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Identifying Cost-Effective Refinery Emission-Reduction Strategies

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Abstract

The RTI integrated refinery emission model (RTI Model) is designed to assess sources of refinery hazardous air pollutants, including benzene, toluene, and xylene (BTX) and other volatile organic compounds (VOCs); dioxins; benzopyrenes and other polyaromatic hydrocarbons; and trace metals and particulate matter. The model can assist petroleum refinery managers and operators in developing both refinery emissions and source characterization data suitable for use in risk assessment models. Users can calculate screening estimates for more than 60 compounds using only process-capacity data, or calculate more-refined estimates using more-detailed data for a specific refinery (stream compositions, unit location, stack heights, etc.). This paper describes the RTI Model, its applications and validation, and presents several case studies that demonstrate how it can be applied to identify cost-effective strategies for reducing emissions.

Model Overview

The RTI refinery emission model (RTI Model) was specifically developed to provide complete emission estimates and source characterization data suitable for use as input to risk assessment models. The characterization of risks associated with refinery emissions has been an area of growing concern in both the United States and in the European regulatory community. This unique tool provides the data needed to perform a risk assessment for a given refinery. The model can also assist petroleum refinery managers and operators in developing emission estimates for their facilities and in identifying cost-effective emission-control strategies.

The RTI Model is an Access database model that can be used to characterize the emissions of hazardous air pollutants (HAPs) from all processes typically present at a petroleum refinery. The model requires, as minimum input data, information on the process capacities of each refinery process unit, such as the information reported in the *Oil & Gas Journal* Worldwide Refining Survey (Stell, 2000). With these minimum input data, the model calculates emission estimates using a variety of reported emission factors, typical process-stream compositional data, as well as calculation protocols developed by RTI. The model can also use either reported emissions data or detailed, process-specific data (e.g., process equipment component counts and stream compositional data), if they are available, to develop more-refined emission estimates.

The RTI Model provides source characteristics and HAP emission estimates for each of the following emission sources:

- Process heaters and boilers
- Flares/thermal oxidizers (includes marine vessel loading emissions)
- Wastewater collection and treatment systems
- Cooling towers
- Fugitive equipment leaks (all processes)
- Tanks (both storage and process tanks)
- Truck and rail (product) loading operations
- Catalytic reforming regeneration vents
- Catalytic cracking regeneration vents
- Sulfur recovery unit (sulfur plant) vents.

The model provides emission estimates for more than 60 compounds typically emitted from petroleum refineries. These chemicals include a variety of volatile organic compounds (VOCs), such as benzene, toluene, and xylene (BTX); polycylic aromatic hydrocarbons (PAHs); dioxins; hydrogen chloride; reduced sulfur compounds; and metals (e.g., nickel and mercury).

The RTI Model is a versatile tool that users can apply to develop emission inventories, identify primary sources of chemical-specific emissions, evaluate the effectiveness of alternative emission-reduction schemes, and provide input for refinery risk assessments.

RTI Model Validation

To ensure that the emission model algorithms used in the RTI Model provide reasonable estimates of refinery emissions, RTI validated the algorithms by comparing emission model estimates with refinery-specific emission inventories prepared by the refineries' owners or operators for their air permit applications. The principal chemical used to validate the model was benzene—one of the primary chemicals of concern from petroleum refineries because of its prevalence in emissions from refinery sources and its relatively high unit risk factor. Emissions comparisons were also made for toluene and hexane. Emissions data for these chemicals were available from 8 refineries ranging in crude capacity from 46,000 to 485,000 barrels per calendar day (bbl/cd). Figure 1 provides a comparison of screening benzene emission estimates calculated by the RTI Model using only process-capacity data reported in the *Oil & Gas Journal* (Stell, 2000) with actual emission inventory estimates prepared by individual refineries.

