating costs for a recuperative incinerator (Anguil Environmental Systems, Milwaukee, WI). The estimated VOC removal efficiency is 99 percent. These estimates are based on a system that would burn 13,000 BTU/hour of fuel for the pilot and 1,060,980 BTU/hour of fuel when fired at a cost of $4.00/MMBTU. The system would use a 7 HP blower and 180 scfm of combustion air at an electricity price of $0.06/KWH. Table 2 provides capital cost estimates for the Mobile Zone System upgrade at the WVA paint booth.

Table 1. Estimated operating costs for VOC control (Anguil Environmental Systems).

Operating Costs	
Fuel Cost	$5.37 /hr
Electricity Cost	$0.30 /hr
Total Operating Cost	$5.67 /hr

Table 2. Capital cost estimates for Mobile Zone System upgrade at WVA paint booth.

Mobile Zone System Retrofit	
$33,000	Three gun barrel dollies
$72,000	Mobile Zone cab, track, and controls
$6,000	Sheetmetal work, blanking off portions of the supply and exhaust plenum, and new doors with filter panels
$16,000	Duct work, connecting the exhaust plenum to the supply plenum through the recirculation fan
$127,000	Mobile Zone subtotal – delivered and installed
VOC Control Equipment	
$125,800	2,000 cfm Anguil thermal recuperative oxidizer
$35,000	Installation
$160,800	VOC control subtotal – delivered and installed
Total Cost	
$287,800	Mobile Zone and VOC control

For comparison, a regenerative incinerator or zeolite concentrator would cost approximately $1.5 million (installed) to treat the entire 70,000 cfm. The operating cost of this full-scale regenerative incinerator would be approximately $30 per hour. Although it can be throttled back, the incinerator must be left on to keep the heat exchanger hot. The zeolite concentrator would have significantly lower operating costs at approximately $18 per hour. It could also be throttled back during periods of non-use. Both pieces of equipment are large and must be installed outside the building. The Mobile Zone system with the recuperative incinerator would save an estimated 81 percent in capital and operating costs over a full-scale regenerative incinerator and 81 percent in capital and 68 percent in operating costs over a full-scale zeolite concentrator.

Little maintenance is required for the Mobile Zone equipment because it has few wearing items, only the air motors and valves. The VOC control equipment does have a life span. Substantial refurbishment costs and/or replacement can be expected after 10 to 15 years of service.

McAlester Army Ammunition Plant

The paint booth at the Harpoon Missile Facility at McAlester AAP does the production painting of casings for the Harpoon Missile and other small miscellaneous parts (Figure 13). The booth is 15-ft wide, 24-ft long, and 9-ft high. The ventilated cross section is 360 ft^2. The exhaust rate is estimated at 36,000 cfm. Under typical operation, a missile casing is loaded on a dolly and manually pushed into the paint booth through a door. Up to eight dollies are pushed in at a time. The painter enters the booth through a door, then walks around and paints the casings. Each dolly is equipped with wheels that allow rotation of the casing as the worker paints, allowing the casing to be painted in one step. After the casings have dried to a tack-free state, they are pushed out of the paint booth. The paint booth is then ready to accept another load.

The exhaust rate would drop to 2,000 cfm with the Mobile Zone System, which is a 94 percent reduction. The Mobile Zone modification would include: (1) removing the existing make-up air heater, (2) joining the exhaust stack to the intake, (3) adding secondary filtration, (4) adding a circulating air heater, (5) installing a Mobile Zone work platform, (6) changing the spray booth door for workpiece entry and exit, (7) adding a spray booth door for entry and exit of the worker, (8) adding VOC control equipment, (9) adding racks to hold multiple missile casings, and (10) installing air conditioning equipment for humidity control and comfort in the work platform.

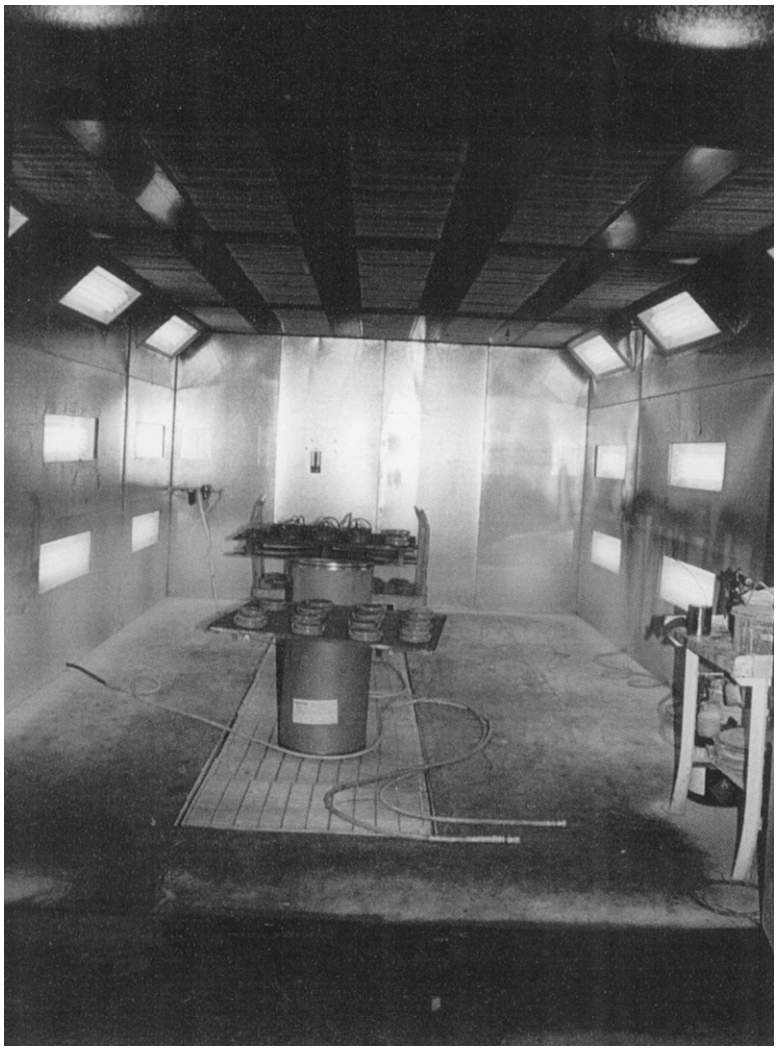


Figure 13. Harpoon Missile Facility paint booth at McAlester AAP.

Figures 14 and 15 show the proposed Mobile Zone retrofit at McAlester AAP. The new racks would hold up to nine casings and still allow the painter to rotate the casings on the rack (Figure 16). In preparation for painting, the painter would push the rack into the spray booth through the workpiece door and then close the door. He/she would then enter the Mobile Zone work platform through a door in the booth and control the position of the platform to access each missile casing. In this case, the freedom of movement would be one degree — back and forth in front of the rack. When the painting is complete, the painter would position the Mobile Zone work platform at the spray booth door and exit. After the missile casings are tack free, the workpiece door would be opened and the rack pulled out of the booth. The booth would then be ready for the next rack. Any miscellaneous parts will be painted in the same way — mounted on a rack that would allow access to all surfaces that need to be painted.

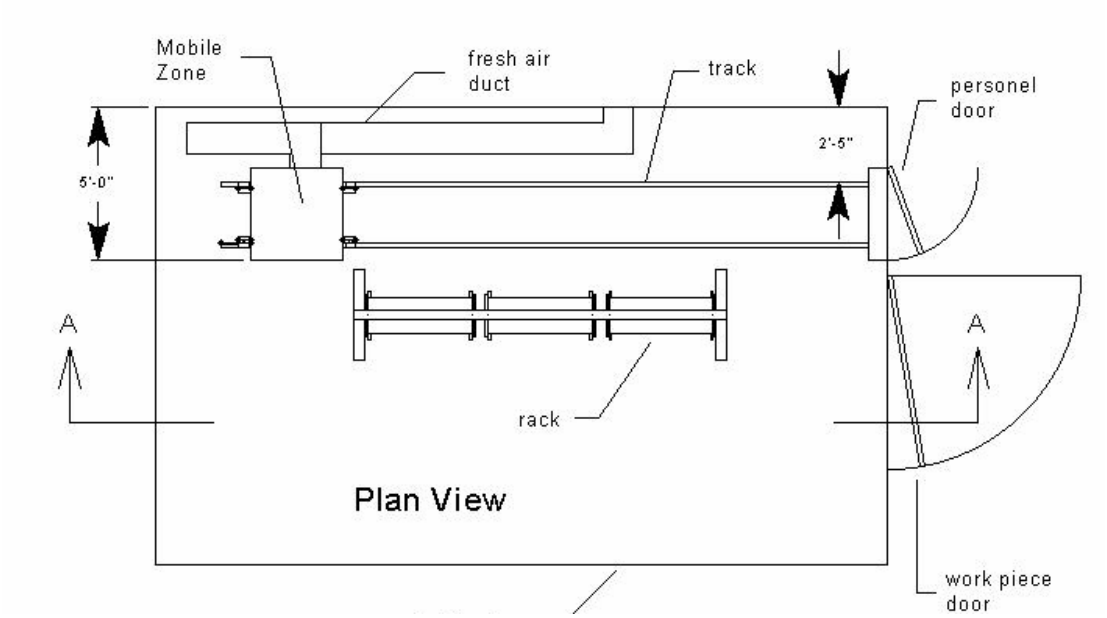


Figure 14. Proposed Mobile Zone retrofit inside paint booth at McAlester AAP (top view).

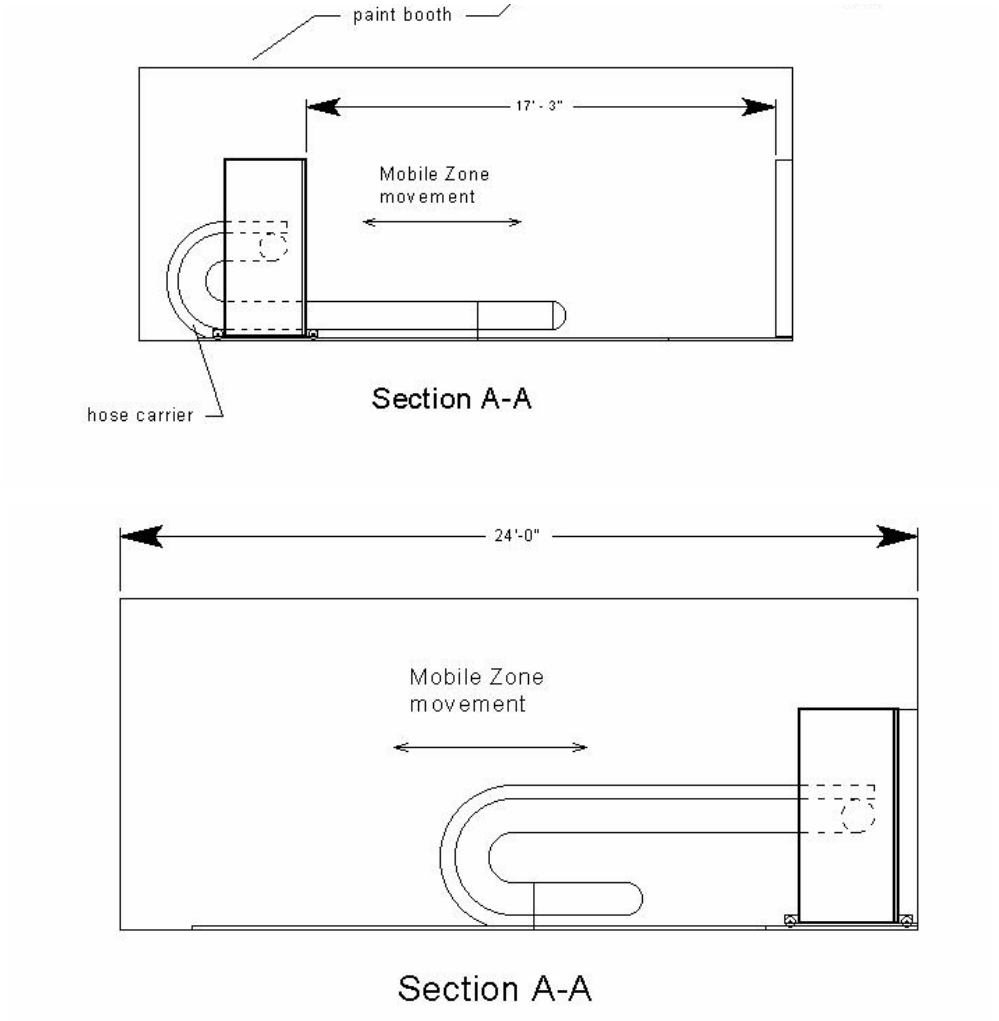


Figure 15. Proposed flexible fresh air duct inside booth at McAlester AAP.

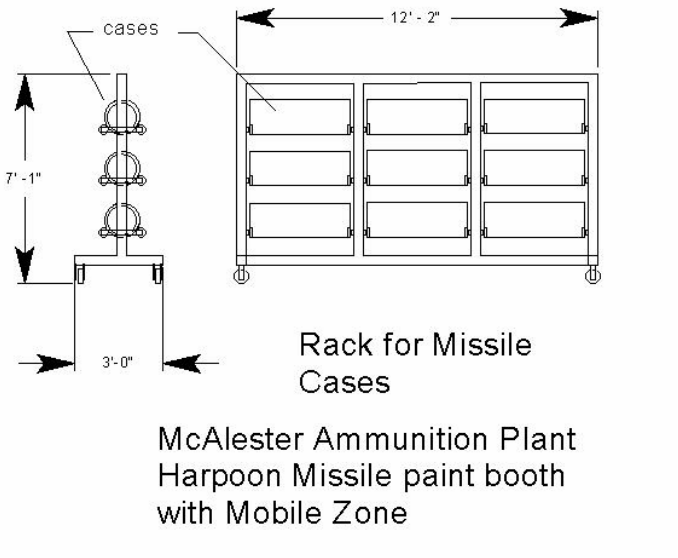


Figure 16. Proposed rack for missile cases at McAlester AAP.

Table 3 shows capital cost estimates for the proposed Mobile Zone System with VOC control equipment at McAlester AAP. This estimate includes two racks for the Harpoon Missile casings but no racks for miscellaneous parts. Those racks would need to be fabricated or purchased as needed.

Table 3. Capital cost estimates for the Mobile Zone System upgrade at McAlester AAP.

