Notice

This Engineering Guide was recently converted to a PC format and it has not been proof read by our engineering staff. Therefore, it is subject to change at a later date.

Ohio EPA

Office of Air Pollution Control

Engineering Section

Engineering Guide #46

Question:

How should capital cost, annualized cost, cost-effectiveness be determined in order to select or evaluate an emission requirement based on Best Available Technology (BAT), Reasonably Available Control Technology (RACT) or Reasonably Available Control Measures (RACM)? (This question was originated by Air Quality Modeling and Planning Section of the Division of Air Pollution Control.)

Answer:

Generally, the more efficient a control device is in reducing emission rate of a pollutant, the greater the cost of the device. Many times in the process of trying to ascertain what is BAT for new or modified sources and RACT or RACM for existing sources, the cost-effectiveness of a control device becomes the primary determining factor.

The following document entitled "Guidance for Estimating Capital and Annual Costs of Air Pollution Control Systems" is a guideline to assist in determining capital costs, annualized costs and other information necessary in calculating the cost-effectiveness of a pollution control device.

Costs associated with a pollution control device include the capital cost and the annualized cost. Capital cost includes the direct cost of purchasing the control device along with the labor and installation costs. Annualized costs are the total expenditures, on an annual basis, required to amortize, operate and maintain the control device. Interest paid on borrowed money for the equipment, plus taxes, insurance and overhead are all included in the annualized cost. Cost-effectiveness is determined by dividing the total annualized cost of the device by the total annual emission reduction achieved by the device, and is normally expressed in dollars per unit weight emission reduction (e.g., $/ton or $/pound).

The determination of whether or not a particular cost-effectiveness value is economically reasonable is not within the scope of this engineering guide. Questions in this regard should be directed to either the Engineering Section or Air Quality Modeling and Planning Section of the Division of Air Pollution Control.

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GUIDANCE FOR ESTIMATING CAPITAL AND ANNUAL COSTS OF AIR POLLUTION CONTROL SYSTEMS

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SECTION 1

INTRODUCTION

1.1 PURPOSE

Regulations of the Ohio Environmental Protection Agency (OEPA) require that any person intending to install a new source - or modify an existing source - of air emissions apply for and obtain a permit-to-install (PTI). The review of PTI applications is conducted by local air agencies and OEPA district offices. Cost analyses are an important aspect of the review and it is extremely important that costs be derived in a consistent manner. The purpose of this document is to provide guidance on cost estimating and related methodologies that will promote statewide uniformity and consistency in the estimating of costs for air pollution control systems. The methods and procedures presented should provide cost estimates accurate to within ±20 to 30 percent for specific cases where adequate data are available.

1.2 SCOPE AND FORMAT

In the preparation of cost estimates for air pollution control systems it is common practice to separate costs into two interrelated cost centers - capital and annualized costs. The capital investment cost includes the direct cost of purchased equipment, the labor and materials to install the system and the indirect costs associated with the design, construction and startup expenses. Annualized cost is the total annual expenditure to operate and maintain the facility and includes the day-to-day operating costs and expenditures for interest on borrowed capital, taxes, insurance and overhead.

A methodology for developing total installed capital cost and total annualized cost estimates is presented. Since the purpose is to establish consistency in estimating techniques a generalized approach is presented and specific process or equipment costs are not included. The methodology is based on the factoring technique developed for the United States Environmental Protection Agency (U.S. EPA) by GARD, Inc. (Reference 1). Emphasis is on costs of systems that employ air pollution control hardware; however, by following the general procedures and basic principles, costs can be derived for control by process change, material or fuel substitution and for the secondary costs associated with the treatment and disposal of waste materials captured by the control system.

Section 2 presents a discussion of the many variables that affect the costs of emission reduction systems and points out process parameters, regulatory and control system requirements that influence system design and cost. The average unit cost, scaling and factoring techniques commonly used to estimate costs are briefly described in Section 3 and the limitations of each technique are explained. The factoring method is best suited to permit review cost analyses since it offers reasonable accuracy, can be adapted to reflect costs for specific installations and can be conducted with moderate effort.

Section 4 discusses capital costs components, suggests sources of cost information and lists average factors for deriving direct and indirect installation costs as a function of purchased equipment expenditures. Adjustment multipliers and criteria for their use in preparing refined estimates for a specific system are provided and the use of cost indexes to equalize costs on a current, constant dollar base is discussed.

Section 5 is devoted to estimation of annualized costs and contains subsections on direct operating costs, indirect operating costs, cost factors and their use. Control system and operational variables have a major affect on direct operating costs, can differ substantially between both similar and dissimilar plants and control systems, are case specific in nature and require judgement in their definition. General guidelines are provided to assist in this judgement. Information, data and formula useful in estimating control system utility requirements and capital recovery costs are provided. Section 6 discusses the cost-effectiveness concept and illustrates the calculation and use of cost-effectiveness and incremental cost-effectiveness values.

SECTION 2

VARIABLES AFFECTING EMISSION CONTROL COSTS

Published air pollution control costs are frequently generalized data representing industry averages and are often presented as cost per capacity parameter (such as dollars per ton of production or per cubic foot of exhaust gas treated per minute). These averages represent a range of costs, may be based on a number of different installations and hide the fact that costs vary widely. The capital and operating costs are subject to many of the same variables that are or should be considered in the selection and design of the control system itself. Variables or factors that influence control system selection, design and costs include:

- Plant/source status - location, new/existing facility.
- Process/source parameters - type, size/capacity, continuous or intermittent, operating methods/cycles.
- Gas stream characteristics - temperature, pressure, volume, pollutant concentration(s), chemical composition, physical nature.
- Regulatory requirements - emission limitations, opacity, performance/process/equipment/monitoring standards.
- System requirements - type, size, auxiliary and gas conditioning equipment, capture/collection system efficiencies and configurations, construction materials, insulation, utilities, instrumentation,

waste disposal/reclaim/treatment, operating and maintenance materials/supplies.

Plant location, local climate, geography and demography may dictate more stringent emission limitations, sophisticated control and increased costs. Retrofit applications can result in installation costs that greatly exceed the costs at new facilities because of space restrictions, difficult tie-ins and out-dated process equipment. Process operating methods and cycles necessarily influence both system design and costs. Cyclic or fluctuating gas flow rates affect system performance, must be accommodated in system design/selection and affect ultimate costs.

Exhaust stream characteristics of major importance include volume, pressure, temperature, moisture content, pollutant concentrations(s), and corrosiveness. Gas conditioning equipment to preclean, cool, dry, humidify or chemically treat the gas stream may be required. Acidic components require that corrosion resistant materials be used in the capture and collection systems. Physical properties of pollutants - such as particle size and electrical properties - affect costs and design.

Collected materials must be handled, store and disposed of in an acceptable manner. Significant expenses can be involved in providing land area, treatment/disposal facilities and in bringing utilities to the disposal site. When collected materials can be reclaimed or recovered a credit may be realized as product, by-product, heat or fuel. Standby (redundant) equipment, safety margin provisions, instrumentation and automated operation to improve reliability and reduce maintenance can have substantial effect on costs.

In summary the total cost of an air pollution control system is influenced by many variables and these variables must be taken into account in making reliable cost estimates. Non-specific cost data based on industry averages can be misleading since the average represents many different types of installations with a wide range of costs. The low end of the range might represent an installation using a minimum of standard equipment installed by plant personnel that just meets regulatory emission limits. The high end of the cost range may be for a sophisticated customized system that included redundant equipment, automation, expensive construction materials, waste treatment/disposal, auxiliaries and other special or custom features. These differences or variables affect both purchased equipment and installation costs. Each variable should be examined and quantified as precisely as possible in order to preserve the accuracy of the estimate.

SECTION 3

METHODS FOR ESTIMATING CAPITAL COSTS

Capital costs of a control system include the cost of the purchased equipment, i.e., the control device, auxiliary equipment and accessories, and all direct and indirect installation costs. The direct installation costs include the labor and material costs for erection and handling, foundations and supports, electrical, piping, insulation, painting, site preparation, facilities and buildings. Indirect installation costs include engineering, supervision, construction and field expense, fees, start-up, performance tests and contingencies.

There are a number of methods for estimating capital costs. The accuracy of any method is directly related to the amount and detail of information available and the manner in which it is used. The estimate may be "order of magnitude" (when based on industry averages), accurate to within ±20 to 30 percent (when derived from preliminary designs) or to within ±5 percent (when prepared from complete plans and specifications). Detailed cost estimates (±5 percent accuracy) require complete and detailed information and data that is site-specific and based on material/energy balances, site/soil surveys, complete process and structure plans/specifications and other engineering works. Less detailed estimates are adequate for permit review needs. Several commonly used estimating methods are discussed below.