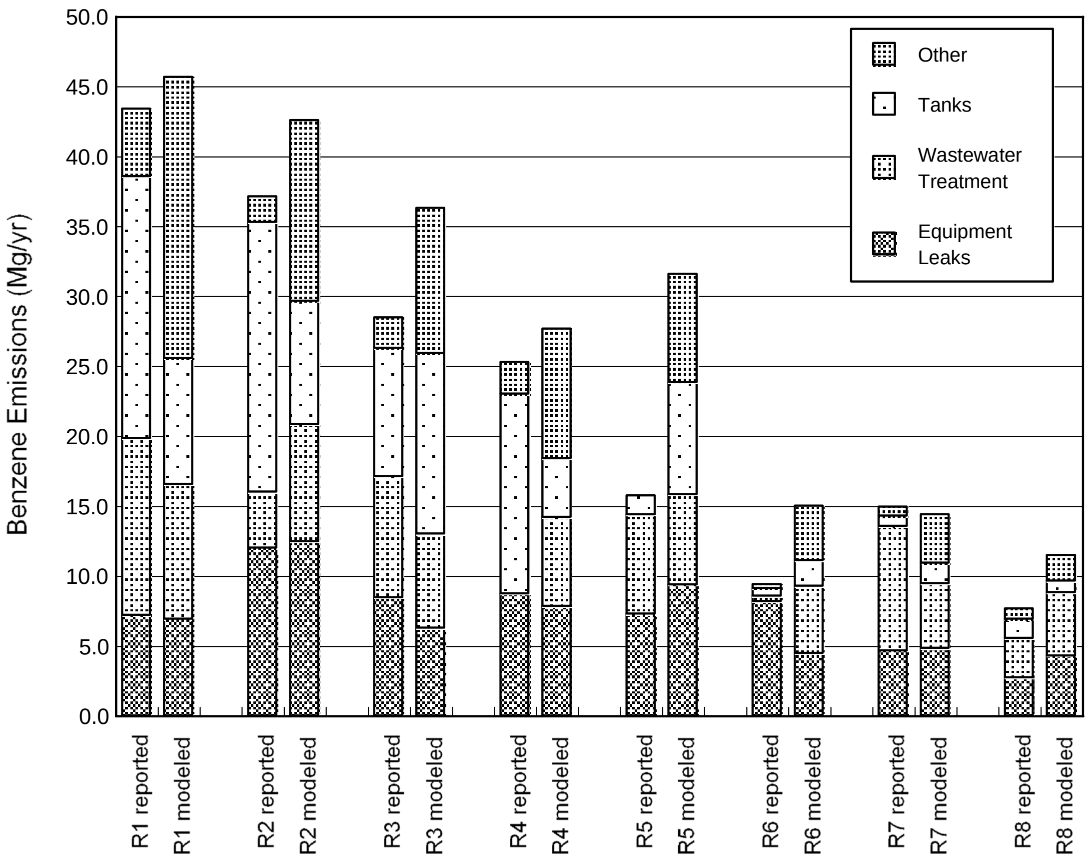

Figure 1. Comparison of RTI Model estimates with actual emission inventories prepared by individual refineries.

In general, the RTI Model provided benzene emission estimates that were within a factor of 2 of the reported emissions for each generalized emission source category (emission estimates for toluene and hexane exhibited similar agreement with reported values). Emission estimates for equipment leaks and wastewater treatment exhibited the best comparison with the reported values.[1]

For the most part, the tank emission estimates did not appear to have a particular bias, but the emission estimates for this source could vary widely from the reported emission estimates. These variations are a direct result of the assumptions used in the RTI Model when only process-capacity information is provided. For example, the tank emissions reported for Refinery 4 are much higher than those projected by the model. This discrepancy is caused predominately by emissions reported from three fixed-roof tanks at the refinery. The RTI Model, when used with only process-capacity information, assumes that all tanks with significant VOC content have floating roofs. These three fixed-roof tanks at Refinery 4 had a significant VOC and benzene loading and therefore higher tank emissions than projected by the RTI Model. On the other hand, the reported tank emissions for Refinery 5 are much lower than those estimated by the model. Refinery 5 operates an aromatics unit that produces toluene and xylene, but does not produce benzene as a product. The RTI Model, when used with only process-capacity information, cannot distinguish among specific aromatics produced in the aromatics unit. The default emission estimates are based on an aromatics unit that produces three aromatic products (benzene, toluene, and xylene). The RTI Model estimates roughly 5 Mg/yr of benzene emissions occur from the benzene product storage tanks. By simply specifying the aromatics produced by the aromatics unit, the resulting tank emissions for this refinery compare well with the reported values. These comparisons indicate how site-specific detail can be incorporated into the RTI Model inputs to provide more-refined emission estimates for a given refinery.

In every case, the RTI Model's estimates for "other" sources are higher than the reported emissions. The "other" sources include emissions from cooling towers, combustion sources, flares, and product-loading operations. Emissions from these sources were not always reported by the refineries in their permit applications. Therefore, it is uncertain if the

[1] Refinery 4 did not report any benzene emissions from the wastewater treatment system; it is unclear if the RTI Model overestimated these emissions or if the refinery underreported them.

emission estimates for "other" sources were overestimated by the RTI Model or underreported in these refinery emission inventories.

The RTI Model emission estimates for the overall refinery were within 30 percent of the reported values for 5 of the 8 refineries and were within approximately 50 percent of the reported values for all but 1 refinery. The emission estimates for Refinery 5 were off by a factor of 2. As discussed previously, this discrepancy is largely due to the lack of benzene product from the aromatics unit for this refinery. Although the tank emission estimates are affected most significantly by the specification of which aromatics are produced in the aromatics unit, the benzene emission estimates for some of the other emission sources (e.g., equipment leaks and wastewater treatment) are also reduced. By entering this one site-specific factor into the model, the RTI Model's estimated overall benzene emissions fall to within 50 percent of the reported emissions for all of the refineries.

The model validation comparisons suggest that the RTI Model is a practical tool for performing facility-wide emission inventories and developing emission estimates for use in risk assessments. Site-specific information can easily be incorporated into the model to provide more accurate emission estimates for a given refinery. The RTI Model outputs can also be used to identify sources that are major contributors to a refinery's air emissions, and this information can help facility managers and operators target cost-effective emission-reduction strategies.

The following case studies illustrate how the RTI Model has been applied to achieve a variety of environmental goals. Although the case studies themselves are hypothetical, they are based on data and characteristics adapted from an actual facility. All three case studies use the same facility, Refinery X, to demonstrate model applications. Case Studies 1 and 2 illustrate how the RTI model can be used to identify sources that are significant contributors to a refinery's emissions or risk level. Case Study 1 shows how the modeling tool can be used to identify primary sources of VOC emissions and identify effective emission-reduction projects to meet the refinery's emission-reduction goals. Case Study 2 shows how the RTI Model can be used to assess risk. These two case studies provide a contrast between an emission-reduction and a risk-reduction paradigm. For the same refinery, these two goals target completely different emission sources, and consequently, different control strategies. Case Study 3 shows how control-cost functions included within the RTI Model provide preliminary cost estimates that can be used to evaluate the cost-effectiveness of alternative control strategies.