$40,000	Air handling system rework including removal of existing make-up air heater, joining of exhaust stack, addition of secondary filtration, and addition of circulating air heater
$30,000	Engineering design
$70,000	Work platform, track, hydraulics, and pneumatic controls
$170,000	VOC control equipment – purchase and installation
$12,000	Air conditioning for work platform
$20,000	Two racks for Harpoon Missile casings
$342,000	**Mobile Zone and VOC control - total**

Fort Riley and Fort Hood

Forts Riley (KS) and Hood (TX) perform maintenance coating of military vehicles including the M1 Abrams Tank, M2 Bradley Infantry Fighting Vehicle, High-Mobility Multipurpose Wheeled Vehicles, various trucks and trailers, and rotary aircraft. The operation and design of the two booths for which this design study was conducted are very similar. Consequently, the proposed Mobile Zone System retrofits are almost identical and are presented here together.

The paint booth in Bay 26 of Building 8100 at Fort Riley is 22-ft wide, 40-ft long, and 15-ft high (Figure 17). The ventilated cross section is 330 ft^2. The existing exhaust rate is estimated at 33,000 cfm, which would drop to 2,000 cfm (a 94 percent reduction) with the Mobile Zone System installed.

The paint booth in Bay 4 of Building 88027 at Fort Hood is 29-ft wide, 56-ft long, and 19-ft high (Figure 18). The ventilated cross section is 550 ft^2. The original exhaust rate was estimated at 55,000 cfm, which would also drop to 2,000 cfm (a 96 percent reduction) with the Mobile Zone System installed.

In the current operation for both booths, the door is opened and a vehicle is driven into the spray booth and parked (most workpieces are self-powered vehicles). Figure 19 shows a typical vehicle type that is painted. After the door is closed, the vehicle is painted and allowed to dry to a tack-free state. The door is opened and the vehicle is driven out and parked. The spray booth is then ready for another vehicle. The painter walks around the vehicle during painting and a helper is often needed to move the hoses. A helper is also needed to hold a ladder for the painter when access to higher surfaces is needed.

Figure 17. Paint booth at Fort Riley.

Figure 18. Paint booth at Fort Hood, Bay 4.

Figure 19. Typical vehicles painted at Fort Hood.

The Mobile Zone modification at either site would include: (1) removing the existing make-up air heater, (2) joining the exhaust stack to the intake, (3) adding secondary filtration, (4) adding a circulating air heater, (5) installing a Mobile Zone work cab, and (6) adding a spray booth door for entry and exit of the worker. The procedures for using the spray booth would be identical to how it was used before the Mobile Zone installation, with the exception of how the painter would move in the booth. The painter would paint the vehicle while standing in the Mobile Zone cab. He/she would control the movement and location of the work platform. A helper is no longer needed since the Mobile Zone cab would carry the hoses and allow for access to all positions in the booth. The cab is a work platform enclosed on three sides. The fresh make-up air would enter the cab from the back wall and move past the painter into the booth. The cab would be capable of moving with four degrees of freedom: (1) raise and lower, (2) rotate, (3) traverse the width of the booth, and (4) traverse the length of the booth. When the painting is complete, the worker would move the cab to a door in the booth where he/she would exit. Table 4 lists capital cost estimates.

Width is particularly important when modifying an existing booth with the Mobile Zone System. If installed at Fort Hood or Fort Riley, it may not be possible to paint the largest vehicles such as pontoon bridges in the booth equipped with the Mobile Zone System because the Mobile Zone cab requires adequate space to move along both sides of the vehicles. These extra large vehicles are the exception, however, and may be painted in other booths. Most vehicles surveyed at these sites would fit in the retrofitted Mobile Zone booth.

Table 4. Capital cost estimates for the Mobile Zone System upgrade at Forts Riley or Hood.

Costs	Mobile Zone Upgrades
$40,000	Air handling system rework including removal of existing make-up air heater, joining of exhaust stack, addition of secondary filtration, addition of circulating air heater, replacement of primary filters, and repair of filter frames
$40,000	Engineering design
$110,000	Work platform, track, hydraulics, and pneumatic controls
$170,000	VOC control equipment – purchase and installation
$12,000	Air conditioning for work platform
$372,000	**Mobile Zone and VOC control – total**

Summary

Design studies were conducted at four Army paint booths for the potential installation of the Mobile Zone System. Table 5 summarizes the similarities and differences of the paint booths. Any of these sites could be retrofitted with the Mobile Zone

System. Fort Hood was chosen for an actual installation mainly because of project management and scheduling convenience. That paint booth retrofit is the subject of the following chapters.

Table 5. Summary of design studies.

Location	Type	Size (ft wide x long x high)	Estimated Existing Ventilation Rate[1] (cfm)	Movement degrees of freedom for Mobile Zone cab	Proposed additional equipment	Mobile Zone capital cost estimate ($K)
Watervliet Arsenal	Production, downdraft	20x35x8	70,000	1	3 dollies for 2 gun barrels	288
McAlester AAP	Production, downdraft	15x24x9	36,000	1	2 racks for 9 missile cas-ings	342
Fort Riley	Maintenance, sidedraft	22x40x15	33,000	4	No	372
Fort Hood	Maintenance, sidedraft	29x56x19	55,000	4	No	372

[1] Based on ventilated cross section.

4 Mobile Zone System at Fort Hood

System Design

The paint booth in Bay 4 of Building 88027 at Fort Hood was retrofitted with the Mobile Zone technology during Spring 2001. The design allows for operation in conventional mode or recirculation mode, either of which the operator may select with an electronic control switch. In the conventional mode, about 38,000 cfm of air moves through the booth to carry away the paint overspray and solvent fumes (this value was originally estimated during the design study at 55,000 cfm based on the cross sectional area of the booth). This air makes one pass through the booth, so that 38,000 cfm of fresh air is drawn in and 38,000 cfm of contaminated air is exhausted to the atmosphere. In the recirculation mode, the 38,000 cfm is recirculated, approximately 2,000 cfm of heated or air-conditioned fresh air is supplied to the painter, and approximately 2,000 cfm is withdrawn to the PCE. The installed PCE is a recuperative catalytic oxidizer. Because only 2,000 cfm rather than 38,000 cfm must be heated, cooled, or controlled, the capital and operating costs to perform these functions are substantially lower.

The following two schematics (Figures 20 and 21) of the sidedraft booth in Bay 4 illustrate the similarities and differences between the operation of the booth in the two different modes. Figure 20 illustrates how the ventilating air makes one pass through the booth and is exhausted to the atmosphere in normal mode. In this case, the intake air may be heated as required by the direct heater. The VOC-contaminated exhaust air is filtered to remove particulate overspray and discharged to the atmosphere. The painter gains access to the workpiece by walking, climbing a ladder, or climbing the workpiece itself.

Since the worker(s) may move anywhere within the confines of the booth, the entire cross section of the booth must be supplied with fresh ventilating air. In normal mode the Mobile Zone subsystem, which includes the Mobile Zone cab, air conditioner, heater, and fan, is not used. The Mobile Zone cab is parked off to the side and out of the way. No negative consequences resulting from the presence of the Mobile Zone subsystem occur in this mode.

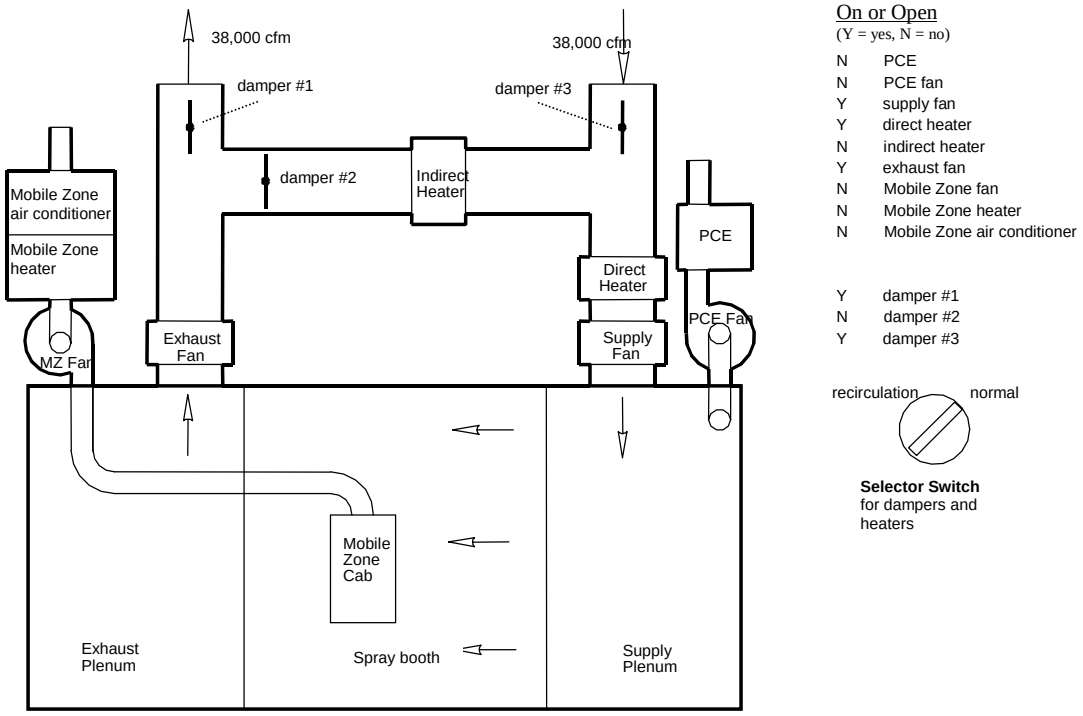


Figure 20. Mobile Zone System in normal ventilation mode.

Figure 21 illustrates the air flow in the recirculation mode. The Mobile Zone cab has four degrees of movement, allowing access to all surface areas around a vehicle in the booth. The cab is suspended from the ceiling by an overhead crane mechanism. The fresh air is provided to the cab through an articulated corridor. This air can be heated or cooled depending on the painter's comfort and temperature requirements of the booth.

Overspray control still requires uniform ventilating air throughout the cross section of the spray booth so that dampers #1 and #3 are closed and damper #2 is opened to allow recirculation. In this mode, 2,000 cfm of exhaust air is pushed through the VOC control device.

Engineer drawings of the Mobile Zone cab suspension system are shown in Figures 22–24. Figure 22 shows the top view of the system. Figure 23 shows the side view and the end view is shown by Figure 24. The booth dimensions are 29-ft wide, 56-ft long, and 23-ft high. A steel frame to suspend the cab is positioned to fit just inside these dimensions as shown by the drawings. Horizontal travel in the length and width of the booth are provided by an overhead crane mechanism driven by pneumatic motors. The cab is capable of rotating in place and extending down to the floor. Pneumatic motors also control these movements. Air to drive the motors is

provided by existing compressors at Fort Hood. The worker controls the cab with joysticks mounted in the cab. The cab is capable of traveling 25 fpm horizontally, 15 fpm vertically, and rotating 1 revolution per minute.

The cab dimensions are 40-in. wide, 52-in. long, and 114-in. tall. The cab is open on one side, and the rear of the cab has a perforated panel (with slots) that provides laminar flow through the cab at a rate of 100 fpm. It has a design load of 400 lb and low-voltage explosion-proof task lighting built into it. The following utility services are provided to the cab: flexible ventilation hose, paint line, compressed air line, breathing line, and electrical line. These utilities are supplied through a retractable energy chain that is supported by a track mounted on the steel frame. The cab is equipped with overload protection to restrict the transmitted force to 200 lb in case it makes contact with an object. For emergency situations, a battery operated flashlight is mounted inside the cab; there is a ladder in the booth for access to the floor; and a secondary control unit cab is located on the lower exterior of the cab so that the cab can be operated from the ground using a provided extension pole.

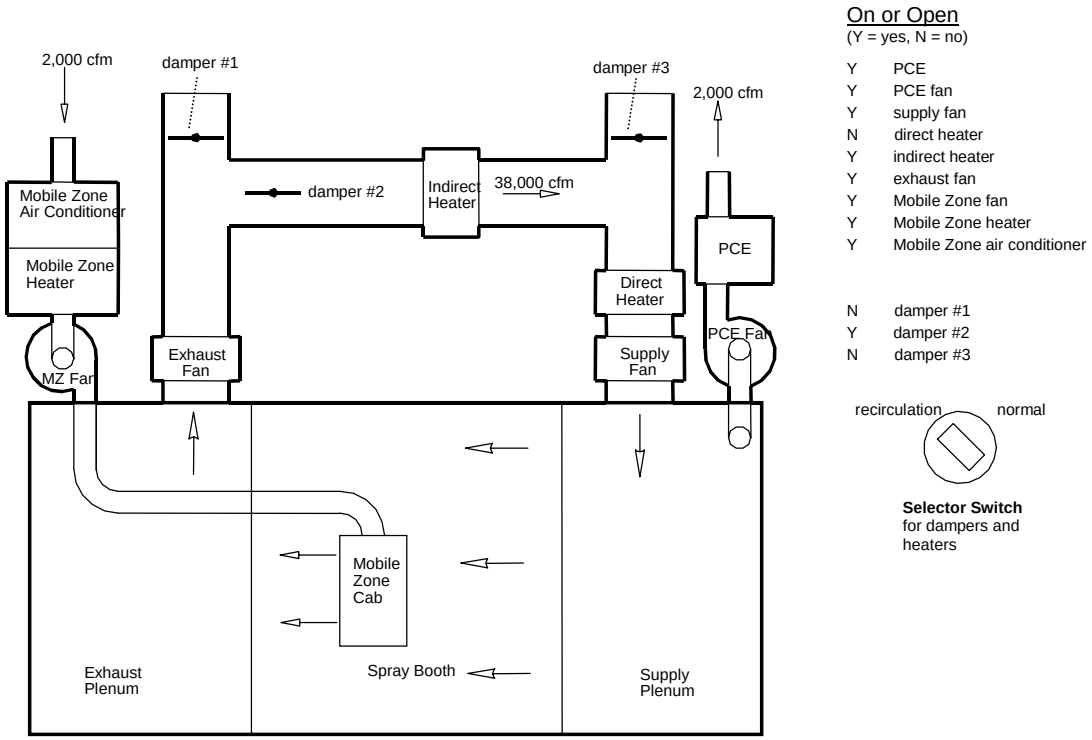


Figure 21. Mobile Zone System in recirculation mode.