3.1 AVERAGE UNIT COST ESTIMATES

This method is based on the average cost per size or capacity parameter. For example the basis of cost estimates may be dollars per 1000 standard cubic feet per minute (scfm) of treated exhaust gas, per kilowatt (kW) of boiler size or per ton of production. The average unit cost represents a range of costs. Non-specific cost data based on industry averages can be misleading and the range of capital costs derived from such data can be very wide. This method leads to an order of magnitude estimate and is best used for general comparison only.

3.2 SCALED ESTIMATES

Where costs are known for a given size or capacity, a scaled estimate can be made to obtain the costs for similar equipment or for control systems of a different size. The "power rule" is a technique for scaling of cost data using the equation:

$$C_a = C_b \frac{(S_a)^n}{(S_b)}$$

Where C_a and C_b are the desired and known costs respectively S_a and S_b are the size or capacity of the "desired" and "known" control device or equipment respectively, and n is the scaling exponent. For equipment costs the exponent or factor has been shown to average 0.6 and the rule is commonly referred to as the "six tenths factor." The scaling factor of six-tenths is most accurate when applied to single equipment items but has been used for approximation of complete system costs. The six-tenths technique may produce errors of 50 percent or more because of differences in size, location, auxiliary equipment, system sophistication, or other dissimilarities. Accuracy is highly questionable when costs are scaled to reflect more than an order of magnitude in size. Since scaling methods are relatively inaccurate they should only be used when no other costs are available. Examples of scaling exponents and an indication of the wide variation in exponents that can be expected are shown in Table 3-1.

3.3 FACTORED ESTIMATES

A factored estimate is a total capital cost estimate based on only one or two items. Accuracies within ±20 to 30 percent are possible using the so-called "factored" method when adequate data are available. An example is the modified Lang method developed for the U.S. Environmental Protection Agency (US EPA). In this method the basic purchase prices of equipment are multiplied by appropriate factors to compute the other costs. The multiplier factors are derived from experience with previous construction and system costs. Adjustment of the multiplier factors allows development of costs that more closely reflect the specifics of a given system. The method is therefore well suited to permit review cost analyses since it offers reasonable accuracy, can be adapted to reflect specific installations and can be conducted with moderate effort. For these reasons the methods for estimating capital and annualized costs presented in Sections 4.0 and 5.0 are those developed for the US EPA by Gard, Inc. (Reference 1).

TABLE 3-1. SCALING EXPONENTS FOR CONTROL DEVICE AND AUXILIARY EQUIPMENT[2]

Equipment item	Scaling exponent	
	Unit	Exponent
Fabric filter	ft^2 cloth	0.95
Electrostatic precipitator	ft^2 plate	0.37
Wet collector	acfm	0.70
Cyclones	acfm	0.80
Absorption units	acfm	0.62
Carbon adsorber	lb carbon	0.90
Catalytic incinerator	acfm	0.60
Thermal incinerator		
• with heat exchanger	acfm	0.70
• without heat exchanger	acfm	0.4-0.5
Condensers	acfm	0.70
Fan system	BHP	0.96
Pump system		
Reciprocating	BHP	0.52
Centrifugal	BHP	0.52
Quench tower	acfm	0.85
Spray chamber	acmf	0.43
Reheater	acmf	0.78
Ductwork	ft^2	0.55
Exhaust stack	ft	1.0
Hoppers	ft^3	0.68

Screw conveyors	length, ft	0.8
Storage tanks		
• Less than 40,000 gal	gal	0.29
• More than 40,000 gal	gal	0.63

SECTION 4

CAPITAL COSTS

4.1 CAPITAL COST COMPONENTS

The capital cost of an air pollution control system is defined as the direct and indirect expenses incurred tot he date when the facility begins full scale or commercial operation and major start-up problems have been resolved. Direct expenses (costs) consist of the purchased equipment cost for the system plus the direct installation costs for labor and materials needed to the install the system. Indirect expenses (costs) are those not directly related to specific equipment but necessary to complete the design, construction and start-up of the overall control system facility. Table 4-1 is a listing of capital cost components categorized as direct costs (the delivered equipment costs) and installation costs - direct and indirect. Examples of each cost component are given and accompanied by appropriate explanatory remarks.

4.1.1 Equipment Costs

Purchased equipment cost is the most important item in a capital cost estimate and includes the price of the control device, auxiliary equipment, instruments, controls, taxes and freight. In a factored estimate the equipment costs provide the basis for developing the remaining capital costs, i.e., the direct and indirect costs of installation. Factored estimates rely upon good estimates of equipment costs because all other costs are derived from them. The important of obtaining good equipment costs and defining what those costs include cannot be over-emphasized.

Sources of Cost Information--

Equipment costs may be obtained from vendors, fabricators and suppliers. Written quotations are preferred because the scope of the equipment or control device supplied at a given cost is better defined than in oral quotations. Several quotations can be obtained to allow a cross-check of costs and project scope. Useful sources containing the names of equipment vendors include the Chemical Engineering Equipment Buyers Guide, the classified section of telephone directories, pollution control magazines and trade journal advertisements. Price from suppliers or vendors are a preferred source of such information. Care must be taken to clearly define what is and is not included when obtaining prices from vendors or other sources. One quote may be for "flange-to-flange" costs only whereas another may include all or part of such items as electricals, instruments, controls, foundations, etc. Because of these variations it is extremely important to determine and define the scope of the project and the coverage of quoted prices.

Published reports and articles in technical journals are another source of cost information. Typical are such examples as the Control Techniques Guideline Documents (CTGD) and the

TABLE 4-1. CAPITAL COST COMPONENTS

Capital cost component	Example items	Remarks
Direct costs		Direct costs consist of the delivered cost of equipment and instrumentation directly related to capture, collection and handling of the exhaust stream and collected pollutants.
Purchased equipment • Control device	Fabric filter, ESP, scrubber, afterburner, absorber, equipment for process change/fugitive emission control, etc.	Where control option is process change the equipment costs may include conveyors, reactors, mixers, etc., i.e., process equipment. A road dust reduction program might include the cost of oiling trucks or additional haul trucks due to vehicle speed reduction controls. Price of items is on an F.O.B. basis.
• Auxiliary equipment	Pumps, fans, hoods/ ductwork, stacks, dust hoppers/conveyors, gas conditioners, sprinklers, mist eliminators, etc.	Process change may involve ductwork changes and add-on retrofit systems may require duct work modifications. Since most ductwork is shop fabricated for the specific application it is included in the auxiliary equipment cost rather than as an installation cost.

Capital cost component	Example items	Remarks
• Instruments/controls	Recorders, sensors, transmitters and control room equipment.	Control device costs may include internal electricals and some or all controls and instrumentation.
• Taxes	Sales/use taxes.	Ohio and many other states exempt certified air pollution control equipment from certain taxes.
• Construction/field expense	Costs of maintaining and supporting a labor force in the field.	These costs are affected by project size.
• Construction fee	Fee covers payroll additions, subcontractor supervision, risk insurance, etc.	Fee size dependent on project size and sophistication, single vs. multiple contractors, in-house vs. vendor vs. contractor erection.
• Startup	Costs of labor, materials, equipment and modifications needed to place system in good operating order.	Startup expenses are those incurred after the facility has been completed.
• Performance test	Cost of acceptance/performance/compliance testing.	Normally a fixed cost item.
• Model study		In unusual circumstances a model study may be necessary where little data is available from past installations.

Capital cost component	Example items	Remarks
• Contingencies	Design changes, completion delays (weather, strikes, etc.) and associated penalties, price increases, etc.	Contingency costs are real costs that may be experienced due to unforeseen circumstances.
• Freight		Cost of loading, rigging, delivery and unloading if not included in purchase price of equipment.
<u>Installation direct costs</u>		These costs consist of the direct expenses for material and labor to install the purchased equipment.
• Foundations/supports	Labor and material for foundation, excavation, steel, concrete, backfill, etc.	In retrofit cases involving installation on an existing structure and reinforcement or modification would be included or, if not necessary, this item would be deleted.
• Erection/handling	Labor and materials to assemble, and set in place and connect.	In retrofit applications this cost includes removal of existing equipment.

