CONTROL STRATEGY TOOL (COST)

COST EQUATIONS DOCUMENTATION

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Document Revision History

Date of Update	Description
June 9, 2010	First version of Cost Equations Documentation
August 31, 2011	Major update to include new CoST cost equations
October 25, 2011	Edits to reflect the current state of the software and control measures database
July 3, 2014	Integration of edits and comments from previous version; addition of Industrial, Commercial, and Institutional (ICI) boiler equations
August 29, 2014	Reorganization of document; addition of appendix for listing the SQL queries used by the CoST equations; addition of appendix for tables of parameter values used by the CoST cost equations
September 4, 2014	Fixed page/chapter numbering and integration of edits and comments from previous version
August 27, 2015	Added Equation Type 13 for ICI boiler NOx controls; reorganized section headers
September 30, 2016	Removed sections for equation types 9, 10, and 11 (these IPM control measures are now obsolete and replaced by Equation Type 1); updated control equation parameters for Equation Type 1
January 11, 2017	Updated Equation Type 2 to the current form; added Equation Types 2a and 2b; updated example cost equation calculations to use only active measures, including new screen shots; replaced source code in appendix with reference to EPA CoST GitHub repository; updated all control measures and parameters in appendix to be current with January 2017 control measures database; added appendix with complete list of SCCs for all control measures; created internal cross-references for all tables and figures to allow automatic numbering
April 12, 2017	Integrated comments from EPA on January 11 version; updated all example calculations to use NEI2014 inventory sources and current control measures
August 2, 2017	Updated equation examples following review of the current equations
April 20, 2018	Revised *Section 1. Introduction* to include discussion of converting emissions inventory units (design capacity, exhaust gas flow rate) to the units required for each cost equation. Removed unit conversions discussions and examples from remainder of the document

1 Introduction

The purpose of EPA's Control Strategy Tool (CoST) is to model the emissions reductions and costs associated with control strategies applied to sources of air pollution. It was developed as a replacement to EPA's AirControlNET (ACN) software. CoST overlays a detailed database of control measure information on EPA emissions inventories to compute source- and pollutant-specific emissions reductions and associated costs at various geographic levels (national, regional, and/or local). The Control Measures Database (CMDB) contained in CoST is composed of control measure and cost information for reducing the emissions of criteria pollutants (e.g., NO_x, SO_2, VOC, PM_{10}, $PM_{2.5}$, and NH_3) as well as CO and Hg from:

- Point sources in the U.S. electric power sector, as reflected in EPA's application of the Integrated Planning Model (IPM) (ptipm emissions inventory sector),
- Point sources other than those contained in IPM (ptnonipm),[1]
- Nonpoint sources (nonpt), and[2]
- Mobile sources (onroad and nonroad).[3]

CoST estimates the costs of emissions control technologies in one of two ways:

1) Cost equations are used to determine engineering costs that take into account several variables for the source when data are available for those variables, or
2) A simple cost factor in terms of dollars per ton of pollutant reduced is used to calculate the annual cost of the control measure.

For nonpoint sources, there are control measures, but the measures don't use cost equations. Cost equations are used for some point sources (ptipm and ptnonipm sources). This document describes the cost equations used in CoST.

This document provides a list of equations and associated variables assigned to specific control measures in CoST. The application of these equations is based on the individual emissions inventory records to which they are applied and the specific characteristics of those records. For example, Equation Type 1 calculates capital cost largely based on a unit's generating capacity in megawatts (MW) and is scaled based on the original control cost calculations. It is applicable to NO_x, SO_2, and $PM_{2.5}$ emissions at ptipm[4] electric generating unit (EGU) sources. For this equation type, variable and fixed operating and maintenance (O&M) costs are also estimated.

Typically, each equation type is applied either to a pollutant-source combination or to a more general grouping of pollutants and sources. The scaling factors, additional variables, and cross-references by control measure and equation type are detailed in this document.

[1] Emissions inventory definitions obtained from "Technical Support Document: Preparation of Emissions Inventories for the Version 4, 2005-based Platform". Available at: http://www3.epa.gov/airtransport/pdfs/2005_emissions_tsd_07jul2010.pdf
[2] Ibid.
[3] Ibid.
[4] "ptipm" refers to the sector of EPA's National Emissions Inventory that is composed of point sources included in EPA's Integrated Planning Model (IPM).

The remainder of this document is divided into chapters by the primary pollutant to be controlled. Chapters 2, 3, and 4 focus on NO_x, SO_2, and PM, respectively. Each chapter is further divided into two major sections; the first focuses on IPM equation types and the second focuses on the non-IPM equation types. Table 1-1 presents the control equipment types and pollutants for each equation type. Table 1-2 includes control equipment abbreviations and related descriptions.

Table 1-1. Equipment Types and Primary Pollutants for each Equation Type

Equation Type	Equipment Type	Primary Pollutants	Section
1	NO_x: LNB, LNBO, LNC1, LNC2, LNC3, NGR, SCR, SNCR SO_2: FGD $PM_{2.5}$: fabric filters	NO_x, SO_2, $PM_{2.5}$	2.1.1, 3.1.1, 4.1.1
2	LNB, Dry Low NOx Combustion, Air to Fuel Ratio Controller, SCR, Catalytic Combustion, EMx and Dry Low NOx Combustion, EMx and Water Injection, SCR+Dry Low NOx Combustion, SCR+steam injection, SCR+water injection, Steam Injection, Water Injection	NO_x	2.2.1
2a	LNB, SCR	NO_x	2.2.2
2b	low emissions combustion	NO_x	2.2.3
3	FGD, sulfuric acid plant	SO_2	3.2.1
8	ESP, fabric filter, paper filter, Venturi scrubber, impingement-plate scrubber	PM	4.2.1
12	SCR, SCR-95%, ULNB, Excess O2 Control	NO_x	2.2.4
13	FGR, LNB, SCR, SNCR	NO_x	2.2.5
14	fabric filters	PM	4.2.2
15	ESP	PM	4.2.3
16	wet scrubber	SO_2	3.2.2
17	DIFF system	PM	4.2.4
18	increased caustic injection rate for existing dry injection control	SO_2	3.2.3
19	spray dryer absorber	SO_2	3.2.4
cost per ton	episodic ban, seasonal ban, LNB, AF Ratio, AF + IR, Mid-Kiln Firing, SCR, SNCR, ULNB, LEA, low emission combustion, and many others	NO_x	2.2.1.3

Table 1-2. Control Equipment Abbreviations in CoST

Equipment Abbreviation	Equipment Description
AF Ratio	Air/Fuel ratio controls
DIFF System	dry injection & fabric filter system
ESP	electrostatic precipitator
Excess O_2 Control	excess oxygen control to combustor
FGD	flue gas desulfurization
FGDW	FGD wet scrubber
FGR	flue gas recirculation
IR	Ignition timing retard (for internal combustion engines)
LEA	low excess air
LNB	low NO_x burner
LNBO	low NO_x burner technology with overfire air
LNC1	low NO_x burner technology w/closed-coupled OFA
LNC2	low NO_x burner technology w/separated OFA
LNC3	low NO_x burner technology w/close coupled/separated OFA
LSD	lime spray dryer
NGR	natural gas reburning
SCR	selective catalytic reduction
SCR-95%	selective catalytic reduction with over 95% NO_x efficiency
SCR+LNB	both selective catalytic reduction and low NO_x burner technology
SCR+steam injection	selective catalytic reduction with steam injection
SCR+water injection	selective catalytic reduction with water injection
SDA	spray dryer absorber
SNCR	selective noncatalytic reduction
SNCR-Urea	selective noncatalytic reduction – urea
SNCR-Ammonia	selective noncatalytic reduction – ammonia
ULNB	ultra-low NO_x burner

The source code for the CoST cost equations are available in the EPA GitHub repository at the link below. This repository will be continually updated with the latest version of the CoST cost equations.

https://github.com/USEPA-OAQPS/emf/blob/master/EMF/deploy/db/cost/functions/cost_equations_v2.sql

1.1 Capital Recovery Factor Equation

Throughout the document we provide equations to estimate annualized capital costs using a capital recovery factor. The following equation is used to estimate the capital recovery factor (CRF) for the case of discrete interest compounding (i.e., not continuous compounding).

$$Capital\ Recovery\ Factor = \frac{Interest\ Rate\ \times (1 + Interest\ Rate)^{Equipment\ Life}}{(1 + Interest\ Rate)^{Equipment\ Life} - 1}$$

Where:

- *Interest Rate* = annual interest rate

- *Equipment Life* = expected economic life of the control equipment

1.2 Emissions Inventory Unit Conversions

The cost equations in this document use various parameters from the emissions inventory to determine the size of the emissions unit, which in turn is used to calculate the capital and other operating costs. Each equation requires specific units for the emissions inventory parameter used in the equation. Nearly all of the units for the emissions inventory parameters used in the equations are prescribed in the format of the inventory (see the SMOKE User's Manual for the required units).[5] For example, the exhaust gas flow rate must be reported as cubic feet per second. However, SMOKE provides flexibility for reporting the design capacity units. This requires a conversion of the units used in the emissions inventory to the units required for each cost equation.

1.2.1 Design Capacity Unit Conversions

The unit conversions for design capacity are relatively straightforward, as shown in the following equation:

$$Design\ Capacity_{equation} = Design\ Capacity_{inventory} \times Conversion\ Factor \times Combustion\ Efficiency$$

Where:

- $Design\ Capacity_{equation}$ = capacity of the emission process in units required by the CoST equation
- $Design\ Capacity_{inventory}$ = capacity of the emission process in units reported in the emissions inventory
- *Conversion Factor* – standard factor used to convert from emission inventory units to cost equation units
- *Combustion Efficiency* = the ratio of the useful energy output by the system to the energy input to the system

The following standard conversion factors are used in the CoST unit conversion algorithm, which first converts inventory units to a common unit (Megawatt Thermal {MWt}) and then converts MWt to the units required for each individual CoST equation. The factors used to convert from inventory units to MWt are as follows:

- 1 MWt = 3.412 million British Thermal Units per hour (MMBtu/hr or E6BTU/HR)
- 1 MWt = 1000 Kilowatt Thermal (KWt)
- 1 MWt = 0.000746 Horsepower (HP)
- 1 MWt = 0.000981 Boiler Horsepower (BLRHP)

[5] The current SMOKE User's Manual is available at: https://www.cmascenter.org/help/documentation.cfm?model=smoke&version=4.5.

The combustion efficiency is based on the Source Classification Code (SCC) and is retrieved from the CoST SCC table. The combustion efficiency is the ratio of the useful *energy output* by the system to the *energy input* to the system. Most of the CoST equations are based on the size of the unit in terms of the *energy input* to the system. In that case, the combustion efficiency is not needed and effectively treated as 100% in the CoST unit conversion algorithm. However, for electric generating units (EGUs), the CoST equations are based on the size of the unit in terms of useful *energy output* from the system. In the electric power industry, there are two values assigned to a unit's design capacity: megawatts electric (MWe) and megawatts thermal (MWt). The former refers to the electricity output capability of the plant, and the latter refers to the input energy required. The efficiency of an EGU is equal to the ratio of the electric output of the plant to the thermal overall power need to generate the electricity. For example, a coal-fired power plant rated at 1000 MWe will require supply of 3000 MWt of heat (e.g., approximately 10,236 MMBTU/HR) from burning coal for every 1000 MW of electricity it produces. The efficiency is specified for each SCC in the SCC table of the Control Measure Database. Typical values are 33 to 35% for coal-fired plants

1.2.2 Exhaust Gas Flowrate Unit Conversions

The exhaust gas flowrate in the emissions inventory must be reported as cubic feet per second, and it is assumed that the flowrate reported in the emissions inventory is at actual stack conditions. Some of the cost equations in this document were developed using the actual flow rate, but others use the flow rate corrected to standardized properties of temperature and moisture content. The following terminology is used when discussing the flowrate in this document:

$$F_a = F_{inventory} \, x \, 60$$

$$F_s = (F_a)\left(\frac{520}{460+T}\right)$$

$$F_d = (F_a)\left(\frac{460+68}{460+T}\right)\left(1-\frac{\%Moist}{100}\right)$$

Where:

$F_{inventory}$	=	Stack gas flowrate (ft^3/s) from the emissions inventory
F_a	=	Actual exhaust flowrate (acfm)
F_s	=	Exhaust flowrate at standard temperature (scfm)
F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
60	=	Seconds to minutes conversion factor
T	=	Stack gas temperature (˚F) from the emissions inventory
%Moist	=	Stack gas moisture content (%) from the CMDB equations table

2 NOx Control Cost Equations

This chapter is divided into two main sections – IPM and non-IPM sources. The types of cost equations, indicated below, for point source NO_x controls are described in their appropriate sections.

- Equation Type 1 for IPM sector external combustion boilers
- Equation Types 2 and 2b for gas-fired turbine point sources and internal combustion engines
- Equation Type 2a for glass manufacturing
- Equation Type 12 for gas-fired process heaters at petroleum refineries
- Equation Type 13 for non-IPM boilers, or industrial, commercial, and institutional (ICI) boilers
- Default cost per ton equations for non-IPM point sources

This chapter describes each equation type, presents the relevant parameters, and provides example calculations. The example calculations provided are prepared using version 2.15 of the CoST software. Appendix A provides tables of parameters and values used with each equation type.

2.1 IPM Sector (ptipm) NO_x Control Cost Equations

Equation Type 1 is the only cost equation applicable to IPM sector (ptipm) point sources requiring NO_x emission reductions. These sources are electric generating units. All of the cost data in CoST for ptipm sources are originally from the Integrated Planning Model (IPM) v3.0[6]; while we have incorporated the IPM data into CoST, we generally rely on output from IPM for input to analyses of costs for EGU sources and controls. NOx control technologies for Equation Type 1 are:

- Low NOx Burner (LNB)
- Low NOx Burner and Over Fire Air (LNBO)
- Low NOx Coal-and-Air Nozzles with Cross-Coupled Overfire Air (LNC1)
- Low NOx Coal-and-Air Nozzles with Separated Overfire Air (LNC2)
- Low NOx Coal-and-Air Nozzles with Cross-Coupled and Separated Overfire Air (LNC3)
- Natural Gas Reburn (NGR)
- Selective Catalytic Reduction (SCR)
- Selective Non-Catalytic Reduction (SNCR)

2.1.1 Equation Type 1 for NO_x - Utility Boilers

The data for this equation type were developed based on a series of model plants.[7] The capacities of these model plants are used along with scaling factors and the emissions inventory's unit-

[6] IPM is a model used by EPA's Clean Air Markets Division to estimate the costs of control strategies applied to electric utilities.
[7] U.S. EPA 2013, Tables 5.6 and 5.7 on pages 5-7 and 5-8.

specific boiler characteristics (e.g., boiler capacity, stack parameters) to generate a control cost for an applied technology.

2.1.1.1 Cost Equations

Capital Cost Equations

The purpose of a capital cost analysis is to put potential uses of capital (e.g., money, equipment) in the same economic terms. This allows a direct comparison to be made between these potential uses. The capital cost equations in CoST provide an estimate of the annualized capital cost of multiple technologies for direct comparison.

When developing Equation Type 1, multiple model plants were designed and the calculations were then simplified. CoST calculates the capital cost associated with a control measure by applying a scaling factor to the calculations for an appropriate model plant; the scaling factor is calculated based on the ratio of the model plant's capacity to the capacity of a boiler measured in megawatts (MW).

$$Scaling\ Factor = \left(\frac{Scaling\ Factor\ Model\ Size}{Capacity}\right)^{Scaling\ Factor\ Exponent}$$

Where:

- *Scaling Factor Model Size* = boiler capacity of the model plant (MW)
- *Scaling Factor Exponent* = an empirical value based on the specific control measure
- *Capacity* = capacity of the boiler (MW) (from the units used in the emissions inventory converted to MW, see Section 1.2.1 for a discussion of unit conversions)

The capital cost associated with these NO_x control measures is a straightforward calculation of the capital cost multiplier, the unit's boiler capacity (MW) (from emissions inventory), and the scaling factor that was calculated.

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times\ Design\ Capacity\ \times\ Scaling\ Factor\ \times\ 1{,}000$$

Where:

- *Capital Cost Multiplier* = an empirical value based on the specific control measure ($/kW)
- *Design Capacity* = capacity of the boiler (MW)
- *1,000* = unit conversion factor

Finally, the following equation calculates the annualized capital cost. This is the cost of capital only; it does not include costs due to operations and maintenance.

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times Capital\ Recovery\ Factor$$

Where the *Capital Cost* and the *Capital Recovery Factor* have been calculated previously.

Operation and Maintenance Cost Equations

Operation and maintenance (O&M) costs, which are also calculated on an annual basis, are in addition to the capital cost of equipment. These O&M costs are divided into fixed costs and variable costs. Fixed costs are incurred because the equipment exists whether or not it is in operation. Examples of fixed costs are property taxes, insurance, and administrative charges. The fixed O&M cost component is also based on the unit's capacity.

$$Fixed\ O\&M = Fixed\ O\&M\ Cost\ Multiplier\ \times Design\ Capacity\ \times 1{,}000$$

Where:

- *Fixed O&M Cost Multiplier* = an empirical value based on the control measure ($/kW)
- *Design Capacity* = capacity of the boiler (MW) (from the emissions inventory)
- *1,000* = unit conversion factor

The variable portion of the O&M costs includes an additional estimate for the unit's capacity factor, which is a factor reflecting the unit's utilization.

$$Variable\ O\&M = Variable\ O\&M\ Cost\ Multiplier\ \times Design\ Capacity \times Capacity\ Factor\ \times\ 8{,}760$$

Where:

- *Variable O&M Cost Multiplier* = an empirical value based on the specific control measure ($/MWh)
- *Capacity Factor* = the capacity factor captures the amount of actual power generated by a power plant as compared to its design capacity or rated output[8]
- *8,760* = assumed number of hours of operation per year

The total annual operations and maintenance cost is then the sum of the annual fixed and variable O&M costs.

$$Total\ O\&M\ Cost = Fixed\ O\&M + Variable\ O\&M$$

Total Annualized Cost Equation

The annualized cost is then estimated using the unit's capital cost times the CRF (derived with an annual interest rate and equipment lifetime expectancy) and the sum of the fixed and variable O&M costs.

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$

2.1.1.2 Example Calculations

This section provides example calculations for an application of Equation Type 1. The example scenario is a utility boiler – coal/wet bottom/tangential/bituminous (SCC 10100211) that requires

[8] If a power plant's design capacity is 500 MW, but the plant runs at 400 MW, it's capacity factor is 80 percent.

NO_x control. The control measure abbreviation is NSCR_UBCT1, the control measure is SCR and the control efficiency is 90%.

Example Equation Type 1 Variables

Capacity (MW) for the boiler is taken from the emissions inventory:

Capacity (MW) = 61.98

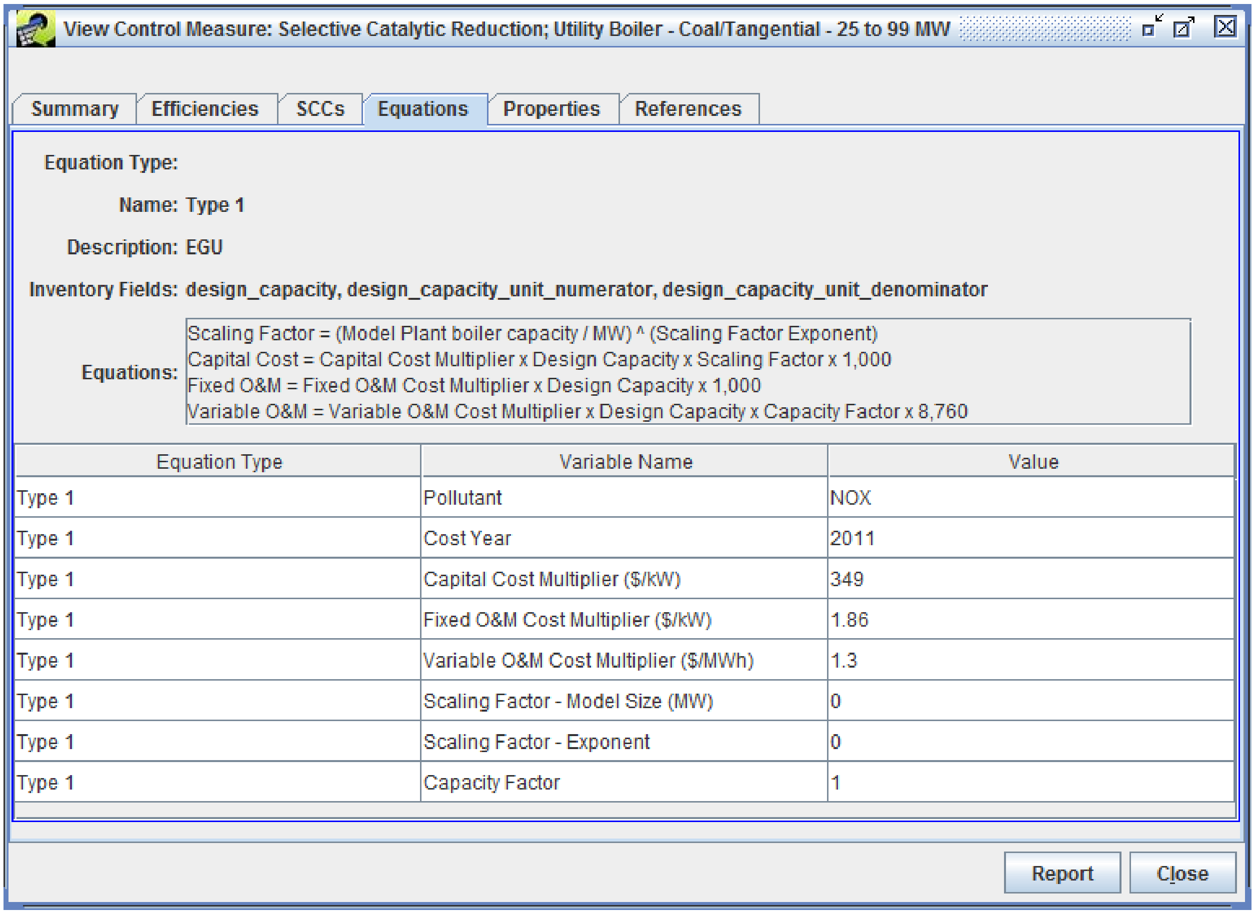
Capital Recovery Factor = 0.0703 (assumes equipment life of 30 years and interest rate of 5.7%, which is provided by IPM)

The following values are shown in the View Control Measure screen in Figure 2-1.[9]

Capital Cost Multiplier ($/kW) = 349
Fixed O&M Cost Multiplier ($/kW) = 1.86
Variable O&M Cost Multiplier ($/MWh) = 1.3
Scaling Factor Model Size (MW) = 0
Scaling Factor Exponent = 0
Capacity Factor = 1
Year for Cost Basis = 2011

[9] The combustion efficiency value is in the SCCs tab in the control measure database.

