EPA/452/B-02-001

Section 2

Generic Equipment and Devices

EPA/452/B-02-001

Chapter 3

Permanent Total Enclosures (PTEs)

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3.1 Introduction

Permanent total enclosures (PTEs) are permanently installed structures that completely surround a source (s) of emissions . PTEs capture all emissions and contain them for discharge to an abatement device such as an incinerator or absorber. PTEs must meet each of the U.S. Environmental Protection Agency's (EPA's) five point criteria listed in Table 3.1.

PTEs are unique because they accommodate production personnel within its structure during operation. Consequently, they have an Occupational Safety and Health Administration (OSHA) regulated system of air flow control for supplying fresh air to the space enclosed. By definition they have a capturing efficiency of 100 percent and do not need to conduct a capture efficiency test. Capture efficiency is a component of overall efficiency, which can be expressed as:

$$OCE = CE \times DE \tag{3.1}$$

where OCE = overall control efficiency,
CE = capture efficiency, and
DE = destruction or recovery efficiency.

Since capturing efficiency is 100%, the overall efficiency will be equal to the control device destruction efficiency.

In addition to avoiding the need for a capture efficiency test, companies may choose to employ PTEs rather than other capture systems because:

1. A high overall control efficiency is required due to regulations or new source review involving best available control technology (BACT). For example, Subpart KK[1], the National Emissions Standards for Hazardous Air Pollutants (NESHAPs) for the printing industry, requires an overall control efficiency of 95 percent for organic hazardous air pollutants (HAPs) for packaging flexographic and rotogravure presses using only add-on control. BACT for rotogravure presses has been established at 98+ percent overall control efficiency for volatile organic compounds (VOCs). Using PTE assures the source it has fully met (and exceeded) its regulatory requirement.

2. Implementation of more stringent standards for measuring the capture efficiency for an emission source. EPA has established rigorous data quality objectives associated with testing techniques for determining capture efficiency specified in Reference Method 204[2]. Installing a PTE can avoid the need for secondary control in the future due to tightening standards.

3. Continuous compliance requirements under Title V[3], the new Compliance Assurance

Monitoring rule[4], New Source Performance Standards [5], and NESHAPs [6]. Using PTE simplifies meeting this requirement for capture efficiency.

Any process or operation whose emissions are not totally captured is a candidate for a PTE. Industries that have used PTEs as part of control systems [7] are:

- Flexographic printing
- Rotogravure printing
- Coating (paper, film, fabric, plastic, and metal)
- Laminating
- Screen printing
- Can coating
- Plastic card coating

Due to the increasing use of PTEs, EPA has developed a methodology for estimating PTE costs. This methodology is presented in Chapter 2 of this Manual. The purpose of this chapter is to provide a quick means to generate study cost estimates for PTEs.

3.2 PTE Criteria

The EPA's five-point criteria given in EPA Method 204 is reproduced in Table 3.1.

Table 3.1: The EPA Method 204: Criteria for a Permanent Total Enclosure[2]

No.	Description	Requirement
1	Location of openings	Any natural draft opening (NDO) shall be at least four equivalent opening diameters from each VOC emitting point unless otherwise specified by the administrator.
2	Areas of openings	The total area of all NDOs shall not exceed 5 percent of the surface area of the enclosureís four walls, floor, and ceiling.
3	Flow rate into enclosure	The average facial velocity (FV) of air through all NDOs shall be at least 3,600 m/hr [200 ft/min (this equates to a negative pressure difference of 0.007†in. of water or 0.013 mm Hg)]. The direction of air flow through all NDOs must be into the enclosure.
4	Access doors/windows	All access doors and windows whose areas are not included in item 2 and are not included in the calculation in item 3 shall be closed during routine operation of the process.
5	Emission capture	All VOC emissions must be captured and contained for discharge through a control device.

3.3 PTE Design Parameters

PTE design takes into account the following factors [8]:

- Compliance with EPA Method 204
- OSHA Standards
  - Health Considerations
  - Safety Considerations
  - Worker Comfort
- Process Configuration
- Access to PTE
- Size of PTE
- Air-Conditioning System
- Makeup Air System

These factors are described in greater detail below.

3.3.1 Compliance with EPA Method 204

Criterion No. 1 :All NDOs must be at least four equivalent diameters from each emission point.

An NDO is a any opening in the PTE that remains open during operation and is not connected to a duct in which a fan is installed. The dimensions of an NDO and its distance from the to the nearest point of emission are measured to ensure compliance with Criterion No. 1.

The equivalent diameter is calculated using the formula:

$$D = \sqrt{\frac{4A}{\pi}} \qquad (3.2)$$

where D = equivalent diameter (in.),
A = area of the NDO (sq. in.) and,
π = 3.1416.

Criterion No. 2: The total area of the NDOs must be less than 5 percent of the enclosure surface area.

Total NDOs and enclosure areas are calculated, including walls, ceiling, and floor of the enclosure.

$$A_{NDO} = \sum_{i=l}^{N} A_i \tag{3.3}$$

$$A_{NDO} < .05\ A_e \tag{3.4}$$

$$A_e = L\ x H \tag{3.5}$$

where A_{NDO} =1% of TCI Total NDO area,
Ai = Individual NDO area,
A_e = Total enclosure area,
L = Total enclousure length, and
H = Enclosure height.

Criterion No. 3: The average face velocity (FV) of air thru all NDOs shall be at least 200 fpm and the direction of flow into the enclosure.

The volumetric flow rate of each gas stream exiting and entering the enclosure are measured or otherwise determined and the facial velocity is calculated using the following equation:

$$FV = \frac{Q_o - Q_i}{A_{NDO}} \tag{3.6}$$

where FV = facial velocity (fpm),
Q_o = the total volumetric flow from all gas streams exiting the enclosure through an exhaust duct or hood (acfm),
Q_i = the total volumetric flow from all gas streams entering the enclosure through a forced makeup air duct; zero if no forced makeup air is provided to the enclosure (acfm), and
A_{NDO} = total area of all NDOs (sq ft).

The FV should be at least 200 fpm (3,600 m/hr) for compliance. Q_o is always greater than Q_i, the difference being made up by the air entering the NDOs and louvers.

The direction of air flow through all NDOs is measured or verified to be inward by measuring the pressure difference between the inside and outside of the PTE . The low pressure leg of the device is connected to tubing that terminates inside the enclosure. The high pressure leg opens to the outside of the enclosure. The outside pressure the PTE should be at least 0.007 in. of H_2O

(0.013 mm of Hg) higher than the inside pressure for compliance. If FV is less than 500 fpm, the continuous inward flow of air is verified using streamers, smoke tubes, or tracer gases. If FV is greater than 500 fpm, the direction of air flow through the NDOs is considered to be inward at all times without verification.

Criterion No. 4: All access doors and windows whose areas are not accounted for in Criterion No. 2 and are not included in the calculation for Criterion No. 3 are kept closed during normal operation of the source(s).

Criterion No. 5: All VOCs emitted within the PTE are delivered to an air pollution control device in order to meet this criterion.

3.3.2 OSHA Standards

Regulation of occupational health and safety in the workplace is the responsibility of the Occupational Safety and Health Administration (OSHA), an organization within the Department of Labor of the Federal government. The following section discusses how OSHA requirements affect the design of PTEs.

3.3.2.1 Health Considerations

OSHA adopted permissible exposure levels (PELs) as the best existing standards for worker exposure for a large number of substances. PELs are expressed in terms of time-weighted average (TWA-generally 8-hour), short-term exposure level (STEL), and ceiling concentration (C). OSHA standards are published in 29 CFR Part 1910 Subpart Z [9]. As new information becomes available, PEL values may be changed or new substances may be added to the existing list.