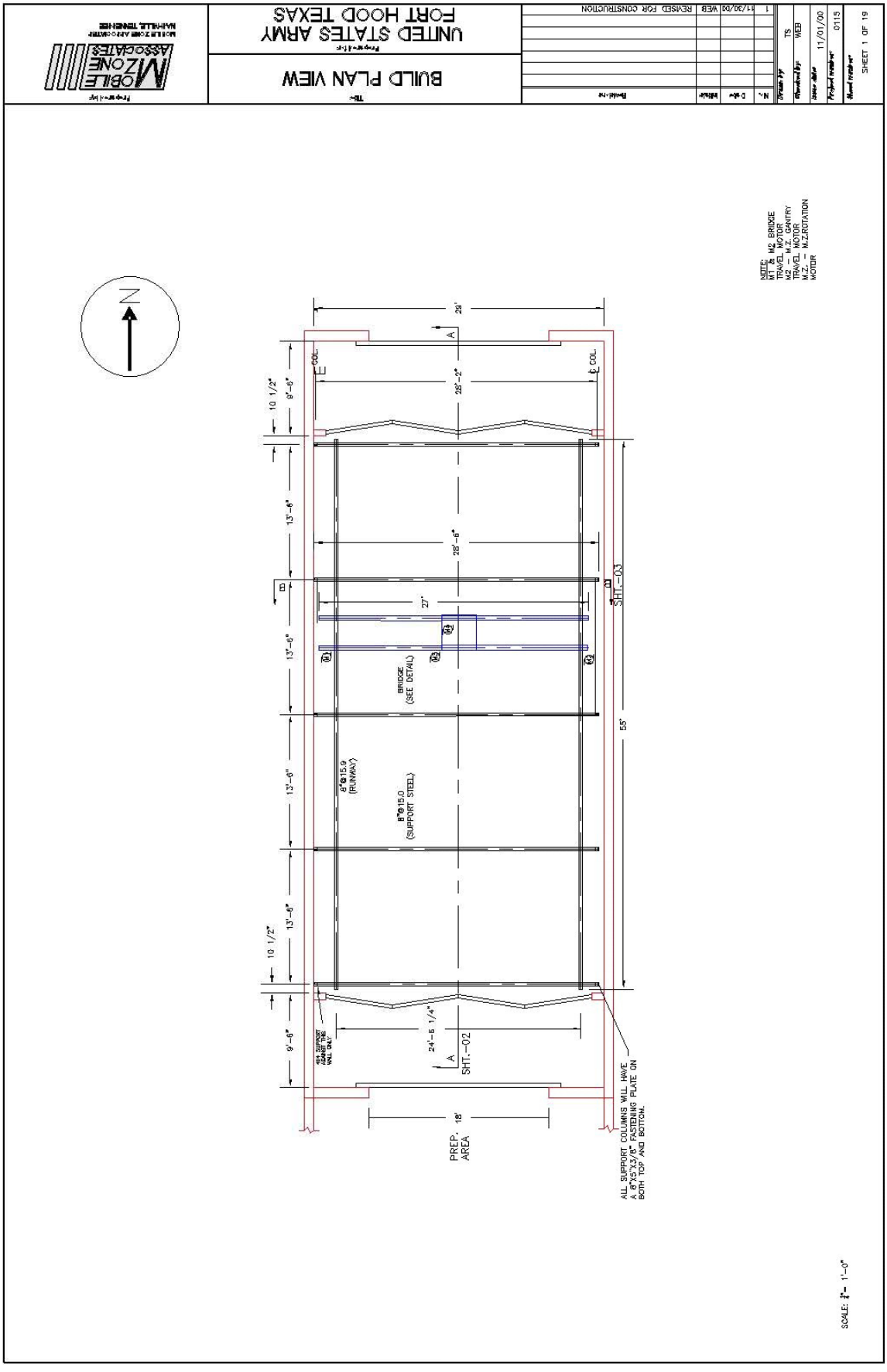


Figure 22. Top view drawing of Mobile Zone cab suspension system, Fort Hood design.

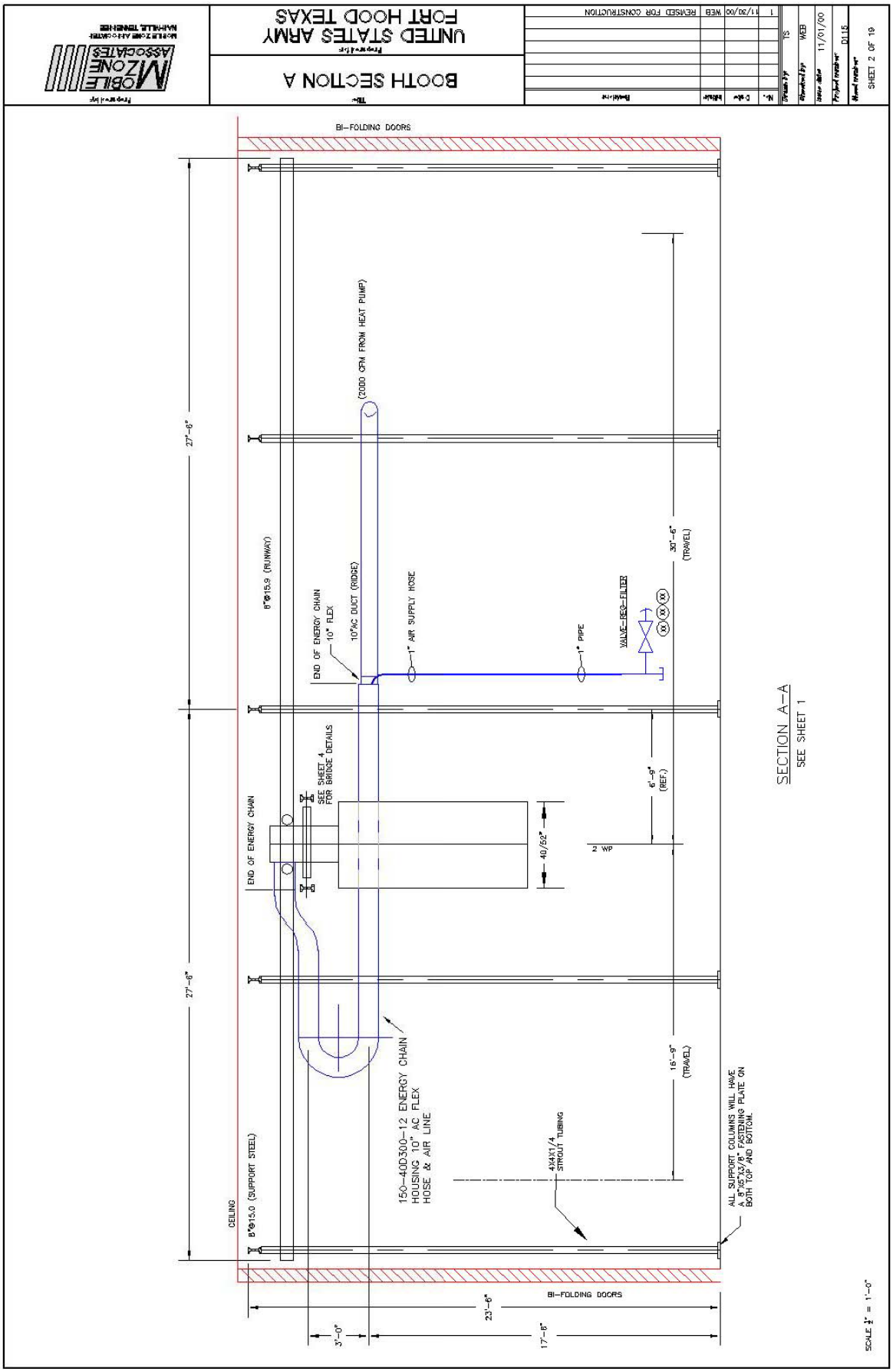


Figure 23. Side view drawing of Mobile Zone cab suspension system, Fort Hood design.

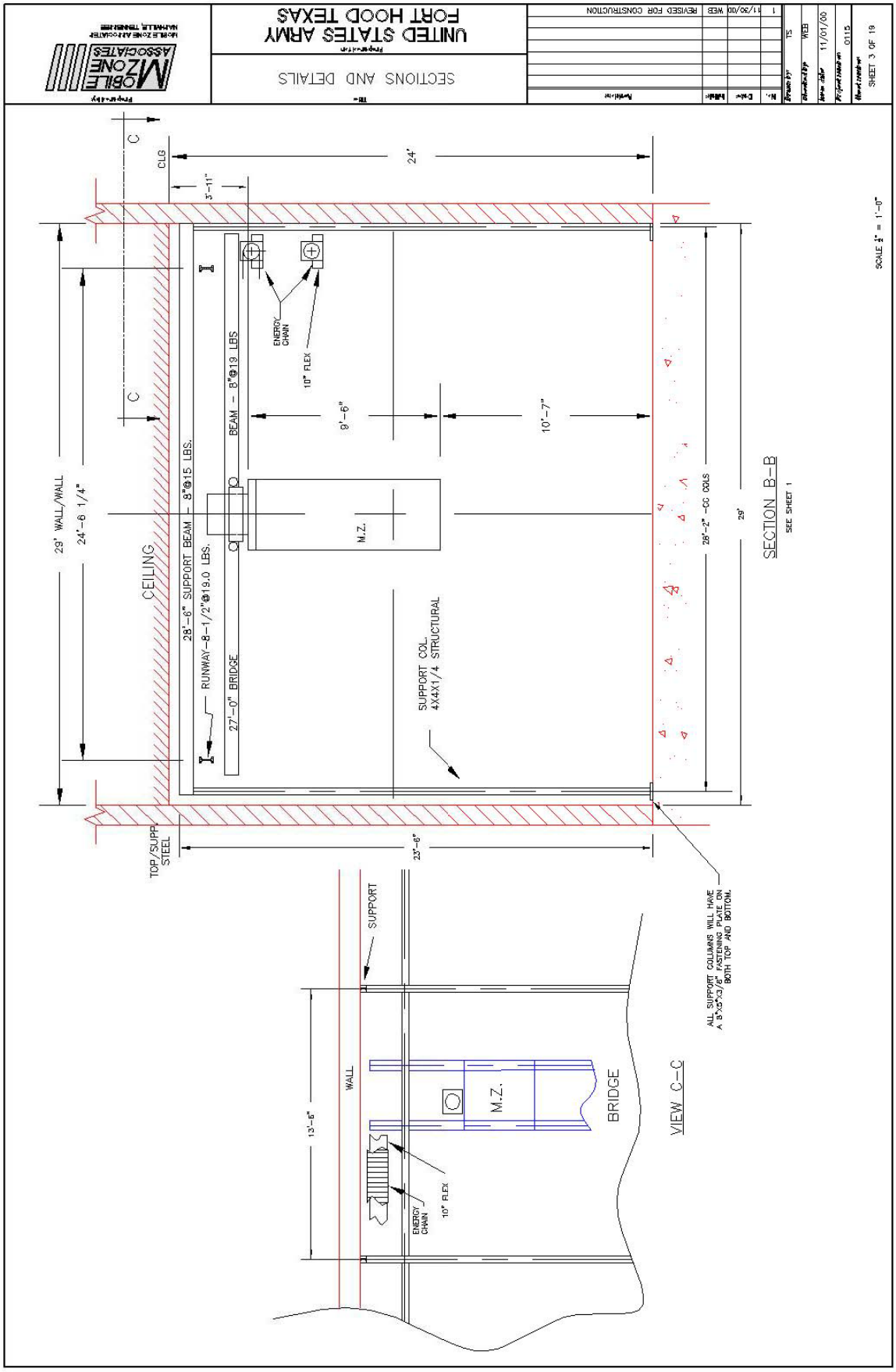


Figure 24. End view drawing of Mobile Zone cab suspension system, Fort Hood design.

The Mobile Zone cab and suspension structure was designed by Mobile Zone Associates of Nashville, TN and fabricated by Kolemba Industries, Inc. of Nashville, TN. When the system was completed, it was dismantled, shipped to Fort Hood, and reassembled in Bay 4. Texas Mechanical Systems, Inc. of Killeen, TX installed the system and performed all of the ventilation system and booth modifications (Figure 25). The ventilation system modifications include installing the recirculation ductwork with dampers and an indirect gas heater, the Mobile Zone subsystem, and their respective controls. The booth modifications included moving the existing ceiling lights to the wall, installing an access door to the booth that is compatible with the cab, and installing a secondary dry filter bank.

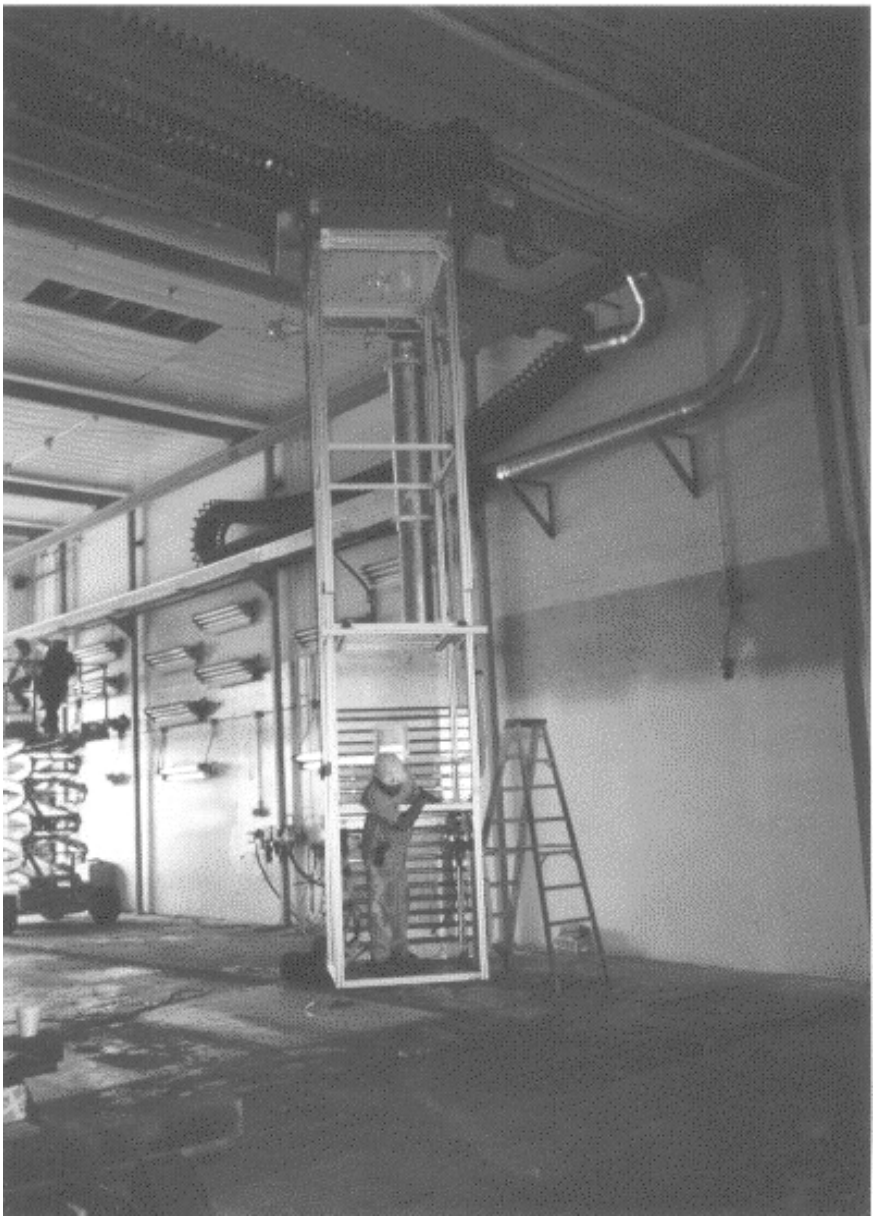


Figure 25. Interior of Bay 4 during installation with Mobile Zone cab extended downward.

