USING RELATIVE RISK ANALYSIS TO SET PRIORITIES FOR POLLUTION PREVENTION AT A PETROLEUM REFINERY

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I. Introduction

In 1989, the Amoco Corporation (Amoco) and the U.S. Environmental Protection Agency (EPA) began a voluntary, joint project to identify opportunities for preventing pollution at the Amoco refinery at Yorktown, Virginia. The project produced one of the most detailed release inventories ever assembled for a major petrochemical facility and identified several previously unrecognized opportunities for significant pollution prevention. More importantly, perhaps, the study raised questions about the cost effectiveness of current government policies for regulating pollution and the barriers they may present to implementing cost-effective prevention strategies. It also suggested potential improvements in technical methods for inventorying refinery emissions and facility management and design.

The study provides both the practicing chemical engineer and the student engineer considering a career in industry or government with important insights into the technical and policy challenges posed by pollution prevention. In particular, it is food for thought for engineers who increasingly find themselves involved in policy or regulatory development and implementation.

This paper also serves as a resource guide for similar future efforts. It identifies tools that engineers may need to accomplish the following:

- Determine sampling and monitoring requirements to fully inventory environmental releases to all media.
- Select sampling methodologies and protocols.
- Include science and technology in a consensus-building process that utilizes the inputs of the entire stakeholder community.
- Rank and weight criteria allowing such diverse elements as costs, tons of releases, environmental impacts, public perceptions, and political factors to be quantitatively assessed.

II. Summary

In late 1989, Amoco and the EPA began a voluntary, joint project to identify opportunities for preventing pollution at an Amoco refinery located along the York River at Yorktown, Virginia. The two-year, $2.3 million study (70% Amoco and 30% EPA funding) involved more than 200 participants from Amoco, government agencies, educational institutions, environmental organizations, and the public.

The study focused on four major tasks:

1. Developing a detailed refinery release inventory that identified sources and quantities of releases.
2. Identifying options for preventing releases and minimizing health and environmental risks.
3. Developing a system for evaluating and ranking the options in light of cost, risk, regulatory requirements, and other factors.
4. Evaluating the incentives and obstacles to implementing the pollution prevention options.

A. Developing a Detailed Refinery Release Inventory

To develop the detailed release inventory, a study team reviewed results from the refinery's monthly mass balance calculation (inputs minus outputs), studied records maintained for compliance with state and federal laws, and undertook a massive sampling program. Mass balance calculations indicated that the refinery had releases of 8400 tons per year. In contrast, compliance records—which cover only those emissions regulated by state or federal law—documented smaller quantities. In addition, emissions of substances covered by the federal Toxic Release Inventory (TRI) were reported to be 371 tons in 1989—or 23 times less than the emissions indicated by the mass balance calculation.

To obtain a more accurate inventory of the refinery's releases, the study team undertook a massive sampling program. Almost 1000 samples of air, groundwater, surface water, soils, and solid waste were collected and analyzed; the database generated by this effort represents one of the most detailed emissions inventories ever assembled for a major petrochemical facility.

Based on results from the sampling program, the study team estimated that the refinery generated 27,500 tons/year of waste materials. Airborne emissions accounted for almost half of the total: 48% (13,200 tons). Solid waste accounted for 29% (8100 tons), surface water pollutants 14% (3700 tons), and biosolids from wastewater treatment 9% (2400 tons).

Roughly half of all wastes generated—44% (12,100 tons)—were reused, recycled, or recovered on the refinery site; 56% (15,400 tons) left the refinery. Of the materials leaving the refinery, more than half—51% (7900 tons)—were non-methane airborne hydrocarbons; 37% (5700 tons) were airborne criteria pollutants such as SO_2, NO_x, CO, and particulates; 11% were materials disposed of on land (1700 tons); and 0.3% (50 tons) were waterborne substances.

The sampling further revealed the following:

- The refinery's existing water treatment plant was very effective in removing waterborne contaminants, with overall removal efficiencies greater than 99% for most organics and inorganics. Except for methyl tertiary-butyl ether (MTBE), most contaminants were not detectable in the treated effluent discharged into the York River.
- The treated effluent discharge contained 50 tons/year of suspended solids and other material. This is 10% of the amount permitted under the refinery's National Pollutant Discharge Elimination System (NPDES) permit (required under the Clean Water Act).
- At the plant boundary, concentrations of benzene—a chemical of concern due to the risk it poses to human and ecological health—were similar to those measured in rural environments; at a residence near the refinery, benzene concentrations were similar to those measured in remote environments.
- Groundwater contamination was significantly less than that documented at other refineries. In part, this finding can be explained by a combination of the original refinery construction methods (atypical of most older refineries), lack of petroleum spills, and the passive action of the refinery's underground sewer system, in which groundwater collects and flows to the wastewater treatment plant.
- The plant released 900 tons of substances covered by the TRI—or 2.4 times more than the plant reported in 1989. Blowdown stacks, whose contribution to releases was previously unknown, accounted for 430 tons of TRI releases; barge loading accounted for 165 tons, although they are not required to be reported under TRI regulations.

B. Identifying Options for Reducing Releases

Having quantified the refinery's releases and identified major sources, the study team began to identify options for reducing releases and minimizing the environmental and human health risks they might pose. In March 1991 the project sponsored a three-day workshop to assist in option identification and development. It involved more than 120 representatives from EPA, Amoco, the Commonwealth of Virginia, academic, environmental and consulting organizations, and the public.

In developing pollution prevention options, workshop participants considered strategies for source reduction (preventing the creation of emissions), recycling, reuse, treatment, and—in the least attractive case—disposal. Overall, 50 distinct options for preventing emissions were identified. Twelve of these options were selected for more detailed analysis. Those chosen were felt to (1) be feasible with current technology, (2) offer significant potential for emissions reductions, (3) have manageable (or no adverse) impact on worker safety, (4) be amenable to more quantitative analysis in the time available, and (5) address concerns in different environmental media.

C. Evaluating and Ranking the Options

A variety of factors and methods were used to evaluate and rank the twelve options. For example, the study team considered the reduction in relative risk to human health achieved by different options. Generally, an option's effectiveness in reducing health risks was evaluated by calculating its effect on exposure to benzene emissions. The study team selected benzene emissions as an indicator because benzene can be found in all waste media (air, water, groundwater, and surface water) and poses a known threat to human health.

Thirteen other factors were also considered in evaluating each option: (1) capital costs, (2) operating and maintenance costs, (3) liability cost rating, (4) timeliness, (5) transferability, (6) revenues, (7) equivalent annual costs, (8) pollution prevention mode, (9) net release reduction, (10) recovery costs, (11) cost effectiveness, (12) resource utilization, and (13) effects of secondary emissions. Finally, data from public opinion polling in the community near the refinery were considered in evaluating potential public support or opposition to different pollution prevention strategies.

1. Ranking Methodologies

A variety of methodologies were employed to rank the twelve options. They included single criteria rankings, multiple criteria rankings and the analytical hierarchy process (AHP) using ranking and weighting criteria. An AHP analysis was performed to compare how the options ranked from both an industry and a regulator's viewpoint. Despite assigning different weights to the AHP ranking criteria, both groups identified the same first choice option for pollution prevention: reducing emissions during barge loading. Implementing this option, which would produce a 55% reduction in benzene exposure, received a score that was two times greater than the next best option.

Overall, five options received generally high rankings: (1) reducing emissions during barge loading, (2) installing secondary seals on storage tanks, (3) upgrading blowdown stacks, (4) reducing soil intrusion into the drainage system, and (5) instituting a periodic leak detection and repair program.

2. *Evaluating Costs and Benefits*

After evaluating the costs and benefits of various options, the study team concluded that implementing options that received high rankings could achieve lower cost pollution prevention than options that are mandated by current law. Existing mandates, for example, will require the refinery to install specific technologies to implement eight of the identified pollution prevention options; this will reduce releases by 7300 tons per year at an annual cost of $17.5 million—or $2400/ton or $8.88/gallon. In contrast, implementing the five high-ranked options (four of which are required by current or anticipated rules) would reduce releases by 6700 tons per year at an annual cost of $2.2 million—or $328/ton or $1.21/gallon, thereby achieving more than 90% of the pollution reduction at 14% of the cost of all the mandated options.

When reducing benzene emissions was considered to be the primary goal, the study team calculated that six high-ranked options together reduced benzene exposure by 90% at an annual cost of $4.5 million. This was only 20% of the annual cost of all the options mandated by regulation.

3. *Evaluating Obstacles and Incentives*

The study team examined current obstacles to and incentives for implementing five of the highly ranked options. At least three major obstacles were identified: (1) limited resources, (2) poor economic return, and (3) regulatory disincentives. The study team concluded that these obstacles create a formidable constraint on implementing pollution prevention strategies that go beyond current regulatory requirements.

D. Discussion of Findings

The effort to identify options for pollution prevention at Amoco's Yorktown refinery provided important insights into both technical and policy issues.

In the technical arena, for example, the project highlights how little may be known about the true quantities and sources of emissions at major petrochemical facilities. It underscores the limitations of using existing measures, such as mass balance calculations and regulatory compliance records, to calculate releases from a major industrial facility. It also emphasizes the need for continued innovation in developing technologies for pollution prevention and new methods for evaluating their effectiveness in reducing health and ecological risks.

In the policy arena, project results suggest that current regulatory requirements may ignore major emissions sources and actually hinder—not promote—the implementation of cost-effective pollution prevention strategies. It suggests that current government efforts to develop alternatives to "command and control" regulatory systems, which mandate specific pollution control technologies, should be encouraged. Establishing programs that incorporate incentives or market-based systems that allow industries and facilities flexibility to achieve environmental performance goals will make the best use of limited resources, encourage innovation, and foster technology development.

Finally, the project highlights the progress that can occur in identifying creative, cost-effective options for pollution prevention when government, industry, and the public establish partnerships rather than operate as adversaries. While each sector of society may have a different perspective on the challenge of preventing pollution, techniques for developing and evaluating potential solutions can often help the parties identify unexpected areas of agreement and establish a common ground for moving forward.

III. Background

Amoco's Yorktown refinery, which began operations in 1956, has a processing capacity of 53,000 barrels/day. Currently, the refinery manufactures gasoline, heating oil, LPG, sulfur, and coke. The refinery is located on the York River in Yorktown, Virginia, near the Chesapeake Bay. The refinery was selected as the study site because it uses "typical" refinery processing technology, is located in an environmentally sensitive area, and is small enough to allow for a relatively complete inventory of emissions during the two-year time frame allotted for the study. The refinery's proximity to Washington, D.C., also allowed easy access by federal agency officials involved in the project.

During the course of this project, more than 100 EPA and Commonwealth of Virginia regulatory personnel visited the refinery for a first-hand view of operations and practices. Figure 1 provides a schematic flowchart of the refinery and illustrates potential releases to all environmental media (air, land, surface water, and groundwater).

The study was designed to assess comprehensively the refinery's releases to all environmental media (i.e., air, water, land, etc.), and then develop and evaluate options for reducing these releases.

A study team identified five specific tasks required to complete the project:

1. Inventory refinery releases to the environment to define their chemical type, quantity, source, and medium of release.

