CO$T-AIR

Control Cost Spreadsheets

Second Edition

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Introduction

Anyone familiar with the *OAQPS Control Cost Manual* (*Manual*) knows that air pollution control costs depend upon a variety of emission stream, control device, and financial parameters. Often this dependency is quite complex, as in the sizing and costing of gas absorbers. For that reason, it is cumbersome and time-consuming to make these sizing and costing calculations by hand, especially if costs are needed for a range of input parameters (e.g., waste gas flowrate).

To allow users to make these calculations more efficiently, in early 1996 we wrote twenty spreadsheet programs, collectively named *CO$T-AIR*, to cover 12 control devices and one category of auxiliary equipment (ductwork). Since then, over 2,500 copies of *CO$T-AIR* have been distributed to users via the OAQPS TTN (Technology Transfer Network) website.[a] For this second edition, all of the spreadsheets have been revised to correct errors, remove ambiguities, and make improvements. Several pages would be needed to describe all of these revisions. However, two examples will illustrate the nature and extent of these changes.

Consider, first, the *carbon adsorbers* spreadsheet. The original (1996) version contained a procedure for estimating the carbon requirement that was based on the Freundlich adsorption isotherms (see *Manual*, Chapter 4). This version provided, in a lookup table, isotherm parameters for 11 organic compounds. The user would enter a number corresponding to the compound to be adsorbed, and the program then would compute the carbon requirement. The revised spreadsheet retains these parameters, but supplements them with parameters for isotherms developed by Dr. Carl Yaws. [b] Yaws parameters are given for approximately thirty compounds, a few of which appear on the list of Freundlich parameters that appeared on the original spreadsheet. What if the compound to be adsorbed should appear on both the Yaws and Freundlich parameter lists? In such a case, the revised spreadsheet would compute the carbon requirement via both sets of parameters and report the higher of the two requirements. This would ensure that the carbon requirement--and cost--estimates would be conservative.

The *flares* spreadsheets also typify the kinds of changes made over the past three years. In the original spreadsheets--one for flares with tip diameters of 60 inches or less, the other for tip diameters larger than 60 inches--equipment components (flare, knockout drum, piping, etc.) were sized via the equations in Chapter 7 of the *Manual*. However, they did not follow the *Manual* equations to the letter. Instead of using the step functions in the *Manual*, the spreadsheet sizing equations were programmed as if the design relationships were continuous over the entire size ranges. For example, the flare tip diameter was computed via an equation that related the diameter to the waste gas volumetric flowrate and the maximum gas velocity at

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[a] URL: HTTP://WWW.EPA.GOV/TTN/CATC/PRODUCTS.HTML#CCCINFO.

[b] Yaws, Carl L., et al., "Determining VOC Adsorption Capacity," *Pollution Engineering*, February 1995, pp. 34-37.

the flare tip. But if this equation yielded a tip diameter of, say, 40.7 inches, the actual flare diameter would be 42 inches, as flare tips larger than 24 inches are only available in 6-inch increments.[a] Recognizing this, the revised spreadsheet automatically rounds the calculated tip diameter to the next *highest* standard size. It does likewise for the knockout drum and piping diameters, and for such parameters as the number of pilot burners.

Another revision made to each spreadsheet concerned the flare height computation. Due to an error in the original spreadsheets, the flare height was fixed at 30 feet. This "constraint" has been removed. Moreover, the algorithm for selecting the optimal flare type (i.e., self-supported, guy-supported, or derrick-supported) has been refined, to allow for the fact that within certain height ranges, more than one type of flare can be built. Whenever that situation arises, the revised spreadsheet computes the equipment cost for each of the workable flare types and reports the least costly of them.

One feature common to all spreadsheets that has *not* been changed is the equipment cost escalation. In each spreadsheet, the user enters the appropriate value of the *VAPCCI* (Vatavuk Air Pollution Control Cost Index) for that device.   Once this is done, the equipment cost is escalated to the desired quarter-and-year.[b] (See Exhibit 1.) Updated quarterly for 11 control device types, the VAPCCI are documented in an EPA report.[c] The indexes are also published in every issue of *Chemical Engineering* (a monthly) and *Environmental Progress* (a quarterly).