Capital cost component	Example items	Remarks
• Electrical	Labor and materials for installation of wiring, switchgear, circuit breakers, substation, etc.	ESP installation may have high electrical costs and require that supplemental power be provided (higher capacity service, substation, transformer, etc.).
• Piping	Labor and materials to install piping, hangers fittings, valves, etc.	This can be a high cost item for wet collection (scrubber) systems and for control by process change.
• Insulation	Labor and materials for installing insulation, steam tracing or other freeze protection.	Insulation and/or heaters on device itself may be included in purchased cost.
• Painting	Labor and materials for painting or coating to provide weather/corrosion protection.	Usually a minor cost item but may be a high cost where gas/liquid streams are corrosive requiring special internal/external liners or coatings.
• Site preparation	Labor and materials for road grading, clearing, piers, sidings, disposal/parking areas, removal of existing structures, etc.	This cost is highly sensitive to case specifics. May require land survey, study, dewatering, etc.

Capital cost component	Example items	Remarks
• Facilities/buildings	Labor and materials for administrative/maintenance/process buildings and other structures directly related to the air pollution control system. Includes access roads, fencing, lighting, heating, cooling, etc.	Some systems may require storage facilities for consumable materials used in the collection system, i.e., oil tanks for oil-fired incinerators, lime storage for flue gas desulfurization systems, etc. Buildings and facilities with heating/cooling, sanitation facilities, shops and offices for system operating personnel are included in this item. Also railroad sidings, truck depot and parking are included as necessary.
<u>Indirect costs</u>		Indirect costs of installation include those costs not directly related to a specific equipment item but necessary to complete the design, construction, startup and operation of the system.
• Engineering/supervision	Design of system, construction supervision and management.	Project size usually determines these costs. Small systems using standard equipment require less engineering and supervision than large prototype systems or process changes.

Background Information Documents (BID) published by US EPA. The difficulty in using this information is that documents are sometimes general in their treatment of processes and control systems and/or are "model" studies for similar but general processes. An exceptional and excellent publication for obtaining equipment costs is the Gard Manual.[1] This manual contains information useful in the sizing of control systems and provides flange-to-flange costs for common control equipment and for auxiliary equipment. When extracting capital expenditures from published information care should be taken to clearly define the scope and basis for the costs. Industry supplied cost information may be obtained from direct query, past purchase orders or from such sources as US EPA Section 114 letters, plant surveys and published reports. Generally such information requires explanation, verification and scope definition to be useful since the cited costs may be equivalent, rather than actual cost data, or may be composites that are not broken down adequately for direct use.

In the absence of other cost information rough estimates can be made using cost indexes, average unit costs and scaling methods. Cost curves that display purchased equipment costs, total capital costs and annualized costs can be found in US EPA documents and other published reports. The accuracy of these curves relative to a specific application depends upon the similarities between the assumptions used in the example curves (frequently not adequately explained) and the conditions under which the system under review will actually be used. Accordingly both the accuracy of the costs and applicability to a given case may be highly questionable.

Cost Escalation--

Since prices vary widely from one time period to another, cost data from various time periods must be adjusted to a constant data base to make meaningful comparisons. A cost index provides a method for upgrading costs to account for inflation without doing in-depth studies of individual project or cost items. The Chemical Engineering Plant Index (EC Index) is frequently used to extrapolate control equipment to current dollars. Reference 1 recommends use of the CD Index in conjunction with the U.S. Department of Labor, Bureau of Labor Statistics (BLS) wholesale price indexes and suggests they be used as shown in Table 4-2. The CE Index is used for updating costs of all major equipment items. Table A-1 of Appendix A is a tabulation of CE Index values for the years 1957 through 1982.

Where costs for one year (B) are known they can be adjusted to another year (A) by simple ratio of costs and indexes.

$$\text{Year A cost} = \text{Year B cost} \times \frac{(\text{Year A Index})}{(\text{Year B Index})}$$

TABLE 4-2. COST ADJUSTMENT INDEXES FOR AIR POLLUTION CONTROL SYSTEM EQUIPMENT

Equipment item	Use of the Index or Composite Index Shown
Control Equipment	
Absorber	CE Fabricated Equipment Index
Absorber	
• Package unit	CE Process Equipment Index
• Custom unit	CE Fabricated Equipment Index
Electrostatic Precipitators	CE Fabricated Equipment
• Insulation*	½ (BLS No. 1392 factor) + (CE Fabricated Equipment Factor)
Fabric Filter	CE Fabricated Equipment Index
• Insulation*	½ (BLS No. 1392 factor) + (CE Fabricated Equipment Factor)
• Stainless steel construction*	BLS No. 10130264 - for adjustment of stainless steel cost only
• Filter media*	BLS No. 0312 or No. 0334 - for filter media cost only
Flare	CE Fabricated Equipment Index
Incinerators-Thermal/Catalytic	
• Package unit	CE Process Equipment Index
• Custom unit	CE Fabricated Equipment Index
Mechanical Collectors	CE Process Machinery Index
Refrigeration	CE Process Equipment Index

Equipment item	Use of the Index or Composite Index Shown
Venturi Scrubber	CE Fabricated Equipment Index
• Rubber liner*	BLS No. 07
Auxiliary Equipment	
Cooling tower	CE Fabricated Equipment Index
Dampers	CE Fabricated Equipment Index
• Automatic control	CE Process Instruments/Controls Index on that portion of price
Ductwork	CE Fabricated Equipment Index
Dust removal/handling	CE Fabricated Equipment Index
Fans/motors/starters	
• Fans	BLS No. 1147 Index
• Motors	BLS No. 1173 Index
• Starters	BLS No. 11750781 Index
• V-belts	BLS No. 11450133 Index
Heat exchanger	CE Fabricated Equipment Index
Pumps	BLS No. 1141 Index
Stacks	CE Fabricated Equipment Index

* Apply index values only to that portion of the price, or the price increment, attributable to the special "add-on" feature or material, i.e., the difference in price between carbon and stainless steel construction, additional price of add-on insulation or rubber lining and mechanical vs. automatic controls.

In summary it is appropriate to re-emphasize that equipment cost is the most important item of a capital cost estimate and the more accurate this information, the better is the capital cost estimate. The parameters and other factors on which the equipment cost is based, the source of cost information, how it was derived and what it does (and does not) include should be clearly understood and specified in the cost statement.

4.1.2 Installation Costs

The installation costs can generally be considered as a fixed percentage of the equipment costs. However this percentage factor is influenced by the type of installation. Many of the individual items in the direct and indirect installation categories are subject to site-specific adjustment. For example installation costs vary depending on: whether or not the installation is new or retrofit (foundations, supports, site preparation factors), the geographic location and topography of the site (site preparation factor), whether the auxiliary and control device equipment are factory or field assembled (erection and handling factors), the availability and proximity of service facilities (electricity, water, etc.) at the site and whether the equipment is to be outside or enclosed in buildings (facility and building factors). While equipment costs represent a firm cost since they are obtainable from supplier's quoted prices it is evident that knowledge of the specific application is important in deriving installation costs. Use of the appropriate cost adjustments is an important aspect of capital cost derivation and proper use can provide cost estimates tailored to a specific installation.

4.2 COST FACTORS AND THEIR USE[1]

Estimation of the capital costs for air pollution control systems requires that information and data be available that clearly define.

- All system details and requirements, i.e., the components, size, configuration, design and operating parameters, gas stream and site characteristics, etc. of the capture, control and disposal systems necessary to satisfy the pollution control requirements for the specific source. Section 2.0 discusses variables that affect system requirements and costs.

- Control device and auxiliary equipment costs. Previous discussion in Section 4.1.1 indicated sources of equipment cost information and emphasized the importance of obtaining accurate prices that specify what is included and/or excluded in the cited price.

The method of estimating costs presented here is based on the factoring technique of establishing direct and indirect installation costs as a function of direct (purchased equipment) costs. Table 4-3 gives average cost factors for common types of air pollution control equipment and Table 4-1 shows example items that are covered by cost factors and indicates applicability. The cost factors are applied to the cost of delivered purchased equipment (direct costs) to estimate the direct and indirect installation costs. The capital cost estimate for the entire system is the sum of direct costs for purchased equipment and the direct and indirect installation costs.