Case Study 1. Detailed Refinery Analysis: VOC Emission-Reduction Goal

Introduction

In this case study, Refinery X sought to reduce its VOC emissions by 50 percent to meet ambient air standards. To achieve this 50 percent reduction in VOC emissions, the refinery had to identify cost-effective control options. In general, the process operations at Refinery X conform with the general assumptions used by the RTI model when estimating emissions from process-capacity data (see Table 1 for process unit capacities for this refinery). However, it has the following special features, which do not conform with the general assumptions:

- The facility has a few miscellaneous process vents (scrubber and stripper overheads, distillation tower condensers/accumulators, flash/knock-out drums, etc.) that have significant VOC emissions, but are uncontrolled.

- The facility has 3 fixed-roof tanks that have significant VOC loadings.

- The equalization basin in the facility's wastewater treatment area is uncovered.

Table 1. Process Data for Refinery X

Process Unit	Capacity (bbl/cd)
Crude	250,000
Vacuum Distillation	90,000
Coking	25,000
Catalytic Cracking	100,000
Catalytic Reforming	40,000
Catalytic Hydrotreating	110,000
Alkylation	40,000
Aromatics	15,000

Methods

The RTI Model was used to calculate emission estimates for this facility using the process capacities presented in Table 1 and the RTI Model default emission estimates for uncontrolled miscellaneous process vents. Additional emissions were estimated for the uncovered equalization basin using the RTI-developed WATER9 emission model (U.S. EPA, 2001). Next, to develop the VOC emission estimates for the refinery, the constituent-specific emission estimates provided by the RTI Model were summed for the volatile compounds. Table 2 lists the refinery-wide emission estimates provided by the RTI Model. These estimates show cooling towers, storage tanks, fugitive emissions, and miscellaneous (intermittent) process vents to be the primary sources of VOC emissions. To achieve the goal of reducing VOC emissions by 50 percent, strategies needed to be developed to reduce emissions from these sources.

Table 2. Refinery VOC Emissions Calculated by the RTI Model before the Emission-Reduction Project

Process Units	Initial VOC Emissions (Mg/yr)	VOC Emissions (% of total)
Catalytic Cracking Regenerator Vents	9.7	1.9%
Catalytic Reforming Regenerator Vents	0.1	0.02%
Cooling Towers	122.0	23.9%
Sulphur Recovery Units	2.9	0.6%
Storage Tanks	94.3	18.4%
Flares	28.0	5.5%
Process Equipment Leaks	114.1	22.3%
Process Heaters	6.9	1.3%
Wastewater Treatment Systems	40.9	8.0%
Miscellaneous Process Vents	92.3	18.1%
Total VOC Emissions	511.2	100%

According to the control strategy being considered for implementation, the RTI Model assumptions were revised to calculate new emissions estimates. These were then used in conjunction with engineering assessments to determine the emission reductions achieved by various control strategies. Costs associated with the various control strategies were estimated based on accepted control-cost algorithms developed by the U.S. Environmental Protection Agency (U.S. EPA, 1996, and U.S. EPA, 1992) and by vendor quotes. All cost estimates were calculated in 2001 U.S. dollars; a VOC recovery credit of $0.16 per kilogram of VOC recovered was used for all applicable emission sources.

Results

The emission-reduction strategies identified to achieve the 50 percent VOC emission-reduction goal are listed in Table 3. Table 3 also provides the emission reductions achieved by and the total annualized costs associated with each control strategy. The targeted strategies reduced the refinery's VOC emissions by more than 260 Mg/yr. The total annualized cost of the overall emissions-reduction project was $231,000/yr. The overall cost-effectiveness of the VOC emission-reduction project was $880/Mg of VOC reduced. The following paragraphs provide additional detail on each of the individual emission-reduction projects.

Table 3. Refinery VOC Emissions before and after the Emission-Reduction Project

Process Units	**Initial VOC Emissions (Mg/yr)**	**Emission-Reduction Strategy**	**Final VOC Emissions (Mg/yr)**	**Total Annualized Cost ($/yr)[1]**
Catalytic Cracking Units	9.7		9.7	-
Catalytic Reforming Units	0.1		0.1	-
Cooling Towers	122.0	Implement LDAR[2] program	14.6	62,800
Sulfur Recovery Units	2.9		2.9	-
Storage Tanks	94.3	Control/replace fixed-roof tanks	80.2	41,200
Flares	28.0		28.0	-
Process Equipment Leaks	114.1	Enhance LDAR program	60.5	77,000
Process Heaters	6.9		6.9	-
Wastewater Treatment Systems	40.9		40.9	-
Miscellaneous Process Vents	92.3	Control (flare) miscellaneous process vents	4.6	50,000
Totals	511.2		248.4	231,000
		Percent Emissions Reduction:	51.4%	

[1]All costs are presented in 2001 U.S. dollars.
[2]LDAR = leak detection and repair.

Cooling Towers. According to AP-42 (U.S. EPA, 1995), monitoring for hydrocarbons and fixing leaks when they occur can result in an 88 percent emission reduction from cooling towers. The total annualized cost for sampling and analysis associated with the monitoring protocol was $48,000/yr;[2] additional cost of labor and parts for repairing the leaks was estimated at $32,000/yr. The product recovery credit was estimated at $17,200/yr. Therefore, the net costs associated with a quarterly leak detection and repair (LDAR) program for heat exchangers was $62,800/yr, or $580/Mg VOC reduced.