We wrote the original *CO$T-AIR* spreadsheets in Eight-in-One™, a spreadsheet program that is compatible with Lotus 1-2-3™ (versions 1A and 2.0), is structured similarly, and embodies many of the same commands. However, the spreadsheet revisions were made entirely in Lotus 1-2-3™ (versions 2.0 or later), a program most users are familiar with and which is compatible with Excel™ , Quatro-Pro™ , and other popular spreadsheet packages.   As explained below, each spreadsheet outputs itemized total capital investment and total annual costs for a given set of input parameters.

The devices and auxiliary for which we wrote spreadsheets are listed in Table 1, alongside the Lotus™ file names and the *Manual* chapters that correspond to them. These file names require some explanation. In each, "TCI" denotes "total capital investment," while the "Wk**n**" (n = 1 or 3) extension denotes the Lotus™ version in which the spreadsheet was written. The character "-L" signifies that the spreadsheet is for "large" units—i.e., those devices whose sizes exceed the upper limits of the cost correlations. As the list indicates, we wrote "large"

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[a] However, flare tip diameters are available only in 2-inch increments from 2 to 24 inches. The minimum diameter available is 1 inch.

[b] This is usually (though not necessarily) the latest quarter for which a final index is available.

[c] *Escalation Indexes for Air Pollution Control Costs* (EPA-452/R-95-006, October 1995). Both the report and quarterly VAPCCI updates are posted on the OAQPS Technology Transfer Network/Clean Air Technology Center website (URL: http://www.epa.gov/ttn/catc).

spreadsheets for thermal and catalytic incinerators, thermal regenerative oxidizers, flares, mechanical collectors, and wet impingement scrubbers. Finally, for the refrigeration systems, "-C" and "-P" denote the spreadsheets for "custom" and "packaged" units, respectively.

Most of the programs were based on design and cost data and procedures in the *OAQPS Control Cost Manual* (Fifth Edition, 1996). The exceptions were the programs for mechanical collectors, venturi scrubbers, and wet impingement scrubbers. Spreadsheets for these three devices were based on information in the book *Estimating Costs of Air Pollution Control* (*ECAPC*).[a]

Spreadsheet Components

Although there are significant differences among the various spreadsheets, some components are found in all. First, each spreadsheet consists of six sections: (1)"Cost Base Date"/"VAPCCI," (2) "Input Parameters," (3) "Design Parameters," (4) "Capital Costs," (5) "Annual Cost Inputs," and (6) "Annual Costs". In the first section, the "Cost Base Date" is the date corresponding to the equipment costs ("base costs") in the *Manual* or *ECAPC*. This date ranges from second quarter 1987 (electrostatic precipitators) to second quarter 1998 (fabric filters). Next, the "VAPCCI" is used by the spreadsheet to escalate the base costs from the base date to the quarter and year selected by the user (e.g., fourth quarter 1998). Eleven VAPCCI have been developed, one for each of the control devices listed in Table 1. (The sole exceptions are the "venturi scrubbers" and "wet impingement scrubbers" categories, which have been combined into one index: "wet scrubbers".) Each spreadsheet is written so that once the user inputs the latest VAPCCI available, the total capital investment cost and capital cost-dependent annual costs will automatically be escalated. Exhibit 1 explains the procedure used to incorporate cost escalation into the spreadsheets.

The second section, "Input Parameters," contains technical data that, in nearly all cases, *must be entered by the user*.[b] The program needs these data to compute the design parameters,

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[a] Vatavuk, William M. *Estimating Costs of Air Pollution Control*. Boca Raton, FL: CRC Press/Lewis Publishers, 1990.

[b] Note, however, that each input parameter cell on the spreadsheet contains an entry. For the most part these were taken from the example problems in the *Manual*. *Nevertheless, the user should not assume that these entries are default values, and should enter data appropriate to the emission source.*

Table 1. CO$T-AIR Spreadsheet Programs[a]