The amount of ventilation air required to maintain VOC concentrations below PELs within an enclosure can be estimated using the following relationship:

$$Q_i = \frac{\sum_{i=1}^{n} K\,E_i}{\left(\frac{60\text{ min}}{\text{hr}}\right) PEL_i} \tag{3.7}$$

where for Q_i = ventilation air flow rate (scfm) required to stay below the PEL VOC i,
i = individual VOC,
Σ = summation over all processes emitting VOC i,
K = fraction of process emissions not immediately captured by the PTE exhaust gas stream,
E_i = process uncontrolled emission rate (lb/hr) for VOC i, and
PEL_i = permissible exposure level (lb/ft^3 at standard conditions — 70^{o}F and 1 atm) for VOC i.

The PELs are generally given in units of milligrams per cubic meter (mg/m^3) and/or parts per million by volume (ppmv). The PEL in lb/ft^3 is obtained by multiplying the PEL in mg/m^3 by 62.43x10^{-9}. The PEL in ppmv is converted to lb/ft^3 at standard conditions by multiplying by a factor of 2.6x10^{-9} M where M is the molecular weight. The volumetric flow rate, scfm, is converted to actual conditions (actual temperature and pressure) using ideal gas laws. The procedure is repeated for every VOC, and the highest value of Q_i is considered the design flow rate, Q.

New equipment is designed to maximize VOC capture, approximately 5 to 10 percent (K = 0.05 to 0.10) of total process emissions escape. For older, poorly maintained equipment (built before 1980), this factor is as high as 30 percent (K = 0.30).

Assuming complete mixing of VOCs within the enclosure, the average VOC concentration in the enclosure is calculated by the following equation:

$$C_{iavg} = \frac{\sum_{i=1}^{n} K\, E_i}{Q\left(\frac{60\ \text{min}}{\text{hr}}\right)} \tag{3.8}$$

where C_{iavg} = average concentration (lb/ft^3) for VOC,
Σ = summation over all processes emitting VOC i,
K = fraction of process emissions escaping into the enclosure,
E_i = process emission rate (lb/hr) for VOC i, and
Q = design flow rate (actual ft^3/min) from the enclosure.

In practice, the mixing of VOCs within an enclosure is rarely complete. Mixing is a function of the performance characteristics of the ventilation system which depend upon a number of variables such as:

- Temperature of the delivery supply air
- Temperature within the PTE

- Amount and locations of supply and exhaust air
- Locations of objects within the PTE
- Shape and size of the PTE
- Presence or absence of heat sources within the PTE
- Injection velocity of the supply air

Thermal stratification due to plant equipment results in the buildup of VOC concentrations in certain areas within the enclosure. To accurately determine such stratification, the engineer needs detailed information about the sources, enclosure, and ventilation system. Proper and detailed design of the ventilation system, accounting for the amount and location of incoming air, source locations, location of the exhaust points, amount of exhausted air, etc.

Local concentrations may vary considerably by factors from 1 for well-designed ventilation systems to 10 for poorly designed systems[10] in comparison to the average concentration (see Figure 3.1). Thus,

$$C_{imax} = K_1 \, C_{iavg} \tag{3.9}$$

where
C_{imax} = maximum concentration (lb/ft^3) for VOCi,
K_1 = 1 to 10 (depending upon the degree of mixing/circulation), and
C_{iavg} = average concentration (lb/ft^3) for VOC .

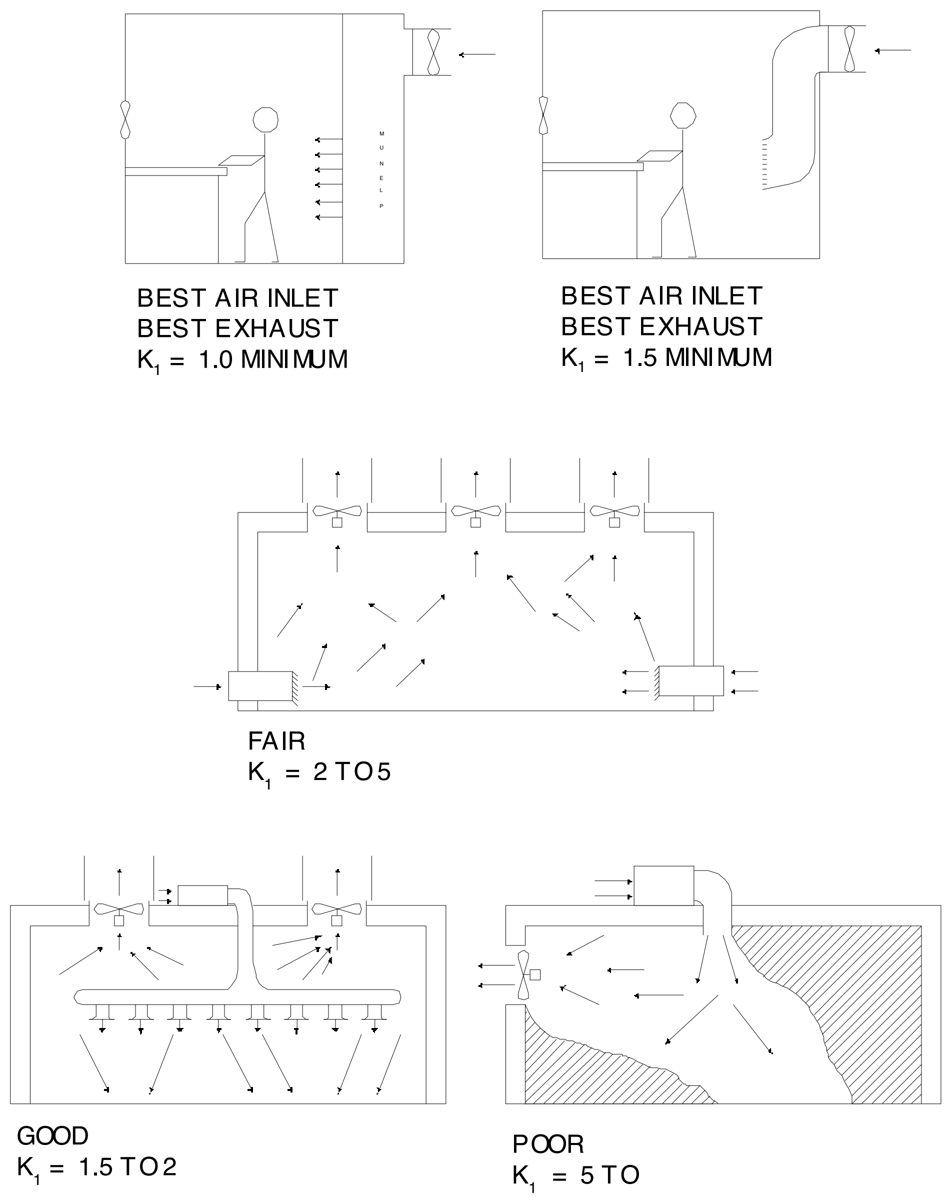

Figure 3.1: Typical K_1 Factors Based on Inlet and Exhaust Locations

Theoretically, C_{imax} should not exceed PEL_i. However, the average concentration, C_{iavg}, within an enclosure is a useful value for comparison to the PEL because a typical operator is constantly moving within the PTE and is not expected to remain at locations with high concentrations for more than a few minutes during the day.

3.3.2.2 Safety Considerations

Combustible gases pose a risk of fire or explosion to personnel and facility. The lowest level at which a gas supports combustion is called the lower flammable limit (LFL) or lower explosive limit (LEL). Below this level the gas is too lean to support combustion. There is a corresponding upper flammable limit (UFL), above which the concentration is too rich to support combustion. Different gases combust at different concentrations.

For fire safety, OSHA requires the concentration of a flammable vapor or mist in a large PTEs, such as an entire building or manufacturing area, not to exceed 25 percent of the LFL. For small PTEs, such as those enclosing a single piece of equipment, concentrations are limited to 10 percent of the LFL.

LFLs rarely govern when evaluating flammable vapor or mist concentrations in an enclosure because PELs are more restrictive. Table 3.2 displays the LFL, safety level, and PEL for many commonly used industrial solvents.