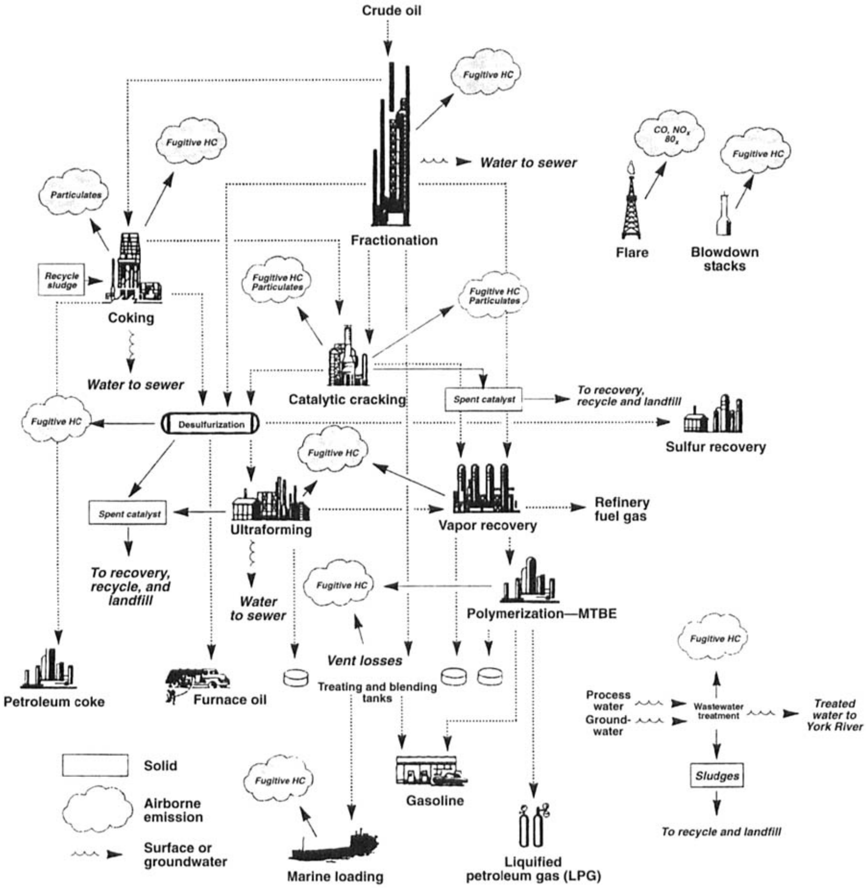


FIG. 1. Yorktown refinery.

2. Develop options to reduce selected releases.
3. Rank and prioritize the options using a variety of criteria and perspectives.
4. Identify and evaluate factors that impede or encourage the implementation of pollution prevention strategies.
5. Enhance participants' knowledge of refinery and regulatory systems.

When the project began, pollution prevention was a concept predicated on reducing or eliminating releases of materials into the environment rather than managing the releases later. The project adopted this general concept but considered all opportunities—source reduction, recycling, treatment, and environmentally sound disposal—as potential methods for pollution management. Since then, Congress, in the Pollution Prevention Act of 1990, and other organizations have put greater emphasis on source reduction as the primary, if not exclusive, means to accomplish pollution prevention.

A necessary requirement of the project was to identify evaluation criteria and develop a system for ranking opportunities for pollution prevention at the Yorktown refinery. It was important that the system recognize such factors as release reduction potential, technical feasibility, cost, environmental impact, human health risk, and risk reduction potential. Due to the inherent uncertainties in risk assessments, the project focused on relative changes in risk compared to current levels, rather than establishing absolute risk levels. Because of difficulties in quantifying changes in ecological impact from airborne emissions, changes in relative risk were based primarily on human health effects indicated by changes in exposure to benzene.

This project focused on normal refinery operations; it did not directly consider options for minimizing emergency events—although this a high priority of Amoco's facility managers—because (1) prevention and control of such events involves significantly different skills, technical resources, and analyses than controlling releases from day-to-day operations (AIChE, 1985); (2) the number, type, and frequency of incidents at Yorktown had been very low; and (3) adequate meteorological and emissions data from emergency releases were not available.

IV. Assembling the Inventory of Refinery Releases

Pollution prevention cannot be adequately implemented or monitored for effectiveness unless facility operators and regulators know what is being released from the facility and its origin. Therefore one of the study team's first tasks was to assemble a detailed inventory of releases from the refinery. At the start of the project, information on all of the refinery's release sources was not available. This was understandable, considering that complex industrial sources such as the refinery contain hundreds, sometimes thousands, of potential release points. It is technically difficult and impractical to monitor and measure each of these points.

Instead, government regulatory systems—such as those established by the Clean Water Act or Resource Conservation and Recovery Act (RCRA)—require refineries and other facilities to monitor and measure releases from a few specific points, such as the end of a discharge pipe, or in specific media, such as groundwater. As a result, monitoring resources are typically allocated to meet permit requirements rather than to measure releases at the point of generation.

To bridge the gaps in existing data, the study team designed and carried out a multimedia sample collection and analysis effort. This sampling program differed from many existing regulatory programs, which dictate the kinds of compounds or mixtures to be reported. Instead, each medium was sampled for selected chemicals such as benzene, toluene, ethylbenzene, and xylene (BTEX), as well as for particular chemical species expected to be present in specific media, such as metals and polynuclear aromatics. One goal was to identify specific chemicals present in all media, both within the refinery and entering the environment beyond the refinery property line.

About 1000 separate samples were collected during the program. They provided the first major database showing all releases from a single facility into all environmental media at one point in time. Figure 2 shows the sample distribution by media, excluding duplicates and field banks required for quality assurance/quality control purposes. The probable accuracy of most measurements is +100 tons/year.

A. Distribution of Releases within the Refinery

Sampling data indicated that the refinery generated an estimated 27,500 tons/year of materials that reached all four environmental media—air, surface water, groundwater, and land. Figure 3 summarizes the generation of pollutants prior to any internal recycling, transfer, or disposal.

Airborne emissions accounted for 48% of the total; solid waste 29%; and surface water 14%. In addition, biosolids from wastewater treatment accounted for 9% of solid wastes. However, the quantity and distribution of the pollutants among the media can shift, depending on natural conditions and the operation of pollution management systems designed for materials recovery and regulatory compliance.

Figure 4 shows how the releases just described were managed in the refinery. About 44% of the material generated did not leave the facility; it was handled onsite through treatment, recovery, and recycling.

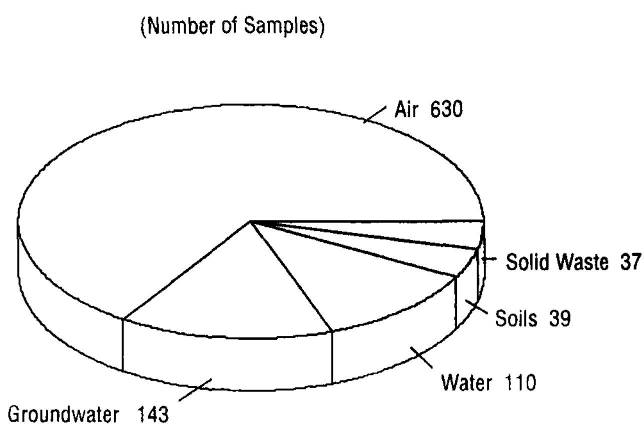


FIG. 2. Pollution prevention sampling program.

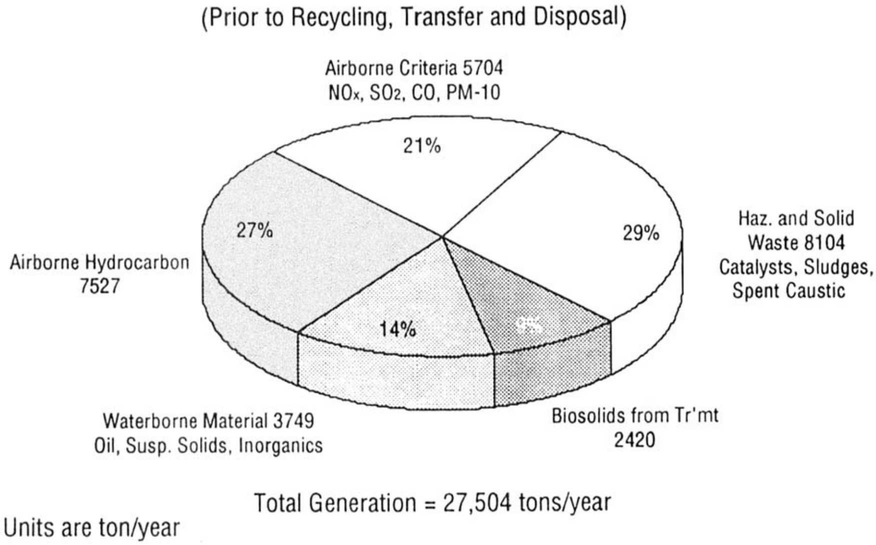


FIG. 3. Pollutant generation within the Yorktown refinery.

1. Water

Wastewater flows to the oil/water separator, where an average of 2700 tons/year of oil (about 50 barrels per day) was recovered and recycled. A small amount of groundwater was also recovered by the drainage system and mixed with process wastewater. The activated sludge wastewater treatment system generated 2400 tons/year of biosolids, which were ultimately recycled on-site with other solid and hazardous wastes. Treated effluent discharged to the York River contained about 46 tons/year of suspended solids and other material. This discharge is normally about 10% of the amount permitted under the refinery's NPDES permit; under infrequent upset conditions, however, the discharge may approach permit limits.

2. Solid and Hazardous Wastes

Spent caustic (3800 tons/year) is sent off-site for recovery of remaining caustic value and naphthenic acids. Most catalysts are recycled for recovery of additional activity or metals. Spent cracking catalyst (600 tons/year) is sent to Amoco's Whiting, Indiana, refinery for use as equilibrium catalyst. Spent ultraforming catalyst is returned to metals reclaimers to recover platinum for reuse in new catalyst. Spent desulfurization catalyst and polymer catalyst are nonhazardous and are buried in an on-site landfill. Sludges from the oil/water separator are a listed hazardous waste under RCRA regulations. They are combined with other solid wastes, such

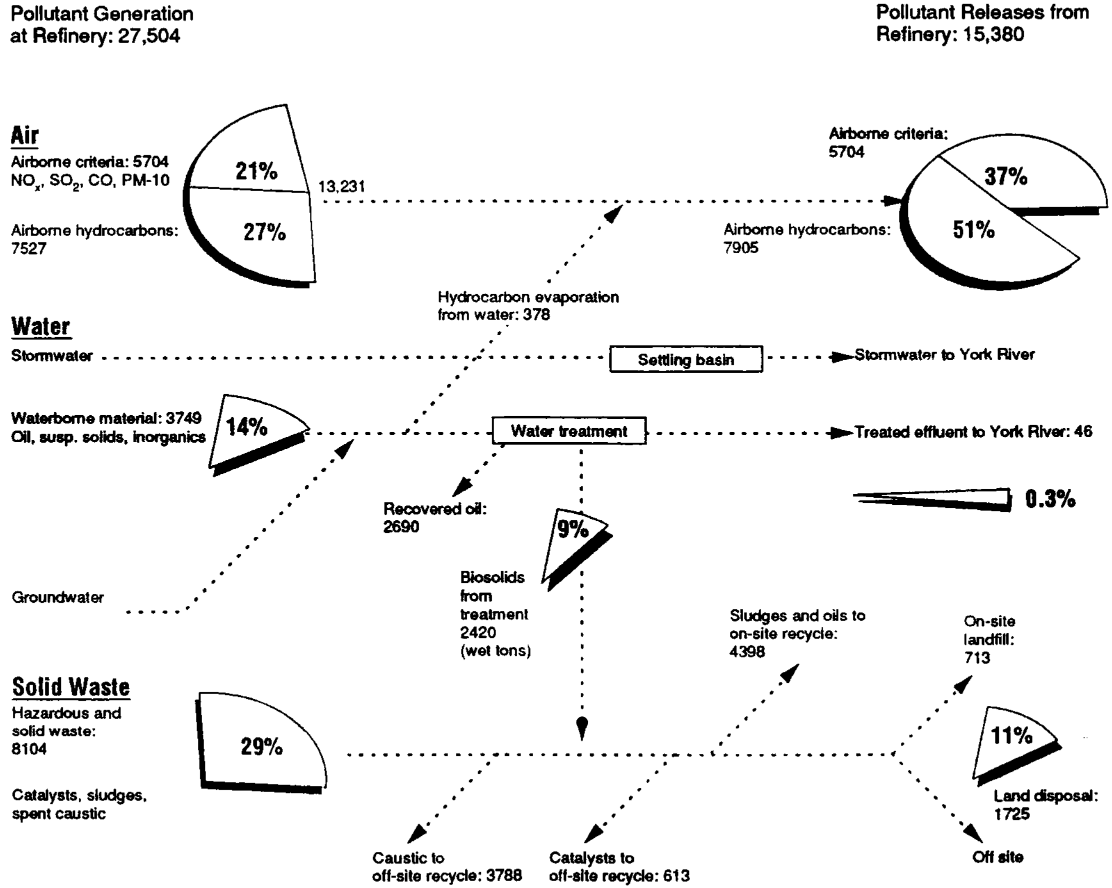


FIG. 4. Pollutant transfers/recycle/treatment within the Yorktown refinery.