Classification	Control Device Type	Manual Chapter	Lotus™ File Name(s)
Particulate emission controls	Electrostatic precipitators	6	TCI-EP3.WK1
	Fabric filters	5	TCI-FF3A.WK3
	Mechanical collectors (cyclones)	None[b]	TCI-MC.WK1 TCI-MC-L.WK1
	Venturi scrubbers	None[b]	TCI-VS3.WK1
	Wet impingement scrubbers	None[b]	TCI-WIS3.WK1 TCI-WS3L.WK1
Gaseous emission controls	Carbon adsorbers	4	TCI-CA5X.WK1
	Catalytic incinerators	3	TCI-CI3.WK1 TCI-CI3L.WK1
	Gas absorbers	9	TCI-GA.WK1
	Flares	7	TCI-FL6.WK3 TCI-FL6L.WK3
	Refrigeration systems	8	TCI-RS-C.WK1 TCI-RS-P.WK1
	Regenerative thermal oxidizers	3	TCI-RT2.WK1 TCI-RT-L.WK1
	Thermal incinerators (recuperative)	3	TCI-TI2.WK1 TCI-TIL2.WK1
Auxiliary equipment	Ductwork	10	TCI-DCTX.WK1

[a] All programs are written in Lotus 1-2-3™.

[b] Design and cost procedures and data for these devices may be found in the book *Estimating Costs of Air Pollution Control*, by William M. Vatavuk (Boca Raton, FL: CRC Press/Lewis Publishers, 1990).

Exhibit 1. Procedure for Escalating Spreadsheet Costs

As explained in the text, each spreadsheet allows the user to escalate the capital and capital-related annual costs simply by entering the latest VAPCCI value. However, as explained in the report *Escalation Indexes for Air Pollution Control Costs* (*Escalation*), the VAPCCI start date is first quarter 1994. Except for fabric filters, escalation from the base date of a device's costs to first quarter 1994 was programmed into the spreadsheet via a one- or two-step procedure, depending on whether the base date was before or after first quarter 1989. Programmed into the spreadsheets, these pre-1994 escalations were done as follows:

Base costs prior to first quarter 1989:

Step 1: Escalate from the base date to first quarter 1989 using the *extrapolated* vendor historical cost data, as given in *Escalation*. In these extrapolations, use the mean annual price change between first quarter 1989 and first quarter 1994.[a] To illustrate, over this five-year period, thermal incinerator prices increased by 20.5%. The mean annual increase (i_m) was:

$$i_m = (1.205)^{1/5} - 1 = 0.0380 \text{ or } 3.8\%.$$

If we assume that thermal incinerator prices changed by this same amount between the base date (April 1988 ≈ first quarter 1988) and first quarter 1989, a period of one year (four quarters), the escalation factor for the first step ($E.F._1$) would be:

$$E.F._1 = 1 + i_m = 1.038$$

For extrapolation over any length of time, we can use this general expression:[b]

$$E.F._1 = (1 + i_m)^{n/4}$$

where: n = number of *quarters* from base date to first quarter 1989

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[a] In other words, we assumed that the control device prices changed by the same annual percentage between the base date and first quarter 1989 as they did between first quarter 1989 and first quarter 1994.

[b] Clearly, the longer the extrapolation—or escalation —period used, the greater the potential error introduced.

Exhibit 1 (cont'd.)

Step 2: Escalate from first quarter 1989 to first quarter 1994 using the relative price data in Table 2 (page 19) of *Escalation*. As noted in step 1, thermal incinerator prices increased by 20.5% between first quarter 1989 and first quarter 1994. Thus, the second-step escalation factor ($E.F._2$) would be:

$$E.F._2 = 1 + (20.5\%/100\%) = 1.205.$$

The overall escalation factor between the base date and first quarter 1994 ($E.F._t$) would be the product of these two escalation factors, or:

$$E.F._t = (E.F._1)(E.F._2) = (1.038)(1.205) = 1.251$$

Base costs first quarter 1989 or later:

This is a one-step procedure, in which solely the historical vendor price data are used. For example, the flare base costs are in March 1990 (≈ first quarter 1990) dollars. The escalation factor for updating them to first quarter 1994 dollars would be the quotient of the flare relative prices for first quarter 1990 and first quarter 1994, respectively, as shown in Table 1 (page 18) of *Escalation*:

$$E.F._t = (113.5)/(104.0) = 1.091$$

Finally, in the spreadsheets for four control devices and ductwork, data *other than* those in *Escalation* were used for escalating prices from base dates to first quarter 1994. These were:

*** Carbon adsorbers:** As no historical vendor data were available for adsorbers, we used a surrogate price indicator. This surrogate was the average of the relative prices for flares and wet scrubbers measured over the third quarter 1989 (carbon adsorber prices base date) to first quarter 1994 period. We used these two devices because carbon steel and stainless steel plate and tubing comprise comparably large fractions of the flare and wet scrubber total equipment prices as they do of the carbon adsorber prices. (For these and other control devices, the price of steel significantly affects the pricing.)