Figure 2-1. Equation Type 1 for NO_x - Example Screenshot from CoST


View Control Measure: Selective Catalytic Reduction; Utility Boiler - Coal/Tangential - 25 to 99 MW

Summary | Efficiencies | SCCs | Equations | Properties | References

Equation Type:

Name: Type 1

Description: EGU

Inventory Fields: design_capacity, design_capacity_unit_numerator, design_capacity_unit_denominator

Equations:
Scaling Factor = (Model Plant boiler capacity / MW) ^ (Scaling Factor Exponent)
Capital Cost = Capital Cost Multiplier x Design Capacity x Scaling Factor x 1,000
Fixed O&M = Fixed O&M Cost Multiplier x Design Capacity x 1,000
Variable O&M = Variable O&M Cost Multiplier x Design Capacity x Capacity Factor x 8,760

Equation Type	Variable Name	Value
Type 1	Pollutant	NOX
Type 1	Cost Year	2011
Type 1	Capital Cost Multiplier ($/kW)	349
Type 1	Fixed O&M Cost Multiplier ($/kW)	1.86
Type 1	Variable O&M Cost Multiplier ($/MWh)	1.3
Type 1	Scaling Factor - Model Size (MW)	0
Type 1	Scaling Factor - Exponent	0
Type 1	Capacity Factor	1

Report Close

Annualized Capital Cost Equation

$$Scaling\ Factor = \left(\frac{Scaling\ Factor\ Model\ Size}{Capacity}\right)^{Scaling\ Factor\ Exponent}$$

$$Scaling\ Factor = \left(\frac{0}{61.98}\right)^{0}$$

$$Scaling\ Factor = 1$$

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times\ Capacity\ \times\ Scaling\ Factor\ \times\ 1{,}000$$

$$Capital\ Cost = 349\frac{\$}{kW} \times\ 61.98\ MW \times\ 1\ \times\ 1{,}000\frac{kW}{MW}$$

$$Capital\ Cost = \$21{,}631{,}481\ (2011\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times Capital\ Recovery\ Factor$$

$$Annualized\ Capital\ Cost = \$21{,}631{,}481\ \times 0.0703$$

$$Annualized\ Capital\ Cost = \$1{,}521{,}392\ (2011\$)$$

Operation and Maintenance Cost Equation

$$Fixed\ O\&M = Fixed\ O\&M\ Cost\ Multiplier\ \left(\frac{\$}{kW}\right) \times\ Capacity\ (MW)\ \times\ 1{,}000$$
$$Fixed\ O\&M = 1.86\frac{\$}{kW} \times 61.98\ MW \times\ 1{,}000\frac{kW}{MW}$$
$$Fixed\ O\&M = \$115{,}285\ (2011\$)$$

$$Variable\ O\&M$$
$$= Variable\ O\&M\ Cost\ Multiplier\ \left(\frac{\$}{MWh}\right) \times Capacity\ (MW)\ \times\ Capacity\ Factor$$
$$\times\ 8{,}760\ (Hours\ Per\ Year)$$
$$Variable\ O\&M = 1.3\frac{\$}{MWh} \times 61.98 MW \times\ 1.0\ \times\ 8{,}760\ Hours$$

$$Variable\ O\&M = \$705{,}843\ (2011\$)$$

$$Total\ O\&M\ Cost = Fixed\ O\&M + Variable\ O\&M$$
$$Total\ O\&M\ Cost = \$115{,}285 + \$705{,}843$$
$$Total\ O\&M\ Cost = \$821{,}129\ (2011\$)$$

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$
$$Total\ Annualized\ Cost = \$1{,}521{,}392\ + \$821{,}129$$
$$Total\ Annualized\ Cost = \$2{,}342{,}520\ (2011\$)$$

2.2 Non-IPM Sector (ptnonipm) NO_x Control Cost Equations

Control costs for some non-EGU point sources where NO_x is the primary pollutant to be controlled are discussed in this section. Equation Type 2 estimates the costs of NO_x controls for natural gas-fired turbines and internal combustion engines (ICE). Equation Type 2 originally also covered Industrial, Commercial, and Institutional (ICI) boilers, but costs of NO_x controls for ICI boilers are now estimated by Equation Type 13. Equation Type 12 estimates emissions control measures for gas-fired process heaters at petroleum refineries. Finally, default cost per ton factors are used for some additional source types.

2.2.1 Equation Type 2 for NO_x – Natural Gas Turbines and ICEs

Costs for low NO_x burners applied to natural gas-fired turbines and lean burn ICE are estimated using Equation Type 2. Equation Type 2 uses the design capacity from the input emissions inventory (converted from emissions inventory units to the unit {MMBtu/hour} required by the cost equations, see Section 1.2.1), as well as a scaling component, such as a capital cost multiplier, that is based on the original Alternative Control Technology or Control Technology

Guidelines (ACT/CTG) analyses used to derive these estimates.[10] NOx control technologies for Equation Type 2 are:

- LNB
- Dry Low NOx Combustion
- Air to Fuel Ratio Controller
- SCR
- Catalytic Combustion
- EMx and Dry Low NOx Combustion
- EMx and Water Injection
- SCR + Dry Low NOx Combustion
- SCR + Steam Injection
- SCR + Water Injection
- Steam Injection
- Water Injection

Equation Type 2-based costs are estimated for units that have a design capacity not exceeding 2,000 million Btu per hour (MMBtu/hour). For those sources above the capacity threshold, default costs per ton are used (see Section 2.2.1.3).

2.2.1.1 Cost Equations

Capital Cost Equation

The O&M costs are calculated by subtracting the annualized capital costs, or the product of *capital costs* × *capital recovery factor* (CRF), from the *total annualized costs*. The CRF value is calculated in CoST using the equipment life and interest rate specified when setting up a CoST run.

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times (Design\ Capacity\ )^{\ Capital\ Cost\ Exponent} + Capital\ Cost\ Base$$

Where:

- *Capital Cost Multiplier* = an empirical value based on the specific control measure
- *Capital Cost Exponent* = an empirical value based on the specific control measure
- *Design Capacity* = the emissions unit design capacity (MMBtu/hour)
- *Capital Cost Base* = value based on the linear fit of the equation to empirical data; not applicable to all control measures

$$Annualized\ Capital\ Cost = Capital\ Cost \times Capital\ Recovery\ Factor$$

Where the *Capital Cost* and the *Capital Recovery Factor* have been calculated previously.

[10] RTI 2014, Section 3.

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Annual\ Cost\ Multiplier\ \times\ (Design\ Capacity)^{Annual\ Cost\ Exponent} + Annual\ Cost\ Base$$

Where:

- *Annual Cost Multiplier* = an empirical value based on the specific control measure
- *Annual Cost Exponent* = an empirical value based on the specific control measure
- *Design Capacity* = the emissions unit design capacity (MMBtu/hour)
- *Annual Cost Base* = value based on the linear fit of the equation to empirical data; not applicable to all control measures

Operation and Maintenance Cost Equation

$$Total\ O\&M\ Cost = Total\ Annualized\ Cost - Annualized\ Capital\ Cost$$

Where the *Total Annualized Cost* and the *Annualized Capital Cost* were calculated previously.

2.2.1.2 Example Calculations

This section provides an example calculation for an application of Equation Type 2. The example scenario is a Natural Gas Turbine that uses catalytic combustion to control NO_x. The control measure abbreviation is NCATCGTNG, and the control measure is catalytic combustion.

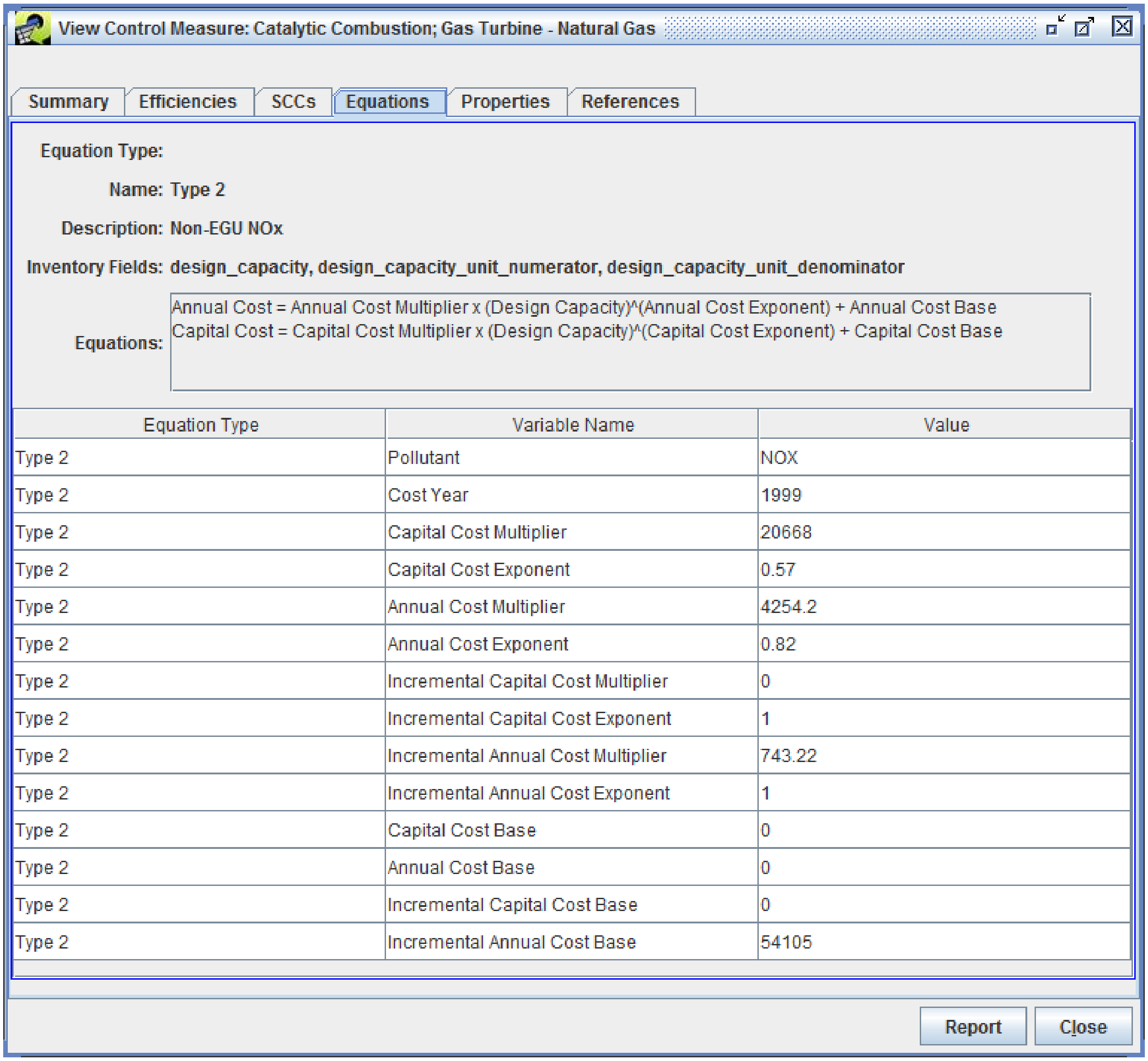
Example Equation Type 2 Variables

Design Capacity (MMBtu/hour) from the emissions inventory = 8.9
Capital Recovery Factor = 0.1098 (assumes equipment life of 15 years and interest rate of 7%)

Many of the following values are shown in the View Control Measure screen in Figure 2-2.

Capital Cost Multiplier = $20,668.0
Capital Cost Exponent = 0.57
Capital Cost Base = N/A
Annual Cost Multiplier = $4,254.2
Annual Cost Exponent = 0.82
Annual Cost Base =N/A
Year for Cost Basis = 1999

Figure 2-2. Equation Type 2 for NO_x - Example Screenshot from CoST


View Control Measure: Catalytic Combustion; Gas Turbine - Natural Gas

Summary | Efficiencies | SCCs | Equations | Properties | References

Equation Type:

Name: Type 2

Description: Non-EGU NOx

Inventory Fields: design_capacity, design_capacity_unit_numerator, design_capacity_unit_denominator

Equations: Annual Cost = Annual Cost Multiplier x (Design Capacity)^(Annual Cost Exponent) + Annual Cost Base
Capital Cost = Capital Cost Multiplier x (Design Capacity)^(Capital Cost Exponent) + Capital Cost Base

Equation Type	Variable Name	Value
Type 2	Pollutant	NOX
Type 2	Cost Year	1999
Type 2	Capital Cost Multiplier	20668
Type 2	Capital Cost Exponent	0.57
Type 2	Annual Cost Multiplier	4254.2
Type 2	Annual Cost Exponent	0.82
Type 2	Incremental Capital Cost Multiplier	0
Type 2	Incremental Capital Cost Exponent	1
Type 2	Incremental Annual Cost Multiplier	743.22
Type 2	Incremental Annual Cost Exponent	1
Type 2	Capital Cost Base	0
Type 2	Annual Cost Base	0
Type 2	Incremental Capital Cost Base	0
Type 2	Incremental Annual Cost Base	54105

Report | Close

Equation Type 2 Example

All costs are in 1999 U.S. dollars because that is the base year for the references for these equations and for the capital-to-annual ratios.

Capital Cost Equation

$$Capital\ Cost = Capital\ Cost\ Multiplier \times (Design\ Capacity\ )^{Capital\ Cost\ Exponent} + Capital\ Cost\ Base$$

$$Capital\ Cost = \$20{,}668 \times 8.9^{0.57}$$
$$Capital\ Cost = \$71{,}854\ (1999\$)$$

Use an implicit price deflator ratio to convert from 1999$ to 2000$.

$$Capital\ Cost = \$71{,}854\ (1999\$) \times \frac{81.887\ (2000\$)}{80.065\ (1999\$)}$$
$$Capital\ Cost = \$73{,}489\ (2000\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times\ Capital\ Recovery\ Factor$$
$$Annualized\ Capital\ Cost = \$73{,}489\ \times\ 0.1098$$
$$Annualized\ Capital\ Cost = \$8{,}069\ (2000\$)$$

Total Annualized Cost Equation

$$Total\ Annualized\ Cost$$
$$= Annual\ Cost\ Multiplier\ \times\ (Design\ Capacity\ )^{Annual\ Cost\ Exponent}$$
$$Total\ Annualized\ Cost = \$4{,}254.20 \times 301.0^{\,0.82}$$
$$Total\ Annualized\ Cost = \$25{,}546\ (1999\$)$$

Convert to 2000$ using the implicit price deflator ratio:

$$Total\ Annualized\ Cost = \$25{,}546\ (1999\$)\ \times \frac{81.887\ (2000\$)}{80.065\ (1999\$)}$$
$$Total\ Annualized\ Cost = \$26{,}127\ (2000\$)$$

Operation and Maintenance Cost Equation

$$Total\ O\&M\ Cost = Total\ Annualized\ Cost - Annualized\ Capital\ Cost$$
$$Total\ O\&M\ Cost = \$26{,}127 - \$8{,}069$$
$$O\&M\ Cost = \$18{,}058\ (2000\$)$$

2.2.1.3 Non-IPM Sector (ptnonipm) NOx Cost per Ton Calculations

When a source qualifies for Equation Type 2 except for the emissions unit capacity (design capacity > 2,000 MMBtu/hour), default cost per ton values are assigned and applied to the annual emissions reduction achieved by the applied control measure.

Total Annualized Cost Equation

When no control is currently in place for the source:

$$Total\ Annualized\ Cost = Emissions\ Reductions \times Default\ Cost\ Per\ Ton$$

Where:

- *Emissions Reductions* = calculated by CoST (tons/year)
- *Default Cost per Ton* = an empirical value based on the specific control measure

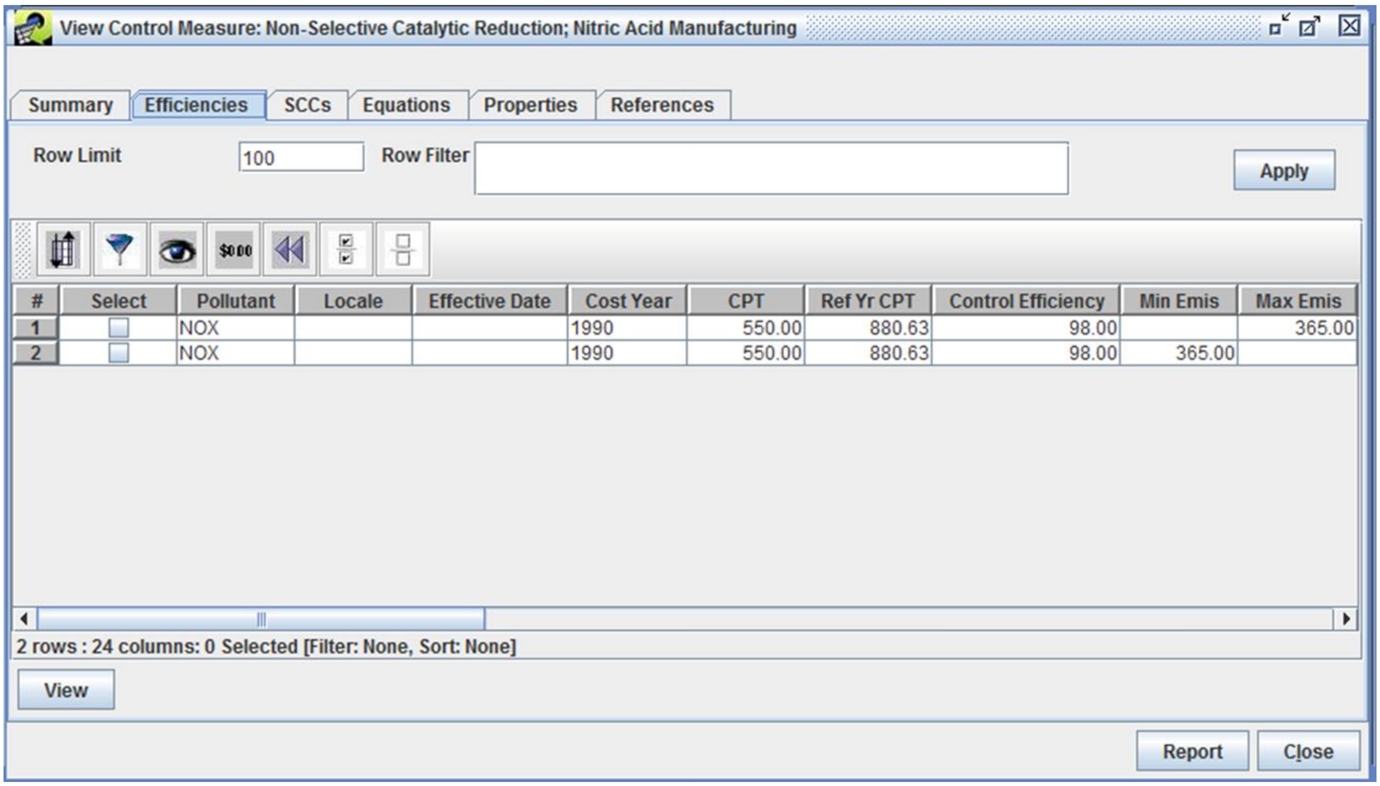
2.2.1.4 Non-IPM Sector (ptnonipm) NO_x Cost per Ton Example

This section provides example calculations for an application of this cost per ton method for NO_x control on a nitric acid manufacturing industrial process (SCC 30101301) that uses non-selective catalytic reduction controls (NNSCRNAMF). Figure 2-3 illustrates the Efficiencies tab of the View Control Measure screen for NNSCRNAMF.

Example Equation Type 2 Variables

Capital Recovery Factor = 0.1098 (assumes equipment life of 15 years and interest rate of 7%)
NO_x Emission Reduction = 24.5 tons/year
Capital to Annual Ratio = 2.4
Default Cost per Ton Reduced = 550.0 (1990$)
Year for Cost Basis = 1990

Figure 2-3: NO_x Control Measure Cost per Ton Non-IPM Sector – Example Screenshot from CoST



Example Calculation when no control measure is in place for the source (Default Reduction)

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Emissions\ Reductions \times Default\ Cost\ Per\ Ton$$
$$Total\ Annualized\ Cost = 24.5\ \times \$550$$
$$Total\ Annualized\ Cost = \$13{,}475\ (1990\$)$$

Use an implicit price deflator ratio to convert from 1990$ to 2000$.

$$Total\ Annualized\ Cost = \$13{,}475\ (1990\$)\ \times \frac{81.887\ (2000\$)}{66.773\ (1990\$)}$$
$$Total\ Annualized\ Cost = \$16{,}525\ (2000\$)$$

Capital Cost Equation

$$Capital\ Cost = Total\ Annualized\ Cost \times Capital\ to\ Annual\ Ratio$$
$$Capital\ Cost = \$16{,}525\ \times\ 2.4$$
$$Capital\ Cost = \$39{,}660\ (2000\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times Capital\ Recovery\ Factor$$
$$Annualized\ Capital\ Cost = \$39{,}660\ \times 0.1098$$
$$Annualized\ Capital\ Cost = \$4{,}354\ (2000\$)$$

Operation and Maintenance Cost Equation

$$Total\ O\&M\ Cost = Total\ Annualized\ Cost - Annualized\ Capital\ Cost$$
$$Total\ O\&M\ Cost = \$16{,}525 - \$4{,}354$$
$$Total\ O\&M\ Cost = \$12{,}171\ (2000\$)$$

2.2.2 Equation Type 2a for NO_x – Glass Manufacturing

Equation Type 2a is used to calculate NOx reductions from glass manufacturing.[11] NOx control technologies for Equation Type 2a include LNB and SCR.

2.2.2.1 Cost Equations

Capital Cost Equation

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times Emissions\ Reduction^{\ Capital\ Cost\ Exponent} + Capital\ Cost\ Base$$

Where:

- *Capital Cost Multiplier* = an empirical value based on the specific control measure
- *Capital Cost Exponent* = an empirical value based on the specific control measure
- *Emissions Reduction* = the change in emissions resulting from application of the control technology (tons/day)
- *Capital Cost Base* = value based on the linear fit of the equation to empirical data; not applicable to all control measures

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Annual\ Cost\ Multiplier\ \times Emissions\ Reduction^{\ Annual\ Cost\ Exponent} + Annual\ Cost\ Base$$

Where:

- *Annual Cost Multiplier* = an empirical value based on the specific control measure

[11] RTI 2014, Section 4.