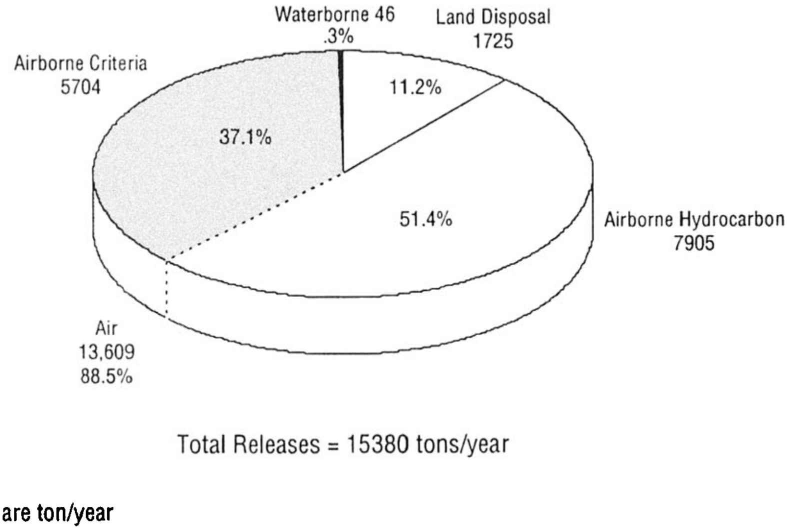


FIG. 5. Total releases entering the environment from Yorktown refinery.

as biosolids from the wastewater treatment plant, and recycled to the refinery's coker (4400 tons/year). In the coker, hydrocarbons are converted into salable products while water is recovered for treatment. Most remaining solid waste is construction debris and contaminated solids, which are landfilled on- and off-site. A total of 1700 tons/year of solid waste was landfilled in 1990.

B. Distribution of Releases Leaving the Refinery

Figure 5 shows total releases to all environmental media leaving the refinery. Nearly 89% (13,600 tons) of the releases to the environment were airborne. The high percentage of airborne emissions leaving the facility focused both the sampling program and subsequent identification of pollution prevention options on this medium. As noted later, groundwater contamination under the facility is small, and was not moving off-property. Four hundred tons of hydrocarbons evaporate each year from refinery drainage and wastewater treatment systems, mixing with other airborne hydrocarbons.

1. Airborne Emissions

Figure 6 shows the division of airborne emissions between criteria pollutants—SO_2, NO_x, CO, and particulates (PM_{10})—and volatile organic compounds (VOCs). Criteria pollutants result primarily from combustion or other

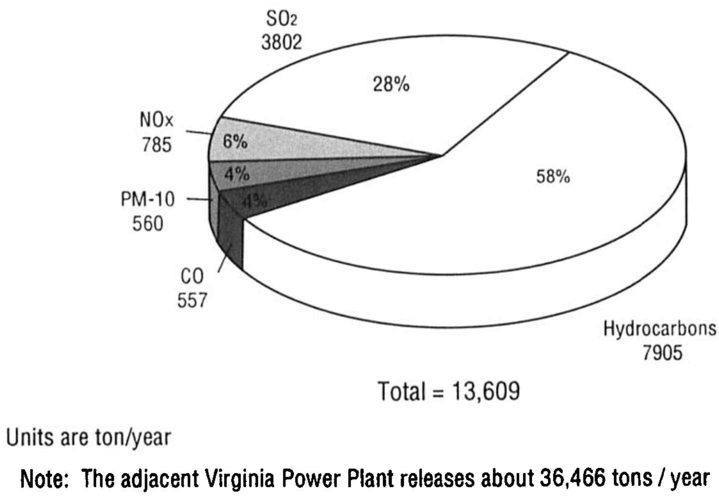


FIG. 6. Total air emissions for Yorktown refinery.

stacks. Nearly 60% of air emissions were VOCs. The sampling program focused on VOCs and their sources because much less was known about these sources.

Within the refinery fence line, maximum observed and/or calculated airborne concentrations of chemicals reported in the annual TRI were below OSHA action and permissible exposure levels for 8-hour time-weighted average exposures. Impacts on air quality by the refinery were calculated using air dispersion modeling techniques and the emissions inventory developed during this study.

Table I compares calculated concentrations of benzene, toluene, and ethylbenzene at several locations near the refinery with reported values for typical urban, rural, and remote settings from past EPA studies (Shah and Heyerdahl, 1988). For benzene, refinery impacts at the fenceline were similar to those observed in a rural environment. At the nearby residence, benzene concentrations were similar to those observed in a remote pristine setting. Ethylbenzene impacts were similar to benzene. Toluene impacts were somewhat higher, falling between typical rural and urban air quality. No comparable data were available for xylene. Automobiles and an adjacent power plant contribute some of these chemicals to the air. Biogenic (natural) sources also contribute. In the entire middle Atlantic region, natural sources provide about 40% of airborne hydrocarbons, with a higher percentage in more rural areas like Yorktown (Placet and Streets, 1989).

2. *Surface Water*

The existing water treatment plant is very effective in removing contaminants from process waters prior to discharge, with overall removal efficiencies greater

TABLE I

COMPARISON OF ANNUAL AVERAGE PREDICTED IMPACTS TO TYPICAL MEASURED CONCENTRATIONS FOR DIFFERENT TYPES OF ENVIRONMENTS FOR BTEX CHEMICALS

Chemical	Maximum Predicted Concentration at the Fence Line[a] ($\mu g/m^3$)	Maximum Predicted Concentration at the Closest Residence ($\mu g/m^3$)	Typical Remote Concentration[b] ($\mu g/m^3$)	Typical Rural Concentration[b] ($\mu g/m^3$)	Typical Urban Concentration[b] ($\mu g/m^3$)
Benzene	1.3	0.6	0.51	1.5	5.7
Toluene	5.4	2.4	0.19	1.3	7.7–12.0
Ethylbenzene	1.6	0.7	0.06	0.7	2.7

[a]Maximum on land.

[b]Shah and Heyerdahl, 1988.

than 99% for most organics and inorganics. Except for MTBE, most contaminants were not detectable in the treated effluent (Amoco/EPA, 1991a).

3. Groundwater

Subsurface contamination, detected during the sampling period, was significantly less than that observed at other petroleum refining facilities (*Los Angles Times,* 1988). Contamination appeared limited to shallow soils and/or groundwater. These unusually low levels of contamination are the result of (1) natural soil conditions, (2) no significant spills, (3) original refinery construction practice which utilized above-grade (rather than below-grade) welded piping (rather than threaded fitting construction), and (4) the underground process sewer system acting as a continuous groundwater recovery system. This sewer system passively collects about 35,000 gallons per day of groundwater and routes it to the wastewater treatment plant. This was an unexpected finding of the study (Amoco/EPA, 1991b).

4. Solid Waste Management

The refinery generated more than 10,500 tons of solid waste and spent caustic in 1990. More than 80% of the solid waste was recycled or treated either on- or off-site and does not enter the environment. Remaining materials are disposed of in approved landfill sites. Most solid wastes result from activities associated with the refinery's process water collection and treatment system. Nearly 1000 tons/year of soils enter the drainage system where they become oil-coated sludge.

5. Cross-Media Transport

Several pollution control technologies at the refinery promote *cross-media transport,* the transfer of pollutants from one medium to another. Wastewater, for example, may contain hydrocarbons that volatilize into the air; at the refinery, the wastewater treatment plant converted these waterborne hydrocarbons into 2400 tons/year of sludge, which were recycled to the coker. Cross-media transport from air to water is not significant for hydrocarbons or chemical that are only slightly soluble in water (Allen *et al.,* 1989). Studies performed by the National Center for Intermedia Transport at the University of California, Los Angeles, for instance, showed that most hydrocarbons released into the air do not transfer rapidly into other media. Therefore, ignoring intermedia transfer when examining air quality impacts is a reasonable analytical approach. Water-soluble compounds, such as methanol and MTBE, can transfer from air into water and soil media under certain conditions (Cohen *et al.,* 1991).

C. Characterization of Releases

1. *Diversity of Emissions*

Crude oil contains thousands of individual hydrocarbon species. Emissions from oil refining operations reflect this diversity. Despite an extended sampling and analysis program, all species emitted could not be identified. Selected samples were analyzed for 150 organic compounds. The analysis identified about 90% of the compounds present. The remaining 10% were probably structural isomers of typical volatile organic hydrocarbons found in petroleum product mixtures. A number of small quantity emissions of unidentified hydrocarbons were found in most of the airborne samples. These compounds would be expected to exhibit similar physical and toxicological properties to compounds identified.

2. *Comparison with TRI Emissions*

The refinery's 1989 TRI report showed 370 tons of reportable chemicals released from all sources to all media. Based on measurements and modeling conducted for this project, releases of TRI chemicals were 900 tons, about 2.4 times higher than reported. This difference reflects (1) the identification of blowdown stacks as a significant source (430 tons) whose contribution was previously unknown and unrecognized, (2) the addition of marine loading losses (160 tons) which are not reportable for TRI (Oge, 1988), and (3) lower emissions from the oil/water separator (−90 tons). Emissions from the inactive landfarm, a coker pond, and sewer vents were also identified as new sources. Figure 7 illustrates these changes.

Table II reconciles the reported TRI values and measurements made for 12 reported chemicals. When reported values and the project's measurements are com-

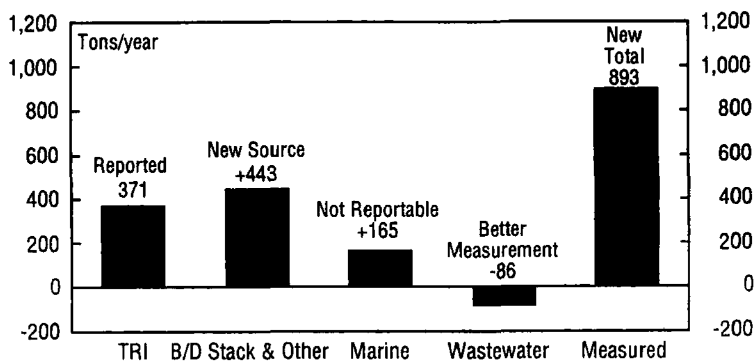


Fig. 7. 1989 TRI inventory compared to measured emissions.

TABLE II

RECONCILIATION OF 1989 TOXIC RELEASE INVENTORY REPORT AND POLLUTION PREVENTION INVENTORY YORKTOWN REFINERY (UNITS OF TONS/YEAR)

Chemical	1989 TRI Report	B/D Stack Additions	Coker Additions	Barge Loading Additions	Wastewater Subtractions	Total
Benzene	41.0	32.4	1.8	15.0	−0.1	90.1
Toluene	91.5	56.6	3.1	52.8	−23.2	180.7
Ethylbenzene	24.5	45.7	1.0	14.0	−7.3	77.9
Xylenes	107.0	121.6	6.3	69.2	−33.2	270.9
Cyclohexane	3.8	26.5			0.3	30.6
Naphthalene	2.8			5.1		7.9
Trimethylbenzene	45.5	42.2	1.1		−22.2	66.6
Ethylene	8.5	40.6				49.1
Propylene	30.5	64.1				94.6
Butadiene	0.036	0.18				0.2
Methanol	3.3					3.3
MTBE	12.1			8.8		20.9
Total	371	430	13	165	−86	893

[a]TRI as % of total VOCs = 11%.

[b]VOCs as % of crude run = 0.3%.

[c]TRI column excludes 0.175 tons chlorine.

[d]TRI reports only 1,2,4-trimethylbenzene. Other columns report 1,2,4- as well as 1,3,5- and 1,2,3-isomers.

[e]Wastewater subtractions include the net effect of reduced emissions from the API separator and increased emissions from sewer vents.

[f]The totals are rounded.

pared on the same basis (excluding marine loading losses and blowdown stack emissions), measured values (300 tons/year) are about 20% lower than reported values (370 tons/year).

3. Emissions Excluded from TRI

The sampling program helped identify and quantify emissions excluded from TRI reporting requirements. Some of these are excluded because they are below the threshold amounts that trigger reporting. Some are excluded because certain operations, such as barge loading, are not considered reportable under some circumstances by EPA (Oge, 1988). Some chemicals are excluded because they are not listed, although they have substantially similar physical and toxicological properties to chemicals that are listed. The isomers of trimethylbenzene illustrate this last point: 1,2,4-trimethylbenzene is a reportable chemical; the 1,3,5- and 1,2,3-trimethylbenzenes are not. All three occur in crude oil, gasoline, and refinery emissions and have similar physical and toxicological properties. Because of the wide diversity of emissions coming from crude oil, the refinery's TRI covered only about 11% of the total hydrocarbon emissions leaving the facility. The unreported emissions were primarily VOCs associated with pertroleum products and processing.