*** Mechanical collectors:** We used the mechanical collectors Producer Price Index (PPI) to escalate the prices for this device. However, because the mechanical collectors price base date (August 1988 ≈ third quarter 1988) precedes the base date of its PPI (June 1989 ≈ second quarter 1989) we simply extrapolated the PPI backward. This extrapolation was done using the average annual PPI change from June 1989 to first quarter 1994.

Exhibit 1 (cont'd.)

*** Ductwork:** The Producer Price Index "Sheet metal work/Air-conditioning ducts and stove pipe" (PCU 3444#1) was used to escalate ductwork prices from the *Manual* base date (second quarter 1993) to first quarter 1994. Moreover, this PPI is used to update ductwork prices from first quarter 1994 onward.

*** Electrostatic precipitators:** No historical vendor prices for ESP's appear in *Escalation*. However, after this report was released, we obtained enough price data to allow us to escalate ESP prices from the base date (second quarter 1987) to first quarter 1994 the costs, or both. Because these input parameters vary so much according to control device designs and applications, there are no "default" values for them. In other words, *the user must provide this information.*

Input parameters include such standard stream parameters as the waste gas volumetric flowrate, temperature, and pollutant loading—the kinds of data that are common to all control devices. Another standard parameter, the control device "pressure drop," also may be a required input. Along with the gas flowrate, the pressure drop is used to calculate the control device fan horsepower requirement which, in turn, accounts for most (if not all) of the control system electricity requirement. In many cases, the user must provide the pressure drop. However, with other devices (e.g., thermal and catalytic incinerators) the pressure drop is calculated from one or more of the input parameters. With the latter devices, the pressure drop would *not* be an input parameter.

The input parameters section also lists data specific to a certain type of device. In the case of gas absorbers, the user must enter various solvent data (molecular weight, density, diffusivity, and viscosity) and packing parameters—data that can be found in Chapter 9 of the *Manual*.

The third section, "Design Parameters," lists data that are primarily calculated by the spreadsheet based on the input parameters. For gas absorbers, these include operating line data, pollutant-air equilibrium information, and such key absorber parameters as the absorption factor, column height, and pressure drop.

The "Capital Costs" section displays the control device total equipment cost (itemized), the purchased equipment cost, and the total capital investment (TCI). Two values are given for the total equipment cost. The first corresponds to the base date of the costs (e.g., second quarter 1987); the second, to the escalation date (e.g., fourth quarter 1998). No costs for auxiliary equipment (e.g., fans), are included, although some "packaged" devices, such as thermal incinerators, come equipped with some auxiliaries.[a]

In this section, both the purchased equipment cost (PEC) and the TCI are "factored" from the total equipment cost (TEC), according to the procedure described in Chapter 2 of the *Manual*. The PEC is figured at either **1.18** times the TEC if the control device cost *does not* include instrumentation and controls or **1.08** times the TEC if it *does*. The TCI is then factored from the PEC. The factor used depends on the type of control device and whether it is a packaged unit. For instance, the factor used with thermal and catalytic incinerators is either 1.25 (packaged units) or 1.61 (custom units). Note that both the PEC and TCI reflect the *escalation date*, not the base date. Consequently, the annual costs that are factored from the TCI (such as capital recovery) *also* reflect the escalation date.

The fifth section, "Annual Cost Inputs," lists nearly all of the parameters needed for the program to calculate the various annual costs. Nonetheless, as with the "Input Parameters" section, *the user must provide all of these inputs* (i.e., there are no default values). Typical values for the parameters are given in the *Manual* chapter covering the device in question.

The first, and probably most important, annual cost input is the "operating factor"—the hours per year the control device operates. This parameter can range from fewer than 800 to more than 8000 hours/year, depending upon the emission source that the device controls. The operating factor is a key input to all of the operating and maintenance costs—labor, utilities, materials, and waste disposal. The operating and maintenance labor rates also depend on the source and its location. However, based on guidance given in Chapter 2 of the *Manual*, the program computes the maintenance labor rate by factoring it from the operating labor rate (i.e., the maintenance rate is 10% higher than the operating) and computes the maintenance materials cost at 100% of the maintenance labor cost.