- *Annual Cost Exponent* = an empirical value based on the specific control measure
- *Emissions Reduction* = the change in emissions resulting from the application of the control technology (tons/day)
- *Annual Cost Base* = value based on the linear fit of the equation to empirical data; not applicable to all control measures

2.2.2.2 Example Calculations

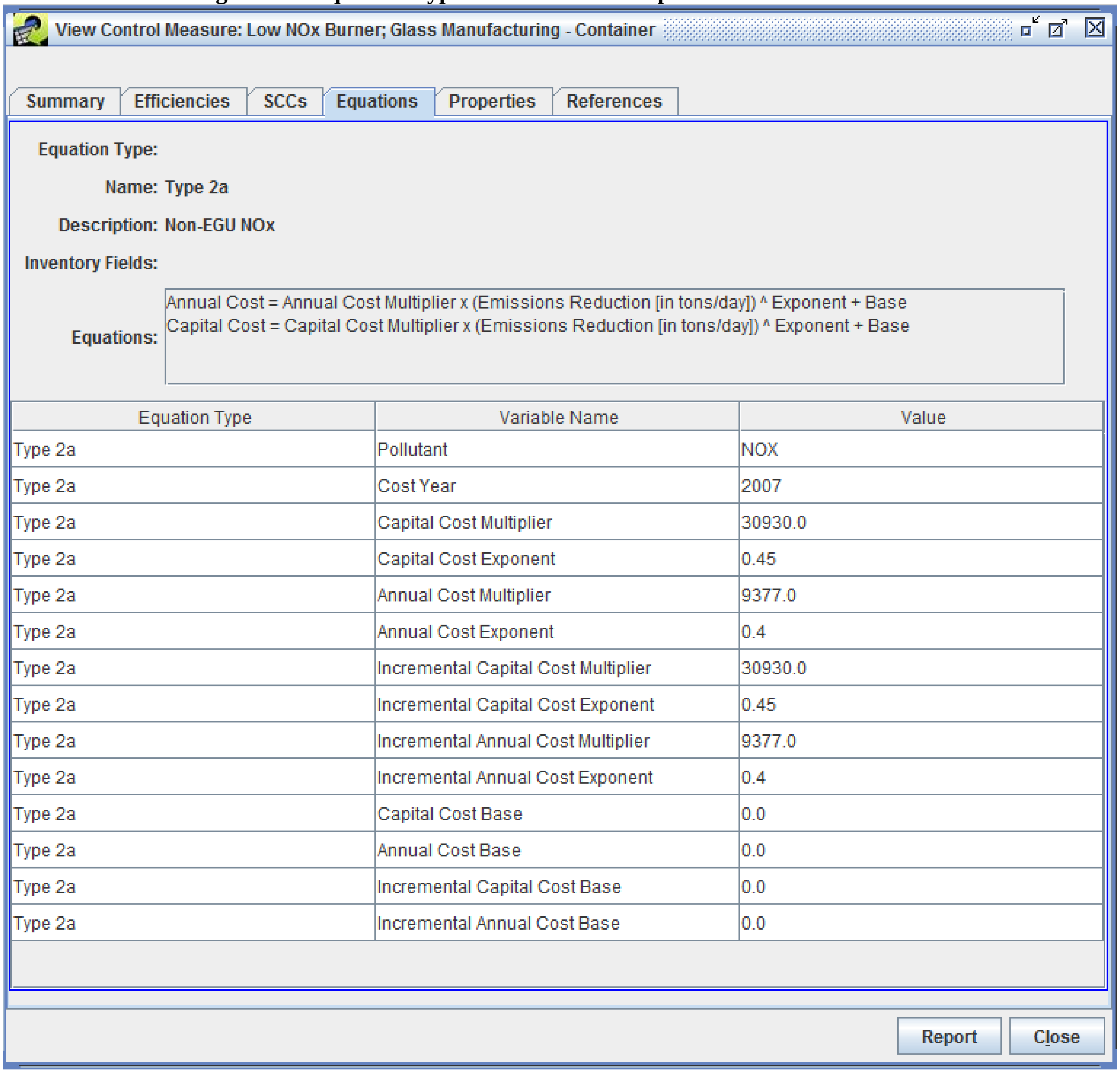
Equation Type 2a Example for NO_x

This section provides example calculations for an application of Equation Type 2a. The example scenario is for a container glass manufacture melting furnace (SCC 30501402) that uses a low NOx burner (NLNBUGMCN). Figure 2-34 illustrates the Equations tab of the View Control Measure screen for NLNBUGMCN.

Example Equation Type 2a Variables

Capital Recovery Factor = 0.1424 (assumes equipment life of 10 years and interest rate of 7%)
Emissions Reduction = 40 tons/year or 0.109589 tons/day (from CoST)
Capital Cost Multiplier = $30,930.0
Capital Cost Exponent = 0.45
Capital Cost Base = 0
Annual Cost Multiplier = $9,377.0
Annual Cost Exponent = 0.4
Annual Cost Base =0
Year for Cost Basis = 2007

Figure 2-4. Equation Type 2a for NO_x - Example Screenshot from CoST



View Control Measure: Low NOx Burner; Glass Manufacturing - Container

Summary | Efficiencies | SCCs | Equations | Properties | References

Equation Type:

Name: Type 2a

Description: Non-EGU NOx

Inventory Fields:

Equations: Annual Cost = Annual Cost Multiplier x (Emissions Reduction [in tons/day]) ^ Exponent + Base
Capital Cost = Capital Cost Multiplier x (Emissions Reduction [in tons/day]) ^ Exponent + Base

Equation Type	Variable Name	Value
Type 2a	Pollutant	NOX
Type 2a	Cost Year	2007
Type 2a	Capital Cost Multiplier	30930.0
Type 2a	Capital Cost Exponent	0.45
Type 2a	Annual Cost Multiplier	9377.0
Type 2a	Annual Cost Exponent	0.4
Type 2a	Incremental Capital Cost Multiplier	30930.0
Type 2a	Incremental Capital Cost Exponent	0.45
Type 2a	Incremental Annual Cost Multiplier	9377.0
Type 2a	Incremental Annual Cost Exponent	0.4
Type 2a	Capital Cost Base	0.0
Type 2a	Annual Cost Base	0.0
Type 2a	Incremental Capital Cost Base	0.0
Type 2a	Incremental Annual Cost Base	0.0

Report | Close

Capital Cost Equation

$$Capital\ Cost = Capital\ Cost\ Multiplier \times Emissions\ Reduction^{Capital\ Cost\ Exponent} + Capital\ Cost\ Base$$

$$Capital\ Cost = \$30{,}930.0 \times 0.109589^{0.45} + 0.0$$
$$Capital\ Cost = \$11{,}436\ (2007\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost \times Capital\ Recovery\ Factor$$
$$Annualized\ Capital\ Cost = \$11{,}436 \times 0.1424$$
$$Annualized\ Capital\ Cost = \$1{,}628\ (2007\$)$$

Annual Cost Equation

$$\begin{aligned}&Total\ Annualized\ Cost\\&= Annual\ Cost\ Multiplier\ \times Emissions\ Reduction^{\ Annual\ Cost\ Exponent}\\&+ Annual\ Cost\ Base\end{aligned}$$

$$Total\ Annualized\ Cost = \$9{,}377.0\ \times\ 0.109589^{0.4} + 0.0$$
$$Total\ Annualized\ Cost = \$3{,}872\ (2007\$)$$

Operation and Maintenance Cost Equation

$$Total\ O\&M\ Cost = Total\ Annualized\ Cost - Annualized\ Capital\ Cost$$
$$Total\ O\&M\ Cost = \$3{,}872 - \$1{,}628$$
$$Total\ O\&M\ Cost = \$2{,}244\ (2007\$)$$

2.2.3 Equation Type 2b for NO_x – Natural Gas ICEs

Equation Type 2b is used to calculate NOx control costs for natural gas lean burn or clean burn ICE with low emissions combustion (LEC) control technology.[12] LEC control technology is described as retrofit kits that allow engines to operate on extremely lean fuel mixtures to minimize NOx emissions. The LEC control technology retrofit may include: (1) redesign of cylinder head and pistons to improve mixing (on smaller engines), (2) precombustion chamber (on larger engines), lower cost, simple versions, (3) turbocharger, (4) high energy ignition system, (5) aftercooler, and (6) air-to-fuel ratio controller.

Based on the cost calculations for engines of varying power (hp), Equation Type 2b was developed for the capital cost and annual costs for LEC on natural gas lean burn engines.

2.2.3.1 Cost Equations

Capital Cost Equations

Calculate single control technology total capital costs with the following equation:

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times\ e^{(Capital\ Cost\ Exponent \times Design\ Capacity\ )}$$

Where:
- *Capital Cost Multiplier* = an empirical value based on the specific control measure
- *Capital Cost Exponent* = an empirical value based on the specific control measure
- *Design Capacity* = emissions unit capacity (converted from emissions inventory units to the unit {hp} required by the cost equations, see Section 1.2.1)

Calculate single control technology annual costs with the following equation:

[12] RTI 2014, Section 5.

Annual Cost Equation

$$Annual\ Cost = Annual\ Cost\ Multiplier\ \times\ e^{(Annual\ Cost\ Exponent\ x\ Design\ Capacity)}$$

Where:

- *Annual Cost Multiplier* = an empirical value based on the specific control measure
- *Annual Cost Exponent* = an empirical value based on the specific control measure
- *Design Capacity* = emissions unit capacity (hp)

2.2.3.2 Example Calculations

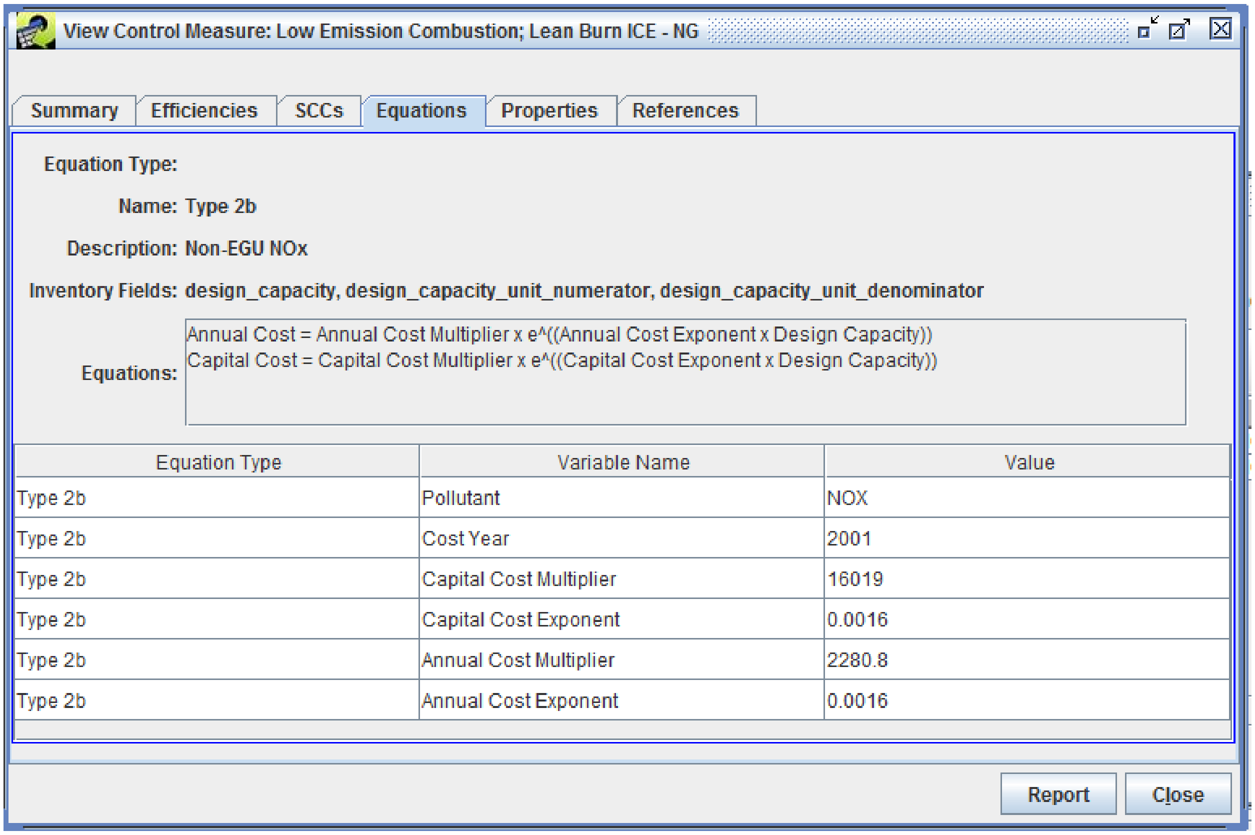
Equation Type 2b Example for NO_x

This section provides example calculations for an application of Equation Type 2b. The example scenario is for a 175 hp natural gas industrial 4-cycle lean burn internal combustion engine (SCC 20200254) with LEC, lean burn controls (NLECICENG). Figure 2-5 illustrates the Equations tab of the View Control Measure screen for Low Emission Combustion: Lean Burn ICE - NG.

Example Equation Type 2b Variables

Capital Recovery Factor = 0.1424 (assumes equipment life of 10 years and interest rate of 7%)
Control Device = LEC
Capital Cost Multiplier = $16,019
Capital Cost Exponent = 0.0016
Annual Cost Multiplier = $2,280.8
Annual Cost Exponent = 0.0016
Design Capacity (hp) = 175
Cost Year = 2001

Figure 2-5. Equation Type 2b for NO_x - Example Screenshot from CoST



Capital Cost Equation

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times\ e^{(Capital\ Cost\ Exponent\ x\ Design\ Capacity)}$$
$$Capital\ Cost = \$16{,}019\ \times\ e^{(0.0016\ x\ 175)}$$
$$\boldsymbol{Capital\ Cost} = \$\mathbf{21,195}\ (\mathbf{2001}\$)$$

$$Annualized\ Capital\ Cost = \$21{,}195 \times 0.1424$$
$$Annualized\ Capital\ Cost = \$3{,}017.72\ (2001\$)$$

Annual Cost Equation

$$Annual\ Cost = Annual\ Cost\ Multiplier\ \times\ e^{(Annual\ Cost\ Exponent\ x\ Design\ Capacity\ )}$$
$$Annual\ Cost = \$2{,}280.80\ \times\ e^{(0.0016\ x\ 175)}$$
$$Total\ Annualized\ Cost = \$3{,}017.79\ (2001\$)$$

Operation and Maintenance Cost Equation

$$Total\ O\&M\ Cost = Total\ Annualized\ Cost - Annualized\ Capital\ Cost$$
$$Total\ O\&M\ Cost = \$3{,}017.79 - \$3{,}017.72$$
$$Total\ O\&M\ Cost = \$0.07\ (2001\$)$$

2.2.4 Equation Type 12 for NO_x – Petroleum Industry Process Heaters

For a select set of gas-fired process heaters at petroleum refineries, control costs are estimated using stack flowrate and temperature represented by Equation Type 12.[13] Control technologies for Equation Type 12 are as follows:

- Excess O3 Control - 80 ppmv NOx outlet concentration
- Ultra-Low NOx Burner (ULNB) - 40 ppmv NOx outlet concentration
- Selective Catalytic Reduction (SCR) - 20 ppmv NOx outlet concentration
- SCR-95% - 10 ppmv NOx outlet concentration

Control costs are estimated for units that have a positive stack flowrate and temperature value. For those sources with missing stack flowrate or temperature, no costs are calculated.

2.2.4.1 Emissions Reduction Equations

This subsection presents an alternative way to calculate emissions reduction potential from process heaters at petroleum refineries.[14] This Equation Type uses the exhaust flowrate at standard temperature (F_s) in standard cubic feet per minute (scfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

Mole Fraction of NOx in outlet gas

The equations that are used to convert from inventory emissions to the concentration of NOx in the stack gas are shown here.

$$VFR_{NOx} = E_{NOx} \times 2{,}000 \times \left(\frac{1}{46.0}\right) \times \left(\frac{1}{Op_{Hrs}}\right) \times \left(\frac{1}{60}\right) \times 379.7$$

$$C_{NOx} = \left(\frac{VFR_{NOx}}{F_s}\right) \times 10^6$$

Where:

VFR_{NOx}	=	Volumetric Flow Rate (ft^3/minute)
E_{NOx}	=	Annual NOx emissions from the emissions inventory (tons/year)
2,000	=	lbs/ton
46.0	=	NOx molecular weight (grams/mol)
Op_{Hrs}	=	Annual operating hours from the emissions inventory (hours)
60	=	Minutes per hour conversion factor
379.7	=	Volume of NOx under standard conditions (ft^3/mol)
F_s	=	Exhaust flowrate at standard temperature (scfm)
C_{NOx}	=	Outlet mole fraction of NOx (ppmv)

[13] U.S. EPA 2015, page 6.
[14] U.S. EPA 2015, page 3.

NOx Emissions Reductions

$$Reduction_{NOx}\ (\%) = \frac{C_{NOx} - CMC_{NOx}}{C_{NOx}}$$

$$NOx_{reduced} = NOx\ * Reduction_{NOx}$$

$$NOx_{Controlled} = NOx - NOx_{reduced}$$

Where:

CMC_{NOx}	=	Control Measure of NOx (ppmv)
$Reduction_{NOx}$	=	NOx Emissions Reduction Percentage (%)
NOx	=	NOx Emissions before Control (tons/year)
$NOx_{reduced}$	=	Reduced NOx Emissions (tons/year)
$NOx_{controlled}$	=	NOx Emissions after Control (tons/year)

2.2.4.2 Cost Equations

Capital Cost Equation

The conditions in the stack are determined from the emissions inventory being processed. This Equation Type uses the exhaust flowrate at standard temperature (F_s) in standard cubic feet per minute (scfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

$$Total\ Capital\ Investment\ (TCI) = (Fixed\ TCI + Variable\ TCI) \times \left(\frac{Stack\ Flowrate\ (scfm)}{150{,}000}\right)^{0.6}$$

Where:

- *Fixed TCI* = an empirical value based on the specific control measure[15]
- *Variable TCI* = an empirical value based on the specific control measure[16]

Operating Cost Equation

$$Annual\ Operating\ Cost\ (AOC) = (Fixed\ AOC + Variable\ AOC)\ \times \left(\frac{Stack\ Flow\ Rate\ (scfm)}{150{,}000}\right)$$

Where:

- *Fixed AOC* = an empirical value based on the specific control measure
- *Variable AOC* = an empirical value based on the specific control measure

[15] MACTEC 2005.
[16] Ibid.

- *Stack Flow Rate* = expected flow rate out of the stack in standard cubic feet per minute (scfm)

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = AOC + CRF \times TCI$$

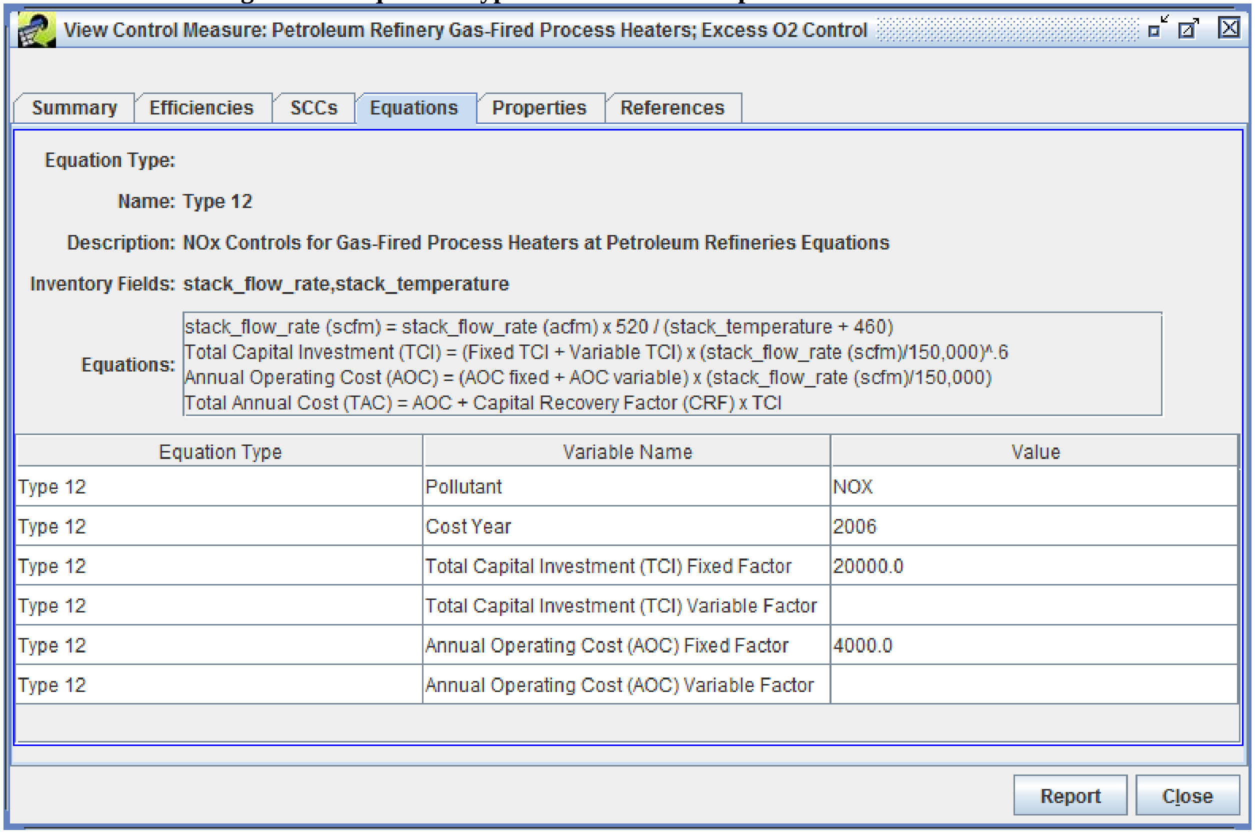
2.2.4.3 Example Calculations

This section provides example calculations for an application of Equation Type 12. The example scenario is a gas-fired process heater at a petroleum refinery (SCC 30600102). The NO_x control mechanism is excess oxygen control (NPRGPHEO2C). Figure 2-6 illustrates the Equations tab of the View Control Measure screen for the Petroleum Refinery Gas-Fired Process Heaters: Excess O2 Control.