Table 3.2: LFLs, Safety Levels, and PELs for Common Industrial Solvents

Solvent	LFL(ppmv)	10% LFL(ppmv)	PEL(ppmv)
Acetone	25,000	2,500	1,000
Benzene	12,000	1,200	1
Ethyl alcohol	33,000	3,300	1,000
Ethyl acetate	20,000	2,000	400
Hexane	11,000	1,100	500
Isopropyl alcohol	20,000	2,000	400
Isopropyl acetate	18,000	1,800	250
Methyl alcohol	60,000	6,000	200
Methyl ethyl ketone	18,000	1,800	200
Methyl methacrylate	17,000	1,700	100
n-propyl acetate	17,000	1,700	250
n-propyl alcohol	22,000	2,200	200
Styrene	9,000	900	100
Toluene	11,000	1,100	200
Xylene	9,000	900	100

The LFL concentration determines safe levels in enclosed spaces such as baking and drying ovens and ductwork to protect against fires and explosions. Concentrations within the enclosure can be calculated using procedures given in Section 3.4.2.1. To estimate the concentration in a duct, use the following equation.

$$C_{di} = \frac{E_i}{Q\left(\frac{60 \text{ min}}{\text{hr}}\right)} \quad (3.10)$$

where C_{di} = concentration in the duct (lb/ft^3) under actual conditions for VOC i,
E_i = emission rate through the duct (lb/hr) for VOC i, and
Q = flow rate through the duct (actual ft^3/min).

For safety, the concentration within the duct should not exceed 25 percent of the LFL.

To safeguard against concentrations reaching unsafe levels, PTEs and associated ducts should be equipped with instruments to monitor concentrations. Additional equipment such as alarms can be provided to sound automatically when concentrations reach unsafe levels. The enclosure may also need a water sprinkler system or fire suppression system. Emergency training for the workers may also be required.

Three widely used fire suppression systems are water sprinklers, carbon dioxide (CO 2), and FM200 (a gas developed by Great Lakes Chemical Corporation as a replacement for halon gas). Water sprinkler systems may not be sufficient for special environments, high risk areas, isolated locations, or unusual hazards. For these cases, FM200 and CO2 systems are required.

3.3.2.3 Worker Comfort

Good ventilation is necessary to ensure worker comfort and provide healthful working conditions. The amount of ventilation required is expressed in terms of room air changes per hour (RACs/hr), calculated using the following equation:

$$\frac{\text{RACs}}{\text{hr}} = \frac{Q\left(\frac{60 \text{ min}}{\text{hr}}\right)}{V} \quad (3.11)$$

where Q = ventilation air required (actual ft^3/min), and
V = volume of enclosure (ft^3) excluding space occupied by equipment.

Generally, it takes 10 to 15 RACs/hr to provide adequate worker comfort within an enclosure. However, the RACs/hr are compared with the amount of ventilation (dilution) air required to safeguard against potential health hazards and fire and explosive conditions.

3.3.3 Process Configuration

Process configuration and the location of emission sources influence PTE design. If sources are located close to each other, a single PTE can be designed to enclose all the sources. In some cases, the entire building or the room can be converted into a PTE with just a change in the ceiling height to satisfy RAC requirements. If the sources are separated by relatively large distances, it may be more appropriate to build several PTEs. In some cases, a PTE is built around only the emitting portion of the source (such as the printing head of a press). For multiple sources within a PTE, there are situations when some of the sources do not need to be controlled to comply with regulations or permit conditions because compliant materials are used. In such cases, a PTE within a PTE allows sources using compliant materials to be vented directly to the atmosphere. If access to the emission point is not required, a small unmanned PTE can be built around it. Such PTEs are constructed as close to the emission point as possible. Although small in size, they require engineering ingenuity for proper design around a complex emission point. Several examples of PTEs are shown in Figures 3.2 through 3.5.

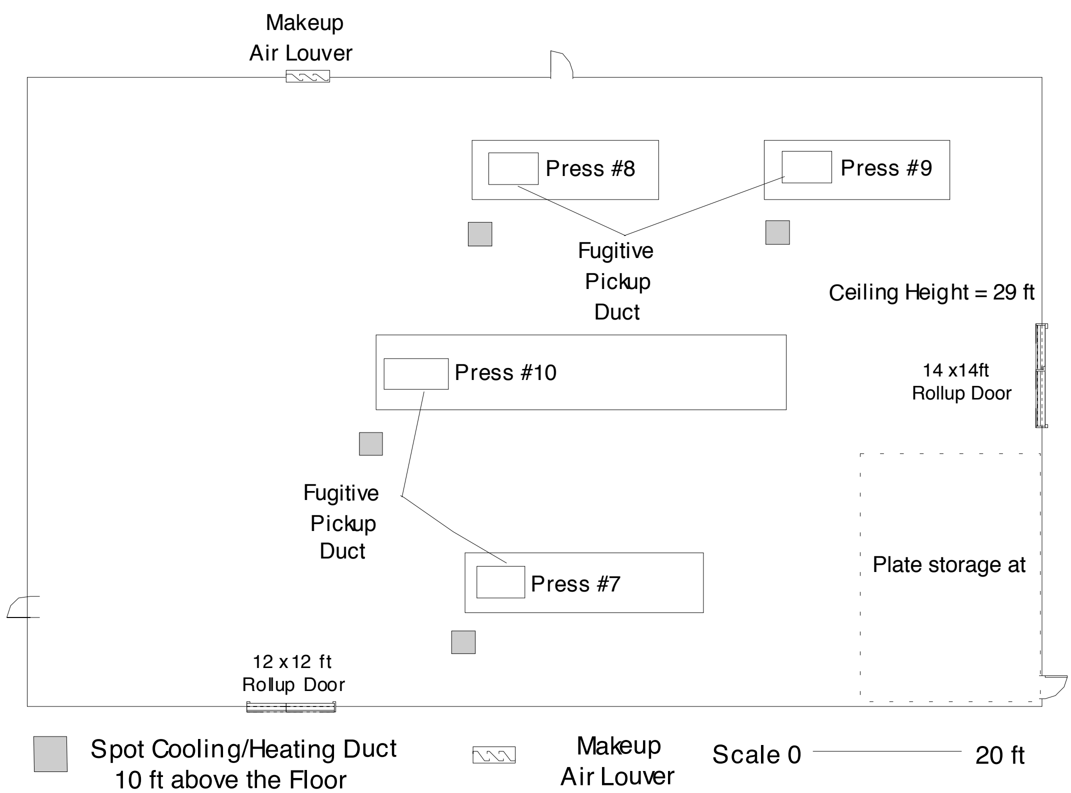

Figure 3.2: Manugacturing Area as a PTE

3.3.4 Access to PTE

Access is needed for material flow into and out of the enclosure. A variety of doors ranging from simple personnel doors to automatic rollup or sliding doors are used. For visual inspection of the process in the PTE, several glass windows are typically recommended.

3.3.5 Size of PTE

The size of a PTE depends largely on two factors: location of the sources and capacity of the existing or proposed air pollution control equipment. Large PTEs require large exhaust flow rates (hence an air pollution control device with a large design flow rate) to provide adequate RACs/hr for worker comfort. If the exhaust flow rate of the control device is relatively small, a smaller PTE is adequate.