The operating and maintenance labor factors—both given in hours/shift—vary according to device type, as some (such as scrubbers) typically require more operator attention and maintenance than others (e.g., incinerators). As a rule, the smaller devices require less attention than the larger, a fact that has been incorporated into these programs. For instance, the operating and maintenance labor factors for thermal and catalytic incinerators are each 0.5 hours/shift, *except for* devices treating gas flowrates less than 20,000 standard cubic feet per minute (scfm). The utility prices—electricity, natural gas, process and cooling water, steam, etc.—are self-explanatory. Nevertheless, as with the other annual cost inputs, the user should be sure that the utility prices reflect the units shown on the spreadsheet. The natural gas price, for example, must be expressed in "$/thousand standard cubic feet," not "$/million BTU".

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[a] The exception here, of course, is *ductwork*, for which a separate spreadsheet has been developed. (See Table 1.) If desired, equipment costs from the ductwork spreadsheet (TCI-DCTX.WK1) can be input to the "auxiliary equipment" cell in any control device spreadsheet. This may be done manually or by the Lotus™ program via a cut-and-paste command.

The "annual interest rate" and "control system life" are the two required inputs to the "capital recovery factor" (CRF). When the CRF is multiplied by the total capital investment (TCI), the capital recovery cost results. In accordance with Office of Management and Budget guidance, the annual interest rate should be 7% (real). Nevertheless, the user can vary this parameter to determine its effect on the total annual cost. The control system life typically varies from 10 years (scrubbers, incinerators, regenerative thermal oxidizers, and carbon adsorbers) to 20 years (ESPs, fabric filters, and mechanical collectors). But, there may be situations when the system life falls outside this range.

The CRF is computed according to the standard formula:

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

where: i = annual interest rate (decimal)
n = control system life (years)

Finally, the "taxes, insurance, admin. [administration] factor" is set at 4% of the total capital investment, consistent with *Manual* guidance, although the user may also vary this parameter if he/she desires.

The "Annual Costs" are displayed in the last section of the program. Appropriately, each cost is given in "dollars/year". The "operating labor" and "maintenance labor" costs are each computed from the operating factor, operating/maintenance labor rate, and operating labor factor—all of which are "Annual Cost Inputs". The "supervisory labor" is factored at 15% of the operating labor cost, however. The 15% supervisory labor factor and the overhead factor (60% of the sum of all labor and maintenance materials costs) are embedded in the program calculation formulas, rather than being listed as annual cost inputs. Still, as both factors are standard *Manual* values contained in Chapter 2, there is little reason to modify them.

The utilities costs—natural gas, electricity, water, steam, etc.—are calculated via the appropriate input parameters, design parameters, and/or annual cost inputs. The equations the program uses to compute these costs are very similar, if not identical, to those in the *Manual*.

For certain devices—namely, carbon adsorbers, catalytic incinerators, and fabric filters—there are also annual costs for replacement parts—carbon, catalyst, and filter bags, respectively. These costs are calculated by multiplying the part cost (*plus* taxes and freight and the part replacement labor cost) by a capital recovery factor that accounts for the interest rate and the part expected life.

The last two costs—"taxes, insurance, administrative" and "capital recovery"—are obtained by multiplying the total capital investment by the "taxes, insurance, admin. [administrative] factor" and the "capital recovery factor," respectively. Whenever there are replacement parts costs, the capital recovery cost is factored from the total capital investment *less* the cost of the replacement parts, the applicable sales and freight taxes, and the cost of installing the parts in the device. (See Chapter 2 of the *Manual* for more guidance on this.)

When applicable, "Recovery credits" are deducted from the total annual costs for carbon adsorbers and refrigerated condensers. A credit can be quite significant, especially if the recovered product has a high value. In some cases, the credit actually can exceed the sum of the annual costs.

Note that the annual cost section includes two more columns: "Wt. factor [Weighting factor]" and "W.F. (cond.) [Weighting Factor, condensed]". The first of these lists the fractional contribution that each annual cost makes to the total annual cost (*without* recovery credits). These fractions range from 0 to greater than 0.97, depending on the various inputs.

Lastly, the "Weighting Factor [condensed]" column lists two numbers. The first "condensation" is the sum of all the labor-related weighting factors: operating, supervisory, and maintenance labor; maintenance materials; and overhead. The second number combines the "taxes, insurance, administrative" and "capital recovery" costs. Both condensations appear in the weighting factor tables.