Example Equation Type 12 Variables

Capital Recovery Factor = 0.2439 (assumes equipment life of 5 years and interest rate of 7%)
Stack Flowrate = 48.984 ft^3/sec
Stack Temperature (˚F) = 600 ˚F
Fixed Total Capital Investment (TCI) = $20,000
Variable TCI = $0
Fixed Annual Operating Cost (AOC) = $4,000
Variable AOC = $0
Year for Cost Basis = 2006

Figure 2-6: Equation Type 12 for NO_x - Example Screenshot from CoST



Capital Cost Equation

$$Stack\ Flow\ Rate\ (scfm) = 48.984 \times 60 \times \left(\frac{520}{600 + 460}\right)$$

$$Stack\ Flow\ Rate\ (scfm) = 1{,}442\,\frac{ft^3}{min}$$

$$Total\ Capital\ Investment\ (TCI) = (Fixed\ TCI + Variable\ TCI) \times \left(\frac{Stack\ Flowrate\ (scfm)}{150{,}000}\right)^{0.6}$$

$$TCI = (\$20{,}000 + 0.0) \times \left(\frac{1{,}442}{150{,}000}\right)^{0.6}$$

$$TCI = \$1{,}232\ (2006\$)$$

Operating Cost Equation

$$Annual\ Operating\ Cost\ (AOC) = (Fixed\ AOC + Variable\ AOC) \times \left(\frac{Stack\ Flow\ Rate\ (scfm)}{150{,}000}\right)$$

$$Annual\ AOC = (\$4{,}000 + 0.0)\ \times \left(\frac{1{,}442}{150{,}000}\right)$$
$$Annual\ AOC = \$38\ (2006\$)$$

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = \text{Annual } AOC + CRF\ x\ TCI$$
$$Total\ Annualized\ Cost = \$38 + 0.2439\ \times\ 1{,}232$$
$$Total\ Annualized\ Cost = \$339\ (2006\$)$$

Mole Fraction of NOx in outlet gas

$$VFR_{NOx} = E_{NOx}\ \times\ 2{,}000\ \times\ \left(\frac{1}{46.0}\right) \times \left(\frac{1}{Op_{Hrs}}\right) \times \left(\frac{1}{60}\right) \times 379.7$$

$$1.680\ \left(\frac{ft^3}{\text{minute}}\right) = 53.33 \times\ 2{,}000\ \times\ \left(\frac{1}{46.0}\right) \times \left(\frac{1}{8736}\right) \times \left(\frac{1}{60}\right) \times 379.7$$

$$C_{NOx} = \left(\frac{VFR_{NOx}}{F_s}\right) \times 10^6$$

$$1164.98(ppmv) = \left(\frac{1.680}{1{,}442}\right) \times 10^6$$

NOx Emissions Reductions

$$Reduction_{NOx}\ (\%) = \frac{C_{NOx} - CMC_{NOx}}{C_{NOx}}$$

$$93.13\ (\%) = \frac{1164.98 -\ 80.0}{1164.98}$$

$$NOx_{reduced} = NOx\ * Redcution_{NOx}$$

$$49.67(\frac{tons}{year}) = 53.33\ * 93.13(\%)$$

$$NOx_{Controlled} = NOx - NOx_{reduced}$$

$$3.66\ (\frac{tons}{year}) = 55.33 - 49.67$$

2.2.5 Equation Type 13 for NO_x – ICI Boilers

Equation Type 13 is used to calculate NOx control costs for a range of sizes of ICI boilers.[17] NOx control technologies for Equation Type 13 are:

- Flue Gas Recirculation (FGR)
- Low NOx Burner (LNB)
- Low NOx Burner and Flue Gas Recirculation
- Selective Non-Catalytic Reduction (SNCR)
- Selective Catalytic Reduction (SCR)
- Low NOx Burner and Selective Non-Catalytic Reduction
- Low NOx Burner and Selective Catalytic Reduction

Equation Type 13 was derived based on a review of previous ICI boiler control costs calculations and outputs from the EPA Coal Utility Environmental Cost (CUECost) model.[18] The costs were generated for control devices on five boiler sizes (i.e., 100, 200, 300, 400, and 500 MMBtu/hour). Although control device costs do not rise in strict proportion to size, the plotted results demonstrated that control costs versus boiler size showed a power-law relationship and this relationship was used to derive Equation Type 13.

2.2.5.1 Cost Equations

Capital Cost Equations

In finding that there are no cost savings from combining different ICI boiler control technologies, control costs for each technology can be treated as additive when multiple control options are available. Calculate single control technology total capital costs with the following equation:

$$Capital\ Cost = Size\ Multiplier\ 1 \times Boiler\ Size\ (\frac{MMBtu}{hour})^{Exponent\ 1}$$

Duel control technology total capital costs are calculated as an extension of the single control technology equation:

$$\begin{aligned}&Capital\ Cost\ (Dual\ Control\ Technology)\\&= Size\ Multiplier\ 1 \times Boiler\ Size\ (\frac{MMBtu}{hour})^{Exponent\ 1}\\&+ Size\ Multiplier\ 2 \times Boiler\ Size\ (\frac{MMBtu}{hour})^{Exponent\ 2}\end{aligned}$$

[17] ERG 2010, Section II, pages 4 through 7.
[18] ERG 2010.

Where:

- *Size Multiplier and Exponent* = empirical values for each control technology that are based on a power law curve fitting of ICI boiler control costs versus boiler sizes
- *Boiler Size* = ICI boiler hourly heat output

Operation and Maintenance Cost Equations

$$O\&M\ Cost$$
$$= Known\ Costs + Size\ Multiplier\ 1 \times Boiler\ Size\ \left(\frac{MMBtu}{hour}\right)^{Exponent\ 1}$$
$$+\ Size\ Multiplier\ 2 \times Boiler\ Size\ \left(\frac{MMBtu}{hour}\right)^{Exponent\ 2}$$
$$+ Flowrate\ Multiplier \times Boiler\ Exhaust\ Flowrate\ \left(\frac{ft^3}{s}\right)$$
$$+\ Emissions\ Multiplier \times Boiler\ Emissions\ \left(\frac{tons}{year}\right)$$

Where:

- *Size Multiplier and Exponent* = empirical values for each control technology that are based on a power law curve fitting of ICI boiler control costs versus boiler sizes
- *Boiler Size* = ICI boiler hourly heat output (MMBtu/hour)
- *Flowrate Multiplier* = empirical value based on the specific control measure
- *Boiler Exhaust Flowrate* = expected flowrate from the boiler in cubic feet per second
- *Emissions Multiplier* = empirical value based on the specific control measure
- *Boiler Emissions* = annual boiler emissions rate (tons/year)

Total Annualized Cost Equation

$$Annualized\ Cost = Capital\ Cost \times CRF + Total\ O\&M\ Cost$$

2.2.5.2 Example Calculations

Equation Type 13 Example for NO_x

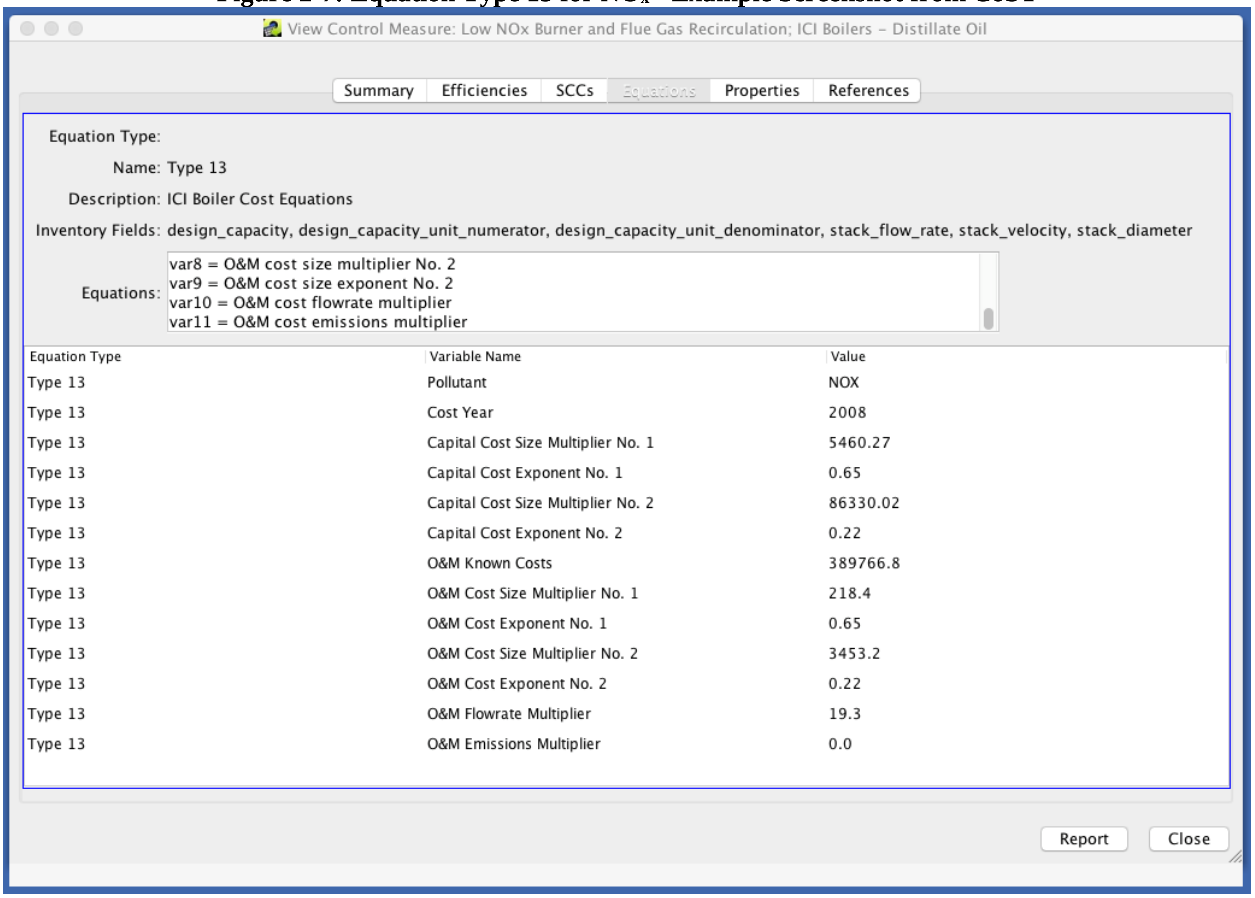
This section provides example calculations for an application of Equation Type 13. The example scenario is for a grade 1 & 2 distillate oil ICI external combustion boiler (SCC 10200501) with an output of 250 MMBtu/hour that is using a low NOx burner for the primary controls and flue gas recirculation for the secondary controls (NLNBFIBDO).

Example Equation Type 13 Variables

Capital Recovery Factor = 0.1315 (assumes equipment life of 15 years and interest rate of 10%)
Control Device (Single) = LNB
Control Device (Dual) = LNB + FGR
Cost Year = 2008

Boiler Size (MMBtu) = 250
Capital Cost Size Multiplier 1 = $5,460.27
Capital Cost Exponent 1 = 0.65
Capital Cost Size Multiplier 2 = $86,330.02
Capital Cost Exponent 2 = 0.22
O&M Known Costs = $389,766.80
O&M Size Multiplier 1 = $218.40
O&M Size Exponent 1 = 0.65
O&M Size Multiplier 2 = $3,453.20
O&M Size Exponent 2 = 0.22
Flowrate Multiplier = 19.3
Boiler Exhaust Flowrate (ft^3/s*)* = 33.33
Emissions Multiplier = 0.0
Boiler Emissions (tons/year) = 100

Figure 2-7: Equation Type 13 for NO_x - Example Screenshot from CoST



Capital Cost Equation (Single Device)

$$Capital\ Cost = Size\ Multiplier\ 1\ \times\ Boiler\ Size\ (\frac{MMBtu}{hour})^{Exponent\ 1}$$
$$Capital\ Cost = \$5{,}460.27\ \times\ 250^{0.65}$$
$$Capital\ Cost = \$197{,}640\ (2008\$)$$

Capital Cost Equation (Dual Device)

$$Captal\ Cost\ (Dual\ Control\ Technology)$$
$$= Size\ Multiplier\ 1\ \times\ Boiler\ Size\ (\frac{MMBtu}{hour})^{Exponent\ 1}$$
$$+\ Size\ Multiplier\ 2\ \times\ Boiler\ Size\ (\frac{MMBtu}{hour})^{Exponent\ 2}$$
$$Capital\ Cost = \$5{,}460.27\ \times\ 250^{0.65} +\ \$86{,}330.02\ \times\ 250^{0.22}$$
$$Capital\ Cost = \$488{,}517\ (2008\$)$$

Operation and Maintenance Cost Equation

$$O\&M\ Cost$$
$$= Known\ Costs + Size\ Multiplier\ 1\ \times\ Boiler\ Size\ \left(\frac{MMBtu}{hour}\right)^{Exponent\ 1}$$
$$+\ Size\ Multiplier\ 2\ \times\ Boiler\ Size\ \left(\frac{MMBtu}{hour}\right)^{Exponent\ 2}$$
$$+ Flowrate\ Multiplier\ \times\ Boiler\ Exhaust\ Flowrate\ \left(\frac{ft^3}{s}\right)$$
$$+\ Emissions\ Multiplier\ \times\ Boiler\ Emissions\ (\frac{tons}{year})$$
$$O\&M\ Cost$$
$$= \$389{,}766.80 + \$218.4\ \times\ 250^{\ 0.65} + \$3{,}453.20\ \times\ 250^{\ 0.22} + 19.3\ \times\ 33.33 +\ 0.0\ \times\ 100$$
$$O\&M\ Cost = \$409{,}950 (2008\$)$$

Annual Cost Equation (Single Device)

$$Annual\ Cost = Capital\ Cost\ \times\ CRF + O\&M\ Cost$$
$$Annual\ Cost = \$197{,}640\ \times\ 0.1315 + \$409{,}950$$
$$Annual\ Cost = \$435{,}935\ (2008\$)$$

Annual Cost Equation (Dual Device)

$$Annual\ Cost = Capital\ Cost\ \times\ CRF + O\&M\ Cost$$
$$Annual\ Cost = \$488{,}517\ \times\ 0.1315 + \$409{,}950$$
$$Annual\ Cost = \$474{,}177\ (2008\$)$$

3 SO_2 Control Cost Equations

This chapter is divided into two main sections – IPM and non-IPM sources. The types of cost equations, indicated below, for point source SO_2 controls are described in their appropriate sections.

- Equation Type 1 for IPM external combustion boilers
- Equation Type 3 for non-IPM external combustion boilers, process heaters, primary metals, glassmaking furnaces
- Equation Type 16 for non-IPM external combustion boilers and select industrial processes
- Equation Type 18 for the same non-IPM sources as equation type 16
- Equation Type 19 for the same non-IPM sources as equation type 16

This chapter describes each equation type, presents the relevant equation parameters, and provides example calculations. The example calculations provided are prepared using version 2.15 of the CoST software.

3.1 IPM Sector (ptipm) SO_2 Control Cost Equations

IPM sector (ptipm) point sources using control cost equations for SO_2 emissions reductions are limited to Equation Type 1. In Equation Type 1, model plant capacities are used along with scaling factors and the emissions inventory's unit-specific boiler characteristics to generate a control cost for an applied technology. SO_2 control technologies for Equation Type 1 include lime spray dryer and limestone forced oxidation.

The parameters for the equation used to calculate control costs for SO_2 from ptipm sources are based on boiler capacity. Controls will not be applied to a source if the inventory record for the source has a blank boiler capacity field. As such, default cost per ton values for SO_2 controls are not used for ptipm point sources.

3.1.1 Equation Type 1 for SO_2 – Utility Boilers

Equation Type 1 involves the application of a scaling factor to adjust the capital cost associated with a control measure to the boiler size (MW) based on the original control technology's documentation.[19] A scaling factor and exponent for model plant size are not used for this estimate.

Restrictions on source size are also shown for the controls that use Equation Type 1. When an application restriction reflects a minimum and maximum capacity, the control is not applied unless the capacity of the source in the inventory falls within that range.[20]

[19] U.S. EPA 2013, Table 5.3 on page 5-4.
[20] An application restriction defines an upper and/or lower capacity (MW) bound for which an equation is applicable.

3.1.1.1 Cost Equations

Capital Cost Equations

The capital cost associated with these ptipm SO_2 control measures is a straightforward calculation of the capital cost multiplier, the unit's boiler capacity (in MW), and the scaling factor exponent.

$$Scaling\ Factor = \left(\frac{Model\ Plant\ Capacity}{Actual\ Capacity}\right)^{Scaling\ Factor\ Exponent}$$

Where:
- *Model Plant Capacity* = the boiler capacity (MW) of the model plant
- *Scaling Factor Exponent* = an empirical value based on the specific control measure
- *Actual Capacity* = the boiler capacity (MW) obtained from the emissions inventory and converted to MW (see Section 1.2.1 for a discussion of unit conversions)

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times Capacity\ \ \times\ Scaling\ Factor\ \times 1{,}000$$

Where:
- *Capital Cost Multiplier* = an empirical value based on the specific control measure ($/kW)
- *Capacity* = the boiler capacity (MW) obtained from the emissions inventory
- *1000* = conversion factor to convert the *Capital Cost Multiplier* from $/kW to $/MW.

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times CRF$$

Operation and Maintenance Cost Equations

The fixed O&M component is based on the unit's capacity. The variable O&M includes an estimate for the unit's capacity factor. The capacity factor accounts for the amount of actual power generated by a power plant as compared to its design capacity or rated output. A value of 1.00 would represent a unit operating at 100% capacity.

The annualized cost is then estimated using the unit's capital cost times the CRF (derived with an annual interest rate and equipment lifetime expectancy) and the sum of the fixed and variable O&M costs.

$$Fixed\ O\&M = Fixed\ O\&M\ Cost\ Multiplier\ \times Capacity\ \times\ 1{,}000$$

Where:
- *Fixed O&M Cost Multiplier* = an empirical value based on the specific control measure ($/kW)
- *Capacity* = obtained from the emissions inventory

- *1000* = a conversion factor to convert the Fixed O&M Cost Multiplier from $/kW to $/MW

$$Variable\ O\&M = Variable\ O\&M\ Cost\ Multiplier\ \times Capacity\ \times\ Capacity\ Factor\ \times\ 8{,}760$$

Where:
- *Variable O&M Cost Multiplier* = an empirical value based on the specific control measure ($/MWh)
- *Capacity Factor* = an empirical value based on the specific control measure
- *Capacity* = obtained from the emissions inventory (MW)
- *8,760* = the number of hours the equipment is assumed to operate a year

$$Total\ O\&M\ Cost = Fixed\ O\&M + Variable\ O\&M$$

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$

3.1.1.2 Example Calculations

Equation Type 1 Example for SO_2

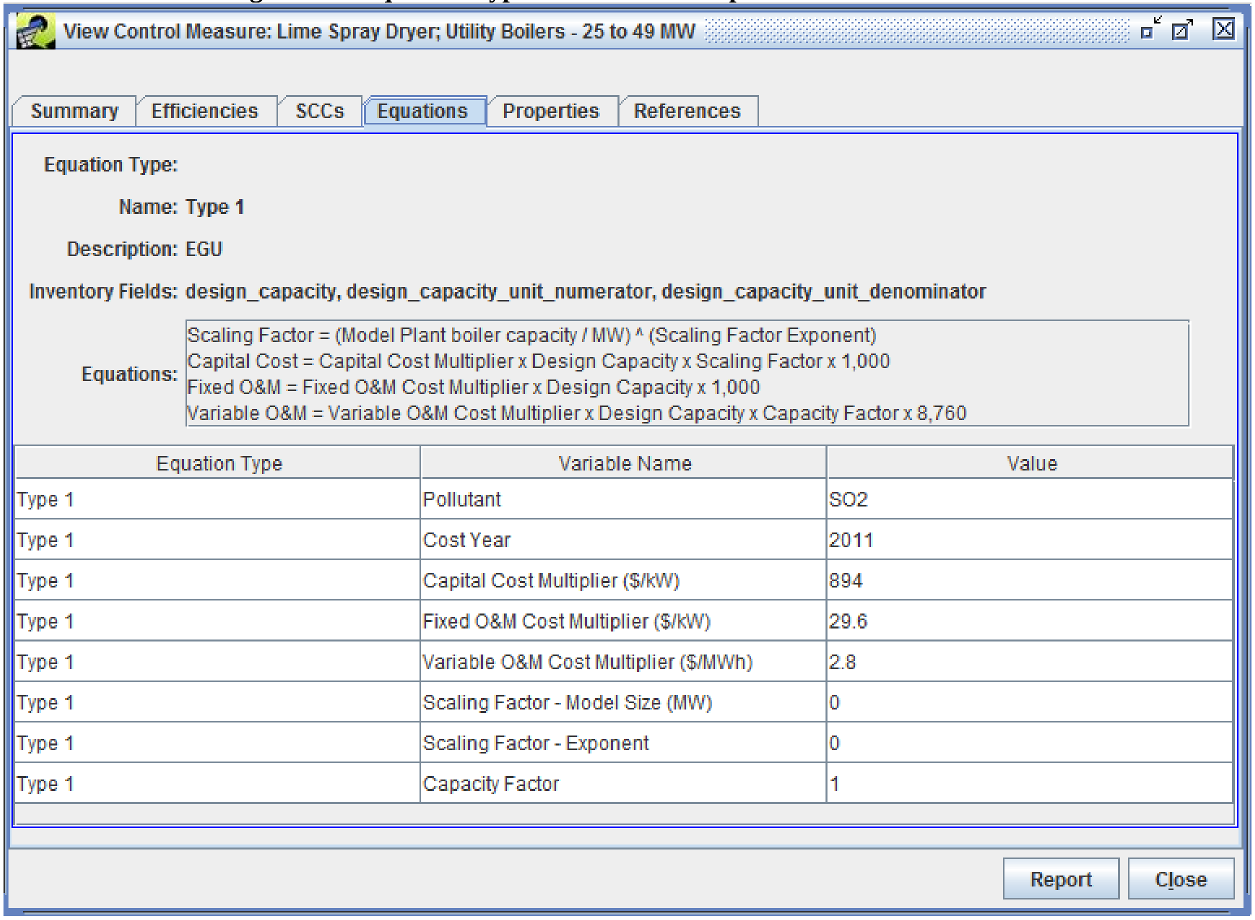
This section provides example calculations for an application of Equation Type 1 where SO_2 is the primary pollutant for this control technology. The example is for a utility external combustion wet bottom tangential fired coal boiler (SCC 10100211) that uses a lime spray dryer applicable to 25 to 49 MW boilers for its control equipment (SLSDUBC1).

Example Equation Variables

Figure 3-1 illustrates the Equations tab of the View Control Measure screen for the Lime Spray Dryer; Utility Boilers – 25 to 49 MW.

Capital Recovery Factor = 0.1010 (assumes equipment life of 15 years and interest rate of 5.7%, which is provided by IPM)
Capacity = 40 MW
Scaling Factor Model Size = 0
Scaling Factor Exponent = 0
Capital Cost Multiplier ($/kW) = 894
Fixed O&M Cost Multiplier ($/kW) = 29.6
Variable O&M Cost Multiplier ($/MWh) = 2.8
Capacity Factor = 1
Year for Cost Basis = 2011

Figure 3-1: Equation Type 1 for SO_2 - Example Screenshot from CoST



View Control Measure: Lime Spray Dryer; Utility Boilers - 25 to 49 MW

Summary | Efficiencies | SCCs | Equations | Properties | References

Equation Type:

Name: Type 1

Description: EGU

Inventory Fields: design_capacity, design_capacity_unit_numerator, design_capacity_unit_denominator

Equations:
Scaling Factor = (Model Plant boiler capacity / MW) ^ (Scaling Factor Exponent)
Capital Cost = Capital Cost Multiplier x Design Capacity x Scaling Factor x 1,000
Fixed O&M = Fixed O&M Cost Multiplier x Design Capacity x 1,000
Variable O&M = Variable O&M Cost Multiplier x Design Capacity x Capacity Factor x 8,760

Equation Type	Variable Name	Value
Type 1	Pollutant	SO2
Type 1	Cost Year	2011
Type 1	Capital Cost Multiplier ($/kW)	894
Type 1	Fixed O&M Cost Multiplier ($/kW)	29.6
Type 1	Variable O&M Cost Multiplier ($/MWh)	2.8
Type 1	Scaling Factor - Model Size (MW)	0
Type 1	Scaling Factor - Exponent	0
Type 1	Capacity Factor	1

Report | Close

Annualized Capital Cost

$$Scaling\ Factor = \left(\frac{Scaling\ Factor\ Model\ Size}{Capacity}\right)^{Scaling\ Factor\ Exponent}$$

$$Scaling\ Factor = \left(\frac{0}{40}\right)^{0}$$

$$Scaling\ Factor = 1.0$$

$$Capital\ Cost = Capital\ Cost\ Multiplier \times Capacity \times Scaling\ Factor \times 1{,}000$$

$$Capital\ Cost = 894\frac{\$}{kW} \times 40\ MW \times 1.0 \times 1{,}000\frac{kW}{MW}$$

$$Capital\ Cost = \$35{,}760{,}000\ (2011\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost \times Capital\ Recovery\ Factor$$

$$Annualized\ Capital\ Cost = \$35{,}760{,}000 \times 0.1010$$

$$Annualized\ Capital\ Cost = \$3{,}610{,}117\ (2011\$)$$

Operation and Maintenance Cost

$$Fixed\ O\&M = Fixed\ O\&M\ Cost\ Multiplier\left(\frac{\$}{kW}\right) \times Capacity(MW) \times 1{,}000$$

$$Fixed\ O\&M = 29.60\frac{\$}{kW} \times 40.0\ MW \ \ \times 1{,}000\frac{kW}{MW}$$
$$Fixed\ O\&M = \$1{,}184{,}000\ (2011\$)$$

$$Variable\ O\&M = Variable\ O\&M\ Cost\ Multiplier\ \left(\frac{\$}{MWh}\right) \times Capacity\ (MW) \times Capacity\ Factor\ \times\ 8{,}760\ (Hours\ Per\ Year)$$
$$Variable\ O\&M = 2.8\frac{\$}{MWh} \times 40\ MW \times 1.0 \times 8{,}760\ Hours$$
$$Variable\ O\&M = \$981{,}120\ (2011\$)$$

$$Total\ O\&M\ Cost = Fixed\ O\&M + Variable\ O\&M$$
$$Total\ O\&M\ Cost = \$2{,}165{,}120\ (2011\$)$$

Total Annualized Cost

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$
$$Total\ Annualized\ Cost = \$3{,}610{,}117 + 2{,}165{,}120$$
$$Total\ Annualized\ Cost = \$5{,}775{,}237\ (2011\$)$$

3.2 Non-IPM Sector (ptnonipm) SO_2 Control Cost Equations

Ptnonipm point sources using control cost equations for SO_2 emission reductions are represented by Equation Types 3, 16, 18, and 19. The equation types vary by control measure. Each equation uses the source's stack flowrate (in ft^3/minute) as the primary variable to estimate cost. Cost equations and default cost per ton reduced values are taken from the original Alternative Control Technology, Control Technology Guidelines (ACT/CTG), or other EPA analyses used to derive these estimates.