4. Comparison with EPA's AP-42 Emission Factors

Emission factors established by the EPA are frequently used to estimate total airborne emissions from different types of refinery equipment. These are called AP-42 emission factors. Most AP-42 factors do not provide information about the composition of emissions. The project's measurement program allowed for direct comparison between several measured or inferred emission rates and emissions calculated using these factors.

For example, actual measurements were taken that supported and validated the base assumptions of the AP-42 emission factors for quantitative assessment of fugitive and tank vent emissions. Measured emissions from the coker pond were about 40% greater than estimated using AP-42 factors. Measured emissions from the oil/water separator were 2100% lower than estimated with AP-42 factors. A combination of reasons can probably explain this discrepancy: (1) the limited database for this emission factor (no measurements), (2) improved refinery operating practices since the original data were collected in 1959, and (3) improved measurement techniques during the last 30 years (API, 1990, 1991). The EPA Office of Air Quality Planning and Standards (OAQPS) has given this emission factor a D rating on a scale of A (good) to E (poor, no data) (EPA, 1985a, 1988). Overall measured emissions from fugitive, tank vent, coker pond, oil/water separator emissions were about 60% of the amounts estimated.

D. Identification of Sources

1. Air Emission Sources

To identify air emission sources, the study team utilized a variety of measurement techniques. Table III summarizes the different techniques used to define the airborne emissions. Emissions from sewer vents, water ponds, the inactive landfarm, and oil/water separator were measured directly (Amoco/EPA, 1991c). In general, mass balance techniques are not sufficiently accurate for most inventory calculations (NRC, 1990). However, since their flow rates were small, easily measurable, and reasonably constant over time, mass balances and inlet/outlet water analyses were used to determine emissions from the cooling tower and wastewater tanks.

Ambient monitoring both upwind and downwind of the refinery was used to infer information about emissions from such fugitive sources as leaks from process valves, flanges, pump seals, and tank vents. Emissions from barge and truck/rail loading operations were calculated using standard AP-42 emission factors (EPA, 1988) and actual refinery loadings for 1990. Emissions from blowdown stacks were calculated using the AP-42 emission factor, which gives a total rate based on refinery throughput. Composition measurements made at Yorktown were used to define chemicals in the total flow.

Figure 8 identifies and quantifies specific air emission sources. The chart reveals a number of useful facts about airborne emissions from the facility. First,

TABLE III
Technique Used to Determine Airborne Emissions

Source Type	Basis of Emission Estimate	Speciated Emissions
API separator	Direct measurement	Direct measurement
Barge loading	AP-42	Proportional to product compositions loaded in 1990
Blowdown stacks	AP-42	AP-42 and direct measurements of composition
Coker pond	Direct measurement	Direct measurement
Cooling tower	Water, sampling, mass balance	Direct measurement
Inactive landfarm	Direct measurement	Direct measurement
Loading rack	AP-42	Proportional to product compositions loaded in 1990
Process fugitive	AP-42 default components	Proportional to compositions measured for similar in-stream equipment at another refinery
Sewer vents	Direct measurement	Direct measurement
Tanks	AP-42	Proportional to product compositions loaded in 1990

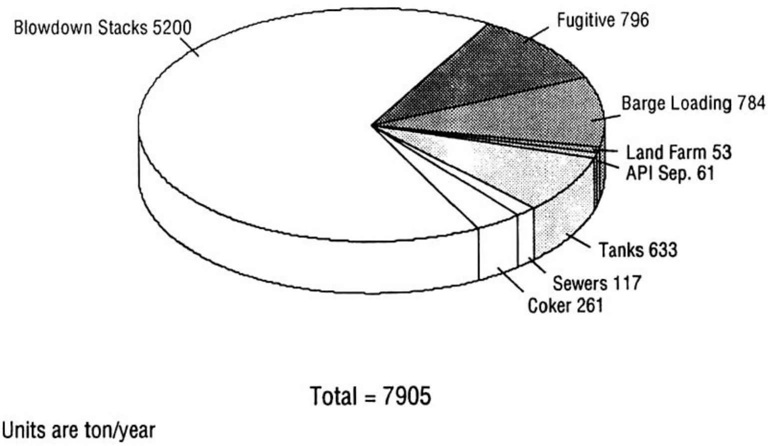


FIG. 8. Yorktown refinery VOC air emission sources.

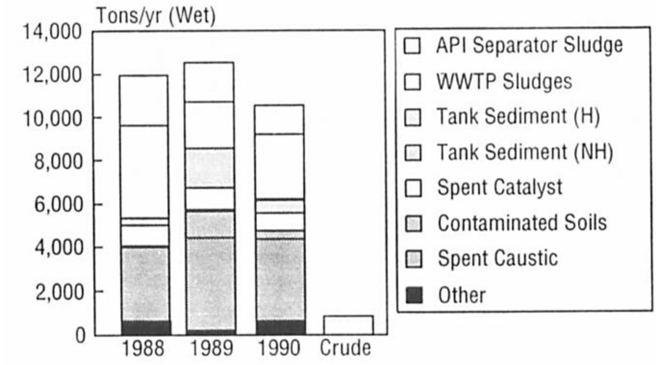
the three process blowdown stacks were identified as the largest source of airborne hydrocarbon emissions. At the beginning of this study, these were thought to be minor sources. Barge loading losses represented a second major source of emissions. Fugitive losses from process equipment and from tank vents were the third and fourth largest sources, respectively. The coker cooling pond was also found to be a significant emissions source. The size and significance of the coker cooling pond in relation to other sources was unknown prior to the study since few of the chemicals in pond emissions are required to be reported in the annual TRI. The refinery sewer system (sewer vents and oil/water separator) is a relatively small contributor to emissions. A single measurement is the basis for the landfarm emission estimate; it should be considered with caution.

2. *Surface Water Sources*

Identification of surface water sources was complicated by an old underground drainage system that was not designed for access and sample collection. Nevertheless, samples from major arteries helped identify the sources of primary pollutants of concern, such as oil and grease, biological oxygen demand (BOD), ammonia, total suspended solids, sulfides, metals, BTEX, and phenol. The crude unit desalter and crude tank water draws were found to have the highest pollutant loadings.

3. *Subsurface Sources*

A combination of groundwater well samples and computer modeling helped identify potential sources to and sinks for the subsurface aquifer. The most signif-



Note: About 1,000 tons of sediment in crude oil is recovered as solid waste.

FIG. 9. Major sources of refinery solids.

icant sources of water reaching the subsurface where natural recharge from rainfall and water from the coke fines settling basin. More important from an environmental impact standpoint, the refinery's underground drainage system was observed to be recovering groundwater and routing it to the wastewater treatment plant. Consequently, there appeared to be no movement of contaminated groundwater off site.

4. Solid Waste Sources

Figure 9 summarizes solid waste sources identified from the sampling program. Sludges accumulated in the drainage and water treatment system accounted for a majority of the solids. Contaminated soils, tank sediments, and spent catalysts accounted for the remaining solids. Spent caustic, although an aqueous solu-

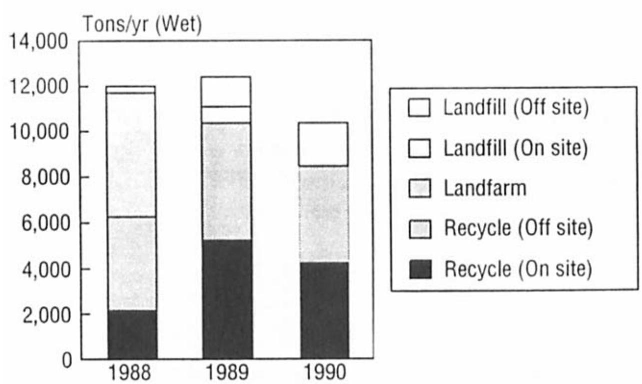


FIG. 10. Solids management.

tion, is usually classified and handled as hazardous waste for waste management purposes. Figures 10 and 11 summarize how these wastes were managed.

Some of the solid wastes, such as spent catalyst and sediment in crude, are by-products of the refining process. Others such as scale in storage tanks and soils swept into the sewer are not directly related to the processing operations. Thus, changing the refining process alone cannot accomplish all the reductions in solid waste generation; changes in other operating practices are required as well. At Yorktown, crude oil naturally contains more than 1000 tons of sediment, which is ultimately deposited in the refinery's oil/water separator or storage tanks. Local soil contributions (about 1000 tons/year) represent a large potential opportunity to reduce solid waste generation.

V. Assessing the Risks Posed by Refinery Releases

To better evaluate pollution prevention options, the project attempted to assess the risks posed to individuals and populations exposed to chemical contaminants released from the refinery. An initial risk assessment analysis was performed to identify chemicals requiring further study, and to establish a baseline by which to judge potential risk reduction opportunities. Since change in exposure to benzene was used as a proxy for evaluating relative risk reductions associated with alternative pollution prevention options, the usual uncertainty associated with risk assessments was not a factor in the option analysis. The uncertainty in absolute risk assessments can arise from multiple sources: the use of animal study results, difficulties with human studies, variation in individual responses to chemical exposures, the impact of differing dose rates, multiple simultaneous exposure to chem-

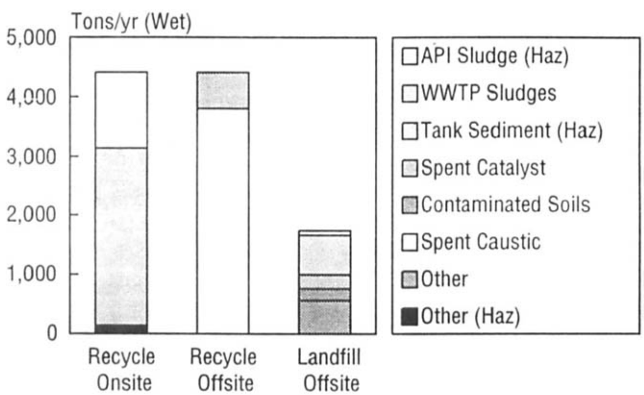


FIG. 11. Solids management by type (1990).

icals, and the use of extrapolation methods to estimate risks from high-exposure populations to low-exposure populations. Therefore, the results of the risk assessment completed for the initial screening should not be interpreted as definitive.

Risk assessment typically begins with a characterization of the risks associated with baseline or current releases. The baseline assessment gives an indication of the potential for human health or ecological risk problems. The predicted changes in emissions and sources are then estimated and the expected risk from the option scenarios is evaluated. The risk evaluation is based on both risk reduction to the most highly exposed individuals and to the exposed population as a whole. Cumulative benefits of risk reduction are estimated by adding the benefits for each risk reduction option.

The project's risk assessment effort followed EPA methods and established agency policy as outlined by the National Academy of Sciences (NAS, 1983) and established in final risk assessment guidelines (EPA, 1986). It involved four steps: (1) hazard identification, (2) determination of dose–response relations, (3) evaluation of human exposure and, finally, (4) characterization of risks.

Boundary conditions for this risk assessment were established so that the risk assessment did not attempt to analyze secondary environmental effects associated with refinery releases such as their contribution to formation of ozone, acid rain, risks associated with occupational exposure, transportation of products or wastes, or the potential for accidental releases.

Screening analysis was conducted for different exposure pathways and chemicals of concern. Using a screening level cutoff of a one-in-a-million excess risk for a 70-year lifetime exposure for the maximally exposed individual (MEI), a set of carcinogenic chemicals was identified for further analysis. For noncarcinogens, MEI exposure levels were compared to health thresholds. If the MEI exposure exceeded the established health threshold, further analysis was done.

A. Air

Based on the screening analysis and methodology described, nickel, vanadium, methanol, carbon tetrachloride, xylenes, toluene, ethylene, propylene, naphthalene, ethylbenzene, polynuclear aromatic hydrocarbons (PAHs), 1,2,4-trimethylbenzene, and cyclohexane were not evaluated further, since their exposure either posed less than a one-in-a-million excess risk or was below the applicable reference dose.