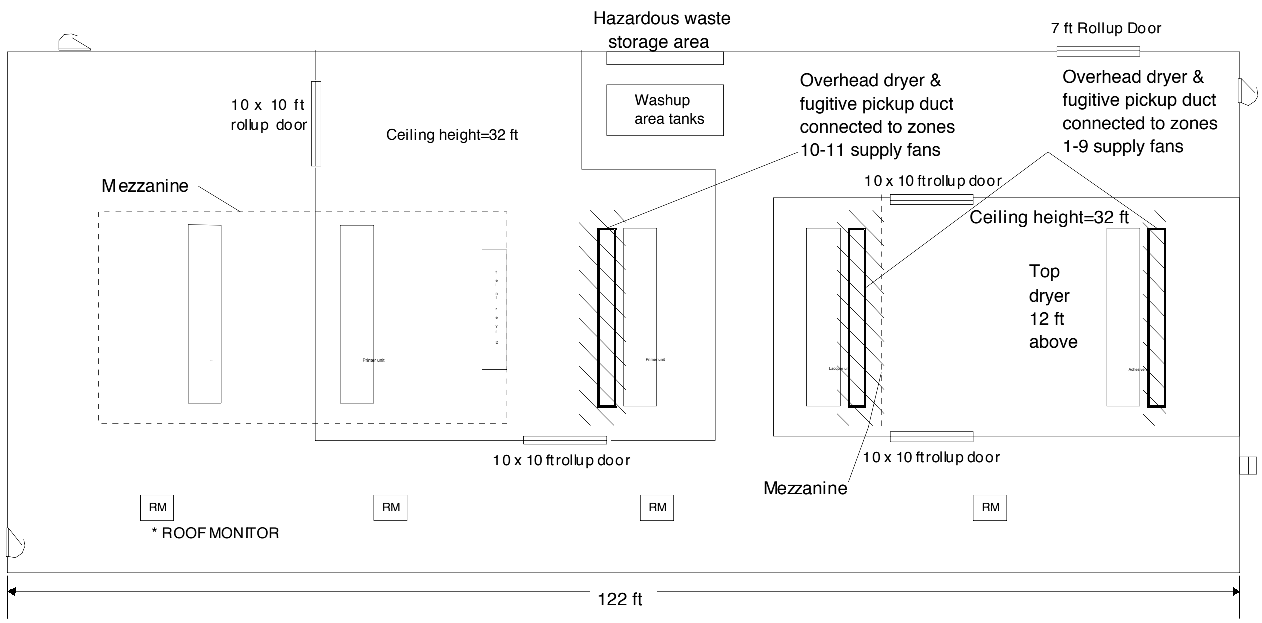

Figure 3.3: PTE Around Several Sources

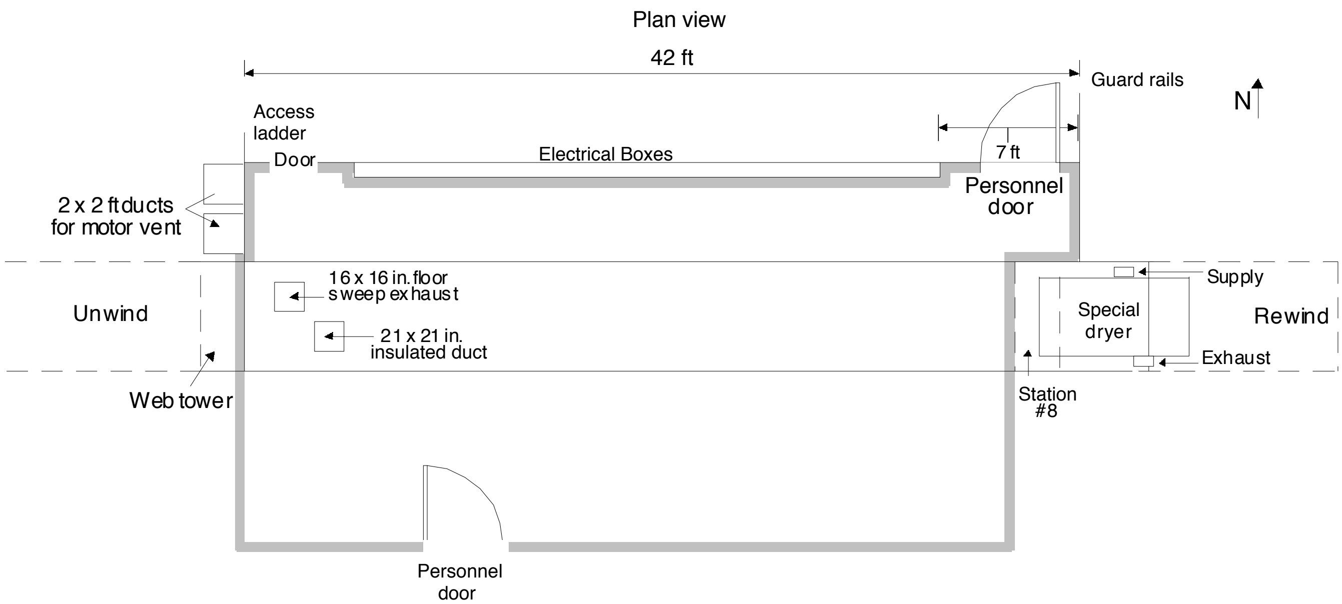

Figure 3.4: PTE Around a Single Source

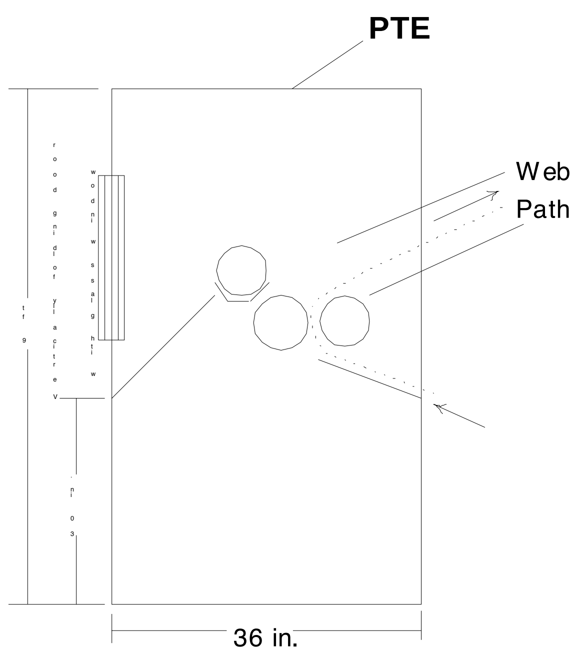

Figure 3.5: Unmanned PTE (Around One Station of a Coater)

3.3.6 Air-Conditioning System

If the installation of a PTE results in heat buildup, some air conditioning can be added. All air conditioning should be of a closed loop design (return air is taken from the interior of the PTE, passes through coils, and is delivered back to the PTE) to avoid violating the PTE criteria. The necessary design criteria for air conditioning are available in the appropriate American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbooks.

3.3.7 Makeup Air System

Whenever air is exhausted from a room or enclosure, supply air must enter the enclosure to take its place. For low exhaust rates, air entering through NDOs, cracks, and incomplete seals may be adequate. Air flow can be increased by installing louvers in the walls of the enclosure. For large exhaust volumes, additional air must be provided by a fan to make up for the difference between the air exhausted and the air entering through the NDOs and cracks. In some cases makeup air is used for spot cooling where air is introduced directly at the work station. The amount of makeup air required is given by the following equation:

$$Q_m = Q_e - Q_{NDO} \tag{3.12}$$

where
Q_m = amount of makeup air (acfm),
Q_e = exhaust flow rate from the PTE (acfm), and
Q_{NDO} = amount of air entering the PTE through NDOs (acfm).

3.3.8 Makeup Air Fan

This section only considers the fan required for makeup air. Exhaust fans that transport gases from the PTE to the control device are part of the control system and not considered in this chapter. The performance of a fan is characterized by its “fan curve” which presents quantitatively the relationship between the volume of air flow, the pressure at which this flow is delivered, the speed of rotation, the power required, and the efficiency. The basic information required to select a fan is the actual volumetric flow rate and the fan static pressure (FSP). Other factors that influence the selection are stream characteristics, drive arrangement and mounting, operating temperatures, inlet size and location, and efficiency. The FSP is defined as follows:

$$FSP = SP_o - SP_i - VP_i \tag{3.13}$$

where
FSP = (in. w.c.),
SP_o = static pressure at outlet (in. w.c.),
SP_i = static pressure at inlet (in. w.c.), and
VP_i = velocity pressure at inlet (in. w.c.).