The PCE is a catalytic recuperative oxidizer unit fabricated by HiTemp Technology Corporation of Ringoes, NJ. It was installed under the supervision of MSE Technology Applications, Inc. (MSE-TA, Inc.) of Butte, MT. The control system includes a fan, heat exchanger, burner, controls and exhaust stack. It was supplied in several components, but could have been completely skid mounted and fully assembled. The installation included a support stand that is mounted along the exterior wall of Bay 4 (Figure 26). Figures 27–28 show the Mobile Zone cab and Figure 29 shows the exterior ductwork.

Figure 26. Pollution control equipment mounted on west side of Bay 4.

Figure 27. Mobile Zone cab with painter.

Figure 28. Painting the back end of a truck using the Mobile Zone cab.

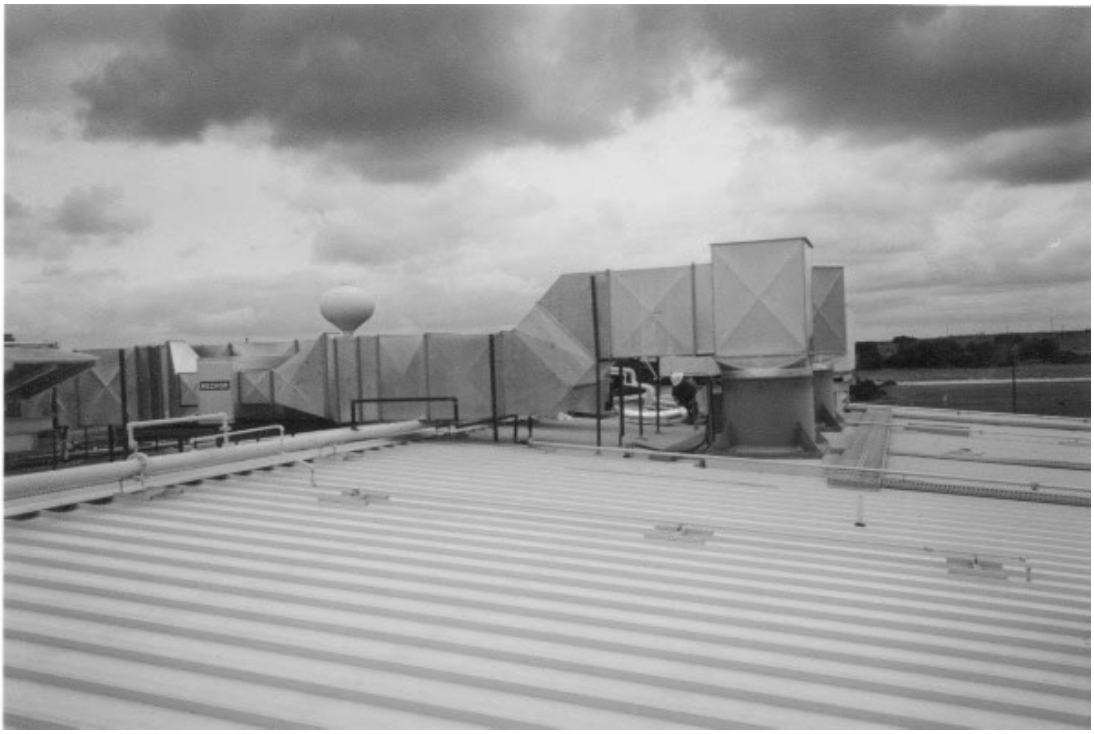


Figure 29. View of recirculation ductwork mounted on roof of Bay 4.

Capital Cost Analysis

Capital costs incurred during the installation of the Mobile Zone System at Fort Hood are shown in Table 6. The installation occurred during 2001 so that the values are listed in 2001 dollars. This was the first complete installation of the Mobile Zone System, which is based on a site-specific design, and therefore required additional effort and occasional redesigning throughout the designing, building, and installation. The costs for these changes are represented as the difference between the original and modified values presented in Table 6. It should be expected that future installations will benefit from these efforts and will ultimately cost less to implement.

Table 6. Capital costs for Mobile Zone System installation at Fort Hood.

Item	Original (2001$)	Modified (2001$)
VOC Control Unit		
Fabricate unit	60,000	66,000
Installation and materials	46,119	60,000
Design, engineering, management	71,000	71,000
Mobile Zone Cab and Support System		
Design and technical oversight	48,000	48,000
Construction	93,200	106,120
Ventilation, Booth Modifications, and Cab Installation	80,372	80,372
Total	**398,691**	**431,492**

Technical Objectives of Installation

The installation of the Mobile Zone System at Fort Hood can be judged by a number of objective and subjective criteria. Most of these were evaluated during field testing while others, mainly the subjective criteria, will depend on the opinions of the painters and users of the technology.

Objective Criteria

1. A minimum 90 percent reduction in the spray booth exhaust rate is expected in the Mobile Zone recirculation mode.
2. No negative impact on production rates or quality.
3. No negative impact on worker safety.
4. The booth shall retain its existing flow ventilation pattern, nominally, a laminar ventilation pattern.
5. The booth shall retain its existing multi-stage dry filtration.

6. The booth's modifications shall meet current NFPA 33 standards (NFPA 1988) and OSHA regulations (29 CFR 1910.94) without a variance.
7. A minimum VOC destruction efficiency of 81 percent.
8. Cost 20 percent less than the cost for conventional VOC control.

Subjective Criteria

1. The equipment shall be designed for longevity, reliability, and maintainability including stock materials and components wherever possible.
2. The equipment will be intuitive to use, requiring little training.
3. The equipment will be convenient to use so that it will be the first choice of the painter, assuring a high utilization rate.

5 Field Testing at Fort Hood

After the complete installation of the Mobile Zone System at Fort Hood, a series of tests were conducted to simulate normal operating conditions. Four tests were conducted over a 3-day period beginning 26 June 2001. The tests were configured as a matrix of two different types of paint processes (chemical reagent resistive coating [CARC] rated paint with no primer coat versus type W959 paint with primer coat), and two different paint booth configurations (baseline versus Mobile Zone recirculating mode). The key objective of the tests was the determination of VOC removal efficiencies of the new control equipment and process as compared to the current methods and equipment being used. MSE-TA, Inc. conducted all sampling activities during these tests.

Test Procedure

The original plan was to conduct a campaign of three tests for each of the two paint booth configurations. Due to time and budget constraints, the test campaign was abbreviated to three tests in the baseline configuration (without recirculation, cab, and PCE) and two tests in the Mobile Zone recirculation configuration. In the first test, it was discovered that one of the four recirculation dampers intermittently failed in the closed position. That test was eliminated and the remaining four tests, numbered 1 through 4, were considered valid. Table 7 summarizes these tests.

Table 7. Test matrix.

	Test Number			
	1	**2**	**3**	**4**
Paint Booth Configuration	Baseline	Mobile Zone	Mobile Zone	Baseline
Paint Application No.	Paint No. 1	Paint No.1	Paint No. 2	Paint No. 2
Vehicle Painted	Utility Truck M1009	Utility Truck M1009	Utility Truck M1009	Utility Truck M1009
Total Primer/Thinner During Priming	None	None	21.2 lb	21.0 lb
Total Paint/Thinner/ Hardener During Painting	20.4 lb	20.4 lb	28.0 lb	27.2 lb
Date of Test	6/27/2001	6/27/2001	6/28/2001	6/28/2001
Time Started	9:06 am	2:18 pm	9:55 am	1:53 pm
Time Completed	10:16 am	3:40 pm	11:48 am	3:12 pm
Total Test Time (approx.)	70 min	82 min	113 min	79 min

The configuration of the paint booth remained essentially unchanged between Tests 1 and 4 (baseline tests) and Tests 2 and 3 (Mobile Zone tests). In addition, the same vehicle type was used, and the same paint operator participated in all four tests.

Paint No. 1 in Table 7 is a routinely used military paint referred to as a CARC. Shades of green or brown CARC paint are typically applied to the field vehicles for protection against chemical agents and other atmospheric conditions. Paint No. 2 is applied to base and depot vehicles that will not normally be called into combat duty. A weighing scale was used to weigh each paint, thinner, or hardener container weight before and after each test to determine the weight of paint used. Table 8 describes the two paint applications.

Table 8. Paint applications used in testing.

	Paint Application Number	
	Paint No. 1	**Paint No. 2**
Primer Type	None	Dupont Variprime 615S
Primer Converter Type	None	Dupont Variprime 616S
Primer Mix Primer/Converter	None	1 gal/1 gal
Paint Type	Sherwin-Williams CARC MIL-C-53039A	Western Automotive W959
Thinner Type	Sherwin-Williams MIL I-81772B	Western Automotive RS8214
Hardener Type	None	Matrix Systems MH-100
Paint Mix Paint/Thinner/Hardener	23 lb/2.0 lb/0 lb	1 gal/.5 gal/.125 gal

Two identical Thermo Environmental Model 51 Total Hydrocarbon (THC) analyzers were used to measure VOC concentrations. They were configured to report results as parts per million by volume (ppmv) and were used with JCT brand heated probes and heated sample hose (probes and hose included temperature controllers). A special calibration solenoid box was used to facilitate the calibration task. For each test, calibration and drift checks were performed. The drift check was performed with certified zero air.

The calibration gas for the THC analyzers was propane mixed with air. A "response factor" (otherwise known as a "carbon equivalent correction factor") of three was used to correct their measured response because propane has three carbons in its molecule. This relationship is described in Equation 1 (EPA Reference Method 25A, Eq. 25A-1).

$$C_c = K\ C_{meas} \quad \textbf{[Eq 1]}$$

where:

C_c = Organic concentration as carbon, ppmv

C_{meas} = Organic concentration as measured, ppmv

K = Carbon equivalent correction factor (3 for propane)

All concentration data are corrected for the response factor and presented as organic concentration as carbon, or C_c, in parts per million on a volume basis (ppmv).

The instrument installation, calibration, test procedure, and data analysis were performed according to 40 CFR 60, Appendix A, Method 25A. This is a regulatory standard used in point-source continuous emissions monitoring, and was applied in this case to ensure the quality of the test data.

VOC Sample Probe Locations

In the baseline test configuration, all air from the paint booth was discharged through two blower stacks on the roof (no PCE). It was assumed that the VOC concentration is homogeneous and identical in both discharge stacks, so that the VOC concentration was measured in only one of the stacks for this test series. A single heated sample probe was mounted at the center of the 4-ft square North discharge duct, just above the fan. It was connected to the analyzer using 150 ft of heated sample hose (100-ft plus 50-ft hose connected together). The measurement range of the analyzer was set from 0 to 100 ppmv THC.

In the Mobile Zone configuration, the air was recirculated in the booth and only treated air was discharged to the atmosphere. The sample probes were positioned to measure the VOC removal efficiency of the Mobile Zone System. They were mounted at the inlet and outlet of the PCE, which is a catalytic recuperative oxidizer. The oxidizer was operating at a temperature of 548 °F (284 °C). The inlet probe was connected using the 50-ft section of heated sample hose, and the outlet probe was connected using the 100-ft hose section; therefore, there was a short time delay between the inlet reading and outlet reading. The measurement range of the inlet analyzer was set from 0 to 1000 ppmv THC, and from 0 to 100 ppmv THC for the outlet analyzer.

Data Acquisition

The data acquisition hardware consisted of a Micron personal computer (MPC Computers, LLC, Nampa, ID) with Microsoft® Windows 98 pre-installed, and a Keithley 8-channel (analog differential-input mode) 16-bit resolution data acquisition card installed into the computer motherboard. Special considerations were given to signal grounding and noise shielding to prevent noise from corrupting the signals. The analyzers were connected to this hardware to record the VOC measurement data in 5-second intervals.

LabVIEW data acquisition software (National Instruments Corp., Austin, TX) was used with a special application developed for compatibility with the Keithley card (Keithley Instruments, Inc., Cleveland, OH) and tailored to the paint booth pilot test. This software provided control over the data acquisition process and provided data graphic display and storage of time-stamped data to the hard disk drive in a Microsoft® Excel spreadsheet-compatible format. This format allowed for easy access to various viewing methods and linkage to word processing and other reporting software tools.

The test results were logged onto the data acquisition computer and periodically recorded manually as a backup check. A logbook of test activities was recorded and Monitoring Summary sheets were filled out. Records of the VOC instrumentation calibration and drift checks were also filled out on the forms.

The data acquisition computer (and the THC analyzers) was installed in a temporary 8 ft by 20 ft environmentally controlled office building. This building also served as an office to collect and record data, test parameters, and perform calibrations.

Air Flow Measurements

Air flow velocity measurements were made using pitot tube traverses according to 40 CFR 60, Appendix A, Method 1. These measurements were conducted at three different locations, the two roof-mounted discharge stacks during baseline configuration and the inlet to the PCE during the Mobile Zone configuration. Both of the 4-ft^2 discharge stacks were metered using pitot tube grid traverses made through five small holes on one side of the duct, all located at the same height on the vertical stack. The 12-in. diameter round duct inlet to the oxidizer was metered using pitot tube traverses through two small holes 90 degrees apart in the duct. All velocities were calculated using differential pressure measurements resulting from the pitot tube placement, and includes actual air density calculated from dry/wet bulb temperatures, barometric pressure, and elevation.

Test Results

Air Flow Measurements

The measured air velocity for the North stack was 1,272 fpm, and calculated volumetric air flow was 20,355 cfm. The measured air velocity for the South stack was 1,069 fpm, and calculated volumetric air flow was 17,106 cfm. The total volumetric air flow for the two stacks is therefore 37,461 cfm. The measured air velocity for the inlet to the PCE was 2,712 fpm and the calculated volumetric air flow was 2,130 cfm. The velocities were assumed to be constant for the duration of the test series.

Emission Data

Table 9 summarizes the emission data for the four tests. Details regarding the methods for calculating the values in Table 9 can be found in Appendix A. The data in Appendix A also show that during the tests under the Mobile Zone configuration, the total THC emissions discharged to the atmosphere were reduced to less than 30 ppmv. The primary results shown in Table 9 are that, for the CARC paint process, the VOC reduction through the PCE is 93 percent, and for the W959 paint process the VOC reduction is 96 percent.

Table 9. Summary of emission data.