Storage Tanks. Tank emission estimates are based on data correlations for typical tank farms that predominately employ floating-roof tanks. The RTI Model estimates the relative amounts of different types of liquid stored (either crude, aromatics, light distillates, or heavy distillates) based on the types and capacities of the processes used by the refinery. Once storage tanks are identified as a potential source of concern, more-detailed modeling of the tank farm emissions is made using site-specific data for individual tanks, to provide improved emission estimates and to identify appropriate control scenarios.

For the most part, Refinery X controls storage tank emissions using floating-roof tanks, but it also employs three 30-meter diameter fixed-roof tanks. Using site-specific data, the TANKS 4.09 software program (U.S. EPA, 1999) was used to provide tank-specific emission estimates for these fixed-roof tanks. The three tanks were estimated to contribute more than 15 Mg/yr to the VOC emissions total. Upgrading these tanks with internal floating roofs or venting the fixed-roof tanks to a common refrigerated condenser were both projected to reduce VOC emissions by 95 percent or more. The total annualized cost for upgrading the three tanks with internal floating roofs was estimated at $43,500/yr; the total annualized cost for installing a refrigerated condenser and venting the three fixed-roof tanks to the condenser was estimated at $143,000/yr. An annual credit of $2,300 was realized from the reduced VOC loss (or VOC recovered) with either option. Based on these costs, the control strategy of upgrading the three fixed-roof tanks with internal floating roofs was selected. Therefore, the net total annualized cost of the storage-tank control option was $41,200/yr, or the cost-effectiveness of the storage tank controls was $2,920/Mg VOC reduced.

Equipment Leaks. LDAR programs must define the frequency of monitoring, the value above which the equipment component is defined to be leaking, and the acceptable percentage of leaking components. The latter two values are optional input parameters to the RTI Model equipment leak algorithm and can be used to assess the emission reduction

[2] All dollar amounts are in 2001 U.S. dollars.

obtainable through different LDAR programs. Regulatory requirements often determine the frequency of monitoring, but a proactive LDAR program should vary monitoring frequency based on the monitoring results. If equipment leak criteria are exceeded, a higher frequency of monitoring is needed; if equipment leak criteria are consistently met, less-frequent monitoring is acceptable. For Refinery X, performing an LDAR that reduced the allowable percentage of leaking components by a factor of 2 (maintaining the current leak definition of 10,000 ppmv) was projected to reduce VOC emissions by 47 percent. The existing LDAR at the refinery used semiannual inspections. The proactive LDAR program used quarterly inspections and reverted back to semiannual monitoring when the percentage of leaking equipment fell below target levels for one year (four consecutive monitoring events). The added annual cost associated with the more stringent LDAR program was estimated at $85,600/yr and included costs for both more-frequent monitoring and more-frequent repairs. A recovery credit of $8,600/yr was realized from lower product loss through leaking equipment. Therefore, the net annual cost was $77,000/yr, or $1,440/Mg VOC reduced.

Miscellaneous Process Vents. Miscellaneous process vents include distillation tower condensers/accumulators, flash/knock-out drums, scrubber and stripper overheads, and vents from blowdown condensers/accumulators. Large miscellaneous process vents are generally controlled by a flare or by venting the gas to the refinery fuel gas system, depending on the vent stream composition. However, small miscellaneous process vents may vent directly to the atmosphere. The uncontrolled miscellaneous vents are characterized based on size, VOC content, and proximity to an existing flare system to identify specific vent streams with a sufficient heating value that could be easily controlled. For Refinery X, approximately 90 Mg/yr of the VOC emissions were attributable to uncontrolled process vents that were amenable to control. The VOC control efficiency of flaring was assumed to be 98 percent. Costs associated with the project included knock-out drums, piping, and one 2.5-centemeter diameter flare. Total annualized costs for the system were estimated at $50,000/yr, or $570/Mg VOC controlled.

The refinery-wide emission inventory provided by the RTI Model enabled primary sources of VOC emissions to be identified, which then allowed appropriate emission-reduction strategies to be targeted to achieve the desired goal. In the end, total VOC emissions were reduced by more than 260 Mg/yr at a total annualized cost of $231,000 (see

Table 3). The overall cost-effectiveness of the VOC emission-reduction project was \$880/Mg VOC reduced.

Case Study 2. Detailed Refinery Analysis: Risk-Reduction Goal

Introduction

In this case study, Refinery X was evaluated to show how the RTI Model could be used to assess risk. This time, the refinery sought to identify cost-effective control options for reducing its cancer risk to humans to below 10^{-6}. The refinery emissions were the same as in Case Study 1, but the focus was now the potency of the individual constituents emitted and the proximity of the emission sources to the most-exposed individual (MEI). The RTI Model was developed specifically to output emissions data and source characterization data for input into a risk assessment model. RTI has the capability to perform multipathway risk assessments using its multimedia, multipathway, multireceptor risk assessment (3MRA) model and its multipathway risk assessment tool (MPRAT). These modeling tools were developed in conjunction with EPA and have been subject to peer review. For this case study, however, only inhalation exposure was evaluated.

Methods

The Industrial Source Complex Short-Term Model, version 3 (ISCST3), was used to calculate dispersion factors based on a unit emission rate (1 $g/m^2/sec$ for area sources and 1 g/sec for point sources). This model is a standard, EPA-approved model for predicting atmospheric dispersion and deposition of chemical species up to 50 km from the source. Cancer risks were calculated using the health benchmarks from EPA's Integrated Risk Information System (IRIS).