Manufacturers provide multi-rating tables for fan selection in Figure 3.6.[11] For every volumetric flow rate and fan static pressure, the required fan speed (RPM) and the fan power (BHP) are given. If values in the table fall between desired values, interpolation is acceptable. The multi-rating tables are based on standard conditions of 70°F and 29.92 in. Hg pressure. For a given flow rate and static pressure, several fan selections are possible and it is not unusual to find four or more fan sizes that provide the required flow rate at a given pressure drop. Usually, the fans in the middle of a rating table are the most efficient (about 75-80 percent efficiency). If the design operating parameters are near the top or the bottom of the table, select a smaller or larger fan.

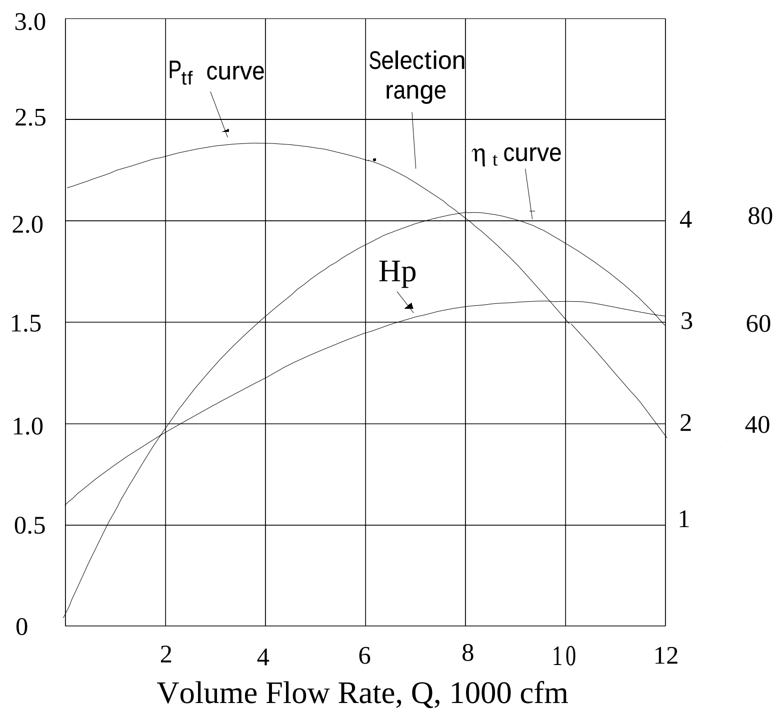

Figure 3.6: Conventional Fan Performance curve used by most manufactures

3.3.9 Example Problem

To illustrate the design process for a PTE, this section provides an example problem and demonstrates how each design parameter meets the EPA five-point criteria previously discussed in Section 3.2.

A high volume specialty packaging products company located in an ozone attainment area has operated an eight-color rotogravure printing press (Press #1) for 6 years, using only high solvent inks to meet customer demands for quality. To meet the state control technology requirement, the company installed a 15,000 scfm thermal incinerator. The existing incinerator has been tested and demonstrated a destruction efficiency of 95 percent. Due to increased demand for its products, the company now plans to install another eight-color rotogravure printing press (Press #2). In order to meet the best available control technology (BACT) requirement under the Prevention of Significant Deterioration (PSD) regulations, the company proposes to install a 15,000 scfm catalytic incinerator and a permanent total enclosure for the new press. The maximum as-applied ink usage for each press is 400 lb/hr and consists of 12 percent ethyl alcohol, 52 percent ethyl acetate, 4.8 percent toluene, 3.2 percent hexane, and 20 percent solids by weight. The existing configuration of the press room is shown in Figure 3.7.

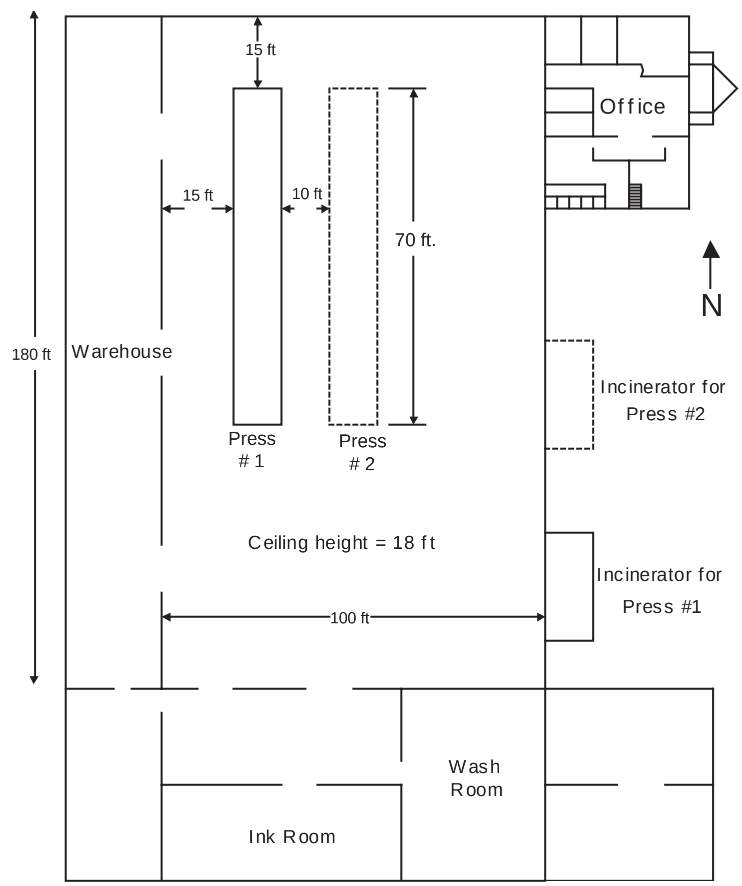

Figure 3.7: Example Plant Layout

The company needs to demonstrate an overall control efficiency of 97 percent for Press #2 as required by the PSD permit. Because the facility is subject to Subpart [KK1] of the MACT standards, an overall control efficiency of 95 percent will have to be demonstrated for Press #1.

To comply with an overall control efficiency of 95 percent, the company must demonstrate a capture efficiency of 100 percent (95/0.95) for Press #1. Assuming the destruction efficiency of the catalytic incinerator to be at least 98 percent, the company must demonstrate a capture efficiency of 99 percent (97/0.98) for Press #2. The designer decided a single PTE around both presses creates fewer obstructions to the work flow and cost less to install.

With a destruction efficiency of 95 percent for the Press #1 incinerator (as tested) and 98 percent for the Press #2 incinerator (as guaranteed), the company can easily demonstrate compliance with the required overall control efficiency.

Size of the PTE

The press room is 100 by 180 ft and the ceiling is 18 ft, resulting in a press room volume of 324,000 cu ft. The exhaust flow rate from the press room is 30,000 scfm (sum of the exhaust flow rates of the two incinerators). Converting the existing press room into a PTE requires the least amount of construction and causes the least amount of disturbance to the occupied space. However, that size enclosure will provide only 5.6 RACs/hr while 10 to 15 air changes provide adequate worker comfort. For this reason, the company decided to build a smaller PTE around the presses.

The existing configuration of the press room is such that a smaller PTE can be built easily by erecting only two additional walls: one on the east side of Press #2 and the other on the south side of the two presses.

In order to provide adequate space for material movement at both ends of the presses, the design places the south wall of the PTE, 15 ft from the nearest end of the presses. On the east side of Press #2, a slightly larger space (20 ft wide)is selected. The overall dimensions of the PTE are 65 ft wide, 100 ft long, and 18 ft high as shown in Figure 3.8, with a volume of 117,000 cu ft. With an exhaust flow rate of 30,000 scfm, this provides 15 RACs/hr.