For MTBE, EPA has not formally established health effects and reference dose. A preliminary estimate of the threshold reference concentration was developed for this risk assessment. Estimated concentrations for the MEI location were 10–15% of the reference concentration. No further evaluation was done for MTBE.

Two other chemicals and one mixture failed this initial screen: benzene, 1,3-butadiene, and VOCs. Benzene is a known carcinogen. It poses a one-in-a-million excess cancer risk at a concentration of 0.12 $\mu g/m^3$ for a lifetime exposure. Air modeling results show the concentration of benzene at the refinery boundary is 2.0 $\mu g/m^3$. At the nearest residence, this concentration is 1.5 $\mu g/m^3$. 1,3-Butadiene is also a known carcinogen. It poses a one-in-a-million excess risk at 0.0036 $\mu g/m^3$ for a 70-year lifetime exposure. Air modeling for this chemical shows a concentration of 0.0057 $\mu g/m^3$ outside the boundary and 0.0050 $\mu g/m^3$ at a residence.

VOCs were present at about 0.2 ppm outside the refinery boundary. VOCs are a complex mixture of hydrocarbons with an unspecified (and variable) composition. In the absence of any reference data that specifies an acceptable concentration of VOCs outside the fence line, it is helpful to compare the concentration data to a common standard used to monitor health in the workplace, the threshold limit value (TLV). The American Conference of Government and Industrial Hygienists (ACGIH) has set a TLV of 300 ppm for workplace exposure to gasoline vapors, another hydrocarbon mixture of unspecified composition (ACGIH, 1990). Since the exposure for workers is different than that of residents outside the refinery, ACGIH TLVs cannot be used to determine exposure limits for the general population; instead, they simply provide a benchmark for this discussion.

There is considerable debate, much uncertainty, and little data on human health effects at the low VOC concentrations expected around the refinery. Recent epidemiology studies of refinery workers, who would be expected to receive a higher exposure to VOCs than the general population, show a lower incidence of total cancer cases than the general population (Wong and Raabe, 1989). However, these studies are not able to differentiate between other potentially confounding factors such as the "healthy worker effect," cigarette smoking, diet, etc. VOC impacts from the refinery were not evaluated further.

B. Surface Water

The refinery has a state water discharge permit covering two outfalls: a combined treated process water mixed with once-through, noncontact cooling water outfall (001), and a stormwater settling basin outfall (002). The surface water analysis used the results from samples of these streams tested for 22 contaminants, total organic carbon, and such physical properties as pH and temperature. Surface water discharge concentrations were generally below the analytic detection limits (Amoco/EPA, 1991a). A screening level analysis identified the potential for risks to either human health or aquatic life based on established federal water quality criteria. This comparison was based on the EPA recommended approach for determining reasonable excursions above water quality criteria (EPA, 1991).

The screening analysis using two data points for these streams shows that copper exceeds EPA criteria for aquatic toxicity. Specifically, the highest copper concentration measured in outfall 002 as 250 μg/liter—about 90 times the marine acute copper criteria of 2.9 μg/liter. The highest copper concentration in outfall 001 exceeded the marine acute copper criteria by 76 times. During 1990 and 1991, the copper concentration in both outfalls have averaged between 66 and 76 μg/liter. Criteria are not the same as standards. However, if federal criteria are adopted as water quality standards in Virginia, these concentrations would constitute an exceedence. It is interesting to note that water from the York River has also exceeded these criteria on occasion. Subsequent analysis on four different occasions in 1992 showed the total recoverable copper concentration in outfalls 001 and 002 averaged 4 and 8 μg/liter, respectively, while the York River averaged 4 μg/liter. Upon evaluation of the data, the Commonwealth of Virginia concluded that no water quality problem existed and recommended that further monitoring was not necessary.

C. Drinking Water

Because the nearest drinking water source is 7 miles from the refinery and the York River is too saline for consumption, drinking water was not considered a potential source of exposure.

D. Groundwater

Groundwater contamination was found to be minimal with no off-site migration (Amoco/EPA, 1991b). Therefore, groundwater appeared to pose little or no risk and was not analyzed further. The sampling program did not find evidence of groundwater contamination from on-site waste disposal.

VI. Measuring Public Perception of the Refinery

To develop another tool that could be valuable in evaluating prevention options, the study team gathered data on the public's perceptions of the refinery and its impact on the local environment. The team believed this information might be useful in characterizing the viability of pollution prevention options. Three activities were undertaken to collect this information: (1) in-depth interviews with 25 thought leaders from state and local governments, community groups, local businesses, educational institutions, and environmental organizations, (2) two focus group meetings, and (3) a telephone survey of 200 households (Amoco/EPA, 1992a).

Probably the strongest conclusion produced by these information gathering activities was that people were generally ambivalent about the refinery, voicing neither major criticisms nor major support. In general, those contacted believed that the refinery complied with environmental laws and that this compliance probably protected the community. Most people felt that there were more pressing problems in the Yorktown area than the refinery. For example, land development, traffic, and sewer and water problems were cited as major quality-of-life concerns. When specifically asked about air pollution, water pollution, and disposal of solid waste, residents indicated that they did have a concern with respect to the oil refinery. These concerns, however, were not strongly felt and not specific.

One important insight gained from the public opinion study was that people obtain information about environmental problems in a random or unstructured way. There was no authoritative source of information about environmental problems accepted as reliable by a majority—or even a significant minority—of people. For example, some people surveyed had concerns about links between the refinery and reduced fishery yields in the Chesapeake Bay despite studies conducted by the Virginia Institute of Marine Science and others showing that refinery effluent was causing no known adverse impact on fish and the aquatic environment (Amoco/EPA, 1992b). This lack of an effective, reliable channel of communication between the refinery and the public could complicate the implementation of new pollution prevention strategies, especially if the public is misinformed about why any obvious change is being made. At the same time, the lack of a reliable communications channel could preclude mustering needed public support for policy or other changes needed to promote pollution prevention.

VII. Developing and Evaluating Options for Reducing Releases

In March 1991, more than 120 representatives from EPA, Amoco, the Commonwealth of Virginia, academic, environmental, and consulting organizations met for a three-day brainstorming workshop in Williamsburg, Virginia. Workshop participants developed options for reducing releases and considered ranking criteria, permitting issues, and obstacles and incentives for implementation. Workshop sessions included a structured review of process synthesis techniques and a more free-wheeling idea generation and discussion session. Participants proposed more than 50 pollution prevention projects for further consideration. Table IV lists all the projects identified.

To meet project schedule and budget constraints, the study team later selected 12 projects for more detailed analysis. Those chosen were felt to (1) be feasible

TABLE IV

POLLUTION PREVENTION OPTIONS IDENTIFIED AT THE WILLIAMSBURG WORKSHOP

Flare
Give away excess gas now flared
Redirect sour water stripper vent gas from flare to sulfur plant
Use gas from crude vacuum unit as fuel rather than as flare
Adjust process conditions to reduce flare gas generation
FCU
Use low attrition catalyst
Use SO_x reduction additive for FCU catalyst
Use more selective catalyst
Capture catalyst fines
Hydrotreat FCU feed
Use oxygen enrichment in regeneration unit
Integrate regeneration energy with air blower
Eliminate fluid-bed reactors
Fugitives
Implement a leak detection and repair (LDAR) program
Reduce barge loading and other transfer/handling losses
Cover sources of volatiles, including double seals on tanks
Track methane as a greenhouse gas
Refinery Water System
Reduce water content of sludge sent to coker
Enclose inside battery limits (ISBL) drains
Contain cleaning fluids to reduce evaporation
Redesign desalter system
Reroute desalter effluent
Keep soils out of sewer
Segregate process water effluent and pretreatment before discharging
Minimize oil/water contact
Use natural gas for stripping in place of steam
Find substitutes for filter aids
Flash difficult emulsions
Optimize sour water system (SWS)
Use stripped sour water as FCU water wash
Energy Integration
Achieve better integration with Virginia Power (VEPCO), including giving away flare gas
Optimize plant-wide energy use
Use oxygen enriched air in furnaces
Other
Perform on-line sampling to improve process control
Remove oxygen from feed streams to eliminate heat exchanger fouling
Recover sulfur in solid instead of a liquid phase
Filter crude to reduce tank sediments
Corporate Ideas
Produce a single grade of gasoline
Eliminate nonbiodegradable products
Desalt at the wellhead and reinject brine and sediment
Use more paraffinic feedstocks

TABLE IV *(Continued)*

Use renewable feedstocks
Institute overall product stewardship
Colocate facilities to maximize recycling
Reprocess used lube oil
Ideas Currently Being Evaluated
Eliminate coker blowdown pond
Move sewer and sewer gas adsorption system above-grade
Segregate process water from rainwater
Enclose or redesign API separator
Redesign product for lower emissions (lower vapor pressure)
Contain waste streams from cleaning operations
General Comments
Track progress in waste minimization to evaluate improvements
Beware of multi-media transfers

with current technology, (2) offer significant potential for release reductions, (3) have manageable or no adverse impacts on worker safety, (4) be amenable to more quantitative analysis in the time available, and (5) address concerns in different environmental media. Table V provides a brief description of each project. Figure 12 shows where each option fits into the overall refinery flow.

A. Option Characteristics

Preliminary material balances and engineering designs were used to analyze each potential option. For each option the following items were determined:

1. *Capital costs.* Estimates with a ±25% accuracy were made for these scoping studies. Additional engineering effort would be required to prepare an estimate with a ±10% accuracy typically needed for management approval.
2. *Operating and maintenance costs.* Costs were estimated as a percentage of total capital cost, with consideration of project complexity. These costs varied between 3 and 6% of total capital.
3. *Liability cost rating.* Each project was evaluated qualitatively for its potential to affect future remediation and catastrophic and product quality liability concerns.
4. *Timeliness.* The number of years needed to complete each project was estimated, subject to current equipment maintenance schedules and operating limitations.
5. *Transferability.* A qualitative assessment was made of the ability to use the project technology at other refineries or in other industries.

TABLE V

SELECTED POLLUTION PREVENTION ENGINEERING PROJECTS

The following projects were identified for further study as a result of the Pollution Prevention Workshop in Williamsburg and subsequent workgroup meetings.

1. **Reroute Desalter Effluent:** Hot desalter effluent water currently flows into the process water drainage system at Combination unit. This project would install a new line and route this stream directly to the API Separator. This reduces volatile losses from the sewer system by reducing process sewer temperature and oil content. Volatile losses at the API Separator increase slightly.
2. **Improve Desalter System:** Evaluate installation of adjunct technology (e.g., centrifuge, air flotation, or other technology) on desalter water stream prior to discharge into the underground process drainage system. This reduces oil and solids waste loads in the sewer system, affecting the wastewater treatment plant and volatile losses from the drainage system.
3. **Reduce FCU Catalyst Fines:** Evaluate possible performance of more attrition-resistant FCU catalyst to reduce fines production. (Subsequent review with catalyst vendors indicated the Refinery was already using the most attrition-resistant catalyst available.) Two other fines reduction options were considered.

3a. **Replace FCU Cyclones:** Assess potential for reducing emissions of catalyst fines (PM10) by adding new cyclones in the regenerator.

3b. **Install Electrostatic Precipitator at FCU:** Assess potential of electrostatic precipitator in reducing catalyst fines (PM10) emissions.

4. **Eliminate Coker Blowdown Pond:** Change operating procedures for coke drum quench and cooldown so that an open pond is no longer needed. This reduces volatile losses from the hot blowdown water.
5. **Install Seals on Storage Tanks:** Double seals or secondary seals will reduce fugitive vapor losses.
   a. Secondary Seals on Gasoline Tanks: Install secondary rim mounted seals on tanks containing gasoline.
   b. Secondary Seals on Gasoline and Distillate Tanks: Install secondary rim mounted seals on tanks containing gasoline and distillate material.
   c. Secondary Seals on All Floating Roof Tanks: Install secondary rim mounted seals on all floating roof tanks.
   d. Option 5c + Internal Floaters on Fixed Roof Tanks: Install secondary rim mounted seals on floating roof tanks and install a floating roof with a primary seal on all fixed roof tanks.

5e. **Option 5d + Secondary Seals on Fixed Roof Tanks:** Install secondary rim mounted seals on all floating roof tanks and then install a floating roof with a primary and secondary seal on all fixed roof tanks.