TABLE 4-3. AVERAGE COST FACTORS FOR ESTIMATING CAPITAL COSTS OF

COMMON EMISSION CONTROL SYSTEMS[1]

Cost category	Electrostatic Precipitator	Venturi scrubber	Fabric filter	Thermal and catalytic incinerator	Carbon adsorber	Gas absorber		Refrigerator
<u>Direct costs</u> Purchased equipment:*								
a) Control device (A)	Purchased cost of control device (A)							
b) Auxiliary Equipment (B)	Purchased cost of auxiliary equipment (B)							
c) Instruments and controls	0.10 x (A + B)							
d) Taxes (unless exempt)	0.05 x (A + B)							
e) Freight	0.05 x (A + B)							
Base price (C)	Total of above							
Installation:**								
a) Foundations and supports	0.04	0.06	0.04	0.08	0.08	0.12	0.08	0.12
b) Erection and handling	0.50	0.40	0.50	0.14	0.14	0.40	0.14	0.40
c) Electrical	0.08	0.01	0.08	0.04	0.04	0.01	0.08	0.01
d) Piping	0.01	0.05	0.01	0.02	0.02	0.30	0.02	0.02
e) Insulation	0.02	0.03	0.07	0.01	0.01	0.01	0.10	0.01

Cost category	Electrostatic Precipitator	Venturi scrubber	Fabric filter	Thermal and catalytic incinerator	Carbon adsorber	Gas absorber		Refrigerator
f) Painting	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01
g) Site preparation***				As required				
h) Facilities and buildings***				As required				
Subtotal-multiplier for direct installation costs	0.67	0.56	0.72	0.30	0.30	0.85	0.43	0.57
Indirect costs Installation:**								
a) Engineering and supervision	0.20	0.10	0.20	0.05	0.05	0.10	0.05	0.10
b) Construction and field expense	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10
c) Construction fee	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
d) Startup	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01
e) Performance test	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
f) Model study	0.02	-	-	-	-	-	-	-
g) Contingencies	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Subtotal-multiplier for indirect installation costs	0.57	0.35	0.45	0.31	0.31	0.35	0.31	0.35

* Direct cost factors (c,d,e) for purchased equipment are the same for all equipment and are applied to the sum of control device (A) and auxiliary equipment (B) costs.
** Cost factor multipliers for direct and indirect installation costs are applied to the base price (C).

*** Costs for site preparation, facilities and buildings, if such are required, are added to the other direct installation costs.

The cost factors in Table 4-3 are typical or average multipliers derived from previous experience with construction and system costs. As discussed in Sections 2.0 and 4.1.1 there are many variables than can affect the overall control system costs - particularly with respect to the cost of installation. Installation costs can vary substantially from one system to another depending on such considerations as whether it is a new or retrofit installation, equipment is delivered as a package unit or requires field assembly, utilities are available at or near the site, equipment is to be enclosed or outside and in or on new or customized or untried prototype equipment. For these reasons it is desirable to adjust those cost items that are heavily influenced by system size, location, sophistication and the like. Table 4-4 presents adjustment factors for selected cost categories that can be used to develop refined estimates that more closely reflect the nature and characteristics of a specific system. The table lists general criteria on which to base use of the adjustment factors. The use of cost factors and adjustments is discussed in the following sections.

4.2.1 Direct Costs

Direct costs consist of the combined purchase price of the primary control (control device) and auxiliary equipment, the instrumentation and control costs, taxes and freight charges. All system components that are not field fabricated should be accounted for and included in the purchased equipment costs. The cost factors in Table 4-3 for calculating instrumentation, taxes

TABLE 4-4. COST ADJUSTMENT FACTORS FOR SELECTED COST CATEGORIES[1]

Cost category and adjusment criteria	Cost adjustment factor
<u>Instrumentation</u>	
1. Simple, continuous, manually operated.	0.5 to 1.0
2. Intermittent operation, modulating flow with emissions monitoring instrumentation.	1.0 to 1.5
3. Hazardous operation with explosive gases and safety backups	3
<u>Freight</u>	
1. Major metropolitan areas in continental U.S.	0.2 to 1.0
2. Remote areas in continental U.S.	1.5
3. Alaska, Hawaii, and foreign	2
<u>Handling and erection</u>	
1. Assembly included in delivered cost with supports, base, and skids included. Small to moderate size equipment.	0.2 to 0.5
2. Equipment supplied in modules, compact area site with duct and pipe runs less than 200 feet. Moderate-size system	1
3. Large system, scattered equipment with large runs. Equipment requires fabrication at site with extensive welding and erection.	1.0 to 1.5
4. Retrofit of existing system; includes removal of existing equipment and renovation of site. Moderate to large system	2
<u>Site preparation</u>	
1. Within boundary limits of existing plant; minimum effort to clear, grub, and level	None
2. Outside plant limits; extensive leveling and removal of existing structures; includes land survey and study	1
3. Requires extensive excavation and land ballast and leveling. May require dewatering and pilings.	2
<u>Facilities and buildings</u>	
1. Outdoor units, utilities at site	None
2. Outdoor units with some weather enclosures. Requires utilities brought to site, access roads, fencing, and minimum lighting	1
3. Requires building with heating and cooling, sanitation facilities, with shops and office. May include railroad sidings, truck depot with parking area.	2
<u>Engineering and supervision</u>	
1. Small-capacity standard equipment, duplication of typical system, turnkey quote	0.5
2. Custom equipment, automated controls	1 to 2
3. New process or prototype equipment, large system	3
<u>Construction and field expenses</u>	
1. Small-capacity systems	0.5
2. Medium-capacity systems	1
3. Large-capacity systems	1.5
<u>Construction fee</u>	
1. Turnkey project, erection and installation included in equipment cost	0.5
2. Single contractor for total installation	1
3. Multiple contractors with A&E firm's supervision	2

Cost category and adjusment criteria	Cost adjustment factor
<u>Contingency</u>	
1. Firm process	1
2. Prototype or experimental process subject to change	3 to 5
3. Guarantee of efficiencies and operating specifications	5 to 10

and freight costs are applied to freight-on-board (FOB), flange-to-flange equipment prices that generally include internals only. Instrumentation and controls are listed as a separate cost factor item since they may be an optional feature and/or may be purchased from a different vendor. Accordingly it is preferable to obtain price quotations and purchase price data for control and auxiliary equipment on a FOB, flange-to-flange basis and to list instrumentation costs separately. Other price bases can be used providing the inclusions/exclusions in the price are well defined so that appropriate adjustment in the use (or non-use) of affected cost factors can be made. The purchased equipment cost - the total cost of FOB equipment, instrumentation/control (if purchased separately or otherwise not included in equipment cost), freight and taxes - is multiplied by adjusted cost factors (Tables 4-3 and 4-4) to obtain direct and indirect installation costs.

4.2.2 Installation Costs - Direct and Indirect

The direct installation costs consist of the direct expenses associated with installation of equipment. They include materials and labor for foundations, structural supports, handling and erection, electrical, piping and ductwork, insulation, painting, site preparation, buildings and facilities. The installation cost factors in Table 4-3 assume that the installation is done by outside contractors rather than plant personnel. Since site preparation and buildings or facilities have little relation to purchased equipment costs appropriate adjustment (Table 4-4 factors) should be made when unusual situations or requirements are encountered such as removal of existing structures, swampy or unstable subsurface, deep excavation, etc. Direct installation costs can also vary considerably and may require adjustment depending on whether equipment is factory assembled or field erected, the installation is new or retrofit and equipment will be located outdoors, enclosed, on the ground, on or in a new or existing structure, etc.

Indirect installation costs include expenses for engineering and supervision, construction and field expenses, construction fees, startup, performance tests, model studies and contingencies. Items such as engineering, construction fees and contingencies are related to contracting methods, complexity and overall size of the project. Cost adjustment is based on system size, contracting arrangement and whether standard, custom or prototype equipment is installed. Model studies are normally not necessary and usually pertain to large electrostatic precipitator systems.

SECTION 5

ANNUALIZED COSTS

Annualized costs consist of the direct expenses for operation and maintenance of the air pollution control system and the indirect operating costs associated with capital investment and overhead. Direct costs include the expenses for operating and maintenance labor, replacement parts, utilities and waste disposal. Indirect operating costs include overhead, taxes, insurance, administration and capital recovery charges. The operating costs are adjusted for any credits obtained from reuse or sale of recovered products or materials or from heat or energy recovery. The sum of the direct and indirect costs (less any credits) is the annualized operating cost.