	CARC Application		W959 Application	
	Test #1	Test #2	Test #3	Test #4
Paint booth configuration	**Baseline**	**Mobile Zone**	**Mobile Zone**	**Baseline**
Total THC measured exiting paint booth (ft^3, entering PCE in Mobile Zone case)	124	28.2	95.4	385
THC Discharged from stack (ft^3, exiting PCE in Mobile Zone case)	124	1.97	4.27	385
Total THC Removed by PCE (ft^3)	NA	26.2	91.1	NA
THC Reduction (%)	NA	93	96	NA
Ratio of Total THC measured exiting the paint booth between Mobile Zone and Baseline Tests	0.23		0.24	

Figure 30 shows the control efficiency versus inlet concentration for Test Runs 2 and 3 (Mobile Zone configuration). The data on this graph was calculated by dividing the PCE outlet concentration by the inlet PCE concentration for each sampling time. As expected, the control efficiency for this PCE increases with increasing input concentration.

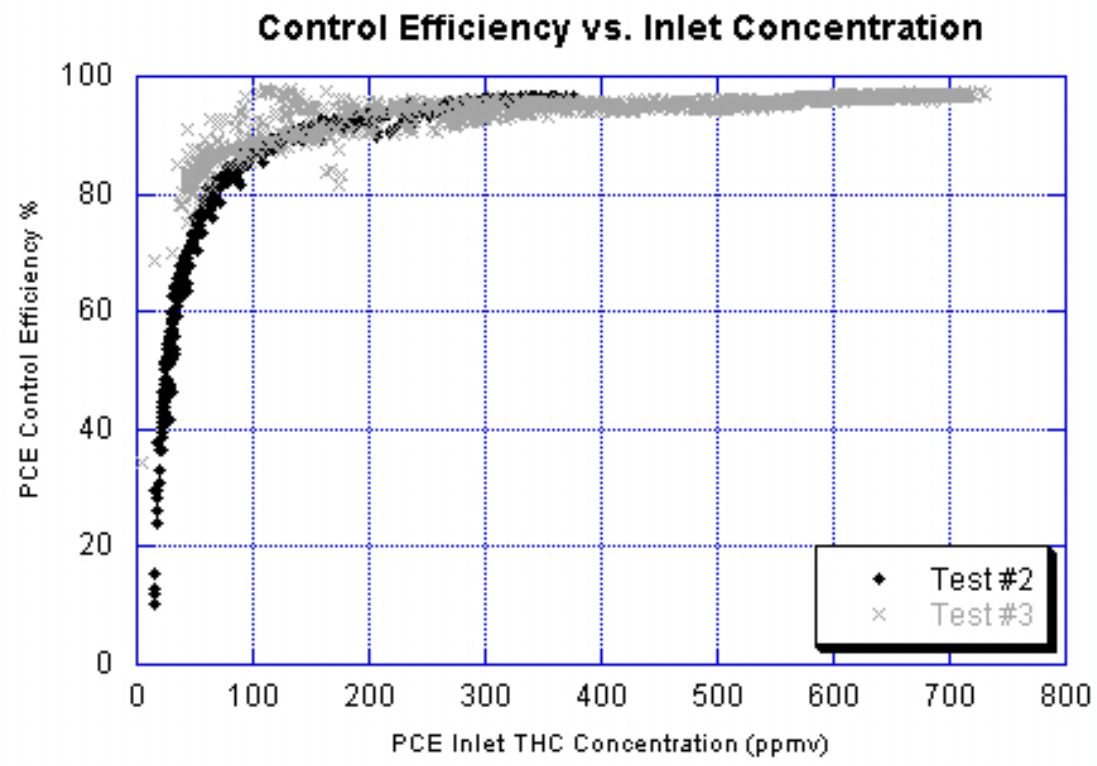


Figure 30. Control Efficiency versus PCE inlet concentration for Test Numbers 2 and 3.

A similar amount of paint was used between the Mobile Zone and baseline tests for each paint application, which suggests that similar amounts of VOCs should be released from the painting process. The explanation for the large difference between measured total THC values is not known; however, the similar ratio of total THC between the Mobile Zone and the baseline configurations suggests that the cause is systemic. One possible explanation is that, in the Mobile Zone test configuration, inadvertent positive pressure occurred within the paint booth due to an imbalance in total blower airflow. This could cause VOC leakage from the paint booth and a reduction in the recorded VOCs at the discharge into the thermal oxidizer. This occurrence would also suggest that the PCE was not receiving the full load of VOCs expected during the test. This is not a concern regarding the PCE destruction efficiency because it tends to increase with increasing VOC inlet concentration as shown by Figure 30. It was determined through inspection at a later date that the PCE exhaust fan was not pulling as much as intended (estimated at no more than 10 percent less) because the centrifugal fan was rotating in the wrong direction. This may explain a very small portion of the difference; however, it is highly unlikely that 75 percent of the VOCs leaked. That amount of leakage would imply that the volumetric flow of the leaks was three times greater than the exhaust rate through the PCE.

Productivity

The time to complete painting operations was less in the baseline configuration when the Mobile Zone platform was not used than when using the platform in the Mobile Zone configuration (see Table 7). The reason for this is twofold:

1. The painter had very little training on the operation of the Mobile Zone platform, which caused a significant reduction in efficiency. There would be a learning curve to get used to operating the joysticks and moving the platform to the right locations. In contrast, the painter was very experienced at painting without the platform.
2. The air pressure in the paint pot was not high enough, and the spray pattern was too small because the diameter of the air line to the paint pot was not large enough. This required more spray passes over the workpiece.

One of the goals for the Mobile Zone System is to enable increased productivity while using the Mobile Zone spray platform. The testing did not show this desired increase. The reasons cited above can be remedied, however, and the prospect of improved productivity still exists.

6 Improvements to the Mobile Zone System

System Improvements

During and after the test campaign, a number of operational problems were listed and improvements were recommended for the Fort Hood Mobile Zone System. The improvements include:

1. The air flow under the Mobile Zone configuration was balanced. The main correction was changing the rotation of the PCE exhaust fan, because it was turning in the wrong direction. Though not measured, the resulting exhaust flow is most likely greater than the 2,130 cfm measured during the testing.
2. The previous task lighting was an explosion-proof 4-ft fluorescent fixture mounted on the top front of the cab. It interfered with painting of vehicles, particularly near the side view mirrors. This prevented the painter from approaching the vehicle to a desirable distance to paint comfortably. The task lights were replaced with two explosion-proof incandescent lights at the front of the cab, above the operator's head. The new lights can be seen in Figure 31, and the old fixture can be seen in Figure 27.
3. The response times of the pneumatic controls on the cab were too slow and the controls were difficult to use. The operator should have good control of the cab when approaching a vehicle to avoid a collision. The existing air lines to the controls were 1/4-in. inside diameter (I.D.) tubing. They were all replaced with 3/8-in. I.D. tubing. New controls and valves were also installed to all of the tubing with 3/8-in. I.D. tubing (Figure 32). A new single joystick control assembly replaced the existing double joystick controls for easier one-handed control (see Figure 35).
4. As mentioned in the previous chapter, the 5/16-in. I.D. paint pot air line was too small. It was replaced with a 3/8-in. I.D. air line.
5. The cab lift power transmission was changed from v-belt to chain drive for improved reliability (Figure 33).
6. The existing safety bar on the cab was too high and had a potential pinch point. A new safety bar was installed at a lower height that bows outward to offer more reach for the painter. The bar has a guard to eliminate the pinch point and allows the new joystick assembly to slide across to accommodate both right- and left-handed painters (Figure 31). As a new safety feature, the safety bar must be in place for the cab to operate.

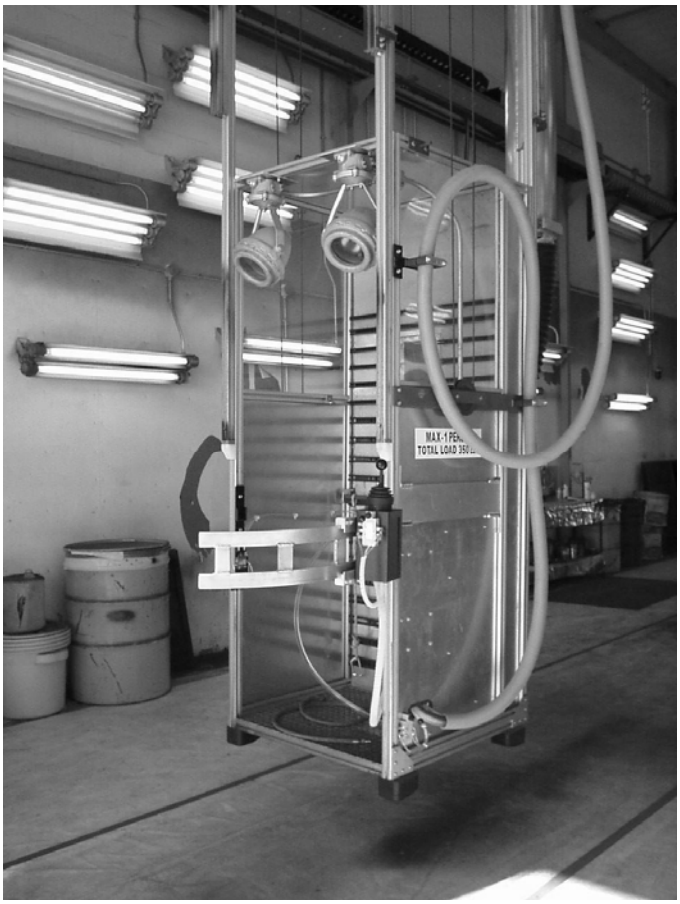


Figure 31. Mobile Zone cab at Fort Hood.

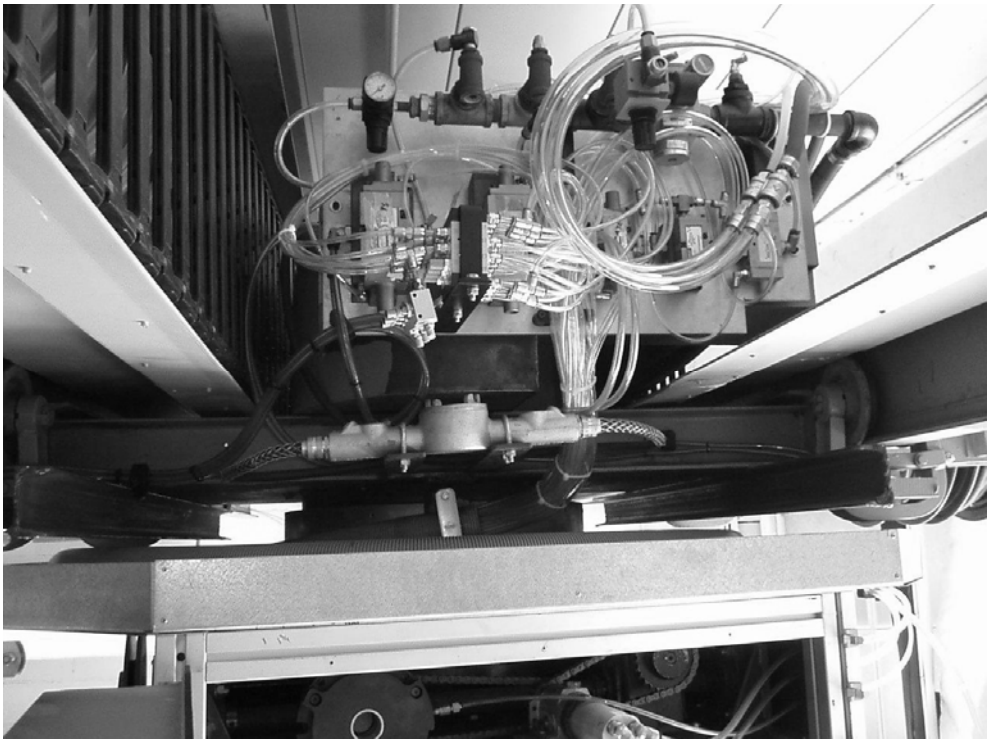


Figure 32. New pneumatic controls and air lines on cab.

Figure 33. Chain drive for cab lift power transmission.

7. The operators requested that the electrical control system that operates the paint booth heating, ventilating, and air-conditioning (HVAC) equipment allow for the use of the Mobile Zone cab while operating the system in the normal baseline configuration. This change was incorporated into the control system.
8. The HVAC equipment was having difficulty providing adequate cooling to the booth. The exterior duct supplying air to the cab was insulated with 1-in. thick spray-on foam with an ultraviolet (UV) barrier topcoat. An additional 5-ton cooling unit was installed upstream of the existing primary cooler. It operates at the same time as the primary cooler but is controlled by an independent outdoor air temperature thermostat. The exterior recirculation ductwork on the rooftop was also insulated with 1-in. thick spray-on foam with a UV barrier topcoat. Figure 34 shows both air coolers and some insulated ductwork.