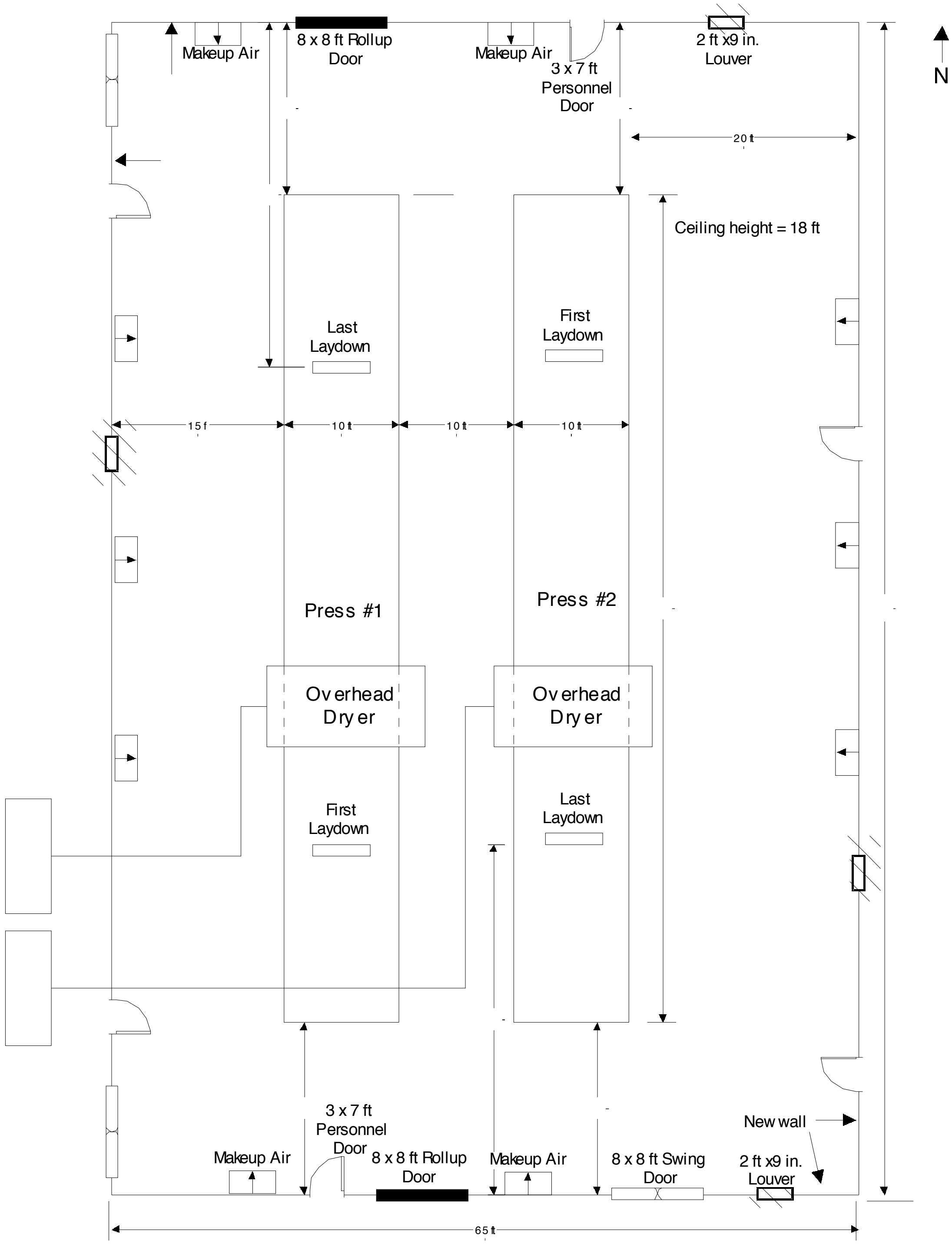

Figure 3.8: Example Permanant Total Enclosure

PTE Wall Material

Typical materials include sheet metal, modular panels, concrete masonry units (CMUs), and drywall. The type of material used depends on the existing equipment and the extent of construction obstructions. In this example, the height of the enclosure is relatively low (18 ft) and the total length of the wall to be constructed is only 165 ft. In addition, there is plenty of room for movement of equipment/material, and there are no obstructions over the presses. Therefore, any appropriate material can be used, depending upon user preference. Due to their ease of construction, portability, and appearance, the engineers selected modular panels for constructing the walls.

Access to the PTE (Doors and Windows)

Most production materials move to the PTE from the warehouse, ink room, and washup areas. Therefore, the design includes two 8 x 8 ft rollup door for the north and south walls of the PTE, (selected to minimize waiting time for material transfers of material in and out of the PTE) three 8 x 8 ft swing doors, two on the west wall, and one on the south wall, and four standard size (3 x 7 ft) personnel doors, one on each wall of the PTE. Windows are not used. In sum, the following access is provided:

Item	Number
Swing doors (8 x 8 ft)	3
Rollup doors (8 x 8 ft)	2
Personnel doors (3 x 7 ft)	4
Windows	None

Louvers

Because of the number of doors specified and the expected frequent opening of the doors on the west and south walls of the PTE, some air movement into the enclosure may occur. However, in order to provide better mixing and ventilation within the PTE, the designers decided to install one large (2ft x 9 in.) louver on each wall of the PTE to minimize the amount of makeup air required. Steel louvers were selected because of their greater durability.

Makeup Air

From the data given in Table 3.3, the total area of the NDOs, not including the louvers, is 198 sq in. (1.38 sq ft). By EPA standards, the average facial velocity must be at least 200 fpm. Furthermore, if the velocity is greater than 500 fpm, the direction of air flow through the NDOs is considered to be inward at all times without verification. The designers used a facial velocity of 600 fpm to provide a margin of safety. With a facial velocity of 600 fpm, the air flow through the NDOs (excluding the louvers) is 728 scfm which is about 3.4 percent of the total air flow (30,000 scfm). By providing louvers (one on each wall of the PTE) , the total NDO area is increased to

1,062 sq in. (7.38 sq ft) changing the total air flow through the NDOs to 4,428 scfm. The makeup air required is 25,572 (30,000 - 4,428) scfm. The intake for the makeup air is on the roof of the building and ducted into the PTE at several locations to enhance mixing.

The makeup air required for the example PTE is at least 25,572 scfm. The required static pressure (system resistance) is determined by summing pressure losses through the system components. Assuming that the fan is located in the center on the roof of the PTE and four ducts are installed to deliver makeup air through the four walls of the PTE, the total length of the duct is 400 ft. Each duct carries about 6,393 cfm (a quarter of 25,572 scfm). The number of 90 degree bends required is 12. The radius of curvature of the bends (elbows) is 1.5. The duct diameter is calculated using equations in Section 2, Chapter 1 "Hood, Ducts and Stacks". The flow through each duct is 6,390 scfm. Since the material being conveyed is fresh air, a transport velocity of 2,000 fpm is selected (See Section 2, Chapter 1 "Hood, Ducts and Stacks"). The duct diameter (D_d) is:

$$D_d = 1.128\ (6{,}390/2{,}000)^{1/2} = 2 \text{ ft}$$

Friction losses are:

$$F_d = 0.136\ (1/2)^{1.18}\ (2{,}000/1{,}000)^{1.8}\ (400/100) = 0.80 \text{ in. w.c. (straight duct)}$$

$$VP = (2{,}000/4{,}016)^2 = 0.25 \text{ in. w.c. (Velocity pressure)}$$

$$F_c = 12\text{x}\ 0.33\text{x}\ 0.25 = 0.99 \text{ in. w.c. (elbows)}$$

$$\text{Total friction loss} = 1.79 \text{ in. w.c} \approx 1.75 \text{ w.c.}$$

.

Since the inlet to the makeup fan will be open to the atmosphere, the velocity pressure at its inlet will be negligible, the designers selected a fan to provide at least 25,572 scfm (70 °F and 1 atm) at a static pressure of at least 1.75 in. w.c.

For a flow rate of 25,572 cfm and static pressure of 1.75 w.c., the wheel diameter of the fan selected is 36.5 in. The required horsepower for the fan selected is 11.0 Hp. Most of the fan manufacturers provide fan motors and starters to match the fan load.

Duct

The example system requires 400 ft of makeup air duct, with a diameter of 2.04 ft. From a number of designs and materials available, the designers choose: duct fabricated from spiral-wound, galvanized carbon steel sheet, four galvanized carbon steel butterfly dampers and twelve 90 degree elbows.