6. **Keep Soils Out of Sewers:** Use road sweeper to remove dirt from roadways and concrete areas which would otherwise blow or be washed into the drainage system. Develop and install new sewer boxes designed to reduce soil movement into sewer system, particularly from Tankfarm area. Estimate cost for installation on a refinery-wide basis. Both items reduce soil infiltration, in turn reducing hazardous solid waste generation.

7A. **Convert Blowdown Stacks:** Replace existing atmospheric blowdown stacks with flares. This reduces untreated hydrocarbon losses to the atmosphere, but creates criteria pollutants.

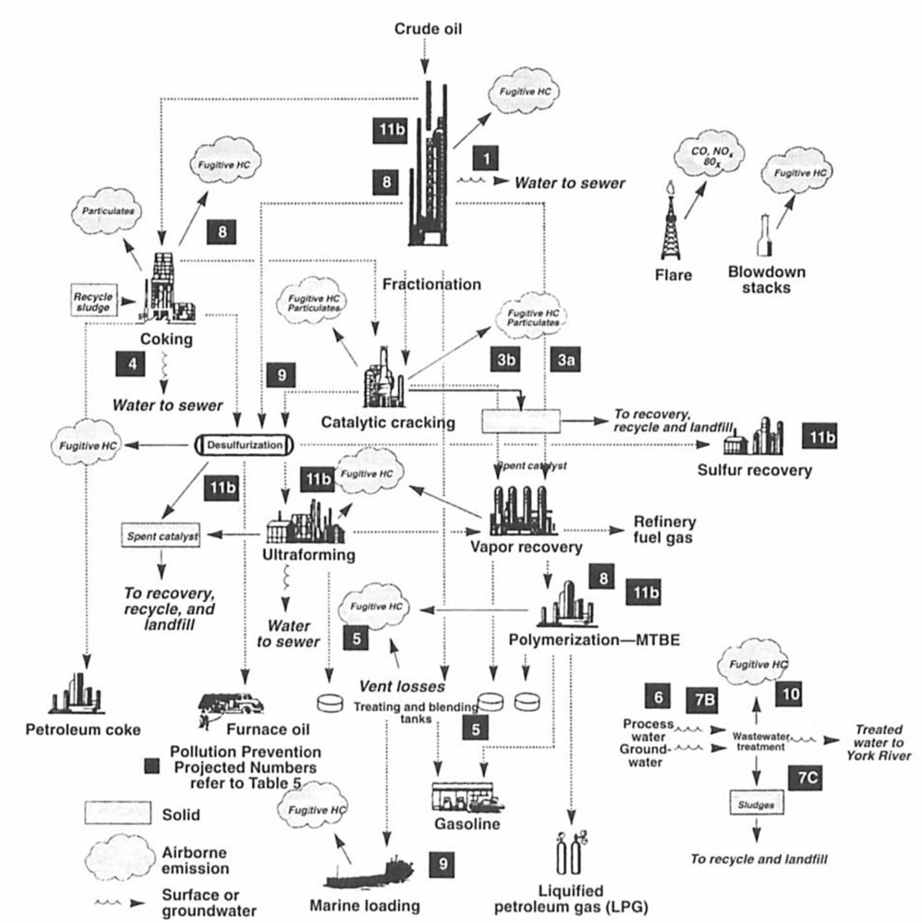
7B. **Drainage System Upgrade:** Install above-grade, pressurized sewers, segregating stormwater and process water systems.

7C. **Upgrade Process Water Treatment Plant:** Replace the API Separator with a covered gravity separator and air floatation system. Capture hydrocarbon vapors from both units.

TABLE V *(Continued)*

8. **Change Sampling Systems:** Install flow-through sampling stations (speed loops) where required on a refinery-wide basis. These replace existing sampling stations and would reduce oil load in the sewer or drained to the deck.
9. **Reduce Barge Loading Emissions:** Estimate cost to install a marine vapor loss control system. Consider both vapor recovery and destruction in a flare.
10. **Sour-Water System Improvements:** Sour water is the most likely source of Refinery odor problems. Follow-up on projects previously identified by Linnhoff-March engineering to reduce sour water production, and improve sour water stripping.
11. **Institute LDAR Program:** Institute a leak detection and repair program for fugitive emissions from process equipment (valves, flanges, pump seals, etc.) and consider costs and benefits.
    a. Annual LDAR Program with a 10,000 PPM hydrocarbon leak level.
    b. Quarterly LDAR Program with a 10,000 PPM hydrocarbon leak level.
    c. Quarterly LDAR Program with a 500 PPM hydrocarbon leak level.

6. *Revenues.* Revenues were estimated for those projects where salable materials were recovered. The quantity of recovered material was equivalent to the emissions reduction. All recovered hydrocarbons were valued as gasoline. This tends to overestimate the actual values, since most VOCs, for example, are the lighter portions of gasoline, rather than whole product.
7. *Equivalent annual costs.* These costs were estimated as the sum of annualized capital costs and all fixed and variable expenses (maintenance, operating, taxes, insurance). Future costs were discounted at 10% (EPA rate) or 15% (Amoco rate) to determine their present value.
8. *Pollution prevention mode.* One or more of the pollution prevention modes in the pollution prevention hierarchy (source reduction, recycle, reuse, treatment, and disposal) was assigned based on review, discussion, and consensus among study team members. These classifications were not obvious in several cases and required extended debate.
9. *Net release reduction.* Estimates of emissions reduction (tons/year) vary in accuracy. Additional emissions sampling and more detailed engineering analysis would be needed to improve these estimates. Where possible, generation and transfer of releases in other media were included in estimating the "net" change in release.
10. *Recovery cost.* For liquid hydrocarbons or VOC emissions the equivalent annual cost was divided by the net release reduction volume to determine an average dollar/gallon for each option. This number is equivalent to the price that would have to be charged per gallon of recovered material to recover capital, operating, maintenance, and distribution costs.
11. *Cost effectiveness.* The equivalent annual cost was divided by the tonnage net release reduction to determine a dollar/ton cost effectiveness for each option.



12. *Resource utilization.* Qualitative estimates were developed for each option's effect on raw materials and utilities requirements.
13. *Effects on secondary emissions.* The impact of each project on other emissions was judged qualitatively. For example, increased power requirements would normally increase emissions from utility systems.

B. Ranking the Options

Ranking and prioritizing these options required specific quantitative and sometimes qualitative data about each choice. Table VI provides estimated reduction in re-

TABLE VI
AMOCO/EPA POLLUTION PREVENTION PROJECT

	Option	Net Release Reduction (tons/yr)	Control Efficiency (%)	Timing Years	Pollution Prevention Mode
1	Reroute Desalter Water	52.4	90.0	1–3	Recycle
2	Improve Desalter System	U/D[a]	U/D	U/D	U/D
3a	Replace FCU Cyclones	245.0	48.0	4–7	Recycle/disposal
3b	Install ESP at FCU	442.0	87.0	4–7	Disposal
4	Eliminate Coker B/D Pond	130.0	50.0	1–3	Source reduction
5a	Install Sec. Seals on Gasoline Tanks	474.7	75.0	>7	Source reduction
5b	on Gasoline and Distillate Tanks	482.1	76.0	>7	Source reduction
5c	on all Floating Roof Tanks	541.0	85.0	>7	Source reduction
5d	Option 5c & Floaters on Fxd Tanks	591.7	93.0	>7	Source reduction
5e	Option 5d & Sec. Seals on Fxd Tanks	592.2	94.0	>7	Source reduction
6	Decrease Soils in Drainage Systems	530.0	50.0	4–7	Source reduction
7A	Blowdown System Upgrade	5096.0	98.0	4–7	Treatment
7B	Drainage System Upgrade	112.5	95.0	1–3	Treatment
7C	Water Treatment Plant Upgrade	58.0	95.0	1–3	Treatment
8	Modify Sampling Systems	63.0	100.0	4–7	Source reduction
9	Reduce Barge Loading Emissions	768.0	98.0	1–3	Recycle
10	Sour Water System Improvements	18.0	100.0	1–3	Recycle/treatment
11a	Annual LDAR Program @ 10,000 ppm	319.5	40.0	<1	Source reduction
11b	Quarterly LDAR Program @ 10,000 ppm	510.5	64.0	<1	Source reduction
11c	Quarterly LDAR Program @ 500 ppm	705.5	89.0	<1	Source reduction

[a]U/D = undefined.

leases (tons/year), type of material released, control technology efficiency, expected time required to complete installation of the particular control technology, and type of release management option used for control (source reduction, recycling, etc.).

1. Quantitative Financial Analysis

Table VII summarizes the quantitative financial analysis. For each option, the table shows the net present value (NPV) of the capital cost, the NPV of

TABLE VII
AMOCO/EPA POLLUTION PREVENTION PROJECT FINANCIAL SUMMARY

	Option	PV of Capital (M$)	PV of O&M (M$)	Annualized Cost (M$/yr)	Cost Effectiveness ($/ton)
1	Reroute Desalter Water	1,000	1,502	329	6,279
2	Improve Desalter System	Undefined	Undefined	Undefined	Undefined
3a	Replace FCU Cyclones	8,300	14,738	3,029	12,363
3b	Install ESP at FCU	9,100	18,153	3,583	8,106
4	Eliminate Coker B/D Pond	2,000	2,807	632	4,862
5a	Install Sec. Seals on Gasoline Tanks	259	426	90	190
5b	on Gasoline and Distillate Tanks	321	531	112	232
5c	on all Floating Roof Tanks	445	734	155	287
5d	Options 5c & Floaters on Fxd Tanks	1,827	3,018	637	1,077
5e	Options 5d & Sec. Seals on Fxd Tanks	2,003	3,306	698	1,179
6	Decrease Soils in Drainage Systems	337	1,207	203	383
7A	Blowdown System Upgrade	5,095	7,303	1,630	320
7B	Drainage System Upgrade	18,800	26,388	5,941	52,809
7C	Water Treatment Plant Upgrade	22,500	33,808	7,403	127,638
8	Modify Sampling Systems	76	129	27	429
9	Reduce Barge Loading Emissions	4,700	7,531	1,608	2,094
10	Sour Water System Improvements	605	909	199	11,056
11a	Annual LDAR Program @ 10,000 ppm	5	695	92	288
11b	Quarterly LDAR Program @ 10,000 ppm	5	1,045	138	270
11c	Quarterly LDAR Program @ 500 ppm	5	1,478	195	276

Notes: All cash flows are discounted at 10%, 15-yr project life. Capital spending for all projects is assumed to begin in 1991. O&M = operation and maintenance costs, depreciation, indirect costs, taxes, and insurance.

operating/maintenance cost minus revenue, the equivalent total annual cost, and the annual recovery cost in dollars/ton. NPV is a useful tool for comparing different options that have different cash flows and different time periods, since all cash flows, present and future, are converted to a current time. The annual cost and recovery cost are in 1991 dollars. Other financial information is on an NPV basis that discounts future cash flows using a 10% discount rate, typical of that used by the EPA for project evaluation purposes. Amoco uses a higher discount rate, 15%, to evaluate cost effectiveness.

2. *Risk Exposure*

Where possible, the study team used computer modeling tools to evaluate how different options would affect risk exposure. Adequate tools were not available for those options that involved changes in releases of solid waste or surface water discharges. However, an independent risk screening showed that neither surface water nor solid waste presented a significant human exposure pathway. No additional modeling was done for options that might affect groundwater, since groundwater near the site is not a source of drinking water.

As noted before, the most significant refinery emissions were airborne. For those options that involved a change in emissions affecting air quality, impacts were modeled using standard air dispersion techniques. Exposure estimates were developed for three classes of chemicals: (1) benzene, toluene, ethylbenzene and xylene (BTEX), (2) other chemicals reported in the refinery's TRI submissions, and (3) criteria pollutants (SO_2, NO_2, PM_{10}, and CO). Similar modeling techniques were used for all three classes. The project focused on the impact of benzene emissions, since benzene turned out to be the chemical species of greatest concern relative to other releases.