In modeling emissions and dispersion from the tank farm, tanks were modeled together as one large area source rather than separately as individual sources. Similarly, process fugitives (equipment leaks) were treated as one large area source within the processing area of the refinery. Wastewater treatment emissions were divided into two area sources: one area source within the processing area of the refinery for the wastewater collection system and one area source for all wastewater treatment units in the wastewater treatment area. The default algorithm developed to estimate emissions from wastewater in the RTI Model assumes that wastewater systems that have benzene loadings of 9 Mg/yr or more apply suppression controls (e.g., water seals on each drain; enclosed or covered sewer lines) for the wastewater collection systems until the point of treatment (e.g., by activated sludge or steam stripping). The default algorithm further assumes that the total emissions estimated from the wastewater collection and treatment system are evenly distributed between the wastewater collection system (an area within the process equipment area) and the wastewater treatment system.

Refinery X employs an open equalization tank in its wastewater treatment system. Therefore, the RTI Model emission estimates for the wastewater treatment plant were augmented by a more-detailed analysis of the wastewater treatment emissions. RTI, in conjunction with EPA, developed the WATER9 emission model (U.S. EPA, 2001). This model can estimate emissions from the point of generation through the collection and treatment system. For the preliminary analysis, emissions from the equalization tank were calculated using WATER9 based on the loading rates estimated by the RTI Model, and these emission estimates were used for the wastewater treatment area.

Emission contributions from the land application area, used to treat tank bottoms and waste solids from the wastewater treatment system, were also added because of the proximity of the land application unit to the receptors. These emissions were estimated using CHEMDAT8, another emission model developed by RTI in conjunction with the EPA (U.S. EPA, 1994).

Results

Figure 2 provides a plot layout of Refinery X and the receptors (i.e., occupied homes) surrounding the refinery. RTI used its digital geographic information systems (GIS) capabilities to map land use and census data to identify receptors for the risk analysis. Based on these data, the nearest residential receptors were to the east of the refinery. No other receptor or group of receptors exhibited cancer risk above 10^{-6}.

Based on the direct inhalation pathway, benzene was the only constituent that provided risk levels exceeding 10^{-6}. Benzene emission results are presented in Table 4 along

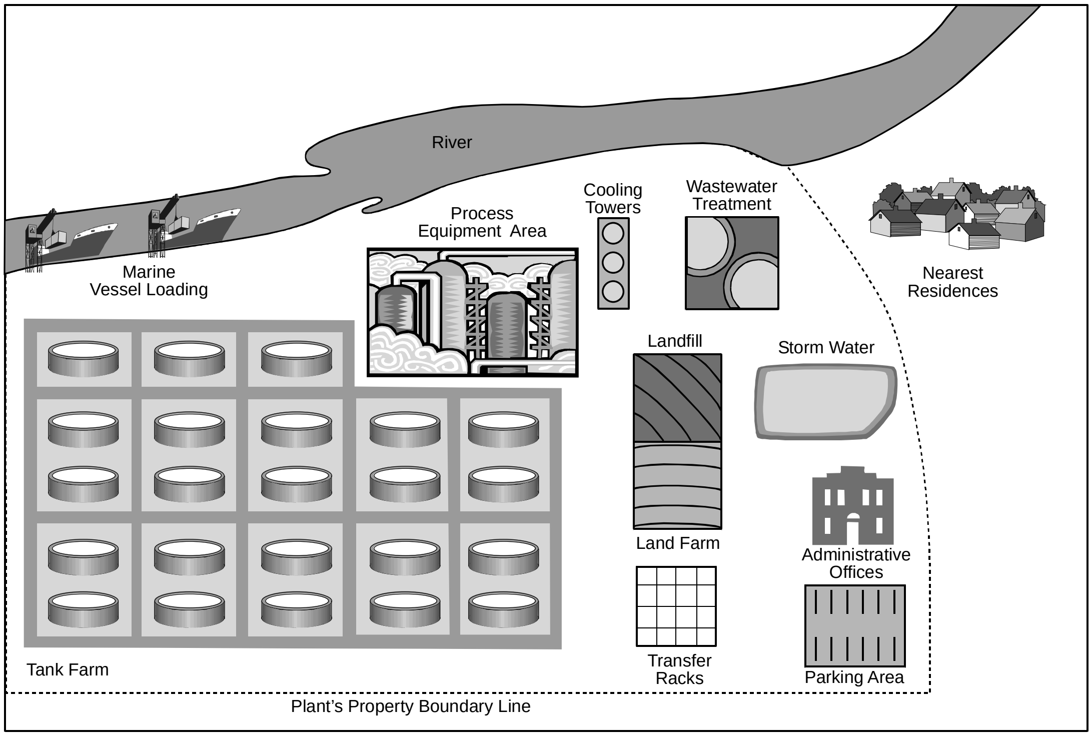

Figure 2. Plot Layout for Refinery X.

Table 4. Summary of Source Contributions to Cumulative Cancer Risk

Emission Sources	Benzene Emissions (Mg/yr)	Source Type	Area Source Size (km^2)	Distance to Nearest Receptor (km)	Dilution Factor ($\mu g/m^3$ per $\mu g/m^2/s$)[a]	Cancer Risk	% of Total Cancer Risk
Cooling Towers	6.8	Area	0.005	1.6	0.0003	1.05E-07	1.82%
Storage Tanks	12.9	Area	3.16	3.5	0.0518	5.27E-08	0.91%
Fugitive Emissions	6.3	Area	0.743	2.4	0.0514	1.09E-07	1.89%
Wastewater Collection Systems	3.1	Area	0.186	2.4	0.0057	2.36E-08	0.41%
Wastewater Treatment Systems	10.1	Area	0.186	1.0	0.4	5.42E-06	93.95%
Land Application Units	0.3	Area	0.10	1.8	0.02	1.25E-08	0.22%
All Vent Sources	6.1	Point	n/a	2.4 to 5	0.03[a]	4.56E-08	0.79%
Cumulative Cancer Risk for the MEI:						5.77E-06	

[a] The dilution factor for point sources has units of $\mu g/m^3$ per g/s of emission. The dilution factor varied based on distance and vent characteristics; a representative value is provided.

with the distance from the emission source to the nearest receptor, or more specifically, to the MEI. Table 4 also provides some source characterization data and the contribution made to the total risk by each emission source.