Other Considerations

Other factors in the design of PTEs are air conditioners, safety equipment, hoods, lighting and instrumentation. Although important, they are not part of the scope of this chapter.

3.4 Estimating Total Capital Investment

This section presents the procedures and data necessary for estimating capital costs for PTEs. Total capital investment, TCI, includes purchased equipment cost and direct and indirect installation cost. Most costs in this chapter are presented in 1st quarter 1997 dollars and represent a national average.

3.4.1 Purchased Equipment Cost

<u>Walls</u>

Materials typically used are concrete masonry units (CMUs), drywall, sheet metal, and modular panels. The cost of these materials is commonly given in terms of $/sq ft.

Table 3.3: Cost for different construction materials[12,18].

Wall Material	Purchased cost (1997 $/sq ft)
CMUs	1.49
Drywall	0.59
Sheet metal	1.69
Modular panels	9.76
Lexan (thermoplastic polymer) -Ω in. thick	8.00
Lexan (thermoplastic polymer) -æ in. thick	12.00

The total area of the wall is 2,970 sq ft. Although modular panels are expensive, they were selected because of their appearance (finished on both sides), strength, and flexibility in modifying or relocating. At a unit cost of $9.76/sq ft, the material cost for walls is:

Wall material cost =$9.76/sq ft x 2,970 sq ft = $28,987

<u>Doors</u>

Doors are made in several standard sizes. Their prices are given by units.

Table 3.4: Cost of different door types[12].

Door type	**Purchased cost (1997 $ each)**
Strip curtain door, 3 x 7 ft	275
Strip curtain door, 8 x 8 ft	575
Personnel door, steel, 3 x 7 ft	575
Sliding door, strip curtain, 8 x 8 ft	780
Sliding door, steel 8 x 8 ft	1,240
Bump door, steel, 3 x 7 ft	1,290
Bump door, steel, 8 x 8 ft	1,830
Rollup door, low speed, 8 x 8 ft	4,255
Rollup door, high speed, 8 x 8 ft	10,165

The estimated cost of the nine doors needed in the design is:

Personnel doors purchased cost	4 doors x $575 each	= $ 2,300
Swing doors purchased cost	3 doors x $1,830 each	= $ 5,490
Rollup doors purchased cost	2 doors x $10,165 each	= $20,330

Auxiliary Equipment

Louvers

Prices for louvers correlate well with the size of the louvers. The following equations can be used to estimate the national average cost of steel and aluminum louvers:

Steel louvers[13]: $$C = 42 + 35\,A \quad (1.5 \leq A \leq 7.75) \tag{3.14}$$

Aluminum louvers[13]: $$C = 47 + 39\,A \quad (1.5 \leq A \leq 7.75) \tag{3.15}$$

where C = cost for each louver in 1997 dollars and
A = surface area of each louver in sq ft.

Four steel louvers (2 ft x 9 in.) are required for the example PTE. The cross sectional area of each louver is 1.5 sq ft. Using equation (3.13), the louvers' purchased cost is:

Purchased cost per louver	42 + (35 x 1.5)	= $94.5 each
Purchased cost for 4 louvers	4 x $94.5 each	= $378

LFL Monitors

Table 3.5: Cost of LFL monitors [12,16,17]

Item	Price(1997 $ each)
%LFL monitor using flame ionization detectors	10,845
%LFL monitor using catalytic bead	3,325

Because of their lower cost, catalytic bead type LFL monitors were selected.

Cost of 2 catalytic bead monitors = 2 x $3,325 = $6,650

Safety Equipment

Table 3.6: Cost of miscellaneous safety equipment[13,17]

Item	Price(1997 $ each)
Smoke detector (ceiling type)	75
Smoke detector (fixed temperature)	28
Alarm bell	70
Alarm siren	131
Alarm signal	50
Flame detector	2,925

Two ceiling type smoke detectors were selected.

Cost of smoke detectors (ceiling type) = 2 x $75 each = $150

Ductwork

Procedures for designing and estimating costs for ductwork systems are given in Section 2, Chapter 1 “Hoods, Ducts and Stacks” of this Manual. The total ductwork cost is comprised of the cost of its components: straight duct, elbows and dampers

Table 3.7: Cost of Ductwork

Item	Quanity	Cost
Straight duct cost ($/ft)	$=1.71(24)^{0.936}$	= $33.49/ft
Total cost for 400 ft	=$33.49/ft x 400 ft	= $13,395
Elbow cost ($)	$=58.9\ e^{0.0633(24)}$	= $269 each
Cost for 12 elbows	=12 x $269	= $3,229
Damper cost ($)	$=50.2\ e^{0.0597(24)}$	= $210 each
Cost for four dampers	=4 x $210	= $840
Total cost for ductwork	**= $13,395 +3,229 + 840 = $17,464**	

Fans, Motors, and Starters for Makeup Air

The fan cost equation is presented as follows:

$$C = 56.3\ D^{1.2} \quad (12.25 \leq D \leq 36.5) \tag{3.16}$$

where C = cost in 1997 dollars, and
D = fan wheel diameter (in.).

The wheel diameter of the makeup air fan is 36.5 in. By substituting in Equation 11.14, the total cost of the fan, belt-driven motor, and starter is $4,219.

Instrumentation

One of the five-point criteria for a PTE is to maintain a negative pressure of 0.007 in. w.c. in the PTE. This requires an extremely sensitive and reliable pressure monitor. In addition to the monitor, most vendors recommend a pressure surge damper (to dampen sudden pressure changes). The prices for the equipment are given below.

Table 3.8: Cost of instrumentation equipment [14]

Item	Price(1997 $ each)
Differential pressure monitor	487
Surge damper	22
Alarm	20
Total cost	**$529**

Freight and Taxes

Freight charges depend upon the distance between the site and vendor. Sales taxes depend upon the location of the site and the vendor. National average values for freight and taxes are 5 percent and 3 percent of the total equipment cost.

Table 3.9: Total Purchase Equipment Cost (PEC)

Item **Basic and Auxiliary Equipment**		**Cost ($)**
Walls		28,987
Doors		29,270
Louvers		378
LFL monitors		6,650
Smoke detectors		150
Makeup air ductwork		17,465
Fan, motor, starter		4,219
Total equipment cost (TEC)		**87,120**
Instrumentation Equipment		529
Freight charges	0.05 x 87,120	4,356
Taxes	0.03 x 87,120	2,614
Total Purchased Equipment Cost (PEC)		**94,619**

3.4.2 Installation Cost

Direct Installation Cost

The direct installation cost consists of installation costs for the basic equipment, auxiliary equipment, and instrumentation.

Walls

Major factors affecting the installation cost for walls are the existing equipment and extent of obstructions. The national average costs of installation for walls assuming moderate obstructions are given in Table 3.10 (multiply these costs by a factor of 1.5 for severe obstruction to construction [12,15]):

Table 3.10: Cost of Wall Installation Based on Material[12,18]

Wall material	Direct installation cost (1997 $/sq ft)
CMU	3.10
Drywall	2.90
Sheet metal	12.91
Modular panels	7.97
Lexan (thermoplastic polymer) -Ω in. thick	2.90*
Lexan (thermoplastic polymer) -æ in. thick	2.90*
*Assumed same as drywall[12,18]	

Installation cost of modular panel walls with an area of 2,970 sq ft:

= $7.97/sq ft x 2,970 sq ft = $23,671

<u>Doors</u>

Table 3.11: Cost of door installation based on type [12]

Door type	Direct installation cost(1997 $ each)		
Strip curtain door, 3 x7 ft	240		
Strip curtain door, 8 x 8 ft	285		
Personnel door, steel, 3 x 7 ft	415		
Sliding door, strip curtain, 8 x 8 ft	890		
Sliding door, steel, 8 x 8 ft	1,745		
Bump door, steel, 3 x 7 ft	730		
Bump door, steel, 8 x 8 ft	2,575		
Rollup door, low speed, 8 x 8 ft	3,045		
Rollup door, high speed, 8 x 8 ft	3,910		
Personnel door installation cost	4 doors x $415 each	=	$1,660
Swing doors installation cost	3 doors x $2,575 each	=	$7,725
Rollup door installation cost	2 doors x $3,910 each	=	$7,820
Total		**=**	**$18,035**

<u>Auxiliary Equipment</u>

Louvers

The labor cost for installing louvers corresponds to the size of the louver. The following equations can be used to estimate the national average cost of installation for steel and aluminum louvers:

Steel louvers[13]:	$C = 8 + 1.7\ A$	each	$(1.5 \leq A \leq 7.75)$	(3.17)
Aluminum louvers[13]:	$C = 9 + 1.9\ A$	each	$(1.5 \leq A \leq 7.75)$	(3.18)

where C = cost in 1997 dollars, and
A = louver surface area in sq ft.