Equation Types 16 and 18 were developed for the ICI boilers and process heater National Emission Standards for Hazardous Air Pollutants (NESHAP) for major sources (Boiler MACT). Equation Type 19 was developed for the commercial and industrial solid waste incinerator NESHAP (CISWI). The equations to calculate flowrates for Equation Types 16 and 18 are provided in section 1.2.2.

3.2.1 Equation Type 3 for SO_2 – External Combustion Boilers and Industrial Processes

SO_2 control technologies for Equation Type 3 include flue gas desulfurization. Cost equation parameters used in Equation Type 3 are found in *Control Measure Evaluations: The Control Measure Data Base for the National Emissions Trends Inventory (ControlNET)*.[21] This Equation Type uses the exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

[21] U.S. EPA 2001, Table IV-2, page 49.

3.2.1.1 Cost Equations

Annualized Capital Cost Equation for Flowrate ≥ 1,028,000 acfm

$$Capital\ Cost = Retrofit\ Factor \times Gas\ Flowrate\ Factor \times Capital\ Cost\ Factor \times Exhaust\ Flowrate \times 0.9383$$

Where:

- $Retrofit\ Factor = 1.1$
- $Gas\ Flowrate\ Factor = 0.486\ \mathrm{kW/acfm}$
- $Capital\ Cost\ Factor = \$192/\mathrm{kW}$
- $Exhaust\ Flowrate =$ exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm)
- $De\text{-}escalation\ factor$ (to adjust dollar years from 1995 to 1990) = 0.9383

$$Annualized\ Capital\ Cost = Capital\ Cost \times CRF$$

Annualized Capital Cost Equation for Flowrate < 1,028,000 acfm

$$Capital\ Cost = \left(\frac{1{,}028{,}000}{Exhaust\ Flowrate}\right)^{0.6} \times Retrofit\ Factor \times Gas\ Flowrate\ Factor \times Capital\ Cost\ Factor \times Exhaust\ Flowrate \times 0.9383$$

Where:

- $Retrofit\ Factor = 1.1$
- $Gas\ Flowrate\ Factor = 0.486\ \mathrm{kW/acfm}$
- $Capital\ Cost\ Factor = \$192/\mathrm{kW}$
- $Exhaust\ Flowrate =$ exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm)$De\text{-}escalation\ factor$ (to adjust dollar years from 1995 to 1990 = 0.9383

$$Annualized\ Capital\ Cost = Capital\ Cost \times CRF$$

Operation and Maintenance Cost Equations

$$Fixed\ O\&M\ Cost = Gas\ Flowrate\ Factor \times Fixed\ O\&M\ Rate \times Exhaust\ Flowrate$$

Where:

- $Gas\ Flowrate\ Factor = 0.486\ \mathrm{kW/acfm}$
- $Fixed\ O\&M\ Rate = \$6.9/\mathrm{kW}$
- $Exhaust\ Flowrate =$ exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm)

$$Variable\ O\&M\ Cost = Gas\ Flowrate\ Factor \times Variable\ O\&M\ Rate \times Hours\ per\ year \times Exhaust\ Flowrate$$

Where:

- *Gas Flowrate Factor* = 0.486 kW/acfm
- *Variable O&M Rate* = $0.0015/kWh
- *Hours per year* = 8,736
- *Exhaust Flowrate* = exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm)

$$Total\ O\&M\ Cost = Fixed\ O\&M\ Cost + Variable\ O\&M\ Cost$$

Total Annualized Cost Equation

The following equation applies whether the annualized capital cost is calculated based on the standard (≤1,028,000 acfm) or large (>1,028,000 acfm) size:

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$

Where *Annualized Capital Cost* and *Total O&M Cost* were calculated previously.

3.2.1.2 Example Calculation

This section provides example calculations for an application of Equation Type 3. The example scenario is an ICI external combustion boiler burning pulverized anthracite coal (SCC 10300101) using flue gas desulfurization (FGD) as the primary control technology for SO_2 (SFGDSSGCO). Figure 3-2 illustrates the Equations tab of the View Control Measure screen for the FGD: Bituminous/Subbituminous Coal (Commercial/Institutional Boilers).

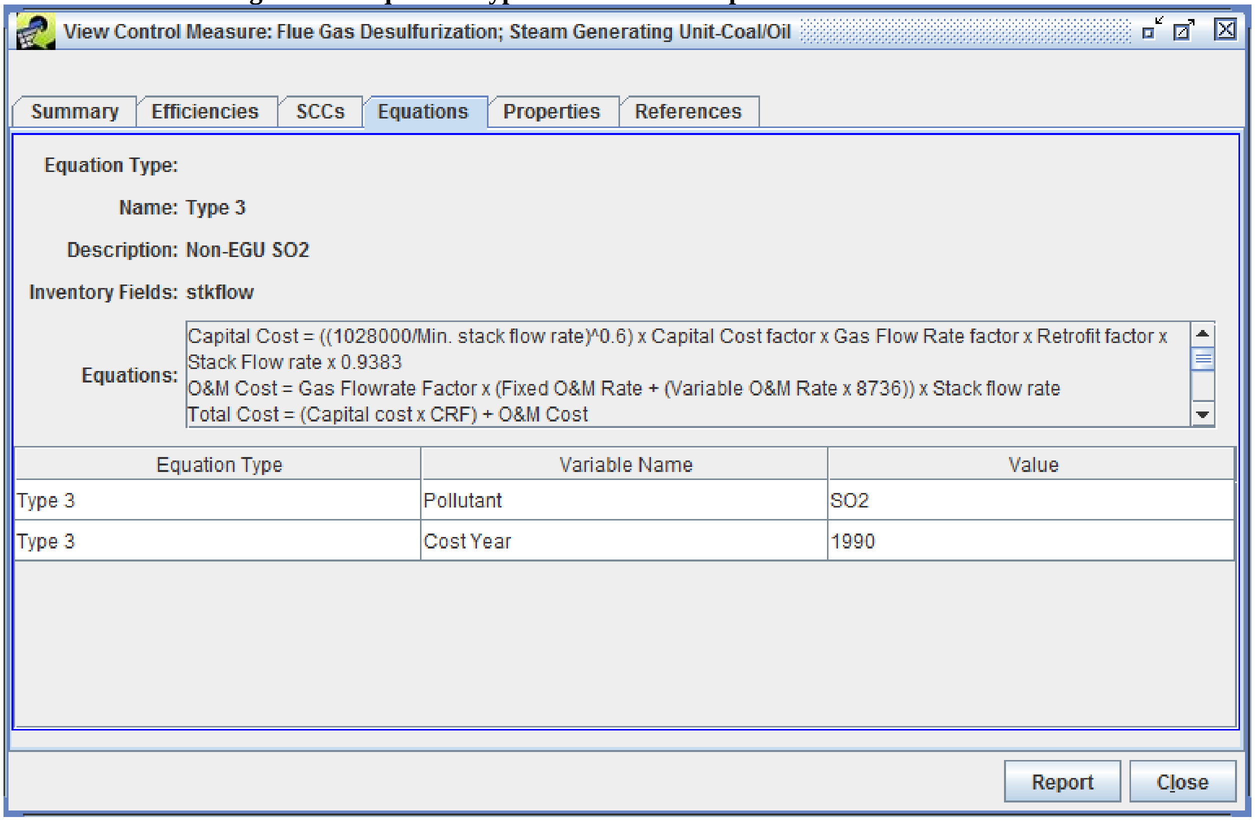
Example Equation Variables

Capital Recovery Factor = 0.1098 (assumes equipment life of 15 years and interest rate of 7%)

$$Exhaust\ Flowrate = 100{,}962\,\frac{ft^3}{min}$$

Retrofit Factor = 1.1
Gas Flow Rate Factor = 0.486 kW/acfm
Capital Cost Factor = $192/kW
Year for Cost Basis = 1990

Figure 3-2: Equation Type 3 for SO_2 - Example Screenshot from CoST



Annualized Capital Costs for Flowrate < 1,028,000 acfm

$$Capital\ Cost = \left(\frac{1{,}028{,}000}{Exhaust\ Flowrate}\right)^{0.6} \times Retrofit\ Factor \times Gas\ Flowrate\ Factor \times Capital\ Cost\ Factor \times Exhaust\ Flowrate \times 0.9383$$

$$Capital\ Cost = \left(\frac{1{,}028{,}000}{100{,}962\,\frac{ft^3}{min}}\right)^{0.6} \times 1.1 \times 0.486\,\frac{\text{kW}}{\text{acfm}} \times \frac{\$192}{kW} \times 100{,}962\,\frac{ft^3}{min} \times 0.9383$$

$$Capital\ Cost = \$39{,}121{,}901\ (1990\$)$$

Use an implicit price deflator ratio to convert from 1990$ to 2000$.

$$Capital\ Cost = \$39{,}121{,}901 \times \frac{81.887\ (2000\$)}{66.773\ (1990\$)}$$
$$Capital\ Cost = \$47{,}989{,}367\ (2000\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost \times Capital\ Recovery\ Factor$$
$$Annualized\ Capital\ Cost = \$47{,}989{,}367 \times 0.1098$$
$$Annualized\ Capital\ Cost = \$5{,}268{,}974\ (2000\$)$$

Operation and Maintenance Cost

$$Fixed\ O\&M\ Cost = Gas\ Flowrate\ Factor\ \times\ Fixed\ O\&M\ Rate\ \times\ Exhaust\ Flowrate$$
$$Fixed\ O\&M\ Cost = 0.486\frac{kW}{acfm} \times \frac{\$6.90}{kW} \times\ 100{,}962\frac{ft^3}{min}$$
$$Fixed\ O\&M\ Cost = \$338{,}566\ (1990\$) \times \frac{81.887\ (2000\$)}{66.773\ (1990\$)}$$

$$Fixed\ O\&M\ Cost = \$415{,}200\ (2000\$)$$

$$Variable\ O\&M\ Cost$$
$$= Gas\ Flowrate\ Factor\ \times\ Variable\ O\&M\ Rate\ \times\ \text{Hours per year}\ \times\ Exhaust\ Flowrate$$
$$\times\ 60$$
$$Variable\ O\&M\ Cost$$
$$= 0.486\frac{kW}{acfm} \times \frac{\$0.0015}{kWh} \times\ 8736\ h\ \times\ 100{,}962\frac{ft^3}{min}\ \ Variable\ O\&M\ Cost$$
$$= \$642{,}981\ (1990\$)\ \times \frac{81.887\ (2000\$)}{66.773\ (1990\$)}$$
$$Variable\ O\&M\ Cost = \$788{,}519\ (2000\$)$$

$$Total\ O\&M\ Cost = Fixed\ O\&M\ Cost + Variable\ O\&M\ Cost$$
$$Total\ O\&M\ Cost = \$415{,}200 + \$788{,}519$$
$$Total\ O\&M\ Cost = \$1{,}203{,}719\ (\$2000)$$

Total Annualized Cost

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$
$$Total\ Annualized\ Cost = \$5{,}268{,}974\ + \$1{,}203{,}719$$
$$Total\ Annualized\ Cost = \$6{,}472{,}694\ (2000\$)$$

3.2.2 Equation Type 16 for SO_2 – ICI Boilers: Wet Scrubber

Equation Type 16 is used to calculate control costs for using wet scrubbers on various external combustion boilers and industrial processes.[22] This control technology provides extensive SO_2 control (95%) and minimal PM reduction (50% to 94%). This Equation Type uses the exhaust flowrate at either actual stack conditions (F_a) in actual cubic feet per minute (acfm) or at standard temperature (F_s) in standard cubic feet per minute (scfm), depending on the equation (see Section 1.2.2 for discussion of flowrate unit conversions).

The equations that are used to convert from inventory emissions to the mole fraction of SO_2 in the stack gas are shown here.

[22] ERG 2013, Appendix B, pages B-4 and B-5.

Mole Fraction of SO_2 in outlet gas

$$VFR_{SO2} = E_{SO2} \times 2{,}000 \times \left(\frac{1}{64.06}\right) \times \left(\frac{1}{Op_{Hrs}}\right) \times \left(\frac{1}{60}\right) \times 379.7$$

$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right)$$

Where:

VFR_{SO2}	=	Volumetric Flow Rate (ft^3/minute)
E_{SO2}	=	Annual SO_2 emissions from the emissions inventory (tons/year)
2,000	=	lbs/ton
64.06	=	SO_2 molecular weight (grams/mol)
Op_{Hrs}	=	Annual operating hours from the emissions inventory (hours)
60	=	minutes/hour
379.7	=	Volume of SO2 under standard conditions (ft^3/mol)
F_s	=	Exhaust flowrate at standard temperature (scfm)
C_{SO2}	=	Outlet mole fraction of SO_2

3.2.2.1 Cost Equations

Total Capital Investment

$$TCI = [(2.88)(\#Scrub)(F_a)] + \left[(1076.54)(\#Scrub)\sqrt{F_a}\right] + [(9.759)(F_a)] + \left[(360.463)\sqrt{F_a}\right]$$

Where:

#Scrub	=	if $F_a < 149602$, then #Scrub = 1 if $149602 \leq F_a < 224403$, then #Scrub = 2 if $244403 \leq F_a < 299204$, then #Scrub = 3 if $299204 \leq F_a < 374005$, then #Scrub = 4 if $F_a \geq 374005$, then #Scrub = 5
F_a	=	Actual exhaust flowrate (acfm)

Total Annualized Costs

$$TAC = \left[(\#Scrub)(TCI)\left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}}-1}\right)\right] + [(0.04)(TCI)] + \left\{(20.014)(\#Scrub)(F_a)(Op_{Hrs})\left[C_{SO2} - (C_{SO2})\left(\frac{100-98}{100-(98)(C_{SO2})}\right)\right]\right\} + [(16.147)(\#Scrub)(Op_{Hrs})] + \left\{(1.17 \times 10^{-5})(F_a)(Op_{Hrs})(\#Scrub)\left[\left((479.85)\left(\frac{1}{\sqrt{F_a}}\right)^{1.18}\right) + (6.895)\right]\right\} + [(1.33 \times 10^{-5})(Op_{Hrs})(\#Scrub)(F_a)]$$

Where:

#Scrub	=	if $F_a < 149602$, then #Scrub = 1 if $149602 \le F_a < 224403$, then #Scrub = 2 if $244403 \le F_a < 299204$, then #Scrub = 3 if $299204 \le F_a < 374005$, then #Scrub = 4 if $F_a \ge 374005$, then #Scrub = 5
TCI	=	Total Capital Investment ($)
i	=	Annual interest rate
Eq_{Life}	=	Estimated equipment life (years)
F_a	=	Actual exhaust flowrate (acfm)
C_{SO2}	=	Mole fraction of SO_2 in exhaust gas
Op_{Hrs}	=	Annual operating hours of unit (hours per year)

3.2.2.2 Example Calculations

This section provides example calculations for an application of Equation Type 16. The example is a wet bottom pulverized bituminous coal EGU boiler (SCC: 10100201) with a wet scrubber for SO_2 control (SWSICIBC).

Example Equation Variables

Capital Recovery Factor = 0.1098 (assumes equipment life of 15 years (Eq_{Life}) and interest rate of 7% (*i*))
#Scrub = 1

$$F_a = 924.88\ \frac{ft^3}{sec} \times 60 = 55{,}493\ \frac{ft^3}{min}$$

T = 500 °F
E_{SO2} = 100 tons/year
Op_{Hrs} = 2,688 operating hours per year
Year for Cost Basis = 2008

Mole Fraction of SO₂ in outlet gas

$$F_s = (F_a)\left(\frac{520}{460+T}\right)$$
$$F_s = (55{,}493)\left(\frac{520}{460+500}\right)$$
$$F_s = 30{,}058.7\,\frac{ft^3}{min}$$
$$VFR_{SO2} = E_{SO2} \times 2{,}000 \times \left(\frac{1}{64.06}\right)\times\left(\frac{1}{Op_{Hrs}}\right)\times\left(\frac{1}{60}\right)\times 379.7$$
$$VFR_{SO2} = 100 \times 2{,}000 \times \left(\frac{1}{64.06}\right)\times\left(\frac{1}{2688}\right)\times\left(\frac{1}{60}\right)\times 379.7$$
$$VFR_{SO2} = 7.35\,\frac{ft^3}{min}$$
$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right)$$
$$C_{SO2} = \left(\frac{7.35}{30{,}058.7}\right)$$
$C_{SO2} = 2.4 \times 10^{-4}$ mole fraction SO_2

Total Capital Investment

$$TCI = [(2.88)(\#Scrub)(F_a)] + \left[(1076.54)(\#Scrub)\sqrt{F_a}\right] + [(9.759)(F_a)] + \left[(360.463)\sqrt{F_a}\right]$$
$$= [(2.88)(1)(55493)] + \left[(1076.54)(1)\sqrt{55493}\right] + [(9.759)(55493)] + \left[(360.463)\sqrt{55493}\right]$$
$= \$1{,}039{,}887$ (2008\$)

Total Annualized Costs

$$\begin{aligned} TAC &= \left[(\#Scrub)(TCI)\left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}}-1}\right)\right] + [(0.04)(TCI)] \\ &+ \left\{(20.014)(\#Scrub)(F_a)(Op_{Hrs})\left[C_{SO2} - (C_{SO2})\left(\frac{100-98}{100-(98)(C_{SO2})}\right)\right]\right\} \\ &+ [(16.147)(\#Scrub)(Op_{Hrs})] \\ &+ \left\{(1.17\times10^{-5})(F_a)(Op_{Hrs})(\#Scrub)\left[\left((479.85)\left(\frac{1}{\sqrt{F_a}}\right)^{1.18}\right) + (6.895)\right]\right\} \\ &+ [(1.33\times10^{-5})(Op_{Hrs})(\#Scrub)(F_a)] \end{aligned}$$

$$= \left[(1)(\$1{,}309{,}887)\left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15}-1}\right)\right] + [(0.04)(\$1{,}309{,}887)]$$
$$+ \Big\{(20.014)(1)(55493)(2688)\Big[(2.4 \times 10^{-4})$$
$$- (2.4 \times 10^{-4})\left(\frac{100-98}{100-(98)(2.4 \times 10^{-4})}\right)\Big]\Big\} + [(16.147)(1)(2688)]$$
$$+ \left\{(1.17 \times 10^{-5})(55493)(2688)(1)\left[\left((479.85)\left(\frac{1}{\sqrt{55493}}\right)^{1.18}\right) + (6.895)\right]\right\}$$
$$+ [(1.33 \times 10^{-5})(2688)(1)(55493)]$$
$$= \$929{,}935 \ (2008\$)$$[23]

3.2.3 Equation Type 18 for SO_2 – ICI Boilers: Increased Caustic Injection Rate

Equation Type 18 is used to calculate control costs for using caustic injection on various external combustion boilers and industrial processes.[24] This equation is used for an increased caustic injection rate for existing dry injection control. Therefore, no new capital investment is required.

This Equation Type uses both the exhaust flowrate at standard temperature (F_s) in standard cubic feet per minute (scfm) and at standard temperature on a dry basis (F_d) in dry standard cubic feet per minute (dscfm), depending on the individual equation (see Section 1.2.2 for discussion of flowrate unit conversions).

Concentration of SO_2 in outlet gas

The equations that are used to convert from inventory emissions to the concentration of SO_2 in the stack gas are shown here.

$$VFR_{SO2} = E_{SO2} \times 2{,}000 \times \left(\frac{1}{64.06}\right) \times \left(\frac{1}{Op_{Hrs}}\right) \times \left(\frac{1}{60}\right) \times 379.7$$
$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right) \times 10^6$$

Where:

VFR_{SO2}	=	Volumetric Flow Rate (ft^3/minute)
E_{SO2}	=	Annual SO_2 emissions from the emissions inventory (tons/year)
2,000	=	lbs/ton

[23] Note that in the example CoST equations inventory distributed with CoST, a second source is picked up by this control measure. The second source was intended for use in Eq. 17 but qualified for this control as well. See the detailed control strategy results for plant ID 13 in the CoST control strategies viewer to see the results that are consistent with the example calculation shown in this document.
[24] ERG 2013, Appendix B, page B-8.

64.06	=	SO_2 molecular weight (grams/mol)
Op_{Hrs}	=	Annual operating hours from the emissions inventory (hours)
60	=	minutes/hour
379.7	=	Volume of 1 mol SO2 under standard conditions (ft^3/mol)
F_s	=	Exhaust flowrate at standard temperature (scfm)
C_{SO2}	=	Outlet concentration of SO_2, dry parts per million by volume (ppmvd)

3.2.3.1 Cost Equations

Total Capital Investment

$$TCI = 0$$

No variables are used in this calculation.