Special Spreadsheet Features

In addition to the common elements just described, some spreadsheets have special features that expedite calculation. However, because the purposes of these "bells and whistles" may not be clear at first glance, some explanation is provided.

*** Thermal and catalytic incinerators; regenerative thermal oxidizers:**

In these spreadsheets, the equipment costs are computed via two features of the Lotus™ spreadsheet program. These features are the "@IF" and "@MAX" statements. First, note that in the thermal and catalytic incinerator spreadsheets, the "primary heat recovery" must be entered as a discrete input parameter. (Allowable heat recovery values are 0, 0.35, 0.50, or 0.70.) Under the "Equipment Costs" portion of the "Capital Costs" section, there are four cells for the incinerator cost, one for each of these values. A different cell is needed for each heat recovery because the incinerator equipment cost increases with increasing heat recovery. (For more information on this, consult Chapter 3 of the *Manual*.) In a given spreadsheet, only one of the cells contains a cost, while each of the others shows "0". To accomplish this, each equipment cost cell was given a formula, such as:

"@IF(D11=0.70,21342*D24^0.2500,0)".

Translation: "If the primary heat recovery equals 70%, the incinerator equipment cost equals 21,342 times the total gas flowrate (D24) raised to the 0.2500 power. If the heat recovery equals some other value, the cost equals 0." The formulas for the other three cells were written similarly.

One might ask, "If there are four values for the incinerator equipment cost—one number and three zeroes—how will the program know which to use to compute the purchased equipment cost?" To solve this problem, the following formula was entered in the PEC cell:

"1.08*@MAX(D30:D33)".

Translation: "The PEC equals 1.08 times the *maximum value* entered in cells D30 through D33." This feature allows the program to ignore the cells containing zeroes.

The regenerative thermal oxidizers (RTO) spreadsheet has an analogous feature. For RTO's, the available heat recoveries are 0.85 and 0.95. Two cells are reserved for calculating the RTO total capital investment, one for each heat recovery value. (No equipment costs are given for RTO's as their vendors typically price them on a TCI basis.) Depending upon which value is entered as an input parameter value, one of the cells will display a cost, while the other will display "0". Here again, the "@IF" and "@MAX" commands have been used by the spreadsheet.

Another feature peculiar to the RTO spreadsheet is the auxiliary fuel requirement. Because the heat recovery is so high, the program, if not modified, could compute a *negative* auxiliary fuel (natural gas) requirement in certain cases. This would occur if the inlet waste gas heat content were high enough to more than offset the enthalpy needed to raise the waste gas to the combustion temperature, after heat recovery. To avoid this anomaly, the program was modified to compute and display a minimum fuel requirement of <u>5% of the waste gas enthalpy, taken at the oxidizer</u> <u>combustion temperature</u>, regardless of the inlet heat content. This minimum fuel requirement would be needed for burner stabilization. (See *Manual*, Chapter 3.) A similar modification was made to each of the thermal recuperative and catalytic incinerator spreadsheets.

*** "Large" units:**

As explained above, we have written spreadsheets for incinerators, wet scrubbers, flares, and other devices to compute costs for units whose sizes exceed the limits of the *Manual* equipment cost correlations. For these "large" units, the same correlations would apply, but that instead of designing and costing a single unit, the spreadsheets would compute costs for multiple units. The size of each multiple unit would be some integer fraction of the total waste gas flowrate.

To illustrate, the upper limit of the thermal and catalytic incinerator correlations is 50,000 scfm. If the total waste gas flowrate were, say, 80,000 scfm, the spreadsheet would size and cost two 40,000 scfm units. This is represented by the "flowrate per unit" cell. However, what would happen if the flowrate were, for example, 120,000 scfm, which is more than twice the upper limit? In that case, the spreadsheet would divide the total flowrate by three and proceed to size and cost three units, each to treat 40,000 scfm of waste gas. This calculation is done by the "flowrate/unit, 2nd iter. [second iteration]" cell on the spreadsheet. The program can accomodate waste gas flowrates up to four times the upper limit. The "flowrate/unit, 2nd iter." cell and the "number of units" cell are inputs to the equipment cost correlations. In each of these correlations, the equipment cost is computed by multiplying the cost per unit by the number of units required.