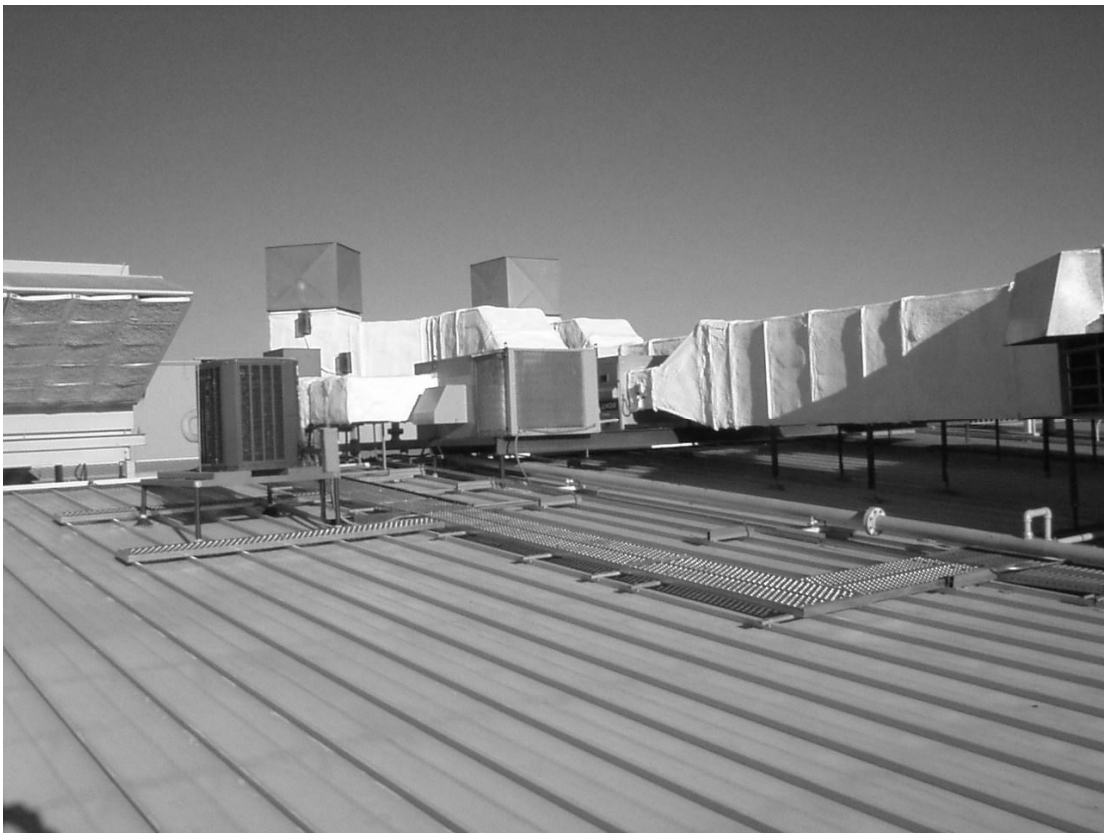
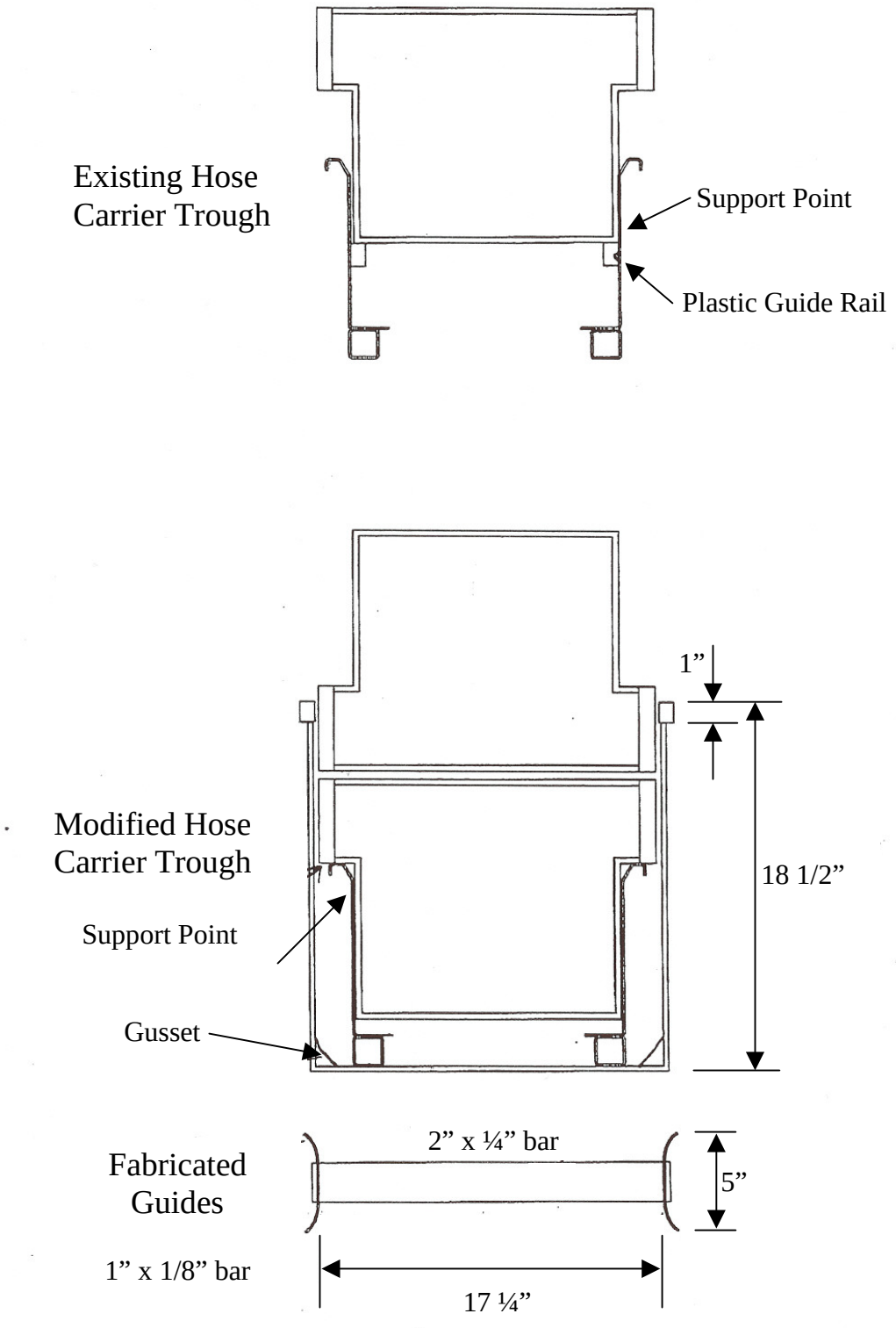


Figure 34. Rooftop view of air conditioners, walkways, and spray-on insulation.

These improvements were completed by the end of 2002. While this work was being completed, there were two other modifications made to the booth. These include extending the rooftop pathway (Figure 34) and remounting some of the fluorescent lights on the side wall of the booth. The additional cost for the redesign and installation of the improvements and these two modifications was $90,257. This cost also included 9 months of maintenance inspections to ensure that the booth operated properly.

Several months into 2003, it was discovered during a maintenance inspection that the air hose carrier system for the Mobile Zone cab was not functioning properly due to a broken rail. This system required a design modification to keep the carrier from derailing. This design change is shown in the cross-sectional view in Figure 35. Fabricated guides were placed along the trough at a frequency of 10 per every 3 ft. This modification cost $10,770 and was completed in November 2003.

Upon completion of all the modifications discussed here, the booth and cab functioned properly. All known problems and deficiencies were corrected. The total cost for the modifications to the Mobile Zone System and the booth since the original testing was $101,027.



Not to scale

Figure 35. Cross-sectional drawings of guides in hose carrier trough.

Operation After Modifications

Between November 2003 and May 2004, a pilot-scale prototype vapor recovery system was installed near Bay 4 at Fort Hood. A 3-in. diameter slipstream line was drawn from the 12-in. diameter inlet to the PCE. Testing was conducted regarding the ability of this prototype to control and recover VOC emissions from the painting process (Ramirez et al. 2004). As a result of these tests, data were collected that provide information regarding the quantity of VOC pulled into the PCE during painting (see next section).

Currently, the painters that use Bay 4 at Fort Hood do not use the Mobile Zone cab. However, the paint booth operates under the Mobile Zone configuration with the PCE operating. The PCE has been permitted and is earning emission credits for the base (Finney 2004). The painters do not want to use the cab because of the potential risk of damage to vehicles, particularly helicopter-related parts. The painters fear that they will lose their jobs if they cause a dent. The risk of causing a dent is mostly just a perception, especially now that improvements have been made to the pneumatic system. Even if a collision were to occur, the force of the cab is not large so a dent would be difficult to cause. Someone standing near the cab could move or stop it easily with one hand on a bottom corner. In addition, the use of the booth under a more VOC-concentrated environment is not particularly advisable or recommended. As can be seen by the test data and the subsequent testing of the pilot vapor recovery system, the concentration in the booth rarely exceeded 700 ppm. This level is fortunately not close to the explosive concentration. However, the painters do wear protective suits and respirators with fresh air. As long as the local industrial hygienist approves these conditions, it is an acceptable manner in which to operate the booth. By not using the cab, however, the painters deny themselves the convenience of easily reaching high places and the comfort of air conditioning during the warm seasons. Figure 36 shows a painter using the modified Mobile Zone cab.

Data from Vapor Recovery System Tests

Some of the data collected during the testing of the prototype vapor recovery system have been compared to the expected amount of VOCs calculated from the respective MSDS. During November and December 2003, data were gathered for two adsorption cycles (specified time periods) with the following calculated VOC generation rates: 1.121 pounds per hour (lb/hr) and 1.548 lb/hr. The respective measured quantities of VOC in the PCE inlet were 1.636 lb/hr and 4.166 lb/hr. This comparison shows a measured amount greater than expected by 46 percent and 169 percent, respectively. Appendix B shows the calculations with more detail.

Some notable differences between these tests and the original testing are that the THC analyzers in the most recent test were calibrated with methyl ethyl ketone instead of propane, the paint applications are different, the sampling was taken in the 3-in. slipstream as opposed to a probe in the 12-in. duct, and the duration of an adsorption cycle involved many painting events while each original test involved only one vehicle. Methyl ethyl ketone was used in this test because it was more similar to the actual paint VOCs than propane, and it was the compound used to calibrate and test the vapor recovery system. Due to these differences, these data and calculations cannot verify nor disqualify any of the previous data. However, because it shows that, under the Mobile Zone configuration, the measured quantity of VOCs is greater than the expected amount from the MSDS information, it contradicts the data from the original testing where the measured data were significantly lower. This does not explain the 75 percent lower values found with the Mobile Zone configuration than with the conventional baseline configuration seen in the initial testing. However, because the MSDS estimated values were even greater than the calculated VOCs generated in those tests, it supports the idea that, under the Mobile Zone configuration, all VOC emissions generated are flowing to the PCE for treatment.

Figure 36. Painter in modified Mobile Zone cab.

7 Evaluation of Mobile Zone System Criteria and Summary

Evaluation of Mobile Zone System Criteria

Objective Criteria

1. *A minimum 90 percent reduction in the spray booth exhaust rate is expected in the Mobile Zone recirculation mode*: During the testing, the total exhaust air flow measured in the conventional mode was 37,462 cfm. The exhaust air flow in the Mobile Zone recirculation mode was measured at 2,130 cfm. This represents a 94.3 percent actual reduction. This criterion has been met.
2. *No negative impact on production rates or quality*: The time to complete the painting was less in the baseline configuration than that of the Mobile Zone configuration. This indicates that the production rate was decreased by the Mobile Zone System. There was no indication that the paint quality was inferior. The production rate portion of this criterion was not met and the quality portion was met. During the testing, the painter was not experienced with operating the cab, and the air pressure in the paint pot was lower than normal. These factors slowed the painting process. The air line to the paint pot has since been replaced, and the painter could easily gain more experience with the cab operation. It is recommended that this criterion be re-evaluated with additional production rate data.
3. *No negative impact on worker safety*: In the Mobile Zone configuration, there is fresh air flowing past the painter at over 100 fpm, and the painter is securely elevated to necessary heights in the booth. In the conventional configuration, the painter has less than 100 fpm based on the measured exhaust air flow, and the painter must either climb the vehicles to paint high or use a ladder. The Mobile Zone System has impacted worker safety in a positive manner. This criterion has been met.
4. *The booth shall retain its existing flow ventilation pattern, nominally, a laminar ventilation pattern*: In the Mobile Zone configuration, the paint booth retains the same amount of air flow through the booth as in the conventional configuration. The only difference is that approximately 6 percent of the flow enters through the cab and exits to the PCE. This insignificant change should not affect the general laminar flow pattern in the booth. However, during painting the cab is located immediately in front of the workpiece so that the flow exiting the cab will have an

immediate influence on the painting activity. Fortunately, the effect is beneficial because the flow is directly at the workpiece so that the painting is "with the wind." It is more difficult and less efficient to paint against the flow or a crossflow than with the flow. A laminar flow exiting the cab was verified during construction of the cab. It is believed that this criterion has been met, but this belief is not substantiated by data.

5. *The booth shall retain its existing multi-stage dry filtration*: The existing dry filter system of Bay 4 was not modified. However, the filter elements were replaced with high efficiency filters by Fort Hood prior to the installation of the Mobile Zone System. This change caused an imbalance between the intake and exhaust fans of the original setup. This imbalance was corrected by changing the exhaust fan during the Mobile Zone installation. This criterion has been met.
6. *The booth's modifications shall meet current NFPA 33 standards (NFPA 1988) and OSHA regulations (29 CFR 1910.94) without a variance*: The exhaust air was measured at 2,130 cfm. Assuming that the air entering the cab is 2,130 cfm, the air velocity is 107 fpm across the painter. This exceeds the OSHA and NFPA 33 standards of 100 fpm for painter ventilation. This criterion has been met.
7. *A minimum VOC destruction efficiency of 81 percent*: Data taken during the testing at Fort Hood showed destruction efficiencies of 93 percent and 96 percent for the CARC and W959 paint applications, respectively. It is noted that only one set of tests was conducted for each paint application, and each test involved the painting of one vehicle. The testing also revealed an issue with accounting for all emissions generated by the painting activity. The initial tests showed an amount of VOC exhausted to the PCE to be 72 percent lower than expected. If this figure is accurate, the remaining VOC exhausted from the booth in a different manner. However, subsequent tests after modifications were made to the system indicated a 46 percent and 169 percent greater amount of VOC exhausted than expected. Also, the destruction efficiency of the PCE tends to increase with increasing VOC inlet concentration for the concentration range seen in this study (see Figure A.3). It is safe to assume that the booth is now exhausting all the VOC generated to the PCE and that it is at least controlling it at the same destruction efficiency as measured in the original test. This criterion has been met.
8. *Cost 20 percent less than the cost for conventional VOC control*: The expected cost to control the paint booth without the Mobile Zone System is estimated at $1.5 million. The cost to install the Mobile Zone System with the small control device to treat the 2,130 cfm exhaust air was $431,492, while the initial estimate was $372,000. Necessary improvements were made to the system for an additional $101,027. This brings the total cost for the system at Fort Hood to $532,519. This cost is 64 percent less than the expected conventional system. The large increase in cost over the initial estimate is due to unexpected design changes and necessary improvements. Implementation at another site would benefit from these enhancements, so the cost would be closer to the original Fort Hood

estimate and an even larger savings can be expected. This criterion has been met.

Subjective Criteria

1. *The equipment shall be designed for longevity, reliability, and maintainability including, wherever possible, stock materials and components*: The cab has malfunctioned once since installation. The fix required a redesign of the hose carrier system that involved custom fabricated brackets. The hose carrier system itself is off-the-shelf. All the parts of the Mobile Zone System are readily available off-the-shelf or can be easily fabricated. The ventilation modifications and PCE have been reliable since they were installed in 2001, but the mobile cab has not been used enough to truly evaluate this criterion. This criterion has not been met.
2. *The equipment will be intuitive to use, requiring little training*: The learning curve for operating the cab was larger than expected. Because the painters are afraid to use the cab due to the perceived risk of denting helicopters, they have not yet become experienced. Future implementations should incorporate training sessions so that the operators are completely comfortable with the controls and operation before painting. This criterion has not been met.
3. *The equipment will be convenient to use so that it will be the first choice of the painter, assuring a high utilization rate*: The paint booth is highly used at Fort Hood but not because the Mobile Zone System is convenient, but rather because it is the largest booth. The painters currently prefer using the booth in the Mobile Zone configuration without the cab. It is not known whether the painters would consider the cab convenient to use if they were experienced and lacked apprehension. This criterion has not been met.

Summary

Design studies of the Mobile Zone Spray Booth Recirculation System were performed at four installations, and it was found that each of the paint booths studied could be retrofitted with this system. Activities conducted at these booths represented both production and maintenance coating operations. The capital cost estimates for implementing these designs range from $287,800 to $372,000. The cost difference is primarily due to the degrees of freedom that the Mobile Zone cab moves, with the higher number of degrees costing more.