The risk-reduction paradigm had a completely different focus than the VOC emission-reduction paradigm. In this case, the wastewater treatment system completely dominated the risk results because of the proximity of the wastewater treatment system to the residential neighborhood. To reduce the cancer risk incidence to the MEI to less than 10^{-6}, the benzene emissions from the wastewater treatment system had to be reduced to 1.21 Mg/yr or less, an 88 percent emission reduction.

Based on the site-specific benzene concentration in the inlet wastewater and more-detailed modeling of the wastewater treatment system with WATER9, it was determined that covering the equalization basin would not sufficiently reduce the benzene emissions from the wastewater treatment system. Even when using site-specific biodegradation rate constants in WATER9, the existing wastewater treatment system could not sufficiently reduce the emissions below the desired levels.

The alternatives remaining were to convert the existing wastewater treatment system to a powdered activated carbon treatment (PACT) system or to install a steam stripper. Based on the Henry's law constant for benzene (a measure of the volatility of a compound in dilute aqueous solution), the removal efficiency of the steam stripper for benzene should exceed 98 percent. As such, the steam stripper was considered the more reliable technology for this application to achieve the desired level of emissions control. The capital investment and annual operating costs to pretreat all of the refinery wastewater (roughly 7,500 m^3/day) were estimated at $4.5 million and $2.75 million, respectively.

In an effort to reduce the project costs, a third alternative was devised to segregate certain wastewater streams from the crude unit, the coker, the reformer, and the aromatics unit for pretreatment with the steam stripper, and to install a cover on the equalization basin. Based on the RTI Model estimates, these units accounted for roughly 75 percent of the refinery's benzene loading to the system in less than one-half the volume of wastewater currently generated by the refinery. The emission reductions effected by a steam stripper for these wastewater streams, coupled with the emission reductions achievable by covering the equalization basin, achieved the necessary 88 percent reduction in benzene emissions from the wastewater treatment system. Although the capital investment of this third alternative was roughly equivalent to the cost of the large steam stripper, the annual operating costs were reduced by $1.4 million compared to steam stripping all of the refinery's wastewater. Application of the RTI Model helped to identify a more cost-effective means of achieving the desired risk-reduction goal.

Case Study 3. Compliance with Particulate Matter Standards

Introduction

In this case study, Refinery X sought to identify cost-effective regulatory compliance strategies for the fluid catalytic cracking unit (FCCU) catalyst regenerator vent. The FCCU catalyst regenerator burns off coke that is deposited on the catalyst during the cracking process. The FCCU catalyst regenerator is the primary source of particulate matter (PM) emissions from a refinery; nickel (Ni) emissions associated with this vent stream are a potential concern with respect to human risk. The FCCU catalyst regenerator may also be a significant contributor to sulfur oxide (SO_x) emissions. Depending on the location of the refinery, the refinery may be subject to PM, Ni, and/or SO_x emission limits from the FCCU catalyst regenerator vent or subject to PM and SO_2 concentration limits at the fence line. This case study specifically evaluated alternative control strategies with respect to meeting a PM emission limit of 50 mg/m^3 from the FCCU catalyst regenerator vent.

Given the premise of this case study, the RTI Model was not needed to identify the primary source of emissions to target emission-reduction strategies. Instead, the regulatory statute dictated the emission source to be controlled. For the most part, cost analyses are performed for specific applications using site-specific parameters. Some generalized costing algorithms are, however, included in the RTI Model. This case study also serves to illustrate how costing algorithms are used in the RTI Model to provide preliminary cost estimates.

Refinery X's FCCU, which has a capacity of 100,000 bbls/cd, is a complete combustion unit with an average coke burn rate at capacity of 28 Mg/hr (62,000 lbs/hr). The FCCU catalyst regenerator flow rate was estimated to be 340,000 standard m^3/hr at full capacity (standard conditions used here were 1 atmosphere and 20°C). Current exhaust-stream PM concentrations ranged from 500 to 1,000 mg/m^3. After energy recovery, the exhaust temperature was approximately 260°C (500°F).

Methods

Based on the desired level of PM control, candidate control options included an electrostatic precipitator (ESP), a venturi scrubber, and a baghouse. Tertiary cyclones on the FCCU regenerator vent were not capable of achieving the desired outlet PM concentration and were therefore not considered in this case study. Baghouses have not historically been used for the control of PM emissions from the FCCU because of concerns regarding baghouse maintenance and ability to endure process upsets. There is only one baghouse used to control FCCU emissions in the United States as part a spray dryer adsorption system. However, based on the application of baghouses in the steel and utility industries for exhaust streams with similar temperature, grain loading, and particle sizes, baghouses appeared applicable to the FCCU, especially for units with well-controlled regenerator combustion characteristics.