*** Venturi and wet impingement scrubbers:**

One of the key parameters in sizing and costing a scrubber is the saturation temperature (t_s) of the waste gas stream after it has been cooled by the scrubber water. This temperature not only heavily influences the scrubber outlet flowrate (and, hence, its equipment cost), but is also a major input to the process water makeup and wastewater flowrates. The saturation temperature is primarily a complex function of the inlet waste gas temperature and absolute humidity and the saturation absolute humidity, all of which are user-supplied parameters. Traditionally, t_s has been determined graphically via a psychometric chart, once the inlet temperature and humidity and the saturation humidity are set. To expedite the process, we programmed the (empirical) saturation humidity-temperature curve and the gas-water enthalpy and mass balances into the spreadsheet.

Now, when the user enters a saturation humidity (typically 0.20 lb/lb bone dry air or less), temperatures are computed in the two cells immediately below (labeled "Saturation enthalpy temperature" and "Saturation temperature," respectively). Upon the first try, these values may differ significantly. Next, the user should enter another saturation humidity value to see if the temperatures begin to converge. This iterative process should be continued until the two temperatures differ by less than the desired variance (e.g., $\pm$ 0.5 $^\circ$F.).

In addition to this feature, the wet impingement scrubbers spreadsheets employ the "@IF" and "@MAX" commands in a manner similar to how they are used in the incinerator and regenerative thermal oxidizer spreadsheets. Here, the user specifies the number of required scrubber stages (trays), the choices being "1," "2," or "3". The number of trays then determines which of the three equipment cost correlations is used. The equipment cost appears in this cell, while zeroes are entered in the other two cells.

*** Electrostatic precipitators:**

The ESP spreadsheet, like most of the others, closely follows the design and costing procedures in the *Manual*. However, the "Design parameters" section incorporates a method to correct an anomaly in one of the two SCA (specific collecting area) computation procedures. The first procedure (the cell labeled "Specific collection area #1") utilizes the traditional Deutsch-Anderson equation, as shown in Chapter 6 of the *Manual*. This procedure depends only on the waste gas flowrate, the overall PM (particulate matter) control efficiency, and a lumped parameter, the "migration velocity," which accounts for various particle, gas stream, and ESP operating parameters.

Though more precise, the second procedure ("SCA#2" or "Specific collection area #2") is much more complex, incorporating such inputs as the number of ESP collecting sections, the type of dust being captured, the electric field, the ESP loss factor, and the waste gas viscosity. The number of ESP sections increases with the overall particulate matter control efficiency. (For example, to capture 0 to < 96.5% of the coal fly ash in a waste gas, two ESP sections are needed, while six sections are needed to capture 99.5% or more. The efficiency range-section number matrix is listed on the spreadsheet.) According to the *Manual* procedure, an SCA is calculated for each section, and the section SCA's are summed to obtain the total SCA for the ESP. For purposes of this spreadsheet, it was convenient to define another parameter, the ratio of the two SCA values, viz.:

SCA ratio = SCA #2/SCA #1

This ratio increases smoothly with increasing PM control efficiency—<u>but only within a given section</u>. However, as the efficiency increases just beyond the upper limit for a section, the ratio <u>drops</u>, sometimes sharply. To illustrate, we computed the SCA ratio for efficiencies ranging from 80% to 96.49%, a range that corresponds to a two-section ESP. The corresponding SCA ratios ranged from 1.93 to 4.30. But, as soon as we increased the efficiency to 96.5%, the SCA ratio *decreased* to 2.50. This indicated an obvious discontinuity in the SCA ratio and, in turn, a discontinuity in the SCA #2 calculation procedure. (There is no discontinuity in SCA #1, as it is computed via an exponential equation that is continuous throughout the entire PM control efficiency range.)

To remove this discontinuity, we modified the spreadsheet SCA calculation procedure by:

(1) Computing SCA ratios for a range of PM control efficiencies within each of the sectional efficiency ranges;

(2) *Averaging* these ratios within each efficiency range;

(3) Based on the overall PM control efficiency (a user-supplied input), having the spreadsheet select an average ratio and multiply this ratio by SCA #1 to obtain an *adjusted* SCA #2. (Example: for an efficiency of 99.5%, four ESP sections would be required, and the average SCA ratio would be 2.89.) The spreadsheet will use the *larger* of SCA #1 and adjusted SCA #2 to compute the ESP equipment cost.