The area of the selected louvers is 1.5 sq. ft, therefore:

Louver installation cost	8 + (1.7 x 1.5)	=	$10.55 each
Installation cost for 4 louvers	4 x $10.55 each	=	$42

LFL Monitors

Table 3.12: Installation cost for LFL monitors

Item	Installation cost(1997 $ each)
%LFL monitor using flame ionization detectors	2,700
%LFL monitor using catalytic beads	1,000

Total Installation cost of two catalytic bead monitors = 2 x $1,000 each = $2,000

Ducts

As discussed in Section 2, Chapter 1, the installation cost for ductwork varies from 25 to 50 percent of the material cost. Assuming an average of 37.5 percent, the installation cost for the makeup air ductwork is estimated as:

Makeup air duct installation cost	=	37.5% x material cost	
	=	0.375 x $17,464	=$ 6,549

Fans, Motors, and Starters for Makeup Air

Installation costs for fans, motors, and starters are given by the following equations:

$$\text{Fans[16]:} \quad C = 51.89\ D - 380.9 \quad (10 \le D \le 20) \quad (3.19)$$

$$\text{Motors[17]:} \quad C = 43 + 2.16\ H \quad (2 \le H \le 100) \quad (3.20)$$

$$\text{Starters[18]:} \quad C = 78.68\ Ln(H) - 15 \quad (2 \le H \le 100) \quad (3.21)$$

where C = cost in 1997 dollars,
D = fan wheel diameter (in.),
H = fan motor and starter horsepower, and
Ln(H) = natural log of horsepower.

Since the installation cost equation applies only to diameters of 10 to 20 in. The installation cost for a 36.5 in. fan can be calculated on the basis of two fans with a wheel diameter of 18.25 in. each. This yields a fan installation cost of $1,132. The installation cost of a single fan 36.5 in. in diameter can also be calculated based on extrapolation of Equation 3.19. This yields:

Fan installation cost = (51.89 x 36.5) - 380.9 = $1,513.

Equation 3.20 yields:

Fan motor installation cost = 43 +(2.16 x 11) = $ 67

Equation 3.21 yields:

Motor starter installation cost = 78.68 Ln(11.0) -15 = $174

Total fan, motor, and starter cost = $1,513+67+174 = $1,754

Instrumentation

Table 3.13: Installation cost for instrumentation components [13,15]

Item	Installation cost(1997 $ each)
Differential pressure monitor	200
Surge damper	20
Alarm	60
Total	280

Indirect Installation Cost

Indirect installation costs are generally estimated from a series of factors applied to the purchased equipment cost. For PTEs, these costs are not dependent on the purchased equipment cost and national average indirect costs related to installation are used.

Table 3.14: Indirect Installation Costs [12,15]

Engineering	$ 5,000
Contractors	15,000
Compliance Test	2,500
Total indirect	$22,500

The total capital investment (TCI) is the sum of the purchased equipment cost, direct installation cost, and indirect installation cost.

Table 3.15: Total Capital Investment

Item	**Cost ($)**
Purchased Equipment	94,619
Direct Installation Cost	
Walls	23,671
Doors	18,035
Louvers	42
LFL monitors	2,000
Smoke detectors	78
Makeup air	6,549
Ductwork	
Fan, motor, starter	1,754
Differential pressure	200
Monitor	
Surge damper	20
Alarm	60
Indirect Installation Cost	22,500
Total Capital Investment	**169,528**

3.5 Estimating Total Annual Cost

The total annual cost is the sum of direct and indirect annual costs and the recovery credit. Recovery credits represent the value of materials or energy recovered by the control system. Recovery credits are usually associated with control equipment not applicable to PTEs.

3.5.1 Direct Annual Cost

There are no costs for operating, supervisory labor, operating materials, or waste disposal allocated to a PTE. Maintenance costs will be minimal, except for such minor expenses as painting, repairs, or calibration of instruments. The operating cost is the one for only utilities electricity used to operate the auxiliary equipment such as supply fans for makeup air and air conditioning if needed.

The national average electricity cost for operating the supply fan is estimated as follows:

$$C_e = \frac{\left(1.175 \times 10^{-4}\right) P_e Q \,\Delta P\, S\, \Theta}{\eta} \qquad (3.22)$$

where

	C_e	=	electricity cost (\$/yr),
	1.175×10^{-4}	=	a dimensionless conversion factor,
	P_e	=	electricity price (\$/kWh),
	Q	=	exhaust flow rate (acfm),
	ΔP	=	static pressure drop through the makeup air system (in. w.c.),
	S	=	specific gravity with respect to air (=1),
	Θ	=	operating hours per year and
	η	=	combined fan-motor efficiency.

The electricity cost is calculated as follows:

Makeup air flow rate	=	26,200 acfm
Static pressure drop	=	1.75 in. w.c.
Electricity price	=	$0.06/kWh
Operating hours	=	8,760 hr/yr (maximum possible in a year)
Overall efficiency	=	0.75

Substituting these values yields a direct annual cost of $3,775 per year.

3.5.2 Indirect Annual Cost

The indirect annual costs for a PTE include property taxes, insurance, general and administrative charges, overhead, and capital recovery costs. These costs can be estimated from the total capital investment (TCI) using standard factors from this Manual as given below:

Table 3.16: Indirect Annual Cost Factors

Item	Factor
Property taxes	1% of TCI
Insurance	1% of TCI
General & administrative	2% of TCI
Capital Recovery	Capital Recovery Factor x TCI

The TCI is $169,528. Overhead is not considered because it is based on the sum of the operating, supervisory, and maintenance labor and materials costs, which are negligible for a PTE. For the example PTE, the cost for the first three items is:

Property taxes	=	0.01 x $169,528	=	1,695
Insurance	=	0.01 x $169,528	=	1,695
General and administrative	=	0.02 x $169,528	=	3,391
Total			=	$6,781

The capital recovery factor (CRF) is a function of the economic life of the equipment and the interest charged on the total capital investment previously discussed in this Manual:

$$CRF = I(1+I)^n/[(1+I)^n - 1]$$

where I = annual interest rate in fraction (i.e., 7% = 0.07) and
n = economic life in years.

For a PTE, the economic life is the same as the life of the building which might be 20-30 years or of the particular equipment enclosed by the PTE which might be less. The interest rate value recommended by the Office of Management and Budget (OMB) is 7 percent. (This replaces the 10 percent rate previously recommended by OMB.) An economic life of 30 years and an interest rate of 7 percent yields a CRF of 0.080586.

Capital recovery	=	0.080586 x TCI	
	=	0.080586 x 169,528	= $13,662
Total annual indirect cost	=	$6,781 +$13,662	= $20,443.

Total annual cost is calculated as follows:

Total direct cost	=	3,775
Total indirect cost	=	20,443
TOTAL	=	$24,218

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16. ABSTRACT

In Spanish, this document provides a detailed methodology for the proper sizing and costing of numerous air pollution control devices for planning and permitting purposes. Includes costing for volatile organic compounds (VOCs); particulate matter (PM); oxides of nitrogen (NOx); SO2, SO3, and other acid gasses; and hazardous air pollutants (HAPs).

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