For benzene (and other BTEX compounds) the emissions inventory was used as input to the industrial source complex short term (ISCST) air dispersion model. The model used 1 year of hourly meteorological data collected at the National Weather Service station at Norfolk, Virginia. Norfolk is located about 50 miles from Yorktown, and experiences similar land–sea breeze conditions. A mathematical receptor grid was established around the refinery containing 859 points. Both a fine grid (250-m resolution) and a coarse grid (1000-m resolution) were used, to give better resolution near the refinery where concentrations changed more quickly. The model calculated ground level concentrations at each receptor point for each hour of the year as well as annual average concentrations. About 7.5 million computer calculations were completed to model impacts of each chemical studied for each different control scenario considered. The modeling proved extremely valuable for calculating the refinery's impact on the environment, identifying the sources of greatest impact, and comparing the effectiveness of various options to reduce exposure. Due to the site-specific nature of the emissions data, meteorology, and the release reduction options, the results are relevant for this facility only.

Modeling results are summarized in several ways. First, Fig. 13 presents isopleths of annual average benzene concentrations overlaid on a United States Geological Survey (USGS) topographic map of the refinery area. Each curved line

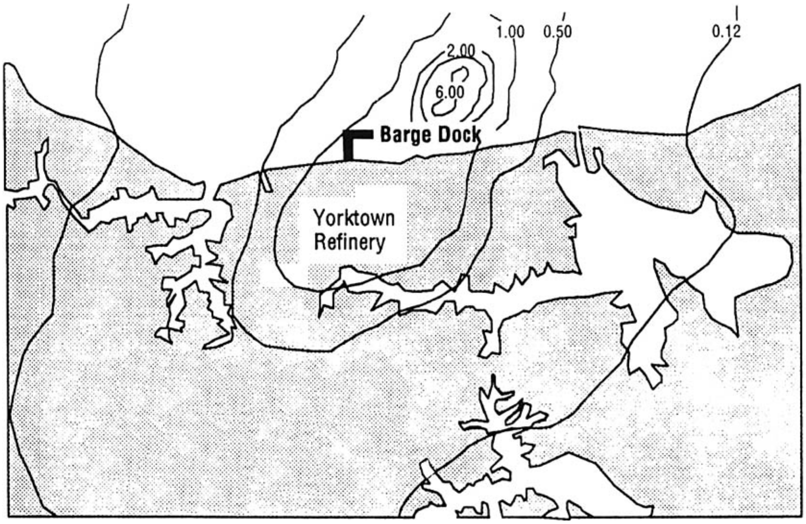


FIG. 13. Baseline emissions for benzene, annual average concentrations (μg/m³).

represents a line of constant benzene concentration, much as elevation lines are used on topographic maps.

Second, Table VIII provides maximum predicted ground-level concentrations in micrograms per cubic meter (μg/m³) for various receptor locations: within the refinery (9.2), beyond the fence line on the York River (6.2), beyond the fence line on land (1.3), and at a nearby residence (0.6).

Third, additional dispersion modeling was performed to identify source–receptor relationships and define culpable sources (those sources that have the largest contributions to the total impact) for the receptor points identified. These results are illustrated in Fig. 14. For example, at the point of highest concentration

TABLE VIII
MAXIMUM ANNUAL AVERAGE PREDICTED CONCENTRATIONS FOR THE YORKTOWN REFINERY FOR BTEX CHEMICALS

Chemical	Inside Plant Fence Line Conc. (μg/m³)	Outside Plant in York River Conc. (μg/m³)	Outside Plant Fence Line on Land Conc. (μg/m³)	Outside Plant Fence Line at a Nearby Residence Conc. (μg/m³)
Benzene	9.20	6.20	1.30	0.64
Toluene	25.50	21.90	5.40	2.37
Ethylbenzene	7.20	5.90	1.60	0.72
Xylene	36.90	5.90	7.20	3.06

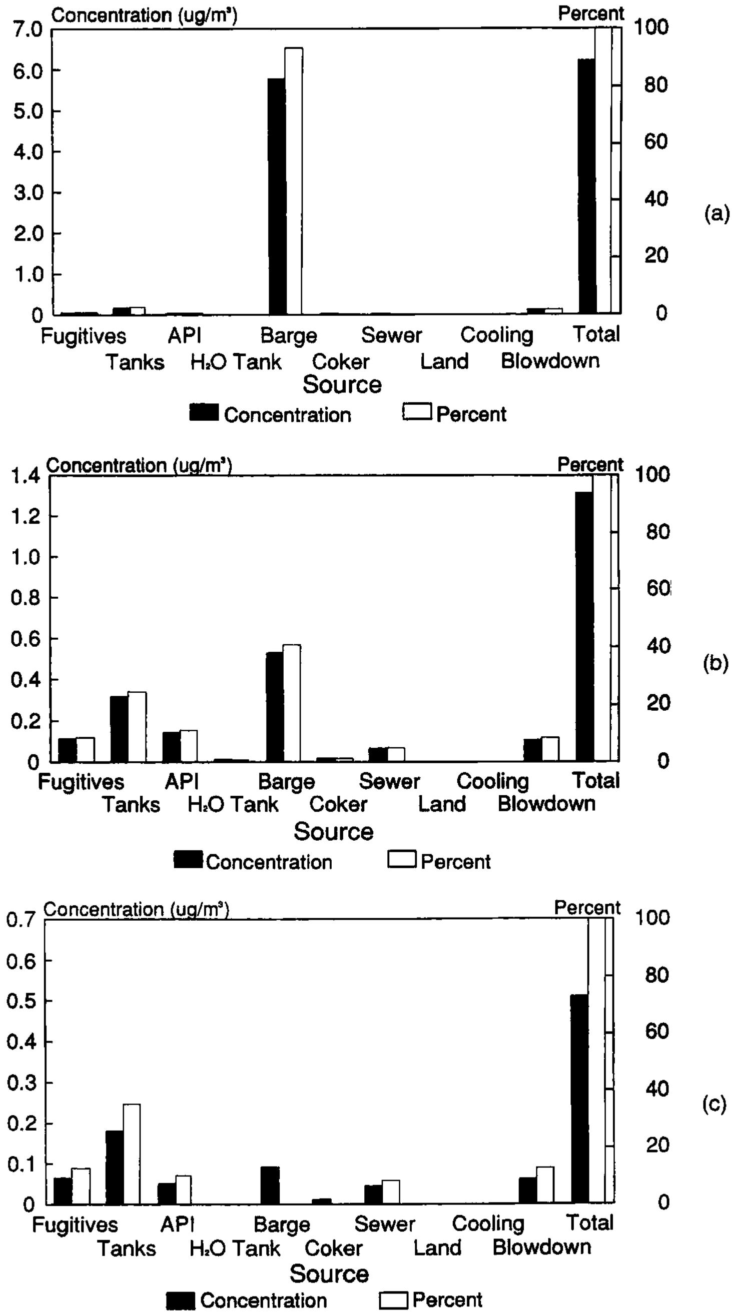


FIG. 14. (a) Source culpability in York River, (b) at fence line on land, and (c) at closest residence.

in the York River, 93% of the impacts resulted from barge loading emissions. In contrast, at a nearby residence, barge loading emissions were responsible for 53% of the total calculated concentration. Storage tank emissions and blowdown stacks accounted for most of the remaining concentration. Barge loading emissions accounted for a significant fraction of the total impacts at both receptor sites.

Changes in emissions resulting from simulating the different pollution prevention options in Table V were also modeled, using identical air dispersion techniques. Again, benzene emissions are discussed here because of their potential health impacts. For each option considered, revised benzene emissions for the affected source(s) were used to calculate a new emissions inventory. For example, recovering barge loading losses could reduce benzene emissions by 11 tons per year. Figure 15 shows a modified histogram reflecting this change. However, the histogram only shows the impact of reduced benzene emissions on the total. It is more helpful to ask how the reduced emissions affect exposure of people outside the fence line. These changes become more apparent when plotted as revised isopleths on the same USGS map used for Fig. 13. Figure 16 shows the new isopleths (shown as "Emissions After Controls") on the original inventory map. The high benzene concentrations around the barge loading area have disappeared. Furthermore, the most outlying isopleth (showing a concentration of 0.12 $\mu g/m^3$) has moved in toward the refinery center. This indicates that the area impacted by refinery emissions has been reduced. Ultimately, the new concentration information can be converted into population exposure and risk estimates. Each pollution prevention option can be viewed and compared in this same way, leading to calculation of changes in relative population risk for each option, compared to current operations at the refinery.

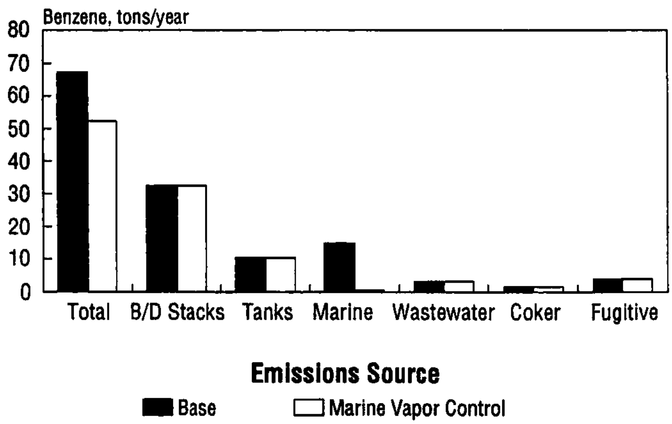


FIG. 15. Histogram of benzene emissions with and without marine loading controls.

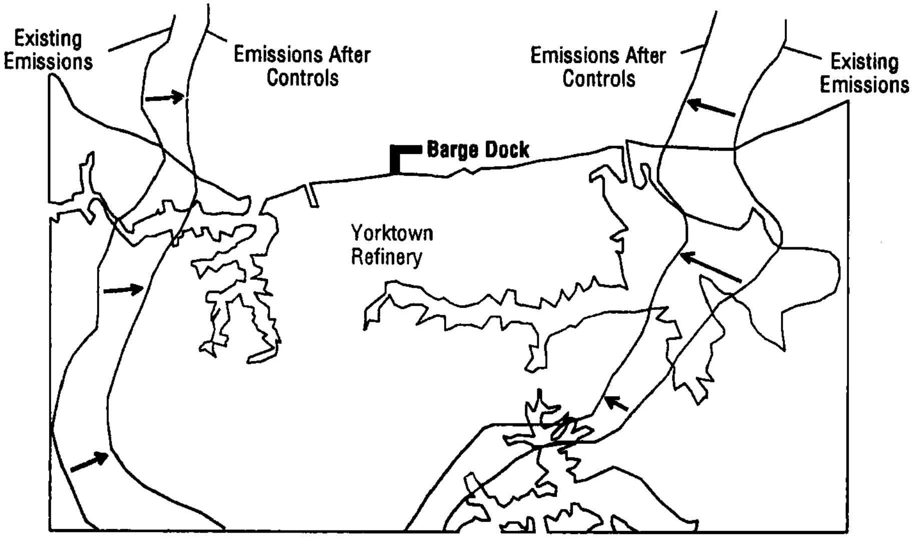


FIG. 16. Effectiveness of barge loading control option for benzene, annual average concentrations.

Changes in benzene exposure were calculated at a nearby residence for each control option. Table IX shows these results. The baseline benzene concentration was 0.26 $\mu g/m^3$. The different pollution prevention options reduce this concentration to between 0.61 and 0.28 $\mu g/m^3$. Current EPA methodology assumes a linear relationship between the dose of a carcinogen that an individual receives over a lifetime and increased risk of cancer. Based on this conservative (health protective) approach, reductions in an individual's cumulative exposure over a lifetime correlate directly with reductions in carcinogenic risk. By looking at this drop in potential benzene exposure as a surrogate for risk reduction, a more quantitative measure of the effectiveness of each option can be developed. The third column in Table IX shows this exposure reduction. Here the existing facility contributes 100% of the controllable benzene exposure. As benzene concentration at the nearby residence decreases, exposure also drops. Table IX indicates that reducing barge loading emissions has the largest potential to reduce benzene exposure. Many of the other options had small or minimal impact on benzene concentrations at a residence and, therefore, small or minimal potential to reduce relative risk.