Finally, note again that the SCA #2 calculation procedure discussed above is based on particulate having the characteristics of coal fly ash. Extrapolation of the method to other types of particulate could introduce error.

*** Ductwork:**

Because ductwork, fans, and similar equipment are auxiliaries, not control devices, their costing is somewhat different. The ductwork spreadsheet reflects these differences. First, note that the total capital investment (TCI) is factored from the purchased equipment cost (PEC) using the installation cost multiplier specific to the control system which the ductwork supports. In almost all cases, ductwork will function in that auxiliary role. However, in those few instances where the user needs to compute the cost of a "stand alone" ductwork system, the spreadsheet incorporates a ductwork-only installation factor of "1.50".

Another feature of the ductwork spreadsheet allows the user to select the form of the equipment cost equation, the options being "power function" and "exponential". The equational form, along with the two equation parameters, the insulation thickness, and the material of construction, determine the actual cost equation used. All of these are user inputs. (However, Chapter 10 of the *Manual* provides ample guidance on their selection.)

Lastly, the ductwork spreadsheet is unique in that the equipment costs are escalated via a Producer Price Index (PCU 3444#1, “Sheet metal work/Air-conditioning ducts and stove pipe"), rather than a VAPCCI. Like the VAPCCI, the PPI must be entered on the spreadsheet by the user. This and the other PPI are available from the Bureau of Labor Statistics via phone (202/606-7705) or the BLS Home Page on the Internet (URL: "http://stats.bls.gov/blshome.html").

*** Refrigeration systems:**

We developed two spreadsheets for this control device category, one each for "custom" and "packaged" refrigeration systems. As *Manual* Chapter 8 explains, with a custom system the refrigeration unit, VOC condenser, and recovery tank are sized and costed separately. Conversely, with a packaged system, the cost of these auxiliaries is factored from the refrigeration unit equipment cost. In both spreadsheets, however, costs are computed for only one of three types of refrigeration units, i.e., "single stage (< 10 tons capacity)," "single stage (> 10 tons)," or "multistage". Zeroes will be entered in the cells for the other two types. The type selected will depend on both the capacity and the condensation temperature required.

*** Fabric filters:**

By several measures, the fabric filters spreadsheet is the most elaborate of those under the *CO$T-AIR* umbrella. First, the list of user inputs is one of the longest. Along with such standard inputs as the waste gas flowrate, temperature, and pollutant loading, the user must enter such parameters as the fabric filter gas/cloth (G/C) ratio factors, the bag material, and the bag prices. (Fortunately, most of these inputs can be found in Chapter 5 of the *Manual,* which was revised in early 1999. Copies may be downloaded from the OAQPS TTN.)

Also, the spreadsheet includes a vertical lookup table ("VLOOKUP") that lists factors for computing the gross bag area from the net bag area. (Such a table is needed because the gross/net area relationship is a step function, not a smooth curve.) Moreover, the bag price used to compute the bag cost for a given fabric filter is the average of the prices listed in the *Manual* (or provided by the user) for the bag material selected. This is done to relieve the user from having to select certain baghouse design options, such as choosing a reverse-air unit with bag snap rings, versus a unit without rings.

Probably the most unique features in this spreadsheet are the capital and annual cost displays. Recall that in the flares spreadsheet, the unit selection is based first on the flare height, then on the equipment cost. That is done because those annual costs that are independent of the TCI are the same regardless of flare type selected. But with fabric filters, both the equipment cost (baghouse shell, insulation, etc.) and the cost of bags (initial and annual replacement) affect the total annual cost. Moreover, the user may not know which type of fabric filter cleaning mechanism would be optimal for a given application.[a] For these reasons, the spreadsheet is structured to present itemized capital and annual costs for up to four baghouse types: "mechanical shaker," "reverse-air," "pulse-jet (modular design)," and "pulse-jet (common housing)". From this matrix of costs, the user then can select the optimal baghouse type, based on least cost or some other measure. (Again, Chapter 5 of the *Manual* provides a thorough discussion of these baghouse types and how they are sized and costed.)

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Those with questions or comments about the *CO$T-AIR* spreadsheets (Second Edition) should contact William M. Vatavuk, at 919/541-5309 (fax: 919/541-0839; e-mail: VATAVUK.BILL@EPA.GOV).

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[a] That is, for a given application, more than one type of baghouse may provide the required PM control efficiency (overall or size-specific).