Given that exhaust stream PM concentrations range from 500 to 1,000 mg/m^3, design control efficiencies of 95 percent or better were required. The exhaust temperature of 260°C (500°F) at the inlet of the control device was near the upper range for operating temperatures for the baghouse control system. The capital costs were based on the use of 316 stainless steel as the material of construction for all control systems. A retrofit cost factor of 1.35 was applied to all capital equipment costs.

ESP costs were developed based on a design control efficiency of 95 percent. The design algorithms in the Office of Air Quality Planning and Standards (OAQPS) *Control Cost Manual* (U.S. EPA, 1996) were used, which yielded an ESP with a specific collection area (SCA) of 98 s/m (500 ft^2/kacfm). This SCA agrees well with the SCA of the best performing ESPs in the refinery industry.

The venturi scrubber was also designed to achieve a 95 percent control efficiency. The costing procedures outlined in EPA's *Handbook—Control Technologies for Hazardous*

Air Pollutants (U.S. EPA, 1991) were used to develop costs for venturi scrubbers. The projected pressure drop across the scrubber was estimated to be 30" of water.

The baghouse is anticipated to achieve a PM removal efficiency of 99 percent or higher. The baghouse was designed as a modular pulse-jet unit with an air-to-cloth ratio of 55 m/hr (3 ft/min). Because of the operating temperature of the control system, fiberglass was selected as the fabric material for the filter bags. Costing procedures followed guidance presented in the *Control Cost Manual* (U.S. EPA, 1996).

Given the control device design parameters, control costs were developed for 6 different exhaust flow rates from 25,000 to 340,000 standard m^3/hr. Control-cost curves were developed using linear regression analyses for the total capital investment and the annual operating costs.

Results

Figures 3 and 4 provide the control-cost curves developed for ESPs, venturi scrubbers, and baghouses. The total annualized costs were calculated for each control device based on a capital recovery factor of 0.0944 (based on 20-year equipment life and a 7% annual interest rate). The total annualized costs are presented in Figure 5.

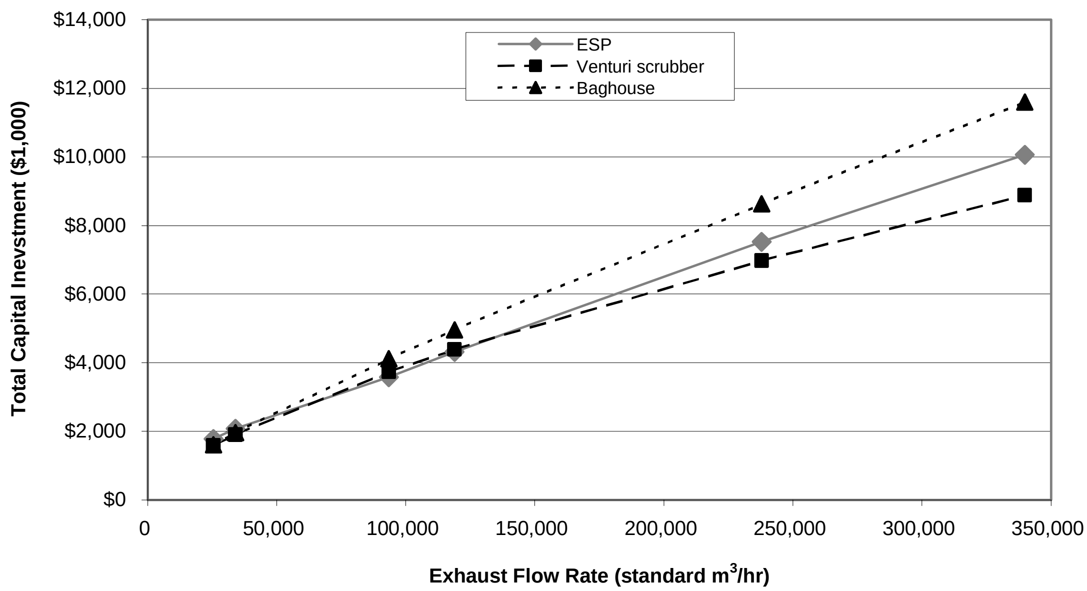

Figure 3. Comparison of total capital costs for candidate PM control devices.

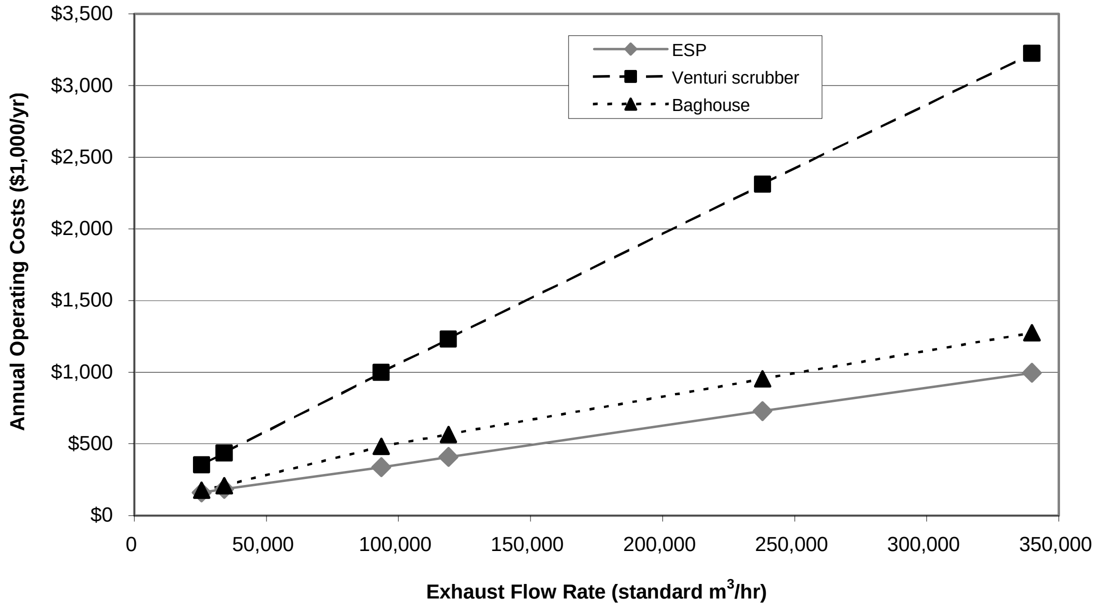

Figure 4. Comparison of annual operating costs for candidate PM control devices.