5.1 DIRECT OPERATING COSTS

System variables (such as degree of system automation) and operational variables (such as continuous or intermittent operation and number of shifts) influence the operating labor and supervision requirements. Maintenance requirements depend on the nature of the gas stream, i.e., corrosiveness or abrasiveness, construction materials, system size and type. The operation and maintenance (O&M) requirements and the associated labor costs can vary substantially between plants and control system types. Accordingly considerable judgement is required in estimating direct operating costs for a specific air pollution control system type and application. Some general guidelines that may be helpful in making these judgements are presented below. In general:

- The labor and material costs for O&M normally range between 2 to 8 percent of the total annualized costs. The remainder is primarily utility costs and capital charges.
- Operating labor and supervision decrease with increased system automation.
- Small systems that operate intermittently or on demand are labor intensive and may require a full time operator in attendance during system operation for purposes of start-up, control and shutdown.
- Larger automated and continuously operated systems may require operator presence for only a short period per shift; primarily for monitoring purposes.
- Total annual labor cost is a function of the number of 8-hour operating shifts per year. For example, small plant operation of one shift per day, 5 days per 50 week year versus three shifts per day, 365 days per year for large plants in the basic metals, petroleum and chemical industries. Therefore the operator labor should be estimated on a man-hours per shift basis for the particular system types.

5.2 INDIRECT OPERATING COSTS

Major cost centers for indirect operating costs are the capital investment and overhead expenses. The annualized capital charges reflect the costs for capital recovery over the depreciable life of the system. Overhead expenses include payroll overhead (salaries of supervisory personnel, plant guards, janitors, etc.) and plant overhead (employee fringe benefits, costs of administrative buildings, cafeterias, change houses, medical facilities, plant protection, auxiliary services for plant operation). Overhead costs are not charged directly but are allocated to the control facility as a percentage of the direct payroll for O&M labor and supervision.

5.3 COST FACTORS AND THEIR USE

Table 5-1 lists annualized cost categories and provides example cost factors and cost data that can be used for estimating annualized costs. As discussed in Section 5.1 the direct operating costs are influenced by system and operational variables that in turn cause fluctuation in unit costs. Accordingly the cost factors are presented as examples that require judgement in their use. The discussion and explanation that follows will be helpful as guidance in proper use of the factors.

5.3.1 Direct Cost Factors

Operating labor depends on the size, type and complexity of the control system. The degree of system automation and the continuity of operation also influence operating labor requirements. A large, Complex system such as a flue gas desulfurization (FGD) system may require the continuous effort of several operators (16 or more hours/shift) whereas a small wet collector may require only occasional observation (0.5 to 1.0 hours/shift). Consequently labor demands are best determined on a case-by-case basis, considering each major system component and

TABLE 5-1. COST FACTORS AND COST DATA
FOR ESTIMATING ANNUALIZED COSTS[a]

Direct operating costs	Cost factor[a]	Reference
Operating labor		
Operator	$10.62/man-hour	3
Supervisor	15% of operator labor	1
Operating materials	As required	
Maintenance		
Labor	$11.36/man-hour	3
Material	100% of maintenance labor	1
Replacement parts	As required	
Utilities		
Electricity	$0.065/Kwh	4,5,6
Fuel oil	$1.05/gal	4,7,8
Natural gas	$5.75/1000 cu. ft.	4,5,9
Plant water	$0.37/1000 gal	1
Water treatment and cooling water	$0.15/1000 gal	1
Steam	$7.53/1000 lb	1
Compressed air	$0.03/1000 ft^3	1
Waste disposal	$7.50-15.00/ton	1
Indirect operating costs	$7.50-15.00/ton	1
Overhead	80% of operating labor and maintenance labor	1
Property tax[b]	1% of capital costs	1
Insurance	1% of capital costs	1
Administration	2% of capital costs	1

Direct operating costs	Cost factor[a]	Reference
Capital recovery cost	0.16275 (as an example of 10% interest rate and an equipment life of 10 years	See Table 5-3 and Table B-1 for other interest rates and equipment lives
Credits		
Recovered product	As required	

[a] All costs are in December 1982 dollars.
[b] Delete this item if facility is certified as tax exempt by the State Department of Taxation.

overall system operation. Reasonable values must be assigned for direct labor costs because some of the other annualized costs are dependent on them. Supervisory personnel are estimated as a percentage (15%) of the direct labor.

Control equipment vendors can often supply good estimates of operating labor needs. The best source of operating labor requirements are those derived from similar or identical operations but such information is often held as proprietary by the company. Published reports provide data that is often based on actual operating systems. For large systems that are automated and continuously operated the values in Table 5-2 can be used to estimate operating labor requirements. As pointed out in Section 5.1, considerable judgement is necessary in establishing operating costs - particularly where the control system is complex or of prototype nature or has redundant subsystems. The general guidelines in Section 5.1 and case-by-case consideration will assist the estimator in adjusting Table 5-2 values to more closely represent operating labor requirements for a specific case. The total man-hours per shift (or hour) is multiplied by the number of shifts per year (or annual system operating hours) and the labor rate to determine annual operating labor costs.

Operating material costs include the delivered cost of raw materials and special chemicals required for operation of certain control systems. Examples are the lime, limestone and soda ash

TABLE 5-2. ESTIMATED LABOR HOURS PER SHIFT[1]

Control device	Operating labor[a] (man-hours/shift)	Maintenance labor[b] (man-hours/shift)
Fabric filters	2 - 4	1 - 2
Precipitators	0.5 - 2	0.5 - 1
Scrubbers	2 - 8	1 - 2
Incinerators	0.5	0.5
Adsorbers	0.5	0.5
Absorbers	0.5	0.5
Refrigeration	0.5	0.5
Flares	-	0.5

[a] Applicable to large, automated and continuously operated control systems.

[b] Preventive maintenance labor only.

for a flue gas desulfurization (FGD) scrubber, absorbent and adsorbent chemicals, sulfur trioxide for electrostatic precipitator (ESP) gas conditioning, wetting agents for dust suppression systems and the chemicals used in wastewater treatment of the effluent from a control device. Prices can be obtained from chemical suppliers and catalogues. Annual consumption is determined and is multiplied by the unit cost to obtain the annual cost of raw materials. Incremental costs for control by fuel and material substitution are computed in the same manner.

Maintenance labor values in Table 5-2 pertain to preventative maintenance only for large capacity systems handling relatively non-corrosive materials. The degree of maintenance required is analogous to operating labor requirements discussed above, i.e., system complexity, exhaust gas conditions, etc. largely determine maintenance needs. For example an FGD system is a highly complex system, frequently has problems with scaling and corrosion, and high maintenance costs can be expected. Conversely a medium energy wet collector controlling an ambient temperature exhaust is an example of a simple system with little mechanization and low maintenance costs. Sources of maintenance labor data are similar to those discussed for operating labor, i.e., vendors published reports, case histories and industry data. The estimator must decide whether maintenance will be low, typical or high based on the information in hand and adjust maintenance labor values accordingly to fit a specific system. Annual maintenance hours are multiplied by the maintenance labor rate to determine annual maintenance labor costs.

In addition to the preventative maintenance costs discussed above some systems require periodic replacement of parts in order to sustain system performance and integrity. Filter bag replacement is an example. The labor costs for parts replacement is in addition to the labor costs for normal preventative maintenance and is generally equal to the cost of replacement parts. The cost of replacement parts is accounted for as a separate cost item (see Table 5-1) and is discussed below.

Replacement parts are those system components or materials which have a limited useful life and are normally replaced on a periodic schedule. Filter bags, catalyst elements and adsorbents are examples of routinely replaced parts. The frequency of replacement is a function of severity of service, operating hours and gas stream characteristics. The annual cost of replacement parts can be determined by dividing their cost by their expected life. Table 5-3 provides estimates of expected life for parts and equipment items. The values are based on a qualitative judgement of the service life expected for differing applications, maintenance service and duty cycles.

Utility costs include outlays for electricity, fuels, water, steam and compressed air to operate the control device and auxiliary equipment including waste treatment/disposal equipment. The utility requirements can be obtained from vendors or other sources and can be estimated by use of the following equations:

- Fan power

$$kwh = 0.746\ (hp)\ (H) = \frac{0.746\ (CFM)(\Delta P)(SG)(H)}{6356\ n}$$

where:

kwh = kilowatt-hours
hp = horsepower
CFM = actual volumetric flow rate, acfm
ΔP = pressure loss, inches WG
n = efficiency, usually 60-70%
H = hours of operation
SG = specific gravity as compared to air @ 70°F, 29.92 inches mercury.

- Pump power

$$kwh = 0.746\ (hp)(H) = \frac{0.746\ (GPM)(hd)(SG)(H)}{3960\ n}$$

where:

GPM = flow rate, U.S. gpm
hd = head of fluid, feet
SG = specific gravity relative to water @ 60°F, 29.92 inches mercury
H,n - same as above

- Precipitator power

  Use an average of 1.5 watts per square foot of c ollection area based on a range of 0.3 to 3 watts per square foot.

- Baghouse power (auxiliaries, motors, etc.)