Total Annualized Costs

$$TAC = (\$0.00000387)(C_{SO2})(F_d)(Op_{Hrs})$$

Where:

C_{SO2}	=	Concentration of SO_2 in stack gas, dry parts per million by volume (ppmvd)
F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
Op_{Hrs}	=	Annual operating hours of the unit (hours/year)

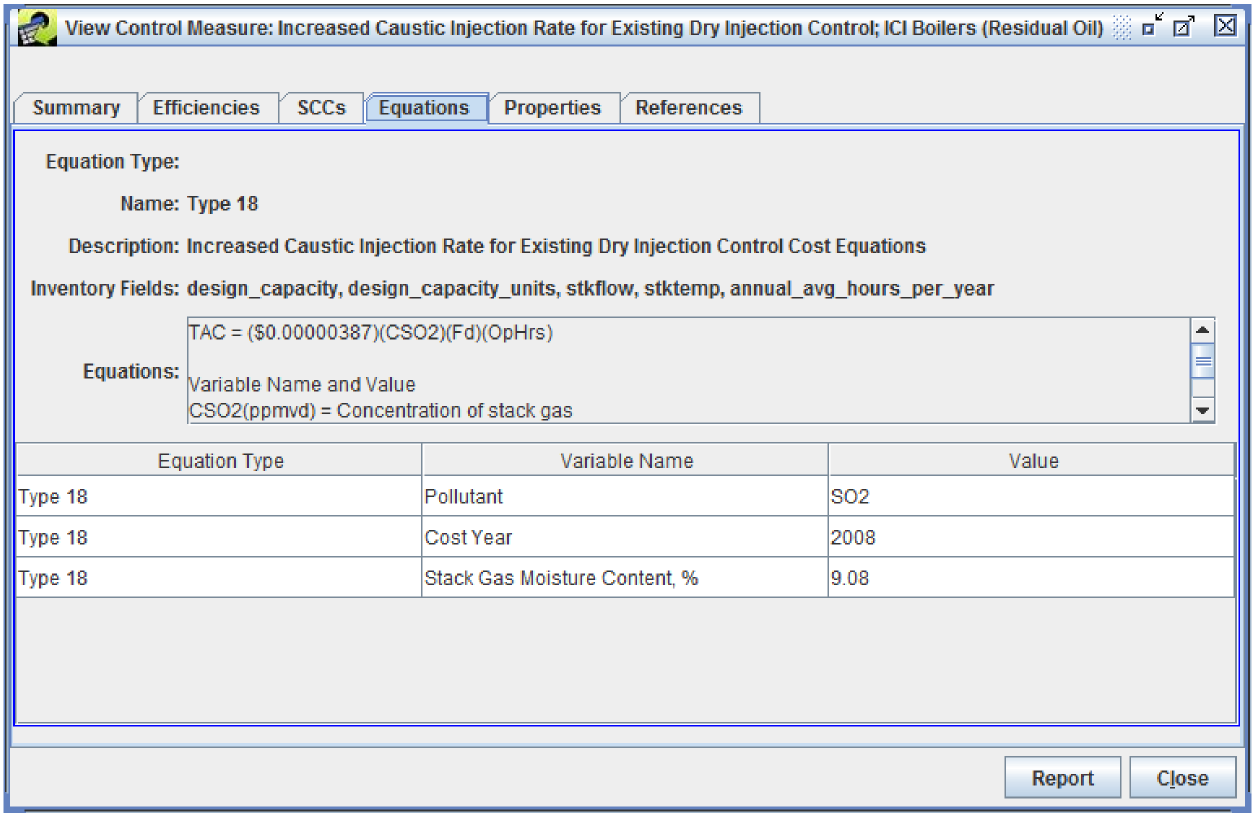
3.2.3.2 Example Calculations

This section provides example calculations for an application of Equation Type 18. The example is an EGU boiler burning grade 6 residual oil (SCC: 10100401) with an increased caustic injection rate for existing dry injection SO_2 control (SICIRIBRO).

Note that for the Boiler MACT rulemaking, sources that responded to the survey reported average annual operating hours for the relevant combustion units. For facilities that did not report annual operating hours, it was assumed that the unit was in operation for 8,424 hours per year, reflecting two weeks of boiler down time per year.

Figure 3-3 illustrates the Equations tab of the View Control Measure screen for the Increased Caustic Injection Rate emissions control method for SO_2.

Figure 3-3: Equation Type 18 for SO_2 - Example Screenshot from CoST



Example Equation Variables

$$F_a = 2{,}100\ \frac{ft^3}{sec} \times\ 60 = 126{,}000\ \frac{ft^3}{min}$$

T = 450 °F

E_{SO2} = 50 tons/year

Op_{Hrs} = 8,424 operating hours per year

% Moist = 9.08%

Year for Cost Basis = 2008

Flowrate calculations

$$F_s = (F_a)\left(\frac{520}{460 + T}\right)$$

$$F_s = (126{,}000)\left(\frac{520}{460 + 450}\right)$$

$$F_s = 72{,}000\ \frac{ft^3}{min}$$

$$F_d = (F_a)\left(\frac{460 + 68}{460 + T}\right)\left(1 - \frac{\%Moist}{100}\right)$$

$$F_d = (126{,}000)\left(\frac{460+68}{460+450}\right)\left(1-\frac{9.08}{100}\right)$$
$$F_d = 66{,}470\ \frac{ft^3}{min}$$

Concentration of SO_2 in outlet gas

$$VFR_{SO2} = E_{SO2} \times 2{,}000 \times \left(\frac{1}{64.06}\right) \times \left(\frac{1}{Op_{Hrs}}\right) \times \left(\frac{1}{60}\right) \times 379.7$$
$$VFR_{SO2} = 50 \times 2{,}000 \times \left(\frac{1}{64.06}\right) \times \left(\frac{1}{8424}\right) \times \left(\frac{1}{60}\right) \times 379.7$$
$$VFR_{SO2} = 1.17\ \frac{ft^3}{min}$$
$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right) \times 10^6$$
$$C_{SO2} = \left(\frac{1.17}{72{,}000}\right) \times 10^6$$
$$C_{SO2} = 16.3\ \text{ppmvd}$$

Total Capital Investment

TCI = $0

Total Annualized Costs

$$TAC = (\$3.87 \times 10^{-6})(C_{SO2})(F_d)(Op_{Hrs})$$
$$TAC = (\$3.87 \times 10^{-6})(16.3)(66{,}470)(8{,}424)$$
$$TAC = \$35{,}294\ (2008\$)$$

3.2.4 Equation Type 19 for SO_2 – ICI Boiler: Spray Dry Absorber

Equation Type 19 is used to calculate control costs for using spray dry absorbers on various external combustion boilers and industrial processes.[25] This control technology, which provides less-than-extensive SO_2 control (80%) and no reduction in PM, was used for the CISWI NESHAP. This Equation Type uses the exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm), at standard temperature (F_s) in standard cubic feet per minute (scfm), and at standard temperature on a dry basis (F_d) in dry standard cubic feet per minute (dscfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

Concentration of SO_2 in outlet gas

The equations that are used to convert from inventory emissions to the concentration of SO_2 in the stack gas are show here.

$$VFR_{SO2} = E_{SO2} \times 2{,}000 \times \left(\frac{1}{64.06}\right) \times \left(\frac{1}{Op_{Hrs}}\right) \times \left(\frac{1}{60}\right) \times 379.7$$

[25] ERG 2013, Appendix B, page B-9.

$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right) \times 10^6$$

Where:

VFR_{SO2}	=	Volumetric Flow Rate (ft^3/minute)
E_{SO2}	=	Annual SO_2 emissions from the emissions inventory (tons/year)
2,000	=	lbs/ton
64.06	=	SO_2 molecular weight (grams/mol)
Op_{Hrs}	=	Annual operating hours from the emissions inventory (hours)
60	=	minutes/hour
379.7	=	Volume of 1 mol SO2 under standard conditions (ft^3/mol)
F_s	=	Exhaust flowrate at standard temperature (scfm)
C_{SO2}	=	Outlet concentration of SO_2, dry parts per million by volume (ppmvd)

3.2.4.1 Cost Equations

Total Capital Investment

$$TCI = [(143.76)(F_d)] + \left[(0.610)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right] + \left[(17412.26)e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right] + \left[(53.973)e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right] + (931911.04)$$

Where:

F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
F_a	=	Actual exhaust flowrate (acfm)
#Ducts	=	if $F_d \leq 154042$, then #Ducts = 1 if $F_d > 154042$, then #Ducts = $F_d/154042$

Total Annualized Costs

$$TAC = (Op_{Hrs})\{[(1.62 \times 10^{-3})(F_d)] + [(6.84 \times 10^{-7})(C_{SO2})(F_d)] + [(3.72 \times 10^{-5})(F_a)] + (21.157)\} + \left\{\left[7.2 \times 10^{-2} + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right](TCI)\right\}$$

Where:

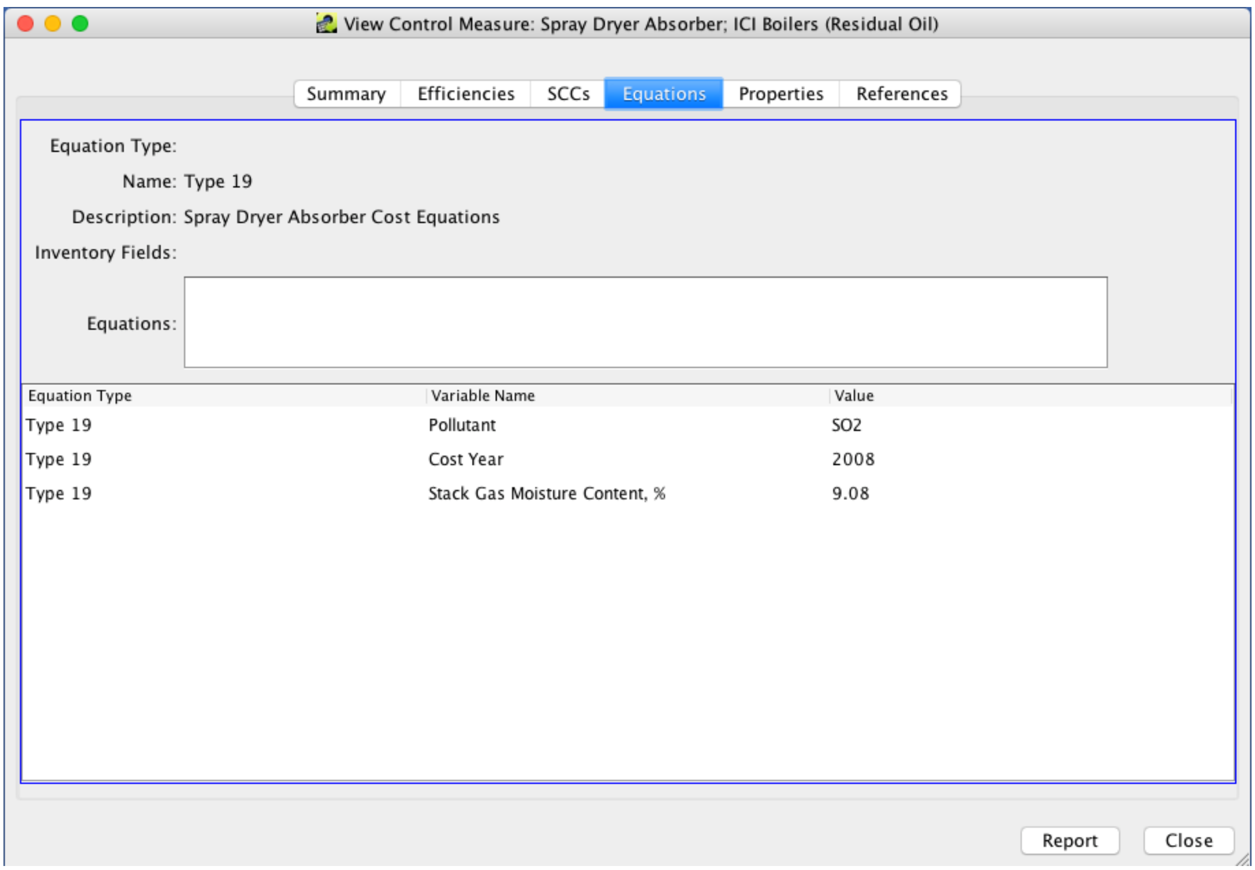
F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)

F_a = Actual exhaust flowrate (acfm)
Op_{Hrs} = Annual operating hours of unit (hours/year) from the emissions inventory
C_{SO2} = Concentration of SO_2 in stack gas (dry parts per million by volume [ppmvd])
TCI = Total Capital Investment ($)
i = annual interest rate
Eq_{Life} = Estimated equipment life (years)

3.2.4.2 Example Calculations

This section provides example calculations for an application of Equation Type 19. The example is an ICI boiler burning grade 6 residual oil (SCC: 10300401) with a spray dry absorber for SO_2 control (SSDAIBRO). Figure 3-4 illustrates the View Control Measure screen for the Spray Dryer Absorber emissions control method for SO_2.

Figure 3-4: Equation Type 19 for SO_2- Example Screenshot from CoST



Example Equation Variables

Capital Recovery Factor = 0.1098 (assumes equipment life of 15 years (Eq_{Life}) and interest rate of 7% (i))

$$F_a = 2{,}100\ \frac{ft^3}{sec} \times\ 60 = 126{,}000\,\frac{ft^3}{min}$$

T = 450 °F
 # Ducts = 1
E_{SO2} = 75 tons/year
Op_{Hrs} = 2,688 operating hours per year
% Moist = 9.08%
Year for Cost Basis = 2008

Flowrate calculations

$$F_s = (F_a)\ \left(\frac{520}{460+T}\right)$$

$$F_s = 126{,}000\ \left(\frac{520}{460+450}\right)$$

$$F_s = 72{,}000\ \frac{ft^3}{min}$$

$$F_d = (F_a)\ \left(\frac{460+68}{460+T}\right)\left(1-\frac{\%Moist}{100}\right)$$

$$F_d = (126{,}000)\ \left(\frac{460+68}{460+450}\right)\left(1-\frac{9.08}{100}\right)$$

$$F_d = 66{,}470\ \frac{ft^3}{min}$$

Concentration of SO_2 in outlet gas

$$VFR_{SO2} = E_{SO2}\ \times\ 2{,}000\ \times\ \left(\frac{1}{64.06}\right)\times\left(\frac{1}{Op_{Hrs}}\right)\times\left(\frac{1}{60}\right)\times 379.7$$

$$VFR_{SO2} = 75\ \times\ 2{,}000\ \times\ \left(\frac{1}{64.06}\right)\times\left(\frac{1}{2688}\right)\times\left(\frac{1}{60}\right)\times 379.7$$

$$VFR_{SO2} = 5.513\ \frac{ft^3}{min}$$

$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right)\ \times 10^6$$

$$C_{SO2} = \left(\frac{5.513}{72{,}000}\right)\ \times 10^6$$

$$C_{SO2} = 76.57\ \text{ppmvd}$$

Total Capital Investment

$$TCI = [(143.76)(F_d)] + \left[(0.610)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right] + \left[(17412.26)e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right] + \left[(53.973)e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right] + (931911.04)$$

$$= [(143.76)(66{,}470)] + \left[(0.610)\left(\frac{\sqrt{126{,}000}}{1}\right)^2\right] + \left[(17412.26)e^{(0.017)\left(\frac{\sqrt{126{,}000}}{1}\right)}\right] + \left[(53.973)e^{(0.014)\left(\frac{\sqrt{126{,}000}}{1}\right)}\right] + (931911.04)$$

$$= \$17{,}842{,}666\ (2008\$)$$

Total Annualized Costs

$$TAC = (Op_{Hrs})\{[(1.62 \times 10^{-3})(F_d)] + [(6.84 \times 10^{-7})(C_{SO2})(F_d)] + [(3.72 \times 10^{-5})(F_a)] + (21.157)\} + \left\{\left[7.2 \times 10^{-2} + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right](TCI)\right\}$$

$$TAC = (2688)\{[(1.62 \times 10^{-3})(66{,}470)] + [(6.84 \times 10^{-7})(76.57)(66{,}470)] + [(3.72 \times 10^{-5})(126{,}000)] + (21.157)\} + \left\{\left[(7.2 \times 10^{-2}) + \left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15} - 1}\right)\right](\$17{,}842{,}666)\right\}$$

$$= \$3{,}611{,}973\ (2008\$)$$ [26]

[26] Note that in the example CoST equations inventory distributed with CoST, a second source is picked up by this control measure. The second source was intended for use in Eq. 18 but qualified for this control as well. See the detailed control strategy results for SCC 10300401 and plant ID 15 in the CoST control strategies viewer to see the results that are consistent with the example calculation shown in this document.

4 Particulate Matter Control Cost Equations

This chapter is divided into two main sections – IPM and non-IPM sources. The types of cost equations for point source particulate matter < 2.5 microns (μm) in diameter ($PM_{2.5}$) controls, indicated below, are described in their appropriate sections.

- Equation type 1 for IPM fabric filter
- Equation type 14 for non-IPM fabric filter
- Equation type 15 for non-IPM ESP
- Equation type 17 for non-IPM dry injection and fabric filter (DIFF)

The subsections in this chapter describe each equation type, present the relevant equation parameters, and provide example calculations. The example calculations provided are prepared using version 2.15 of the CoST software.

4.1 IPM Sector (ptipm) PM Control Cost Equations

Equation Type 1 is used in the control cost calculation for IPM sector PM controls. In Equation Type 1, model plant capacities are used along with scaling factors and the emissions inventory's unit-specific boiler characteristics to generate a control cost for an applied technology.

Restrictions on source size are also shown for the controls that use Equation Type 1. When an application restriction reflects a minimum and maximum capacity, the control is not applied unless the capacity of the source in the inventory falls within that range.

4.1.1 Equation Type 1 for $PM_{2.5}$ – Utility Boilers (Coal)

Equation Type 1 uses a pulse jet type fabric filter to control $PM_{2.5}$ emissions from coal utility boilers. Equation Type 1 involves the application of a scaling factor to adjust the capital cost associated with a control measure to the boiler size (MW) based on the original control technology's documentation.[27]

4.1.1.1 Cost Equations

Capital Cost Equations

The Equation Type 1 capital cost for ptipm $PM_{2.5}$ control measures uses a capital cost multiplier, the unit's boiler capacity (in MW), and the scaling factor exponent. For $PM_{2.5}$ controls, the scaling factor is 1.0.

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times Capacity\ \times\ Scaling\ Factor\ \times 1{,}000$$

Where:

[27] U.S. EPA 2013, Table 5.17 on page 5-30.

- *Capital Cost Multiplier* = an empirical value based on the specific control measure ($/kW)
- *Capacity* = boiler capacity from the emissions inventory (MW) (from the units used in the emissions inventory converted to MW, see Section 1.2.1 for a discussion of unit conversions)
- *Scaling Factor* = 1.0
- *1000* = conversion factor to convert the *Capital Cost Multiplier* from $/kW to $/MW

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times Capital\ Recovery\ Factor$$

Where the *Capital Cost* and the *Capital Recovery Factor* have been calculated previously.

Operation and Maintenance Cost Equations

The fixed O&M component is based on the unit's capacity. The variable O&M includes an estimate for the unit's capacity factor. The capacity factor accounts for the amount of actual power generated by a power plant as compared to its design capacity or rated output. A value of 1.00 would represent a unit operating at 100% capacity.
The annualized cost is than estimated using the unit's capital cost times the CRF and the sum of the fixed and variable O&M costs.

$$Fixed\ O\&M = Fixed\ O\&M\ Cost\ Multiplier\ \times Capacity\ \times\ 1{,}000$$

Where:

- *Fixed O&M Cost Multiplier* = an empirical value based on the specific control measure ($/kW)
- *Capacity* = boiler capacity from the emissions inventory (MW)
- *1000* = a conversion factor to convert the Fixed O&M Cost Multiplier from $/kW to $/MW

$$Variable\ O\&M = Variable\ O\&M\ Cost\ Multiplier\ \times\ Capacity\ \times\ Capacity\ Factor\ \times\ 8{,}760$$

Where:

- *Variable O&M Cost Multiplier* = an empirical value based on the specific control measure ($/MWh)
- *Capacity Factor* = an empirical value based on the specific control measure
- *Capacity* = boiler capacity from the emissions inventory (MW)
- *8,760* = the number of hours the equipment is assumed to operate a year

$$Total\ O\&M\ Cost = Fixed\ O\&M + Variable\ O\&M$$

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$

Where the *Annualized Capital Cost* and the *O&M Cost* were calculated previously.

4.1.1.2 Example Calculations

Equation Type 1 Example for $PM_{2.5}$

This section provides example calculations for an application of Equation Type 1 to an EGU boiler burning pulverized anthracite coal (SCC: 10100101) in which $PM_{2.5}$ is the primary pollutant for this control technology. The example is for a 75 MW utility boiler that uses a pulse jet type fabric filter for its control equipment (PFFPJUBC1).

Example Equation Variables

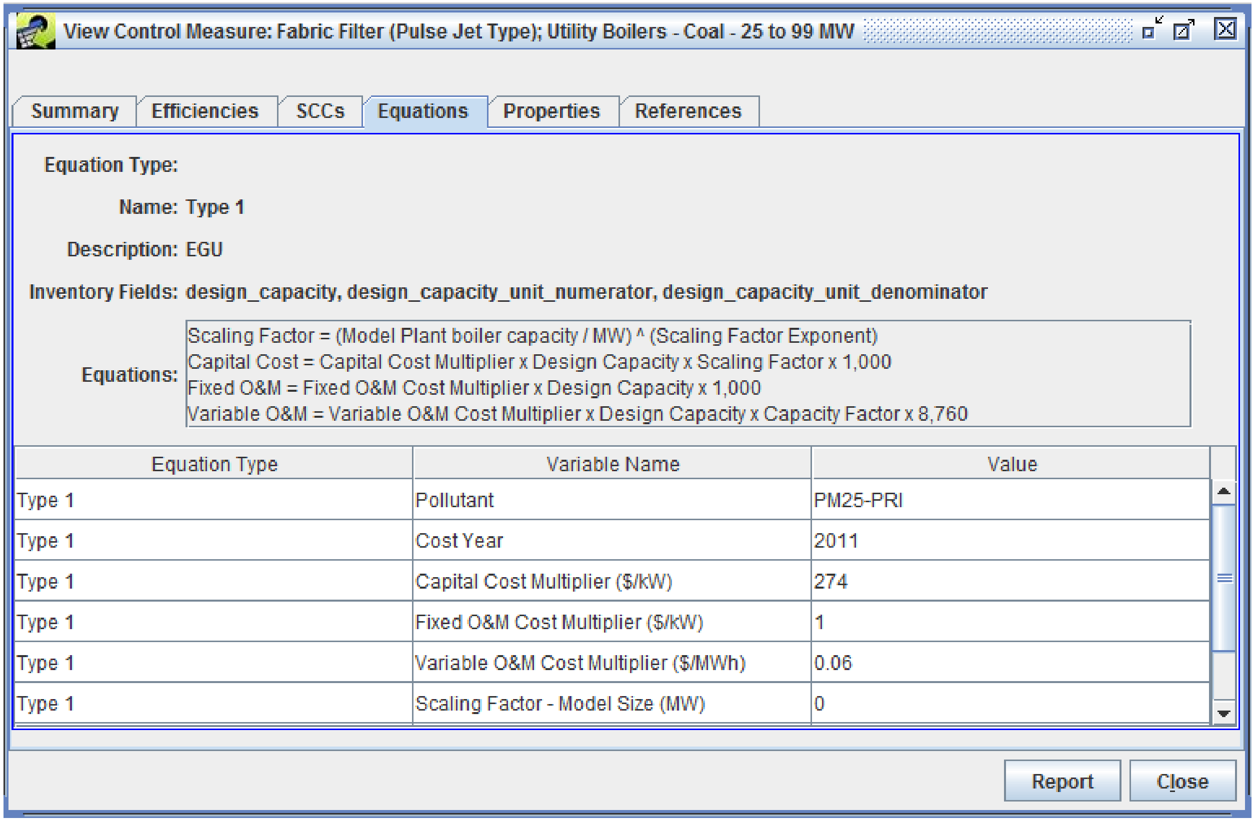
Figure 4-1 illustrates the Equations tab of the View Control Measure screen for the Fabric Filter (Pulse Jet Type); Utility Boilers – Coal – 25 to 99 MW.[28]

Capital Recovery Factor = 0.1010 (assumes equipment life of 15 years and interest rate of 5.7%, which is provided by IPM)

Capacity = 25.5 MW
Scaling Factor = 1.0
Capital Cost Multiplier ($/kW) = 274
Fixed O&M Cost Multiplier ($/kW) = 1.00
Variable O&M Cost Multiplier ($/MWh) = 0.06
Capacity Factor = 1
Year for Cost Basis = 2011

[28] The combustion efficiency value is in the SCCs tab in the control measure database.