The Mobile Zone System was installed in 2001 at Fort Hood in Bay 4 of Building 88027. Testing of the PCE took place in 2002. Test results showed destruction efficiencies of 93 and 96 percent for two paint applications. Incomplete mass balances

left emissions unaccounted for during these tests. Subsequent field tests suggest that all the generated VOCs are exhausting to the PCE.

Modifications and improvements to the Mobile Zone System were implemented by November 2003. The total cost of the system, including all modifications, was $532,519. Seven of the eight objective criteria for installation and testing of this technology were met (part of Criterion #2 was not met; Criterion #4 requires substantiation). However, none of the three subjective criteria can be considered met. For the most part, the Mobile Zone System performed as expected; however, the current level of user acceptance is inadequate.

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Appendix A: Emission Data and Calculations

This appendix gives the emission results summarized in Chapter 5 and a description of the calculations that were performed to obtain the data in Table 9 and Table A.1. Table A.1 summarizes the values calculated for the mass balances. The emission results are given below separately for each test.

Table A.1. Results of mass balance calculations.

	CARC Application		W959 Application	
	Test #1	Test #2	Test #3	Test #4
Paint booth configuration	**Baseline**	**Mobile Zone**	**Mobile Zone**	**Baseline**
Calculated mass of VOC discharged from stack (lb)	5.7	0.091	0.17	16
Calculated Total Mass of VOC exiting paint booth from THC data (lb)	5.7	1.3	3.9	16
Estimated Total Mass of VOC exiting paint booth from MSDS (lb)	7.53	7.53	31.1	30.5
Ratio of Calculated to Estimated Total Mass of VOC exiting paint booth	0.76	0.17	0.13	0.52

Test Number 1

The first test was conducted using the baseline configuration and the CARC paint application (no primer). The test used 20.4 lb of paint and thinner. The measured average THC concentration and total volume of THC emitted to the atmosphere for the painting period 9:04 a.m. to 10:03 a.m. were 55.0 ppmv and 124 ft^3, respectively. The total volume was calculated by integrating the concentration data presented in Figure A.1, which is in ppmv THC, and converting it to THC volume in cubic feet based on the known total exhaust volume for the given time period (note that the THC volume is not an actual volume but a representative volume as if each VOC molecule had one carbon, such as methane). In Figure A.1, the first THC spike at approximately 9:06 a.m. is correlated to the painting operator loading paint thinner into the spray pot. The plot displays the typical VOC reduction curve due to normal purging when the paint operation stops at approximately 9:40 a.m.

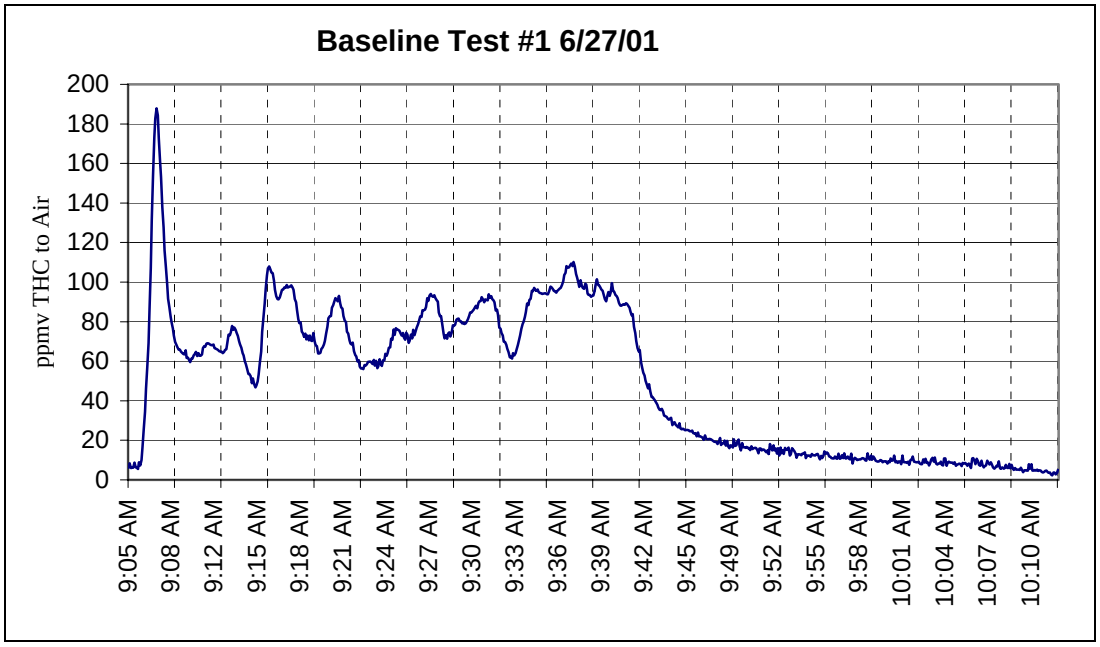

Figure A.1. Test number 1 results without recirculation using CARC paint (no primer).

A rough material balance on the VOC amounts is calculated through the following steps. Based on the amount of VOCs listed on the Material Safety Data Sheet (MSDS) for the CARC application, the mass of the VOCs used in the vehicle CARC painting is 7.53 lbs including thinner. To calculate the mass of VOCs from the measured THC concentrations, it is assumed that a single compound with the average number of molecular carbons and average molecular weight can represent the actual VOC concentration. According to the weight percentages of components in the MSDS, the calculated average molecular weight is 123 g/mole and the average number of molecular carbons is 6.8. The predominant VOCs in this application are isobutyl isobutyrate (52 percent mass of VOCs), methyl propyl ketone (18 percent), 1-methoxy-2-propyl acetate (10 percent), methyl ethyl ketone (6 percent), n-butyl acetate (3 percent), toluene (2 percent), and xylene (2 percent). The mass of VOCs discharged is then calculated by using the following equation:

$$M_{VOC} = \left(\frac{C_{THC}}{N} \right) \cdot \rho_{AIR} \cdot MW \cdot V \cdot t \qquad \textbf{[Eq A.1]}$$

where:

M_{VOC} = Mass of VOCs discharged, lbs,

C_{THC} = THC concentration, ppmv,

N = Average number of molecular carbons,

ρ_{AIR} = Molar density of air, moles/ft^3,

MW = Average molecular weight of VOCs, lb/mole,

V = Volumetric air flow, ft^3/s,

t = duration of test, s.

The ideal gas law was used to determine the molar air density (1.1 moles/ft^3 at 0.982 atm and 90 °F, ChemiCool). The calculated mass of VOCs exhausted from the discharge stack is 5.7 lb. This value is 72 percent of the MSDS value. This is a reasonable balance, especially when considering some of the released VOC may not have volatized or been measured during the test time period and that this comparison relies on data found in the MSDS.

Test Number 2

The second test was conducted using the Mobile Zone recirculation configuration and the CARC paint application (no primer). This test also used 20.4 lb of paint and thinner. The measured THC concentrations at the PCE inlet and outlet are shown in Figure A.2. The spikes (outlet) seen near the beginning of the test (2:24 p.m.) were due to improperly configured sample lines, and those data are rejected. The large spike at the end (inlet) was due to solvent used in the cleaning of the spray equipment.

The average concentration of THC entering the PCE for the painting period from 2:29 p.m. to 3:38 p.m. was 190 ppmv, while the average concentration of THC exiting the PCE, and emitting to the atmosphere, was 13.2 ppmv. The volumes of THC entering the PCE and exiting the PCE were 28.2 ft^3 and 1.97 ft^3, respectively. This represents an overall control efficiency of 93 percent. The total mass of VOCs entering the PCE during this test, which was calculated by using the same method discussed for Test Number 1, is 1.3 lb. This value is only 17 percent of the mass based on the MSDS data (7.53 lb), and 24 percent of the calculated mass in the baseline test (Test Number 1).

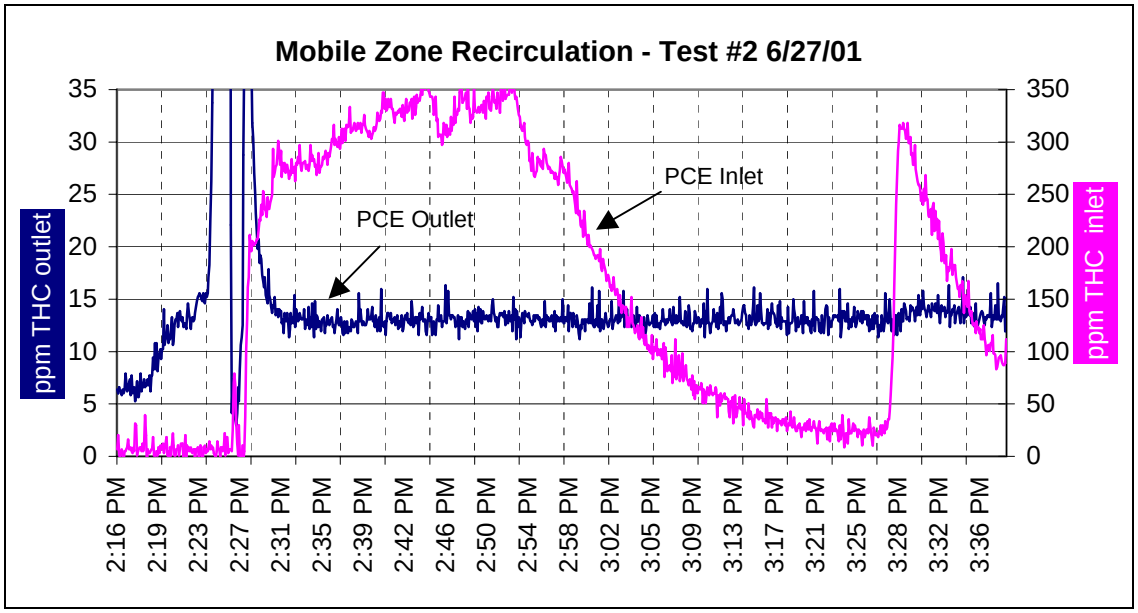

Figure A.2. Test number 2 results with recirculation using CARC paint (no primer).

Test Number 3

The third test was conducted using the Mobile Zone recirculation configuration and the W959 paint and a primer application. This test used 21.2 lb of primer/thinner and 28.0 lb of paint/thinner/hardener. The measured THC concentrations at the PCE inlet and outlet are shown in Figure A.3. The primer and painting applications each show as distinct increases in THC output. The cleaning of the painting equipment shows as a small spike at the end of the primer application (10:28 a.m.). The spike on the outlet THC at the end of the test (11:40 a.m.) is attributed to an accidental bump of a control switch on the analyzer, and that datum was rejected.

The average concentration of THC entering the PCE for the painting period from 9:59 a.m. to 11:45 a.m. was 411 ppmv, while the average concentration of THC exiting from the PCE and emitting to the atmosphere was 18.4 ppmv. The volumes of THC entering the PCE and exiting the PCE were 95.4 ft^3 and 4.27 ft^3, respectively. This represents an overall control efficiency of 96 percent.

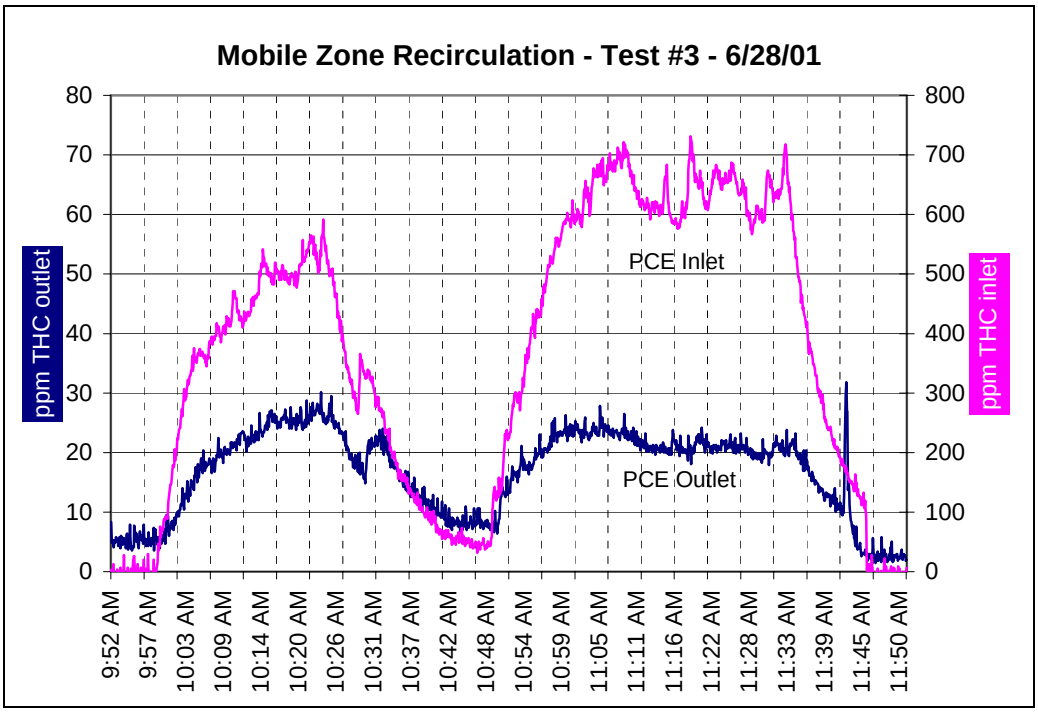

Figure A.3. Test number 3 results with recirculation using W959 paint and primer.

From the MSDS, the predominant VOCs in this application are toluene (17 percent mass of VOC), xylene (14 percent), n-butyl alcohol (13 percent), butyl acetate (11 percent), heptane (11 percent), acetone (8 percent), ethanol (4 percent), isopropyl alcohol (4 percent), methanol (4 percent), methyl isobutyl ketone (3 percent), 1-methoxy-2-propyl acetate (3 percent), and ethylbenzene (2 percent). According to the weight percentages of these components, the calculated average molecular weight and number of molecular carbons of the VOCs in this application are 91 g/mole and 5.6. The total mass of VOCs entering the PCE during this test was calculated by using the same method discussed for Test Number 1. The calculated mass of VOCs entering the PCE is 3.8 lb. This value is only 12 percent of the expected mass based on the MSDS data (31.1 lb).

Test Number 4

The fourth test was conducted using the baseline configuration and the W959 paint and a primer application. This test used 21.0 lb of primer/thinner and 27.2 lb of paint/thinner/hardener. The measured THC concentrations in the exhaust stack are shown in Figure A.4. The average THC concentration and total volume of THC emitted to the atmosphere for the painting period 1:53 p.m. to 3:12 p.m. were 129 ppmv and 385 ft^3, respectively. In the figure, the high levels starting at approximately 2:30 p.m. briefly exceeded the maximum measuring range of the THC analyzer. Solvent equipment cleaning occurred twice at 2:24 p.m. and 2:55 p.m.