  Use 0.25 kwh per 1000 square feet of cloth area to estimate the power requirements for baghouse shaker motors, reverse air fan motors, etc.

- Incinerator fuel

  The exhaust rate and the inlet, outlet and combustion temperatures determine the fuel requirements for incinerators. EPA publication 450/3-76-031, "Report of Fuel Requirements, Capital Cost and Operating Expense for Catalytic and Thermal Afterburners," September 1976 can be used in deriving utility costs for incinerators.

TABLE 5-3. GUIDELINES FOR PARTS AND EQUIPMENT LIFE[1]

	Service life expectancy, years		
	Low[a]	Average[b]	High[c]
Equipment life			
Electrostatic precipitators	5	20	40
Venturi scrubbers	5	10	20
Fabric filters	5	20	40
Thermal incinerators	5	10	20
Catalytic incinerators	5	10	20
Adsorbers	5	10	20
Absorbers	5	10	20
Refrigeration	5	10	20
Flares	5	15	20
Materials and Parts Life			
Filter bags	.3	1.5	5
Adsorbents	2	5	8
Catalyst	2	5	10
Refractories	1	5	10

[a] Low life expectancy based on continuous operation, handling moderate to high temperature gas streams with high concentrations of corrosive or abrasive materials.

[b] Average life expectancy based on continuous operation for three shifts per day, five to seven days per week and handling moderate concentrations of non-corrosive or non-abrasive materials.

[c] High life expectancy based on intermittent operation or approximately one shift per day handling gas streams with low concentrations and low temperature.

Waste disposal cost as listed in Table 5-1 is based on the removal, handling and disposal of a dry, inert and non-toxic contaminant. The factor assumes disposal is done by an independent contractor at a nearby landfill. Compared to this "base" cost, waste disposal requiring unusual handling, pre-disposal treatment, precautionary, safety and other special measures would obviously entail greater expense and conversely the cost for in-house and/or on-site disposal would be less. In general the waste disposal cost item applies only when the collected material has no value, must be removed and discarded. Disposal within the control system - such as combustion of hydrocarbons in an incinerator or flare - would have little or no operating cost and could provide an economic benefit (operating credit) in the form of recoverable heat.

Cost factors and annual costs for other disposal techniques are not readily available. Annual waste disposal costs can, however, be estimated by following Table 5-1 format, identifying the costs of the individual items (O/M labor, materials, replacements, utilities, etc.) associated with waste treatment/disposal, and combining (or incorporating) these costs into those for the control system.

5.3.2 Indirect Cost Factors

Non-income taxes, insurance and administrative portions of indirect operating costs can collectively be estimated as four percent of the installed capital cost. For pollution control facilities certified by the taxing authority as tax exempt the tax component (1%) should be deleted and a value of three percent used to cover insurance and administration.

Overhead costs include both plant and payroll overhead and typically are 80 percent of the combined labor charges for operation and maintenance of the control system.

Capital recovery costs are the annualized capital charges associated with capital recovery over the depreciable life of the system. The capital recovery cost is a function of the interest rate and overall life of the equipment, i.e., a combination of depreciation and interest charges. Depreciation represents the money put aside each year to replace the system at the end of its useful life. Interest charges are the costs for borrowing money to pay for the emission control system. Capital charges can be estimated by multiplying the capital recovery factor by the total capital investment for the system. The capital recovery factor combines interest on borrowed funds and depreciation of equipment into a single factor. The equation for the capital recovery factor (CRF) is:

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1}$$

where:

i = interest rate, expressed as a decimal
n = economic life of the system, years

Capital recovery costs = (capital cost) x (CRF)

Table 5-3 gives expected equipment life (n) for control devices and Table B-1 of Appendix B lists the capital recovery factors for various interest rates and equipment lives.

Product recovery credits are applied against annual costs whenever the captured pollutant can be economically recovered, has value and can be used or sold. The value on a unit basis (pound, gallon, Btu, etc.) must first be determined. Purity, concentration and other marketability/useability factors must be considered when establishing a fair unit value for the captured material. If the collected pollutant is recycled the unit (actual) value can be assumed to be the final product price less processing costs. The annual amount of captured material actually re-used is multiplied by the net unit value to determine product recovery credit. Where captured materials are sold the unit value of salable materials should be adjusted for handling, packaging, transportation and other expenses associated with the marketing effort or with meeting customer use specifications. Credits for heat recovery, such as from high temperature incinerator exhausts, should be estimated when applicable.

A common error in estimating annualized costs is the erroneous assessment of marketability or use of the captured materials. For example, in some areas a sulfuric acid byproduct is either not a marketable commodity or sale would result in a loss because of handling and transportation costs. The relative purity of a captured material such as recovered solvents may preclude or limit marketability. Heat recovery credits pertain only to that portion of the heat recovered from, and attributable to, the combusted pollutant; heat recovery associated with the auxiliary fuel is excluded.

SECTION 6

COST EFFECTIVENESS

Several feasible techniques usually are available for the control of an emission source. The control efficiencies and costs of the several candidate systems may differ and in general the more efficient the control device, the greater the cost. Cost-effectiveness relationships are useful in comparing the emission reduction costs of alternate control methods and in selecting a control option based on costs and affordability.

Cost-effectiveness is computed by dividing the total annualized cost (dollars) of the control system by the annual amount (pounds) of emission reduction achieved by the system and is expressed in dollars per unit weight of pollutant removed (dollars per pound, $/lb).

Example: Assume that the annualized cost of an air pollution control system is estimated at $172,000, the overall control efficiency of the system is 99 percent, the uncontrolled emission rate is 112 pounds per hour (lb/h), and annual operating time is 8000 hours. Cost-effectiveness is determined as follows:

$$\text{Amount of pollutant controlled} = 0.99 \times (112\ \text{lb/h}) \times (8000\ \text{h/yr})$$
$$= 887{,}040\ \text{lb/yr}$$

$$\text{Cost-effectiveness} = \frac{\$172{,}000\ /\text{yr}}{887{,}040\ \text{lb/yr}}$$

$$= \$0.194/\text{lb pollutant collected}$$

The "incremental (marginal or differential) cost-effectiveness" is useful in comparing the costs of a "base case" control with alternate controls that could provide greater emission reduction, i.e., reduction of residual emissions exiting the base case control device. Incremental cost-effectiveness values provide a means of comparing the economics of alternate control options for a given source and are comparative values calculated by dividing the difference in annualized cost (AC) of two systems (a and b) by the difference in emission reduction (ER) of the two systems. In terms of dollars per weight unit of pollutant collected,

$$\text{Incremental cost effectiveness} = \frac{(AC_a - AC_b)}{(ER_z - ER_b)}$$

The following example illustrates the calculation and use of incremental cost-effectiveness values.

> Example: Assume that an engineering study shows that an uncontrolled source of 4200 tons per year can be brought into compliance by either of three control systems - a venturi scrubber, a low efficiency electrostatic precipitator (ESP), or a high efficiency ESP. The respective collection efficiencies for the three systems are 90 percent, 95 percent and 99 percent. Further assume that the annualized costs and emission reduction quantities are as shown in Table 6-1. (In constructing tables of incremental cost-effectiveness the control system options should be ranked in order of increasing emission reduction as shown in Table 6-1.)
>
> The cost-effectiveness values (column C of Table 6-1) are calculated as shown in the previous example, i.e., by dividing the annualized cost (column B) by the annual emission reduction (column A). In this example the range of

cost-effectiveness values (column C) for the three control options is relatively small.

TABLE 6-1. EXAMPLE COST-EFFECTIVENESS DATA FOR CONTROL SYSTEM OPTIONS[a]

	A	B	C	D	E	F
Control system	Emission reduction, 1000 lb/yr	Annualized control costs, $/yr	Cost-effective-ness, annualized control cost per pound collected (B + A), $/1000 lb	Incremental emission reduction, 1000 lb/yr	Incremental annualized control costs, $/yr	Incremental cost-effectiveness, incremental annualized control cost per pound collected (E + D), $/1000 lb
Venturi scrubber (base case)	7,560	450,000	59.5	-	-	-
Low efficiency ESP	7.980	348,400	43.7	420	(-101,600)	(-242)
High efficiency ESP	8,320	442,300	53.2	340	93,900	276

[a] Example of a tabular display of cost-effectiveness and incremental cost-effectiveness.