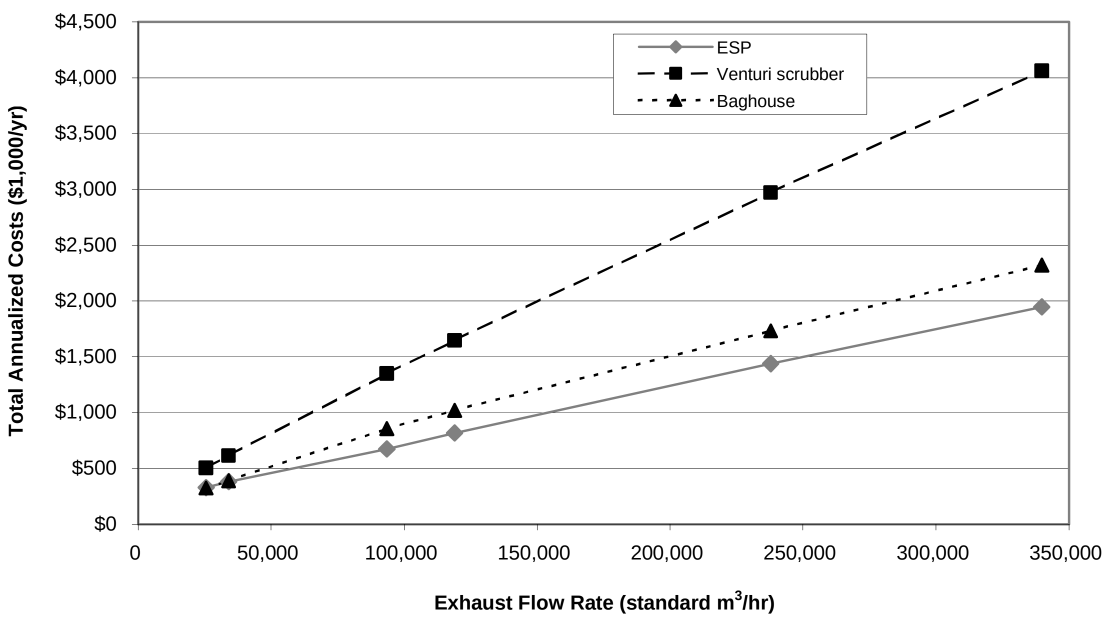

Figure 5. Comparison of total annualized costs for candidate PM control devices.

These control-cost curves were developed based on typical characteristics of the FCCU vent stream. Site-specific conditions have to be considered in developing detailed cost analyses for a particular unit. However, these cost functions provide a mechanism with which the RTI Model can output preliminary cost estimates for various control scenarios, and, consequently, they provide an easy mechanism to evaluate the cost-effectiveness of candidate control options. These cost curves indicate that ESPs are the most cost-effective means of controlling PM emissions, followed closely by baghouses. The cost curves for the baghouse and ESP are so close together that the baghouse may be considered for further analysis. However, based on the limited experience of baghouses controlling FCCU regenerator vent emissions, an ESP was the control device of choice for this case study. The relative cost-effectiveness of these control devices is likely to shift if SO_x emission control is also needed or if more stringent PM standards are imposed.

For the 100,000 bbl/cd FCCU with a maximum air flow rate at capacity of 340,000 standard m^3/hr in this case study, the total capital equipment cost of the ESP was estimated at $11.6 million/yr and the total annualized costs were estimated at just under $1.95 million/yr. The PM emission reduction was estimated to be 2,100 Mg/yr for a cost-effectiveness of $930/Mg PM reduced.

Conclusions

These case studies illustrate how the RTI Model is a versatile tool that can be used to assist refinery owners and operators in achieving a variety of environmental goals. Case Studies 1 and 2 illustrate how the RTI model can be used to identify sources that are significant contributors to the refinery's emissions or risk level. These two case studies provide a contrast between an emission-reduction and a risk-reduction paradigm. Case Study 1 shows how the modeling tool can be used to identify cost-effective emission-reduction projects to meet the refinery's VOC emission-reduction goal. Case Study 2 shows how the RTI Model can be used to identify cost-effective emission-reduction projects to meet the refinery's risk-reduction goal. Even though the same refinery was used in both of these case studies, the different goals resulted in significantly different control strategies. Case Study 3 shows how control-cost functions included within the RTI Model provide preliminary cost estimates that can be used to evaluate the cost-effectiveness of alternative control strategies for a particular emission source.

The RTI Model is a unique tool that can be used with a minimum of process data to develop emission inventories, identify primary sources of chemical-specific emissions, and provide input for refinery risk assessments. Additional site-specific process information can be entered into the model to provide more accurate emission inventories or risk assessments. When combined with control-cost analyses, the RTI Model provides an excellent tool for developing cost-effective control strategies.

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