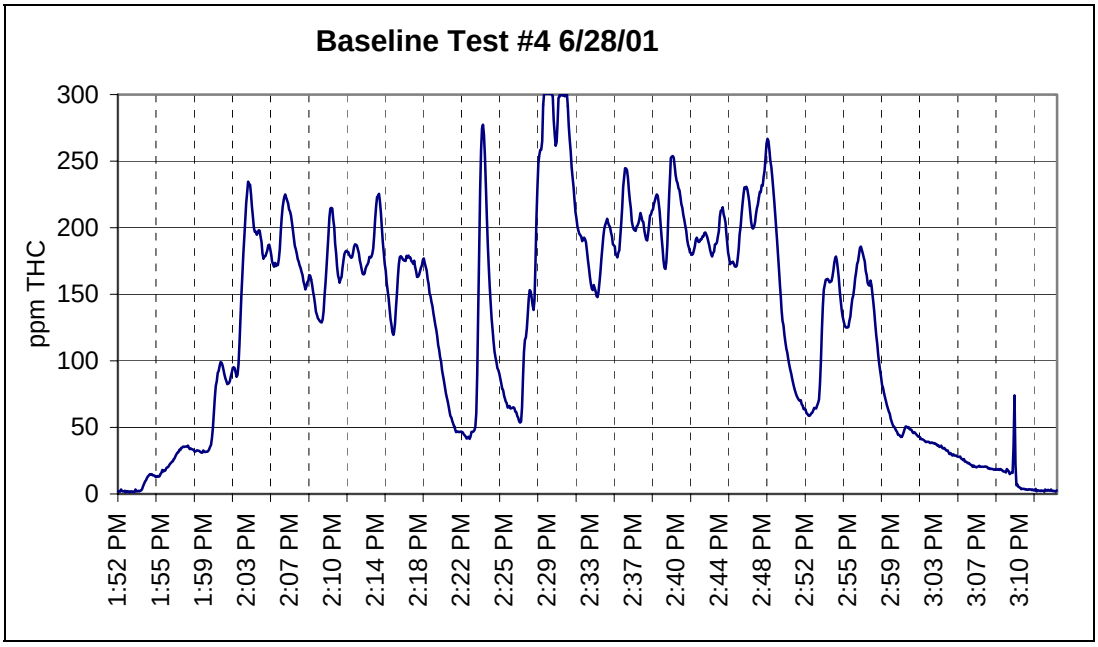

Figure A.4. Test number 4 results without recirculation using W959 paint (with primer).

Using the same method to calculate the mass used for the previous runs, the calculated mass of VOCs exhausted is 16 lb. This value is 50 percent of the MSDS value (30.5 lb). The mass emitted during Test Run 3 is 25 percent of the expected VOCs based on this baseline emission data.

Appendix B: Quantification of VOC Mass Emission Rates

This appendix shows the calculations that were performed to estimate the amount of VOCs generated by the painting process at Fort Hood, TX. The data used for these calculations were collected during November and December 2003 during the pilot-scale field testing of a prototype vapor recovery system. These estimates are important because they support the assumption that all of the VOCs generated are treated by the PCE of the Mobile Zone System.

Mass Balance of Vapor Emissions from Paint Booth 4 at Fort Hood

Prepared by D. Ramirez, E. Vidal, and M.J. Rood
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March 4, 2004

Summary

Volatile organic compound mass emission rates from a paint booth at Ft. Hood, TX were quantified by four separate methods and during two separate time periods. The tests occurred while evaluating an electro-thermal swing adsorption (ESA) system that removes organic vapors from the gas stream emitted from the paint booth. Therefore the cycle number of the adsorber differentiates the two time periods. Tests occurred during November and December of 2003. The volatile organic compounds emitted were methyl amyl ketone, methylcyclohexane, toluene, n-heptane, and 1,2,4-trimethyl benzene. A summary of the test results is provided in Table 1.

Table 1. Emissions at selected locations.

Measurement Location	Adsorption Cycle 1	Adsorption Cycle 2
1) Generation of VOCs in Paint Booth (lb VOC/hr)	1.121	1.548
2) Emission of VOCs in stack gas (lb VOC/hr)	1.636	4.166
3) Mass of VOC removed (lb VOC/hr)	1.594	4.098
4) Liquid recovered (lb condensate/hr)	0.542	1.556

Detailed Calculations

ADSORPTION CYCLE 1

1. Emissions from Paint Booth based on MSDS and Painting Operations

A. The total consumption of acrylic enamel reducer (DTR602) for painting barrels is 1 gallon/adsorption cycle. Based on the composition according to the MSDS, the content of volatile organic compounds is 3.79 lb/gallon enamel.

Therefore,

VOC emitted = (1)(3.79) = 3.79 lb VOC/adsorption cycle

VOCs present in the enamel include methylcyclohexane, toluene, n-heptane, and 1,2,4-trimethyl benzene.

The total consumption of acrylic enamel (DR3794) for painting barrels is 2 gallon/adsorption cycle. Paints manufactured by the same company have an average amount of 4 lb VOC/gallon of paint.

Therefore,

VOC emitted = (2)(4) = 8 lb VOC/adsorption cycle

B. The total consumption of Henzten paints (08605GUZ-LVOC, 08610KUZ-LVOC, and 08609TUZ-LVOC) for painting 2 Hummers and 1 Jeep is 2 gallons. According to the MSDS, the VOC content is 1.48 lb VOC/gallon paint. Therefore,

VOC emitted = (1.48 lb VOC/gallon)(2 gallons) = 2.96 lb VOCs

VOC present is methyl amyl ketone (MAK).

The total amount of VOCs emitted during this adsorption cycle = 3.79 + 8 + 2.96 = 14.75 lb VOC/adsorption cycle. The total time of the adsorption cycle is 13.16 hrs. Then,

14.75 lb VOC / 13.16 hr = **1.121 lb VOC/hr**

Calculations are based on composition data from MSDS.

2. Emissions from Paint Booth based on Stack Data

The volumetric flow rate of vapor emissions exhausted from the paint booth to be treated by the thermal oxidizer is reported to be 2,130 ft^3/min. The volumetric flow rate sampled for the pilot-scale ESA system is 46 ft^3/min (2.16 % of total gas exhausted from paint booth) with a standard deviation of 2.6 ft^3/min. The mean concentration of organic vapors, the ambient temperature and pressure in the inlet gas stream during the adsorption cycle is 44.7 ppmv, 16°C, and 0.96 atm, respectively. Based on these parameters and using the molecular weight of MAK, the mass rate of organic vapors is $1.28x10^{-5}$ lb VOCs/ft3. Therefore, the mass emission rate of organic vapors emitted from the paint booth is as follows:

2,130 ft^3/min (60 min/hr)(1.28x10-5 lb VOC/ft^3) = **1.636 lb VOC/hr**

3. Mass of Pollutants Removed by the ESA System

The mass rate of organic vapors sampled by the ESA system is as follows:

46 ft^3/min (60 min/hr)(1.28x10-5 lb VOC/ft^3) = 0.035 lb VOC/hr

The mean concentration of organic vapors, the ambient temperature and pressure at the outlet of the ESA system during the adsorption cycle is 0.69 ppmv, 19.5°C, and 0.96 atm, respectively. Based on these parameters and using the molecular weight of MAK, the mass concentration of organic vapors exhausted from the ESA system is $1.95x10^{-7}$ lb VOC/ft^3. The mass emission rate of organic vapors emitted from the ESA system is as follows:

49 ft^3/min (60 min/hr)($1.95x10^{-7}$ lb VOC/ft^3) = $5.7x10^{-4}$ lb VOC/hr

Therefore, the mass flow rate that would be removed by the ESA system assuming all exhaust emissions from paint booth are treated by the ESA system is as follows:

$m_{removed}$ = (0.035 lb VOC/hr – $5.7x10^{-4}$ lb VOC/hr)((2,130 ft^3/min)/(46 ft^3/min))

= 1.594 lb VOC/hr

4. Mass of Pollutants Emitted and Liquefied by the ESA System

The amount of liquid condensate is 0.154 lb/adsorption cycle. The mass of organic vapors exhausted from the ESA system is 0.007 lb/adsorption cycle. The balance 0.198 lb/adsorption cycle remains adsorbed on the cartridges and 0.116 lb/adsorption cycle is directed to the second adsorber during adsorption. The amount of liquid condensate

would be larger if the system was operated under steady-state conditions, the tests were completed for individual cycles.

The mass flow rate that would be liquefied by the ESA system assuming that all emissions from paint booth are treated by the ESA system is as follows:

$m_{removed}$ = (0.154 lb condensate/13.16 hr)((2,130 ft^3/min)/(46 ft^3/min))

= **0.542 lb condensate/hr**

ADSORPTION CYCLE 2

1. Emissions from Paint Booth based on MSDS and Painting Operations

A. The consumption of paint Tan Hentzen (08609TUZ-LVOC) for painting trucks is 1.67 gallons paint/truck. According to the MSDS, the content of VOCs is 1.484 lb VOC/gallon paint. Therefore,

VOC emitted per truck = (1.67)(1.484) = 2.478 lb VOC/truck

Based on EPA definition of VOC and direct communication with personnel of Hentzen Coatings, Inc., the only VOC present in the paint is methyl amyl ketone (C7H14O, M.W. 114.2 lb/lb-mole, CAS No. 110430).

During December 5 and 8-11, eight trucks were painted in the paint booth. Then, the total amount of VOC emitted is as follows:

(2.478 lb VOC/truck)(8 trucks/adsorption cycle) = 19.824 lb VOC/adsorption cycle

Calculations are based on composition data from MSDS.

B. The consumption of epoxy primer (MIL-P-23377), polyurethane paint (MIL-C-46168D), and thinner (MIL-T-81772B) for helicopter blades is 1 pint primer/blade, 1 quart paint/blade, and 1 pint thinner/blade, respectively. According to the MSDS, the content of volatile organic compounds is 4.1 lb VOC/gallon primer, 3.92 lb VOC/gallon paint, and 7.086 lb VOC/gallon thinner. Therefore,

VOC emitted per blade = (0.125)(4.1)+(0.25)(3.92)+(0.125)(7.086)
= 2.378 lbVOC/blade

VOCs present in the primer, paint and thinner are toluene, methyl ethyl ketone, n-butyl acetate, xylene, and hexyl acetate.

During December 5 and 8, two blades were painted in the paint booth. Then, the total amount of VOC emitted is as follows:

(2.378 lb VOC/blade)(2 blades/adsorption cycle) = 4.756 lb VOC/adsorption cycle

The total amount of VOC emitted during this adsorption cycle = 19.824 + 4.756 = 24.58 lb VOC. The total time of the adsorption cycle is 15.88 hr. Then,

24.58 lb VOC / 15.88 hr = **1.548 lb VOC/hr**

Calculations are based on composition data from MSDS.

2. Emissions from Paint Booth based on Stack Data

The volumetric flow rate of vapor emissions exhausted from the paint booth to be treated by the thermal oxidizer is 2,130 ft^3/min. The volumetric flow rate sampled for the pilot-scale ESA system is 50 ft^3/min (2.35 % of total vapors exhausted from paint booth) and standard deviation 1.7. The mean concentration of organic vapors, the ambient temperature and pressure in the gas stream during the adsorption cycle is 113.2 ppmv, 15°C, and 0.96 atm, respectively. Based on these parameters and using the molecular weight of MAK, the mass concentration of organic vapors is $3.26x10^{-5}$ lb VOC/ft^3. Therefore, the mass emission rate of organic vapors exhausted from the paint booth is as follows:

2,130 ft^3/min (60 min/hr)($3.26x10^{-5}$ lb VOC/ft^3) = **4.166 lb VOC/hr**

3. Mass of Pollutants Removed by the ESA System

The mass rate of organic vapors sampled by the ESA system is as follows:

50 ft^3/min (60 min/hr)($3.26x10^{-5}$ lb VOC/ft^3) = 0.098 lb VOC/hr

The mean concentration of organic vapors, the ambient temperature and pressure at the outlet of the ESA system during the adsorption cycle is 1.88 ppmv, 19 °C, and 0.96 atm, respectively. Based on these parameters and using the molecular weight of MAK, the mass concentration of organic vapors exhausted from the ESA system is $5.33x10^{-7}$ lb VOC/ft^3. The mass rate of organic vapors exhausted from the ESA system is as follows:

(55.8 ft^3/min)(60 min/hr)($5.33x10^{-7}$ lb VOC/ft^3) = $1.8x10^{-3}$ lb VOC/hr

Therefore, the mass flow rate removed by the ESA system is as follows:

$m_{removed}$ = (0.098 lb VOC/hr – $1.8x10^{-3}$ lb VOC/hr)((2,130 ft^3/min)/(50 ft^3/min))

= **4.098 lb VOC/hr**

Calculations based on the total inlet flow rate, concentration and temperature, and ambient pressure, provides a total mass of organic vapors entering the ESA system of 1.49 lb.

4. Mass of Pollutants Emitted and Liquefied by the ESA System

The amount of liquid condensate is 0.58 lb. The mass of organic vapors exhausted from the ESA system is 0.03 lb. The balance 0.71 lb remains adsorbed on the cartridges and 0.17 lb is directed to the second adsorber during adsorption. The amount of liquid condensate would be larger if the system was operated under steady-state conditions, the tests were completed for individual cycles.

The mass flow rate that would be liquefied by the ESA system assuming that all emissions from the paint booth are treated by the ESA system is as follows:

$m_{removed}$ = (0.58 lb condensate/15.88 hr)((2,130 ft^3/min)/(50 ft^3/min))

= **1.556 lb condensate/hr**

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14. ABSTRACT

Army painting operations emit a large quantity of Hazardous Air Pollutants n the form of Volatile Organic Compounds (VOCs). Increasing regulatory pressure is beginning to impact these operations, which is resulting in the consideration of installing air pollution control devices. Controlling the ventilation of once-through paint booths is extremely costly. The Mobile Zone Spray Booth Recirculation System recirculates the air in the paint booth and exhausts less than 90 percent of conventional once-through systems, which is much less costly to treat. The system uses a mobile cab that moves with up to four degrees of freedom and provides the worker with fresh climatized air. Design studies for the Mobile Zone Spray Booth Recirculation System were conducted at four Army installations to demonstrate its applicability and cost effectiveness. The system was installed at Fort Hood, Texas with a recuperative catalytic oxidizer as the control device. Testing of the VOC control conducted in 2002 showed control efficiencies of 93 and 96 percent for two different paint applications. The system has undergone modifications and corrections since the testing. The system has met seven of the eight objective criteria related to performance and cost but has yet to meet the three subjective criteria related to usability and acceptance.

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