Figure 4-1: Equation Type 1 for $PM_{2.5}$ - Example Screenshot from CoST



Annualized Capital Cost

$$Capital\ Cost = Capital\ Cost\ Multiplier\ \times Capacity\ \times\ Scaling\ Factor\ \times 1{,}000$$
$$Capital\ Cost = 274\frac{\$}{kW} \times 25.5\ MW\ \times\ 1.0 \times 1{,}000\frac{kW}{MW}$$
$$Capital\ Cost = \$6{,}987{,}000\ (2011\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times Capital\ Recovery\ Factor$$
$$Annualized\ Capital\ Cost = \$6{,}987{,}000 \times 0.1010$$
$$Annualized\ Capital\ Cost = \$705{,}366\ (2011\$)$$

Operation and Maintenance Cost

$$Fixed\ O\&M = Fixed\ O\&M\ Cost\ Multiplier\ \left(\frac{\$}{kW}\right) \times Capacity(MW)\ \times\ 1{,}000$$
$$Fixed\ O\&M = 1.00\frac{\$}{kW} \times 25.5\ MW\ \times\ 1{,}000\frac{kW}{MW}$$
$$Fixed\ O\&M = \$25{,}500\ (2011\$)$$

$$Variable\ O\&M = Variable\ O\&M\ Cost\ Multiplier\ \left(\frac{\$}{MWh}\right) \times\ Capacity\ (MW) \times$$
$$Capacity\ Factor\ \times\ 8{,}760\ (Hours\ Per\ Year)$$

$$Variable\ O\&M = 0.06 \frac{\$}{MWh} \times 25.5\ MW\ \times\ 1.0\ \times 8{,}760\ Hours$$
$$Variable\ O\&M = \$13{,}403\ (2011\$)$$

$$Total\ O\&M\ Cost = Fixed\ O\&M + Variable\ O\&M$$
$$Total\ O\&M\ Cost = \$25{,}500 + \$13{,}403$$
$$Total\ O\&M\ Cost = \$38{,}903 (2011\$)$$

Total Annualized Cost

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + Total\ O\&M\ Cost$$
$$Total\ Annualized\ Cost = \$705{,}366 + \$38{,}903$$
$$Total\ Annualized\ Cost = \$744{,}269\ (2011\$)$$

4.2 Non-IPM Sector (ptnonipm) PM Control Cost Equations

Equation Types 8, 14, 15, and 17 are used to calculate PM control costs for non-IPM point sources. Equation Type 8 uses the unit's stack flowrate (in scfm) as the primary variable for control cost calculation. The control costs for Equation Type 8 are based on calendar year 1995. If a unit's stack flow is either missing or less than 5 cubic feet per minute (cfm), then the control cost equation is not applied to the specific unit and instead a default cost per ton calculation is used.

Equation Types 14, 15 and 17 were developed for the ICI boilers and process heater NESHAP for major sources (Boiler MACT). The control costs calculated by these equations are based on the calendar year 2008.

Although applicability and control costs are based on PM_{10} emissions, these equations may also be used to estimate control costs of $PM_{2.5}$ reductions. Some PM control measures are primarily directed at reducing larger particulates (PM_{10}) while others are primarily for the purpose of reducing fine particulates ($PM_{2.5}$). The CMDB identifies the form of PM to which each control measure is primarily applicable.

4.2.1 Equation Type 8 for PM – ICI Boilers

The parameters for Equation Type 8 can be found in *Stationary Source Control Techniques Document for Fine Particulate Matter*.[29] The control efficiencies for both PM_{10} and $PM_{2.5}$ are provided in this table. This Equation Type uses the exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

[29] U.S. EPA 1998, Section 5.2.6, pages 5.2-21, 5.2-23, and 5.2-25; Section 5.3.6, pages 5.3-22, 5.3-23, and 5.3-29; and Section 5.4.6, pages 5.4-25, 5.4-26, and 5.4-33.

4.2.1.1 Cost Equations

Capital Cost Equation

$$Total\ Capital\ Cost = Typical\ Capital\ Cost\ \times Exhaust\ Flowrate$$

Where:
- *Typical Capital Cost* = based on the specific control measure
- *Exhaust flowrate* = exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm)

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times CRF$$

Where the *Capital Cost* and the *Capital Recovery Factor* were calculated previously.

Operation and Maintenance Cost Equation

$$Total\ O\&M\ Cost = Typical\ O\&M\ Cost\ \times Exhaust\ Flowrate$$

Where:
- *Typical O&M Cost* = based on the specific control measure
- *Exhaust flowrate* = exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm)

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + 0.04\ \times\ Total\ Capital\ Cost + Total\ O\&M\ Cost$$

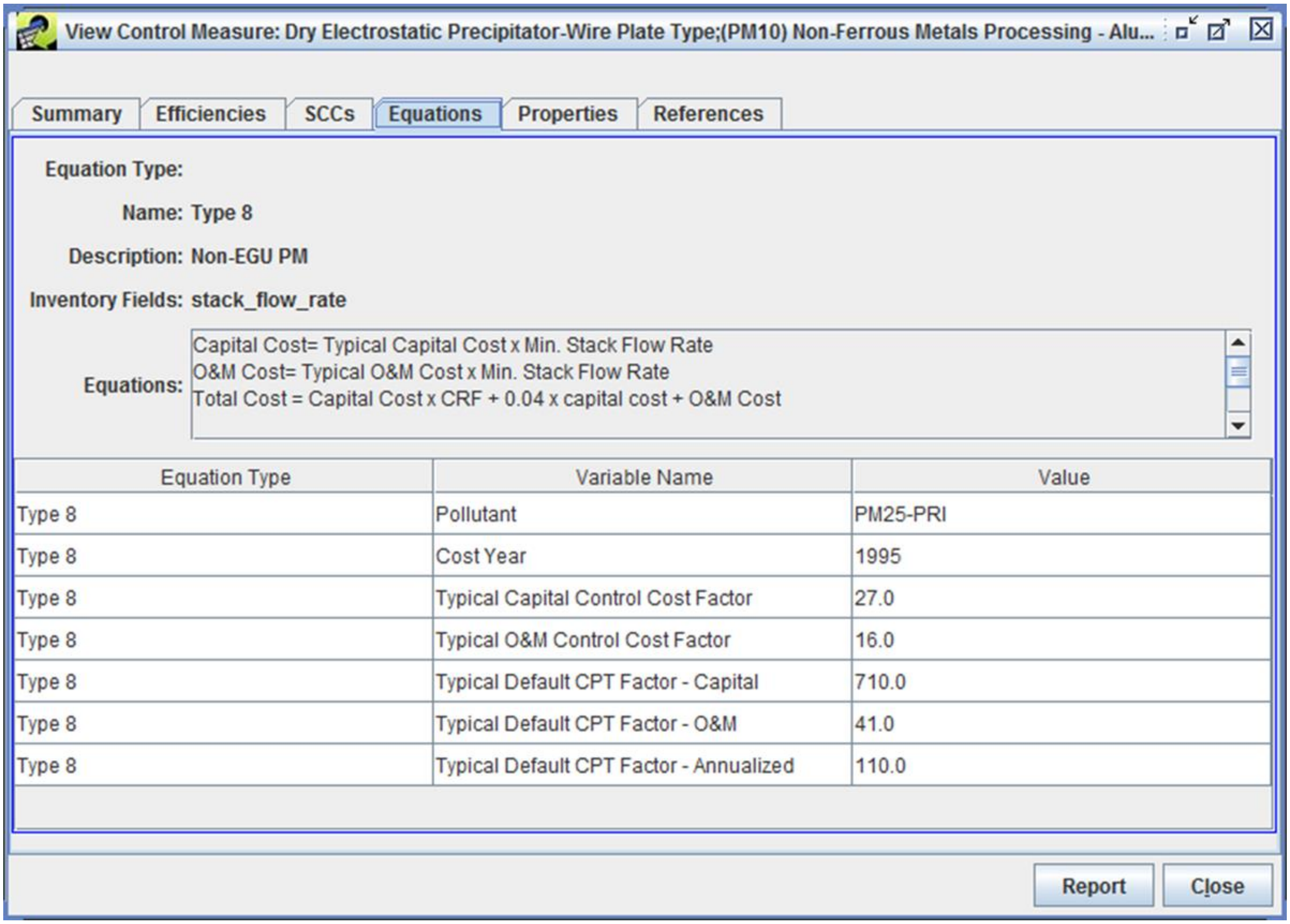
Where:
- *0.04* = 4% of the Capital Cost, which represents fixed annual charge for taxes, insurance, and administrative costs.

Annualized Capital Cost and *Total O&M Cost* were calculated previously.

4.2.1.2 Example Calculations

This section provides example calculations for an application of Equation Type 8 to a non-EGU plant. The example scenario is for a bauxite ore crushing and handling process at a primary metal production facility (SCC: 30300001) using a dry ESP – wire plate type for PM control (PDESPMPAM). Figure 4-2 is the View Control Measures screen for a Dry ESP – Wire Plate Type.

Figure 4-2: Equation Type 8 for $PM_{2.5}$ - Example Screenshot from CoST



View Control Measure: Dry Electrostatic Precipitator-Wire Plate Type;(PM10) Non-Ferrous Metals Processing - Alu...

Summary | Efficiencies | SCCs | Equations | Properties | References

Equation Type:

Name: Type 8

Description: Non-EGU PM

Inventory Fields: stack_flow_rate

Equations:
Capital Cost= Typical Capital Cost x Min. Stack Flow Rate
O&M Cost= Typical O&M Cost x Min. Stack Flow Rate
Total Cost = Capital Cost x CRF + 0.04 x capital cost + O&M Cost

Equation Type	Variable Name	Value
Type 8	Pollutant	PM25-PRI
Type 8	Cost Year	1995
Type 8	Typical Capital Control Cost Factor	27.0
Type 8	Typical O&M Control Cost Factor	16.0
Type 8	Typical Default CPT Factor - Capital	710.0
Type 8	Typical Default CPT Factor - O&M	41.0
Type 8	Typical Default CPT Factor - Annualized	110.0

Report | Close

Example Equation Variables

Capital Recovery Factor = 0.0944 (assumes equipment life of 20 years and interest rate of 7%)
Typical Capital Cost ($/acfm) = 27.0
Typical O&M Cost ($/acfm) = 16.0
PM_{10} Emissions Reductions = 162.78 tons
$Exhaust\ Flowrate = 283.69\ \mathrm{ft^3/sec}$
Year for Cost Basis = 1995

Capital Cost Equation

$$Capital\ Cost = Typical\ Capital\ Cost\ \times Exhaust\ Flowrate \times 60$$

$$Capital\ Cost = \$27/acfm\ \times 283.69\frac{ft^3}{sec} \times 60\frac{sec}{min}$$

$$Capital\ Cost = \$459{,}578\ (1995\$)$$

Use an implicit price deflator ratio to convert from 1995$ to 2000$.

$$Capital\ Cost = \$459{,}578\ \ (1995\$)\ \times \frac{81.887\ (2000\$)}{75.324\ (1995\$)}$$
$$Capital\ Cost = \$499{,}621\ (2000\$)$$

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times Capital\ Recovery\ Factor$$
$$Annualized\ Capital\ Cost = \$499{,}621\ \times\ 0.0944$$
$$Annualized\ Capital\ Cost = \$47{,}161\ (2000\$)$$

Operation and Maintenance Cost Equation

$$O\&M\ Cost = Typical\ O\&M\ Cost\ \times Exhaust\ Flowrate \times 60$$
$$O\&M\ Cost = \$16/acfm\ \times 283.69\frac{ft^3}{sec} \times 60\frac{sec}{min}$$
$$O\&M\ Cost = \$272{,}342\ (1995\$)$$
$$O\&M\ Cost = \$272{,}342\ \ (1995\$)\ \times \frac{81.887\ (2000\$)}{75.324\ (1995\$)}$$
$$O\&M\ Cost = \$296{,}072\ (2000\$)$$

Total Annualized Cost Equation

$$Total\ Annualized\ Cost = Annualized\ Capital\ Cost + 0.04 \times Capital\ Cost + O\&M\ Cost$$
$$Total\ Annualized\ Cost = \$47{,}161 + 0.04 \times \$499{,}621 + \$296{,}072$$
$$Total\ Annualized\ Cost = \$363{,}217\ (2000\$)$$

4.2.1.3 Equation Type 8 for PM Control Cost per Ton Calculations

When the exhaust flowrate is either less than 5.0 cfm or unavailable in the inventory, Equation Type 8 defaults to a cost per ton equation.

$$Capital\ Cost = Emissions\ Reduction \times Default\ Capital\ Cost\ Per\ Ton$$

$$O\&M\ Cost = Emissions\ Reduction \times Default\ O\&M\ Cost\ Per\ Ton$$

$$Total\ Annualized\ Cost = Emissions\ Reduction \times Default\ Annualized\ Cost\ Per\ Ton$$

Where:

- *Emissions Reduction* = emissions reduction (tons/year) calculated by CoST
- *Default Capital Cost per Ton* = $710.0/ton
- *Default O&M Cost per Ton* = $41.0/ton
- *Default Annualized Cost per Ton* = $110.0/ton

4.2.2 Equations Type 14 for PM – Fabric Filter Control on ICI Boilers

Equation Type 14 is used for fabric filters when approximately 99% PM control is required and no SO_2 reduction is needed.[30] This Equation Type uses the exhaust flowrate at actual stack conditions (Fa) in actual cubic feet per minute (acfm), at standard temperature (Fs) in standard cubic feet per minute (scfm), and at standard temperature on a dry basis (Fd) in dry standard cubic feet per minute (dscfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

Concentration of PM in outlet gas

The equations that are used to convert from inventory emissions to the concentration of $PM_{2.5}$ in the stack gas are shown here.

$$C_{PM} = E_{PM} \times 1.725 \times \left(\frac{15.4323584}{F_d}\right)$$

Where:

E_{PM}	=	Annual PM emissions from the emissions inventory (tons/year)
1.725	=	(grams/minute PM)/(tons/year PM)
15.4323584	=	grains/gram of PM
F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
C_{PM}	=	Outlet concentration of PM, grains per dry standard cubic foot (gr/dscf)

4.2.2.1 Cost Equations

Total Capital Investment Equation

$$TCI = (105.91)(F_d) + 699754.7 + \left[(0.560)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right] + \left[(1096.141)e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right] + \left[(33.977)e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right]$$

Where:

F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
F_a	=	Actual exhaust flowrate (acfm)
#Ducts	=	if $F_d \leq 154042$, then #Ducts = 1

[30] ERG 2013, Appendix B, page B-1.

if $F_d > 154042$, then #Ducts = F_d / 154042

Total Annualized Costs Equation

$$TAC = [(17.44)(Op_{Hrs})] + \left\{(TCI)\left[(0.072) + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right]\right\} + \left\{(F_a)\left[(4.507) + (1.24 \times 10^{-5})(Op_{Hrs}) - (4.184)\left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right]\right\} + \{(F_d)(Op_{Hrs})[(3.76 \times 10^{-3}) + (1.81 \times 10^{-3})(C_{PM})]\}$$

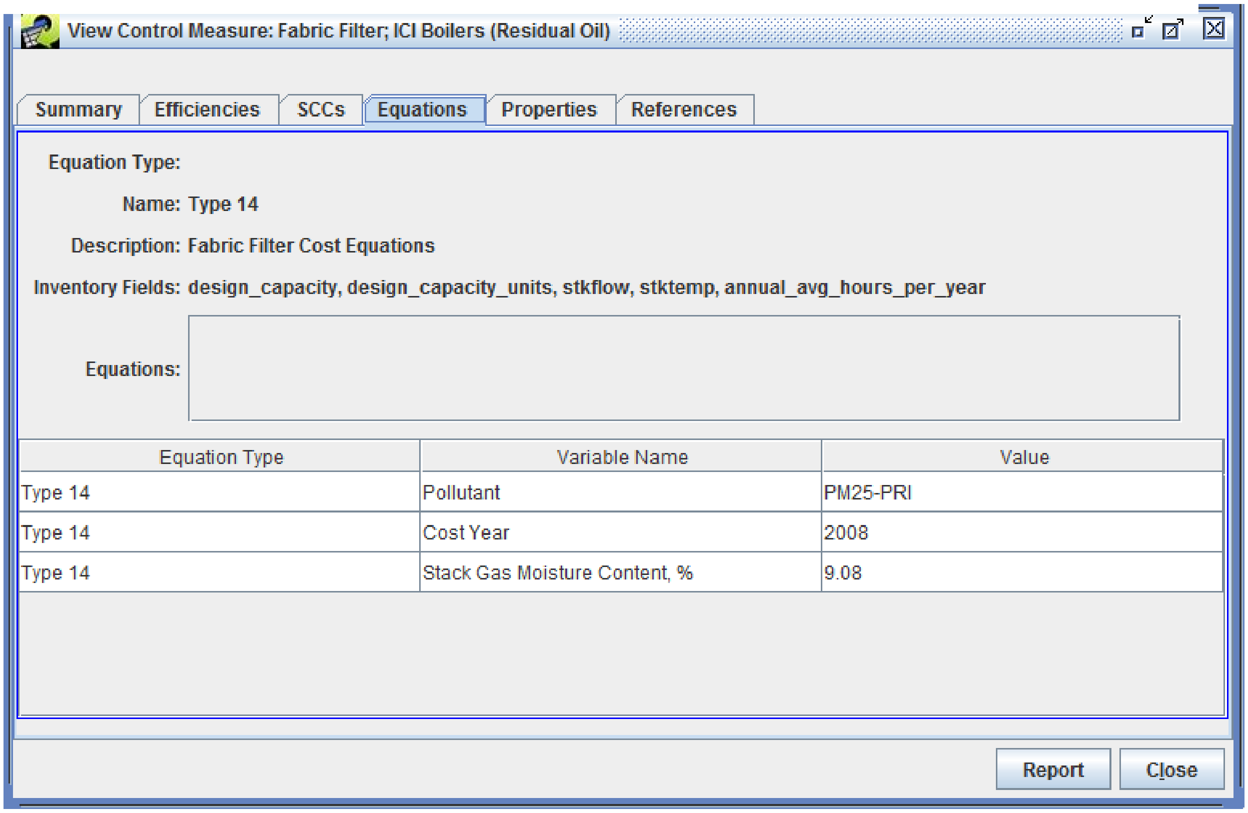
Where:

F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
Op_{Hrs}	=	Annual operating hours of unit from the emissions inventory (hours/year)
TCI	=	Total Capital Investment ($)
F_a	=	Actual exhaust flowrate (acfm)
C_{PM}	=	Concentration of PM in stack gas (grains per dry standard cubic foot [gr/dscf])
i	=	Interest rate
Eq_{Life}	=	Estimated equipment life (years)

4.2.2.2 Example Calculations

The example scenario for Equation Type 14 is for an industrial boiler that is burning grade 6 residual oil (SCC: 10200401). The boiler uses a fabric filter as its emissions control equipment for PM (PFFICIBRO). Figure 4-3 illustrates the View Control Measure screen for the Fabric Filter emissions control method for ICI boilers (Residual Oil) emitting PM.