For calculating the incremental cost-effectiveness the values in columns A and B are used to determine the increments (differences) between the emission reductions and annualized costs of two systems. For instance in comparing the venturi scrubber and the low efficiency ESP systems the respective values for the two systems are subtracted to obtain the increment in emission reduction (7980 - 7560 = 420) and in annualized cost (348,000 - 450,000 = -101,600). The differential comparison of the low and high efficiency ESP systems is made in the same manner. The incremental cost-effectiveness values (column F) are obtained by dividing incremental annualized control costs (column E) by the incremental emission reduction (column D). For the venturi scrubber vs. low efficiency ESP,

$$\text{Incremental cost effectiveness} = \frac{(-101{,}600)}{420} = -\$242 \text{ per 1000 lb of emissions collected}$$

For this example case the values in Table 6-1 indicate that:

- The cost effectiveness of the three options is approximately the same, i.e., about 50 dollars per pound of emission collected.
- The incremental cost-effectiveness of the high-efficiency ESP versus the low efficiency ESP is 276 dollars per thousand pound collected. The cost of additional emission reduction (340,000 lb/yr) using a high efficiency vs. a low efficiency ESP at 276 dollars per thousand pound would cost more than six times the cost (43.7 dollars per thousand pound) of the initial poundage collected by the low efficiency ESP - a significant economic penalty.
- The low efficiency ESP will reduce emissions at a lower cost than the venturi scrubber. The incremental cost-effectiveness is negative or "favorable" because the low efficiency ESP will collect more emissions (420,000 lb/yr) and at a lesser annualized cost (-$101,600) than the venturi scrubber.

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APPENDIX A

CHEMICAL ENGINEERING COST INDEXES - 1957 THROUGH 1982

TABLE A-1. CHEMICAL ENGINEERING PLANT AND EQUIPMENT COST INDEXES[a]

Index	1982 Annual[b]	1981 Annual	1980 Annual	1979 Annual	1978 Annual	1977 Annual	1976 Annual	1975 Annual	1974 Annual	1973 Annual	1972 Annual	1971 Annual	1970 Annual
CE plant index	314.3	297	261.1	238.7	218.8	204.1	192.1	182.4	165.4	144.1	137.2	132.3	125.7
Engineering and supervision	314.0	268.5	214.0	185.9	161.9	162.1	150.8	141.8	134.4	122.8	111.9	111.4	110.6
Building	290.4	274.9	238.3	228.4	213.7	199.1	187.3	177.0	165.8	150.9	142.0	135.5	127.2
Construction labor	263.8	242.4	204.3	194.9	185.9	178.2	174.2	168.6	163.3	157.9	152.2	146.2	137.3
Equipment, machinery supports	335.4	323.9	292.2	264.7	240.3	220.9	205.8	194.7	171.2	141.8	135.4	130.4	123.8
Fabricated equipment	325.1	321.8	291.6	261.7	238.6	216.6	200.8	192.2	170.1	142.5	136.3	130.3	122.7
Process machinery	315.0	301.5	271.8	250.0	228.3	211.6	197.5	184.7	160.0	137.8	132.1	127.9	122.9
Pipe, valves, and fittings	379.6	360.1	330.0	301.2	269.4	247.7	232.5	217.0	192.3	151.5	142.9	137.3	132.0
Process instruments and controls	298.3	287.9	249.5	231.5	216.0	203.3	193.1	181.4	164.7	147.1	143.9	139.9	132.1
Pumps and compressors	414.3	388.5	330.3	280.4	257.5	240.2	220.9	208.3	175.7	139.8	135.9	133.2	125.6
Electric equipment and materials	238.7	222.4	206.1	183.2	167.8	159.0	148.9	142.1	126.4	104.2	99.1	98.7	99.8

Index	1982 Annual[b]	1981 Annual	1980 Annual	1979 Annual	1978 Annual	1977 Annual	1976 Annual	1975 Annual	1974 Annual	1973 Annual	1972 Annual	1971 Annual	1970 Annual
Structural supports, insulation, and paint	332.2	322.0	297.7	273.6	248.9	226.0	209.7	198.6	171.6	140.8	133.6	126.5	117.9
CE plant index	119.0	113.6	109.7	107.2	104.2	103.3	102.0	101.5	102.0	101.8	101.8	99.7	98.5
Engineering and supervision	110.9	108.6	107.9	106.9	105.6	104.2	103.4	102.6	101.7	101.3	102.5	99.3	98.2
Building	122.5	115.7	110.3	107.9	104.5	103.3	102.1	101.4	100.8	101.5	101.4	99.5	99.1
Construction labor	128.3	120.9	115.8	112.5	109.5	108.5	107.2	105.6	105.1	103.7	101.4	100.0	98.6
Equipment, machinery supports	116.6	111.5	107.7	105.3	102.1	101.2	100.5	100.6	100.2	101.7	101.9	99.6	98.5
Fabricated equipment	115.1	109.9	106.2	104.8	103.4	102.7	101.7	101.0	100.1	101.2	100.9	99.6	99.5
Process machinery	116.8	112.1	108.7	106.1	103.6	102.5	102.0	101.9	101.1	108.1	101.8	100.1	98.1
Pipe, valves, and fittings	123.1	117.4	113.0	109.6	103.0	101.6	100.7	100.6	101.1	104.1	103.3	98.8	97.9
Process instruments and controls	126.1	120.9	115.2	110.0	106.5	105.8	105.7	105.9	105.9	105.4	102.9	100.4	96.7
Pumps and compressors	119.6	115.2	111.3	107.7	103.4	101.0	100.1	101.1	100.8	101.7	102.5	100.0	97.5
Electric equipment and materials	92.8	91.4	90.1	86.4	84.1	85.5	87.6	89.4	92.3	95.7	101.0	100.6	98.4
Structural supports, insulation, and paint	112.6	105.7	102.1	101.0	98.8	98.3	97.3	99.2	99.8	101.9	101.6	100.4	98.0

[a] The indexes for the years 1970 through 1981 are from April 19, 1982 issue of Chemical Engineering.
The index for the year 1981 is based on revised figures for December 1981 in the April 19, 1982 issue of Chemical Engineering. Indexes for the years 1957 through 1969 are from Reference 1.

[b] The index for the year 1982 is based on the preliminary figures for December 1982 in the February 7, 1983 issue of Chemical Engineering.

APPENDIX B

CAPITAL RECOVERY FACTORS

TABLE B-1. CAPITAL RECOVERY FACTORS

Equipment life, yr	Annual Compounded Interest, %							
	5	6	7	8	10	12	15	20
1	1.05000	1.06000	1.07000	1.08000	1.10000	1.12000	1.15000	1.20000
2	0.53780	0.54544	0.55309	0.56077	0.57619	0.59170	0.61512	0.65455
3	0.36721	0.37311	0.38105	0.38803	0.40211	0.41635	0.43798	0.47473
4	0.28201	0.28859	0.29523	0.30192	0.31547	0.32923	0.35027	0.38629
5	0.23097	0.23740	0.24389	0.25046	0.26380	0.27741	0.29832	0.33438
6	0.19702	0.20336	0.20980	0.21632	0.22961	0.24323	0.26424	0.30071
7	0.17282	0.17914	0.18555	0.19207	0.20541	0.21912	0.24036	0.27742
8	0.15472	0.16104	0.16747	0.17401	0.18744	0.20130	0.22285	0.26061
9	0.14069	0.14702	0.15349	0.16008	0.17464	0.18768	0.20957	0.24808
10	0.12950	0.13587	0.14238	0.14903	0.16275	0.17698	0.19925	0.23852
11	0.12039	0.12679	0.13336	0.14008	0.15396	0.16842	0.19107	0.23110
12	0.11283	0.11928	0.12590	0.13270	0.14676	0.16144	0.18448	0.22526
13	0.10646	0.11296	0.11965	0.12652	0.14078	0.15568	0.22526	0.17911
14	0.10102	0.10758	0.11434	0.12130	0.13575	0.15087	0.21689	0.17469
15	0.09634	0.10296	0.10979	0.11683	0.13147	0.14682	0.17102	0.21388
16	0.09227	0.09895	0.10586	0.11298	0.12782	0.14339	0.16795	0.21144
17	0.08870	0.09544	0.10342	0.10963	0.12466	0.14046	0.16537	0.20944
18	0.08555	0.09236	0.09941	0.10670	0.12193	0.13794	0.16319	0.20781
19	0.08275	0.08962	0.09675	0.10413	0.11955	0.13576	0.16134	0.20646
20	0.08024	0.08718	0.09439	0.10185	0.11746	0.13388	0.15976	0.20536
21	0.07800	0.08500	0.09229	0.09983	0.11562	0.13224	0.15842	0.20444
22	0.07597	0.08305	0.09041	0.09803	0.11401	0.13081	0.15727	0.20369
23	0.07414	0.08128	0.08871	0.09642	0.11257	0.12956	0.15628	0.20307
24	0.07247	0.07968	0.08719	0.09498	0.11130	0.12846	0.15543	0.20255
25	0.07095	0.07823	0.08581	0.09368	0.11017	0.12750	0.15470	0.20212
26	0.06956	0.07690	0.08456	0.09251	0.10916	0.12665	0.15407	0.20176
27	0.06829	0.07570	0.08343	0.09145	0.10826	0.12590	0.20176	0.15353
28	0.06712	0.07459	0.08239	0.09049	0.10745	0.12524	0.20122	0.15306
29	0.06605	0.08385	0.08145	0.08962	0.10673	0.12466	0.20102	0.15265
30	0.06505	0.07265	0.08059	0.08883	0.10608	0.12414	0.20085	0.15230