Figure 4-3: Equation Type 14 for PM2.5 - Example Screenshot from CoST



Example Equation Variables

Capital Recovery Factor = 0.1098 (assumes equipment life of 15 years (Eq_{Life}) and interest rate of 7% (i))
#Ducts = 1

$$F_a = 924.88\,\frac{ft^3}{sec} \times\ 60 = 55{,}493\,\frac{ft^3}{min}$$

T = 450 °F
Op_{Hrs} = 2,688 operating hours per year
E_{PM} = 300 tons/year
% Moist = 9.08%
Year for Cost Basis = 2008

Flowrate calculations

$$F_d = (F_a)\left(\frac{460+68}{460+T}\right)\left(1-\frac{\%Moist}{100}\right)$$

$$F_d = (55{,}493)\left(\frac{460+68}{460+450}\right)\left(1-\frac{9.08}{100}\right)$$

$$F_d = 29{,}274\ \frac{ft^3}{min}$$

Concentration of PM in outlet gas

$$C_{PM} = E_{PM} \times 1.725 \times \left(\frac{15.4323584}{F_d}\right)$$
$$C_{PM} = 300 \times 1.725 \times \left(\frac{15.4323584}{29{,}274}\right)$$
$$C_{PM} = 0.273\ gr/dscf$$

Total Capital Investment

$$TCI = (105.91)(F_d) + 699754.7 + \left[(0.560)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right] + \left[(1096.141)e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right] + \left[(33.977)e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right]$$

$$TCI = (105.91)(29274) + (699754.7) + \left[(0.560)\left(\frac{\sqrt{55493}}{1}\right)^2\right] + \left[(1096.141)e^{(0.017)\left(\frac{\sqrt{55493}}{1}\right)}\right] + \left[(33.977)e^{(0.014)\left(\frac{\sqrt{55493}}{1}\right)}\right]$$
$$TCI = \$3{,}892{,}334\ (2008\$)$$

Total Annualized Costs

$$TAC = [(17.44)(Op_{Hrs})] + \left\{(TCI)\left[(0.072) + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right]\right\} + \left\{(F_a)\left[(4.507) + (1.24 \times 10^{-5})(Op_{Hrs}) - (4.184)\left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right]\right\} + \{(F_d)(Op_{Hrs})[(3.76 \times 10^{-3}) + (1.81 \times 10^{-3})(C_{PM})]\}$$

$$TAC = [(17.44)(2688)] + \left\{(3892334)\left[(0.072) + \left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15} - 1}\right)\right]\right\} + \left\{(55493)\left[(4.507) + (1.24 \times 10^{-5})(2688) - (4.184)\left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15} - 1}\right)\right]\right\} + \{(29274)(2688)[(3.76 \times 10^{-3}) + (1.81 \times 10^{-3})(0.273)]\}$$
$$TAC = \$1{,}315{,}676\ (2008\$)$$

4.2.3 Equation Type 15 for PM – Electrostatic Precipitator Controls on ICI Boilers

Equation Type 15 is used for electrostatic precipitators (ESP) when approximately 98% PM control is required and no SO_2 reduction is needed.[31] Note that it is assumed that the pressure drop through the ESP is 0.38 inches of water (in H_2O). This Equation Type uses the exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

PM emissions in lb/MMBtu

The equation to convert from inventory emissions in tons/year to lb/MMBtu is shown here.

$$E_{PM} = EI_{PM} \times 2000 \times \left(\frac{1}{365}\right) \times \left(\frac{1}{24}\right) \times \left(\frac{1}{3.412 \times \ Design\ Capacity}\right)$$

Where:

E_{PM}	=	Annual PM emissions (lb/MMBtu)
EI_{PM}	=	Annual PM emissions from the emissions inventory (tons/year)
2000	=	lbs/ton
365	=	days/year
24	=	hours/day
Design Capacity	=	Unit design capacity from inventory (MMBtu/hour)

4.2.3.1 Cost Equations

Total Capital Investment Equation

$$TCI = \{(12.265)(EC_1)[(5.266)(F_a)]^{EC_2}\} + \left[(0.784)\left(\frac{F_a}{\#Ducts}\right)\right] + (\#Ducts)\left\{\left[(2237.13)\left(e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + \left[(69.345)\left(e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + (17588.69)\right\}$$

Where:

EC_1	=	First equipment cost factor for ESP if $F_a \geq 9495$, $EC_1 = 57.87$ if Fa < 9495, $EC_1 = 614.55$
F_a	=	Actual exhaust flowrate (acfm)
EC_2	=	Second equipment cost factor for ESP if $F_a \geq 9495$, $EC_2 = 0.8431$

[31] ERG 2013, Appendix B, pages B-2 and B-3.

		if Fa < 9495, EC_2 = 0.6276
#Ducts	=	if F_a < 308084, #Ducts = 1
		if 308084 ≤ F_a < 462126, #Ducts = 2
		if 462126 ≤ F_a < 616168, #Ducts = 3
		if F_a ≥ 616168, #Ducts = 4

Total Annualized Costs Equation

$$
\begin{aligned}
TAC &= [(10.074)(Op_{Hrs})] + [(0.052)(F_a)] \\
&+ \left\{(6.56\times10^{-3})\left(1.04+\left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}}-1}\right)\right)\left((EC_1)[(5.266)(F_a)]^{EC_2}\right)\right\} \\
&+ [(0.021)(Op_{Hrs})(E_{PM})(DC)] \\
&+ \left\{(1.17\times10^{-5})(F_a)(Op_{Hrs})\left[(1.895)+\left((479.85)\left(\frac{1}{\sqrt{F_a}}\right)^{1.18}\right)\right]\right\} \\
&+ [(7.15\times10^{-4})(Op_{Hrs})(F_a)] \\
&+ \left\{\left(0.04+\left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}}-1}\right)\right)(\#Ducts)\left[(0.783)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right.\right. \\
&\left.\left.+ (2237.44)\left(e^{(0.0165)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)+(69.355)\left(e^{(0.0140)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)+(17591.15)\right]\right\}
\end{aligned}
$$

Where:

Op_{Hrs}	=	Annual operating hours of unit (hours/year)
F_a	=	Actual exhaust flowrate (acfm)
i	=	Interest rate
Eq_{Life}	=	Estimated equipment life, years
EC_1	=	First equipment cost factor for ESP
		If F_a ≥ 9495, EC_1 = 57.87
		If F_a < 9495, EC_1 = 614.55
EC_2	=	Second equipment cost factor for ESP
		If F_a ≥ 9495, EC_2 = 0.8431
		If F_a < 9495, EC_2 = 0.6276
E_{PM}	=	PM emission rate, pounds per million British thermal units (lb/MMBtu)
DC	=	Design capacity of boiler from inventory (MMBtu/hour)
#Ducts	=	If F_a < 308084, #Ducts = 1
		If 308084 ≤ F_a < 462126, #Ducts = 2
		If 462126 ≤ F_a < 616168, #Ducts = 3
		If F_a ≥ 616168, #Ducts = 4

4.2.3.2 Example Calculations

The example scenario for Equation Type 15 is for an ICI boiler burning grade 4 distillate oil (SCC 10300504) that uses an ESP as its emissions control equipment for PM (PESPICIB).

Example Equation Variables

Capital Recovery Factor = 0.1098 (assumes equipment life of 15 (Eq_{Life}) years and interest rate of 7% (i))
EC_1 = 57.87
Exhaust Flowrate = 924.88
EC_2 = 0.8431
#Ducts = 1
Op_{Hrs} = 2,688
EI_{PM} = 240 tons/year
Design Capacity (DC) = 180 MMBtu/hour = 52.75 MW
Year for Cost Basis = 2008

Flowrate calculations

$$F_a = Exhaust\ Flowrate \times 60$$
$$F_a = 924.88 \times 60$$
$$F_a = 55{,}493\ acfm$$

PM emissions in lb/MMBtu

$$E_{PM} = EI_{PM} \times 2000 \times \left(\frac{1}{365}\right) \times \left(\frac{1}{24}\right) \times \left(\frac{1}{3.412 \times DC(MW)}\right)$$
$$E_{PM} = 240 \times 2000 \times \left(\frac{1}{365}\right) \times \left(\frac{1}{24}\right) \times \left(\frac{1}{3.412 \times 52.75}\right)$$
$$E_{PM} = 0.3044\ lb/MMBTU$$

Total Capital Investment

$$TCI = \{(12.265)(EC_1)[(5.266)(F_a)]^{EC_2}\} + \left[(0.784)\left(\frac{F_a}{\#Ducts}\right)\right] + (\#Ducts)\left\{\left[(2237.13)\left(e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + \left[(69.345)\left(e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + (17588.69)\right\}$$

$$TCI = \{(12.265)(57.87)[(5.266)(55493)]^{0.8431}\} + \left[(0.784)\left(\frac{55493}{1}\right)\right] + (1)\left\{\left[(2237.13)\left(e^{(0.017)\left(\frac{\sqrt{55493}}{1}\right)}\right)\right] + \left[(69.345)\left(e^{(0.014)\left(\frac{\sqrt{55493}}{1}\right)}\right)\right] + (17588.69)\right\}$$
$$= \$28{,}977{,}396\ (2008\$)$$

Total Annualized Costs

$$
\begin{aligned}
TAC &= [(10.074)(Op_{Hrs})] + [(0.052)(F_a)] \\
&+ \left\{(6.56 \times 10^{-3})\left(1.04 + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right)\left((EC_1)[(5.266)(F_a)]^{EC_2}\right)\right\} \\
&+ \left[(0.021)(Op_{Hrs})(E_{PM})\left(DC\ (\frac{MMBtu}{hr})\right)\right] \\
&+ \left\{(1.17 \times 10^{-5})(F_a)(Op_{Hrs})\left[(1.895) + \left((479.85)\left(\frac{1}{\sqrt{F_a}}\right)^{1.18}\right)\right]\right\} \\
&+ [(7.15 \times 10^{-4})(Op_{Hrs})(F_a)] \\
&+ \left\{\left(0.04 + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right)(\#Ducts)\left[(0.783)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right.\right. \\
&\left.\left. + (2237.44)\left(e^{(0.0165)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right) + (69.355)\left(e^{(0.0140)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right) + (17591.15)\right]\right\}
\end{aligned}
$$

$$
\begin{aligned}
TAC &= [(10.074)(2688)] + [(0.052)(55493)] \\
&+ \left\{(6.56 \times 10^{-3})\left(1.04 + \left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15} - 1}\right)\right)\left((57.87)[(5.266)(55493)]^{0.8431}\right)\right\} \\
&+ [(0.021)(2688)(0.3044)(180)] \\
&+ \left\{(1.17 \times 10^{-5})(55493)(2688)\left[(1.895) + \left((479.85)\left(\frac{1}{\sqrt{55493}}\right)^{1.18}\right)\right]\right\} \\
&+ [(7.15 \times 10^{-4})(2688)(55493)] \\
&+ \left\{\left(0.04 + \left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15} - 1}\right)\right)(1)\left[(0.783)\left(\frac{\sqrt{55493}}{1}\right)^2 + (2237.44)\left(e^{(0.0165)\left(\frac{\sqrt{55493}}{1}\right)}\right)\right.\right. \\
&\left.\left. + (69.355)\left(e^{(0.0140)\left(\frac{\sqrt{55493}}{1}\right)}\right) + (17591.15)\right]\right\}
\end{aligned}
$$

$TAC = \$187{,}820$ (2008$)[32]

4.2.4 Equation Type 17 for PM – Dry Injection and Fabric Filter Control in ICI Boilers

Equation Type 17 is used for dry injection and fabric filter (DIFF) systems when PM reductions of approximately 99% and SO_2 reductions of approximately 70% are required.[33] Equation Type

[32] Note that in the example CoST equations inventory distributed with CoST, a second source is picked up by this control measure. The second source was intended for use in Eq. 14 but qualified for this control as well. See the detailed control strategy results for SCC 10300504 and plant ID 19 in the CoST control strategies viewer to see the results that are consistent with the example calculation shown in this document.

[33] ERG 2013, Appendix B, pages B-6 and B-7.

17 is presented in this section instead of Section 3.2 because the primary reduction is achieved for PM. This Equation Type uses the exhaust flowrate at actual stack conditions (F_a) in actual cubic feet per minute (acfm), at standard temperature (F_s) in standard cubic feet per minute (scfm), and at standard temperature on a dry basis (F_d) in dry standard cubic feet per minute (dscfm) (see Section 1.2.2 for discussion of flowrate unit conversions).

Concentration of PM in outlet gas

The equations that are used to convert from inventory emissions to the concentration of $PM_{2.5}$ in the stack gas are shown here.

$$C_{PM} = E_{PM} \times 1.725 \times (\frac{15.4323584}{F_d})$$

Where:

E_{PM}	=	Annual PM emissions from the emissions inventory (tons/year)
1.725	=	(grams/minute PM)/(tons/year PM)
15.4323584	=	grains/gram of PM
F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
C_{PM}	=	Outlet concentration of PM, grains per dry standard cubic foot (gr/dscf)

Concentration of SO_2 in outlet gas

The equations that are used to convert from inventory emissions to the concentration of SO_2 in the stack gas are show here.

$$VFR_{SO2} = E_{SO2} \times 2{,}000 \times \left(\frac{1}{64.06}\right) \times \left(\frac{1}{Op_{Hrs}}\right) \times \left(\frac{1}{60}\right) \times 379.7$$

$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right) \times 10^6$$

Where:

VFR_{SO2}	=	Volumetric Flow Rate (ft^3/minute)
E_{SO2}	=	Annual SO_2 emissions from the emissions inventory (tons/year)
2,000	=	lbs/ton
64.06	=	SO_2 molecular weight (grams/mol)
Op_{Hrs}	=	Annual operating hours from the emissions inventory (hours)
60	=	minutes/hour
379.7	=	Volume of 1 mol SO2 under standard conditions (ft^3/mol)
F_s	=	Exhaust flowrate at standard temperature (scfm)
C_{SO2}	=	Outlet concentration of SO_2, dry parts per million by volume (ppmvd)

4.2.4.1 Cost Equations

Total Capital Investment Equation

$$TCI = [(143.76)(F_d)] + \left[(0.610)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right] + \left[(1757.65)\left(e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + \left[(59.973)\left(e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + (931911.04)$$

Where:

F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
F_a	=	Actual exhaust flowrate (acfm)
#Ducts	=	if $F_d \leq 154042$, #Ducts = 1 if $F_d > 154042$, #Ducts = $F_d/154042$

Total Annualized Costs Equation

$$TAC = [(1.62 \times 10^{-3})(Op_{Hrs})(F_d)] + [(17.314)(Op_{Hrs})] + [(1.05 \times 10^{-6})(C_{SO2})(F_d)(Op_{Hrs})] + [(3.72 \times 10^{-5})(Op_{Hrs})(F_a)] + [(1.81 \times 10^{-4})(Op_{Hrs})(C_{PM})(F_d)] + \left[(0.847)\left(1 - \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right)(F_a)\right] + \left[(0.04) + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right]\left\{[(0.032)(TCI)] + \left[(0.606)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right] + \left[(1757.65)\left(e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + \left[(53.973)\left(e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + (13689.81)\right\}$$

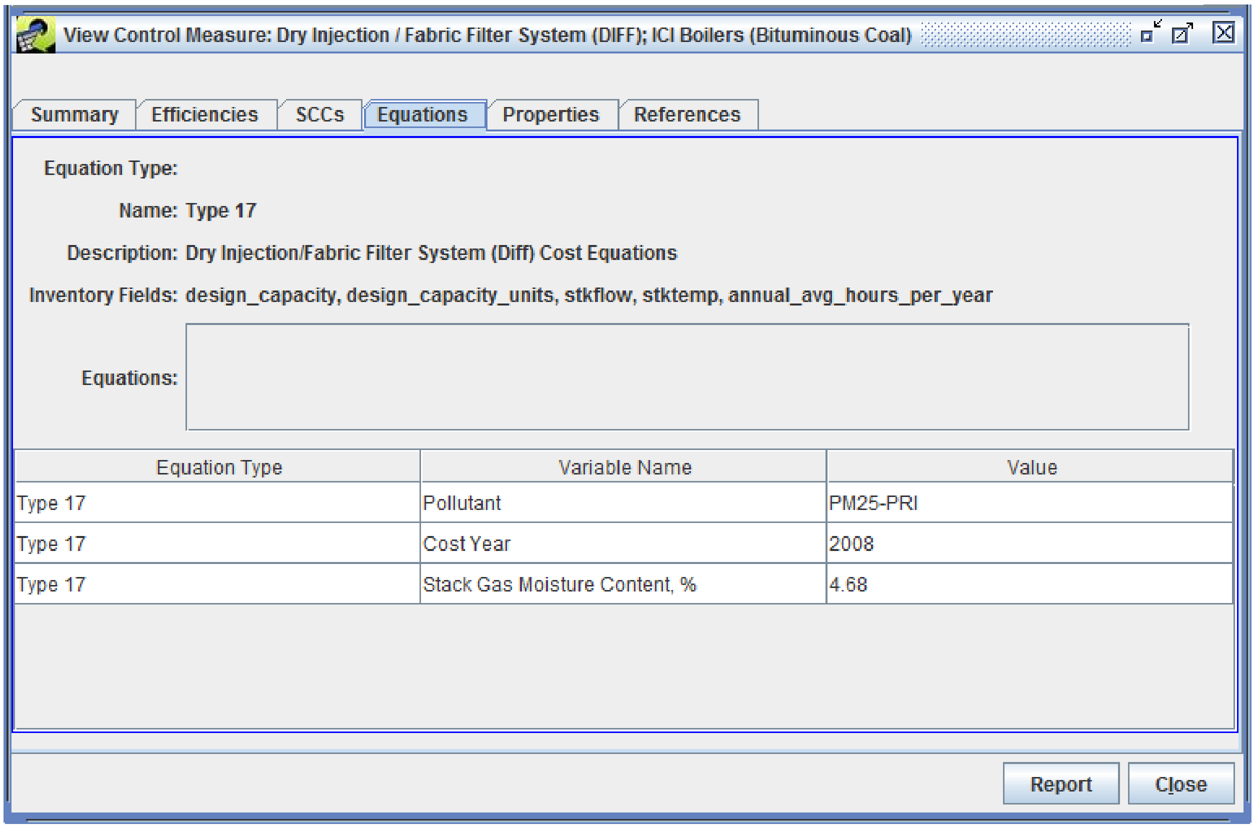
Where:

F_d	=	Exhaust flowrate at standard temperature on a dry basis (dscfm)
Op_{Hrs}	=	Annual operating hours of unit, from emissions inventory (hours/year)
C_{SO2}	=	Concentration of SO_2 in stack gas, dry ppm by volume (ppmvd)
F_a	=	Actual exhaust flowrate (acfm)
C_{PM}	=	Concentration of PM in the stack gas (gr/dscf)
i	=	Interest rate
Eq_{Life}	=	Estimated equipment life (yrs)
#Ducts	=	If $F_d \leq 154042$, #Ducts = 1 If $F_d > 154042$, #Ducts = $F_d/154042$

4.2.4.2 Example Calculations

The example calculation for Equation Type 17 is for a dry bottom pulverized bituminous coal ICI boiler (SCC: 103002016) using a dry injection fabric filter system for PM and SO_2 controls (PDIFFIBBC). Figure 4-4 illustrates information from the View Control Measures screen showing the Dry Injection/Fabric Filter (DIFF) System for Equation Type 17.

Figure 4-4: Equation Type 17 for $PM_{2.5}$ - Example Screenshot from CoST



Example Equation Variables

Capital Recovery Factor = 0.1098 (assumes equipment life of 15 years (Eq_{Life}) and interest rate of 7% (i))
Exhaust Flowrate = 924.88 acfs
T = 450 °F
E_{PM} = 300 tons/year
E_{SO2} = 120 tons/year
% Moist = 4.68%
#Ducts = 1
Op_{Hrs} = 2688 hours/year
Year for Cost Basis = 2008

Flowrate calculations

$$F_a = Exhaust\ Flowrate\ \times\ 60$$
$$F_a = 924.88\ \times\ 60$$
$$F_a = 55{,}493\ acfm$$

$$F_d = (F_a)\ \left(\frac{460+68}{460+T}\right)\left(1-\frac{\%Moist}{100}\right)$$
$$F_d = (55493)\ \left(\frac{460+68}{460+450}\right)\left(1-\frac{4.68}{100}\right)$$
$$F_d = 30{,}691\ dscfm$$

$$F_s = (F_a)\ \left(\frac{520}{460+T}\right)$$
$$F_s = (55493)\ \left(\frac{520}{460+450}\right)$$
$$F_s = 31{,}710\ scfm$$

Concentration of PM in outlet gas

$$C_{PM} = E_{PM}\ \times 1.725\ \times\ (\frac{15.4323584}{F_d})$$
$$C_{PM} = 300\ \times 1.725\ \times\ (\frac{15.4323584}{30691})$$
$$C_{PM} = 0.26\ gr/dscf$$

Concentration of SO_2 in outlet gas

$$VFR_{SO2} = E_{SO2}\ \times\ 2{,}000\ \times\ \left(\frac{1}{64.06}\right)\times\left(\frac{1}{Op_{Hrs}}\right)\times\left(\frac{1}{60}\right)\times 379.7$$
$$VFR_{SO2} = 120\ \times\ 2{,}000\ \times\ \left(\frac{1}{64.06}\right)\times\left(\frac{1}{2688}\right)\times\left(\frac{1}{60}\right)\times 379.7$$
$$VFR_{SO2} = 8.82\ \frac{ft^3}{min}$$

$$C_{SO2} = \left(\frac{VFR_{SO2}}{F_s}\right)\ \times 10^6$$
$$C_{SO2} = \left(\frac{8.82}{31710}\right)\ \times 10^6$$
$$C_{SO2} = 278.2\ ppmvd$$

Total Capital Investment

$$TCI = [(143.76)(F_d)] + \left[(0.610)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right] + \left[(1757.65)\left(e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + \left[(59.973)\left(e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + (931911.04)$$

$$TCI = [(143.76)(30691)] + \left[(0.610)\left(\frac{\sqrt{55493}}{1}\right)^2\right] + \left[(1757.65)\left(e^{(0.017)\left(\frac{\sqrt{55493}}{1}\right)}\right)\right] + \left[(59.973)\left(e^{(0.014)\left(\frac{\sqrt{55493}}{1}\right)}\right)\right] + (931911.04)$$

$$TCI = \$5{,}475{,}959\ (2008\$)$$

Total Annualized Costs

$$\begin{aligned} TAC &= [(1.62 \times 10^{-3})(Op_{Hrs})(F_d)] + [(17.314)(Op_{Hrs})] + [(1.05 \times 10^{-6})(C_{SO2})(F_d)(Op_{Hrs})] \\ &+ [(3.72 \times 10^{-5})(Op_{Hrs})(F_a)] + [(1.81 \times 10^{-4})(Op_{Hrs})(C_{PM})(F_d)] \\ &+ \left[(0.847)\left(1 - \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right)(F_a)\right] \\ &+ \left[(0.04) + \left(\frac{(i)(1+i)^{Eq_{Life}}}{(1+i)^{Eq_{Life}} - 1}\right)\right]\left\{[(0.032)(TCI)] + \left[(0.606)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)^2\right]\right. \\ &\left.+ \left[(1757.65)\left(e^{(0.017)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + \left[(53.973)\left(e^{(0.014)\left(\frac{\sqrt{F_a}}{\#Ducts}\right)}\right)\right] + (13689.81)\right\} \end{aligned}$$

$$\begin{aligned} &= [(1.62 \times 10^{-3})(2688)(30691)] + [(17.314)(2688)] \\ &+ [(1.05 \times 10^{-6})(278.2)(30691)(2688)] + [3.72 \times 10^{-5}(2688)(55493)] \\ &+ [(1.81 \times 10^{-4})(2688)(0.26)(30691)] + \left[(0.847)\left(1 - \left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15} - 1}\right)\right)(55493)\right] \\ &+ \left[(0.04) + \left(\frac{(0.07)(1+0.07)^{15}}{(1+0.07)^{15} - 1}\right)\right]\left\{[(0.032)(5475959)] + \left[(0.606)\left(\frac{\sqrt{55493}}{1}\right)^2\right]\right. \\ &\left.+ \left[(1757.65)\left(e^{(0.017)\left(\frac{\sqrt{55493}}{1}\right)}\right)\right] + \left[(53.973)\left(e^{(0.014)\left(\frac{\sqrt{55493}}{1}\right)}\right)\right] + (13689.81)\right\} \end{aligned}$$

$$TAC = \$303{,}555\ (2008\$)$$

5 References

Eastern Research Group, Inc. 2013. "ICI Boiler Control Measures."

Burklin, C. and B. Lange, Eastern Research Group, Inc. 2010. "Evaluation and Development of NOx Control Technologies Cost Equations for Industrial/Commercial/Institutional Boilers."

MACTEC Engineering and Consulting, Inc. 2005. "Petroleum Refinery Best Available Retrofit Technology (BART), Engineering Analysis."

RTI International 2014. "Update of NOx Control Measure Data in the CoST Control Measure Database for Four Industrial Source Categories: Ammonia Reformers, NonEGU Combustion Turbines, Glass Manufacturing, and Lean Burn Reciprocating Internal Combustion Engines."

U.S. Department of Energy 2012. "Improve Your Boiler's Combustion Efficiency."

U.S. Environmental Protection Agency. 2015. "Assessing NOx Controls for Gas-Fired Process Heaters at Petroleum Refineries."

U.S. Environmental Protection Agency. 2013. "Documentation for IPM Base Case v.5.13), Chapter 5. Emission Control Technologies."

U.S. Environmental Protection Agency. 2001. "Control Measure Evaluations: The Control Measure Data Base for the National Emissions Trends Inventory (Control NET)." EPA-452/D-01-001.

U.S. Environmental Protection Agency. 1998. "Stationary Source Control Techniques Document for Fine Particulate Matter." EPA-452/R-97-001.