Equipment life, yr	Annual Compounded Interest, %							
	5	6	7	8	10	12	15	20
31	0.06413	0.07179	0.07980	0.08811	0.10550	0.12369	0.15200	0.20070
32	0.06328	0.07100	0.07907	0.08745	0.10497	0.12328	0.15173	0.20059
33	0.06249	0.07027	0.07841	0.08685	0.10450	0.12292	0.15150	0.20049
34	0.06176	0.06960	0.07780	0.08630	0.10407	0.12260	0.15131	0.20041
35	0.06107	0.06897	0.07723	0.08580	0.10369	0.12232	0.15113	0.20034
40	0.05828	0.06646	0.07501	0.08386	0.10226	0.12130	0.15056	0.20014
45	0.05626	0.06480	0.07350	0.08259	0.10139	0.12074	0.15028	0.20005
50	0.05478	0.06344	0.08246	0.08174	0.10086	0.12042	0.15014	0.20002

APPENDIX C

COST STATEMENT AND EXAMPLE FORMATS FOR PRESENTING COSTS

APPENDIX C

COST STATEMENT AND EXAMPLE FORMATS FOR PRESENTING COSTS

Definition of the basis for, and limits of, the cost estimate are of paramount importance since without such definition accuracy is compromised and the estimate will be of questionable and limited use. An essential first step is determining what is to be costed, i.e., the equipment, structures, instruments/controls, auxiliaries, etc. that are directly related to the capture, collection and handling of the exhaust stream and of the collected pollutants (including disposal and treatment) and are necessary to its installation and satisfactory operation. The cost analysis is generally preceded by an engineering evaluation of the proposed control system as regards source applicability, adequacy and compliance capability. This review and/or the information and data contained in a complete application packageshould provide an adequate basis for:

- Detecting, defining and quantifying the variables that affect costs. (Section 2.0 lists and discusses the many variables that can affect the costs of air pollution control systems.)
- Establishing the "boundaries" and requirements of the control facility, i.e., define what is - and is not - a functional,

operational and/or a necessary part of the facility and is to be included (or excluded) in the cost estimate. (Table 4-1 lists examples of capital cost component items and can serve as an abbreviated checklist or reminder in defining system "boundaries" and cost estimate scope).

Cost Statement

A cost estimate should be accompanied by a cost statement that clearly and concisely sets forth the basis for, and the limits of, the cost estimate. The cost statement should be both positive and negative; it should state both what is - and is not - included in the cost items so that no question remains in the mind of the reader. Additionally and importantly the statement should explain the basis, rationale and reason for including/excluding cost items and for modifying costs. In brief the cost statement should:

- Provide a general description of the function and operation of the control facility as a whole and explain the purpose or role of the subsystems within the facility.
- List the items that are included in each category of capital cost components and specify what is included in the cost of each such item.
- Indicate the cost items, components or categories that are not included in the estimate and give the reasons for exclusions.
- Document the source(s) of cost information and the basis for - and date of - the cited costs.
- Explain the basis, rationale and reason for any adjustments that are made with respect to cited or derived costs and/or the use of cost adjustment factors.

The results of a cost estimate are well suited to tabular display in a ledger type format that lists the major cost categories and the contribution components in each category. In the estimating procedure described herein the basic purchase of equipment is multiplied by appropriate factors to compute other costs. It is convenient to combine the cost computations and to display the results on a single form. Tables C-1 and C-2 are example formats that can be used to compute and present capital and annualized costs.

TABLE C-1. EXAMPLE FORMAT FOR COMPUTING AND PRESENTING CAPITAL COSTS

Cost Item	Computation Method			Cost, dollars	
Direct costs					
Purchased equipment:					
Basic equipment (A)	Purchased cost of control device			______	
Auxiliary equipment (B)	Purchased cost of auxiliaries			______	
Total equipment costs (A + B)	Total of above (A + B)			______	
	Average cost factor x	Adjustment factor x	(A + B)		
Instruments/controls	(0.10)	( )	( )	______	
Taxes (unless exempt)	(0.05)		( )	______	
Freight	(0.05)	( )	( )	______	
Base price (C)	Subtotal of above plus (A + B)				______ (C)
Installation costs, direct:	Average cost factor x	Adjustment factor x	(C)		
Foundations/supports	( )		( )	______	
Erection/handling	( )	( )	( )	______	
Electrical	( )		( )	______	
Piping	( )		( )	______	
Insulation	( )		( )	______	
Painting	( )		( )	______	
Site preparation[b]	Estimate ( ) x adjustment ( )				
Facilities/buildings[b]	Estimate ( ) x adjustment ( )				
Total installation costs (D)	Subtotal of above				______ (D)
TOTAL DIRECT COSTS (E)	Base price (C) + installation cost (D)				______ (E)
Installation costs, indirect:	Average cost factor x	Adjustment factor x	(C)		
Engineering/supervision	( )	( )	( )	______	
Construction/field expenses	( )	( )	( )	______	
Construction fee	(0.10)	( )	( )	______	
Start-up	( )		( )	______	
Performance test	(0.01)		( )	______	
Model study	( )	( )	( )	______	
Contingencies	(0.03)	( )			
TOTAL INDIRECT COSTS (F)	Total of above indirect costs				______ (F)
TOTAL CAPITAL COSTS (G)	Direct costs (E) + indirect costs (F)				______ (G)

[a] Absence of parenthesis in the adjustment factor column means no such factor is available.

[b] Costs for these are unrelated to equipment costs (C) and are developed independently on an individual item

basis. General estimates for these items can be modified with cost adjustment factors. Case specific estimates are entered directly in the cost column.

TABLE C-2. EXAMPLE FORMAT FOR COMPUTING AND PRESENTING ANNUALIZED COSTS

Cost Item	Computation method	Cost, dollars	
Direct operating costs			
Operating labor			
Operator	______, $/h x ______ h/yr	_______ (a)	
Supervision	15% of operator labor cost	_______	
Operating materials	As required		
Maintenance (general)			
Labor	______, $/h x ______ h/yr	_______ (b)	
Materials	100% of maintenance labor	_______	
Replacement parts	As required	_______	
Labor	100% of replacement parts cost	_______	
Utilities		_______	
Electricity	______, $/kWh x ______ kWh/yr	_______	
Fuel oil	______, $/gal x ______ gal/yr	_______	
Gas	______, $/$10^3$ft^3 x ______ 10^3ft$^{3/yr}$	_______	
Water	______, $/$10^3$ gal x ______ 10^3gal/yr	_______	
Steam	______, $$10^3$ lb x ______ 10^3 lb/yr	_______	
Other (specify)	As required	_______	
Waste disposal	______, $/ton x ______ ton/yr	_______	
Wastewater treatment	______, $/$10^3$ gal x ______ 10^3gal/yr	_______	
TOTAL DIRECT OPERATING COSTS (A)	Subtotal of above		______ (A)
Indirect operating (fixed) costs			
Overhead	80% of O/M labor costs (a + b)	_______	
Property tax	1% of capital costs ($ _______)*	_______	
Insurance	1% of capital costs*	_______	
Administration	2% of capital costs*	_______	
Capital recovery	CRF ____ (at ____%, ____yrs) x capital costs*	_______	
TOTAL FIXED COSTS (B)	Subtotal of above		______ (B)
Credits			
Product recovery	______, $/ton x ______ ton/yr	(______)	
Heat recovery	______, $/$10^6$ Btu x ______ 10^6 Btu/yr	(______)	
TOTAL CREDITS (minus C)	Subtotal of above		(____) (C)
TOTAL ANNUALIZED COSTS (D)	(A + B) minus (C)		(____) (D)

* Total capital costs (G) from Table C-1.