Figure 17 shows the changes in the outlying concentration isopleth that result from implementing barge loading controls, adding secondary seals to gasoline storage tanks, and upgrading the blowdown stacks. Qualitatively they show a significant change over a fairly wide area, indicating a potentially effective control strategy. Figure 18 shows a similar plot, but this time the changes reflect the im-

TABLE IX
MAXIMUM ANNUAL AVERAGE BENZENE CONCENTRATIONS AND BENZENE EXPOSURE ASSOCIATED WITH VARIOUS POLLUTION PREVENTION OPTIONS

	Option[a]	Benzene Conc. at Nearby Residence ($\mu g/m^3$)	Percent of Benzene Exposure Compared to Base Case	Percent Reduction in Benzene Exposure
0	Base Case	0.62	100	-0-
1	Desalter Control	0.61[b]	99	1
4	Coker Pond Control	0.61	98	2
5a	Secondary Seals on Gasoline Tanks	0.51	82	18
5e	Secondary Seals on all Tanks	0.50	80	20
7A	Blowdown Stacks to Flare	0.55	89	11
7B	Drainage Controls	0.59	95	5
7C	Trtm't Plant Upgrade	0.59	95	5
7C + 7B	Combination	0.56	90	10
9	Capture Barge Loading Losses	0.28	45	55
11a	Annual LDAR	0.61	98	2
11b	Quarterly LDAR	0.60	97	3

[a]See Table V for descriptions.

Notes: 1. Options 5a and 5e cover the range of control which includes option 5c.
2. Options 3a, 3b, 6, 8, and 10 do not affect benzene emissions.

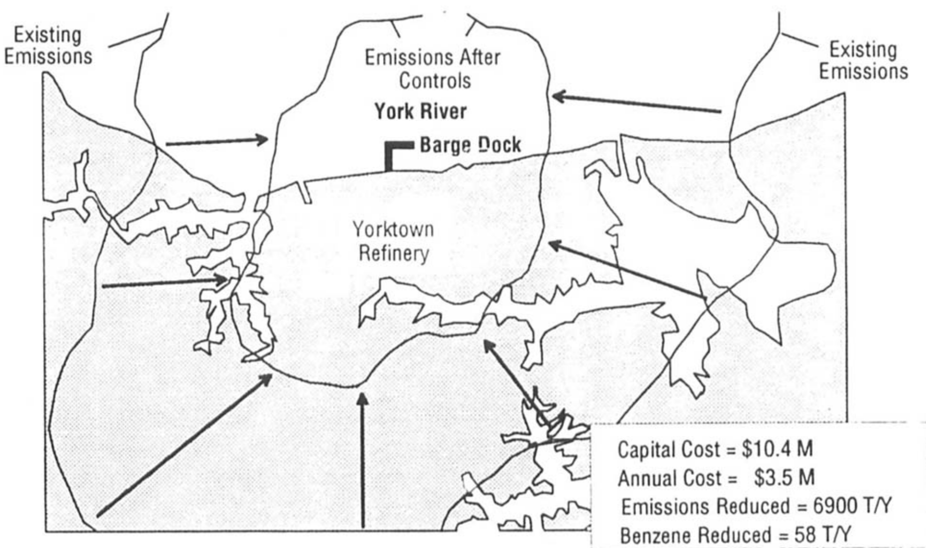


FIG. 17. Effectiveness of recommended controls for benzene, annual average concentrations.

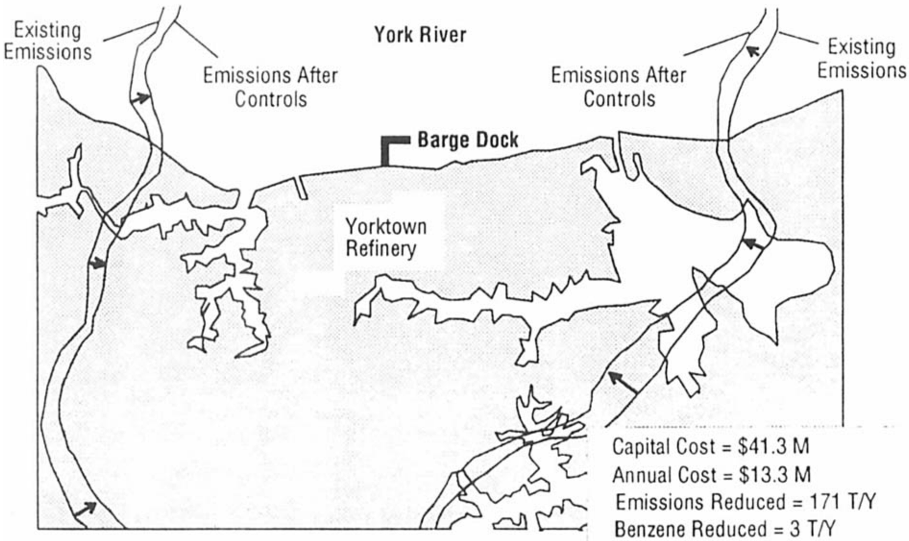


FIG. 18. Effectiveness of mandated sewer controls for benzene, annual average concentrations

pacts of control options for the oil/water separator and underground drainage system. In contrast to Fig. 17, the curves show that almost no impact on air quality would occur in residential areas. This combination of options has a small effect over a narrow area and, therefore, appears to be a relatively ineffective control strategy.

VIII. Ranking Methods and Results

A. OPTIONS FOR REDUCING TOTAL RELEASES

The study team selected 12 options from the 50 identified at the Williamsburg workshop. Important characteristics of the 12 options, and their alternatives, are summarized in Table X. For three options—3, 5, and 11—only one of the several alternatives considered would be implemented. Two options reduce solid wastes (catalyst fines and listed hazardous wastes), while the remaining 10 focus on air emissions (VOC, HC, H_2S, and NH_3). Five of the 12 options employ source reduction to reduce releases. Modifying sampling (option 8) eliminates venting of lines into the environment just prior to sampling. Capital costs range from a low of $10,000 to a high of $22.5 million. Annual costs, based on capital, operating, and maintenance costs at a 10% discount rate, range from $30,000 to $7.4 million.

TABLE X

AMOCO/EPA PROJECT POLLUTION PREVENTION OPTION CHARACTERISTICS

#[a]	Project	Materials	Cost Effective ($/ton)	Benzene Exposure Reduction (%)	Cost Eff BzExRed ($M/%BzE)	Statutory Program	Expected Compliance Year	Impl'n Time (yr)
1	Reroute Desalter	VOC	6,279	1	329			1–3
3a	Replace FCU Cyclones	Cat. fines	12,363	0				4–7
3b	Install FCU ESP	Cat. fines	8,106	0				4–7
4	Elim. Coker Pond	VOC	4,862	2	316	RCRA/CAA	1994	1–3
5a	Sec. Seals-Gasoline Tks	VOC	190	18	5	MACT, Nonatmt Oz	1994	>7
5b	Sec. Seals-Gaso/Dist Tks	VOC	232	18	6	MACT, Nonatmt Oz	1994	>7
5c	Sec. Seals-All FltRfTk	VOC	287	18	9	MACT, Nonatmt Oz	1994	>7
5d	Opt 5c + Flit on FixTk	VOC	1,077	18	35	MACT, Nonatmt Oz	1994	>7
5e	Opt 5d & S. Seal FixTk	VOC	1,179	20	35	MACT, Nonatmt Oz	1994	>7
6	Soils Control	Listed HW	383	0				4–7
7A	B/D Upgrade	VOC	320	11	148	BzNESHAP/Nonatmt Oz	1993	4–7
7B	Drainage Upgrade	VOC	52,809	5	1,188	BzNESHAP/Strmwtr Oz	1994	1–3
7C	Treatment Plit Upgrade	VOC	127,638	5	1,480	BzNESHAP/Nonatmt Oz	1993	1–3
8	Modify Sampling	VOC/HC	429	0		MACT or HON	1995	4–7
9	Barge Loading	VOC	2,094	55	29	MACT, Nonatmt Oz	1994	1–3
10	Sour Water Improvement	H_2S, NH_3	11,056	0				1–3
11a	Ann. LDAR (10,000 ppm)	VOC	288	2	46	Ozone nonattainment	1994	<1
11b	Quart LDAR (10,000 ppm)	VOC	270	3	46	Ozone nonattainment	1994	<1
11c	Quart LDAR (500 ppm)	VOC	276	3	46	Ozone nonattainment	1994	<1

[a]# refers to projects listed in Table V.

Sour water improvement, and materials = H_2S, NH_3.

The cost per ton reduction in environmental releases (cost effectiveness of release reduction) is given for each option in Table X. The most cost-effective options, on the basis of release reductions, are three leak detection and repair (LDAR) alternatives (11a, 11b, and 11c), requiring an average of $278 per ton, and three secondary seal alternatives (5a, 5b, and 5c), which require an average of $236 per ton. Three other options are also low cost, $429 per ton or less. However, the cost for each of the other seven options is $2000 per ton or more. The wastewater treatment plant upgrade represents the least cost-effective option, requiring an annual cost of $127,000 for each ton of VOC recovered. Another way of viewing an option's cost effectiveness is to determine the price at which the recovered material would have to be sold in order to offset the cost of recovery. The recovered material would have to be sold at $0.90 per gallon for the LDAR and secondary seal options to break even, and at $415 per gallon for the most expensive option, treatment plant upgrade. For comparison, the refinery price was about $0.75 per gallon during the study period.

1. Benzene Exposure Reduction Options Ranking

The ranking analysis discussed in the remainder of this section used benzene exposure at a nearby residence as a proxy for the risk associated with population exposure to refinery releases. In Table X, the share each option represents of the total benzene exposure reduction achieved by implementing all options is given in the column labeled "Benzene exposure reduction." The barge loading option accounts for 55% of the benzene exposure reduction attributable to all options. In cost-effectiveness terms, the cost for a 1% benzene exposure reduction ranges from $9000 for secondary seals to $1.48 million for upgrading the wastewater treatment plant.

2. Options and Regulatory Requirements

The statutory requirements addressed by each option are identified in the seventh column of Table X titled "Statutory program." The specified compliance dates for each statutory program are also shown in the table, as are the implementation times for each option. Since the maximum achievable control technology (MACT) requirements have not yet been specified by EPA, projects directed toward those requirements have not yet been undertaken. That being the case, the implementation times identified indicate that options 5, 8, and 9 may have difficulty achieving timely compliance with these regulatory requirements. To proceed with the analysis,. requirements that might be imposed under MACT were hypothesized to specify the performance characteristics of the associated pollution prevention options. It should be noted that only those options related with compliance with the Benzene Waste NESHAP (National Emissions Standard for

Hazardous Air Pollutants) requirements deal specifically with benzene release options; other rules address emissions of hydrocarbon and VOCs, not only benzene.

3. *Single Criterion Rankings*

The project's Peer Review Committee suggested the options be ranked according to a single criterion: risk reduction. In addition to risk reduction, two other single criterion rankings are of interest: total tonnage reduction and cost.

a. Risk Reduction. A risk proxy of benzene exposure at a nearby residence was used to complete ranking of options. Calculated benzene concentrations at a nearby residence were assumed to provide a reasonable indicator for measurement of population exposure, and the exposure reductions achievable by implementing a particular option. Using this measure, and the option characteristics developed by Amoco engineers, several rankings were produced.

The results of ranking the options using benzene exposure reduction as the sole criterion are shown in Table XI. Reducing barge loading emissions is the outstanding option using this metric. No other option comes close to the exposure reduction achieved by reducing barge loading emissions. The other ranking values provide insight into which options generally provide greater exposure reduction. For example, all secondary seal alternatives achieve significant exposure reduction, and the blowdown system upgrade also performs effectively in this regard. Four options achieve no benzene exposure reduction because those options deal with release sources that do not emit benzene.

In reviewing the exposure reduction rankings and other rankings, it is important to bear in mind that the rankings are intended to provide an approximate guide to which options rank near the top with regard to certain criteria and which rank near the bottom. On this basis, options that consistently rank near the top across all criteria felt by the decision maker to be important are generally preferred. Options that receive comparable scores during the ranking process should be considered equivalent independent of their rank. For example, from an exposure reduction perspective Table XI indicates that (1) controlling barge loading emissions is the best single action; (2) installing secondary seals and implementing an upgrade of the blowdown also will achieve beneficial exposure reductions; and (3) that the remaining options achieve minimal or no reduction in benzene exposure.

b. Release Reduction. The results obtained when pollution prevention options are ranked by extent of release reduction are shown in the first set of columns of Table XI. The blowdown system upgrade is the clear winner, reducing releases by more than six times that of the nearest competitor. The remaining options dimin-

TABLE XI
SINGLE CRITERION RANKINGS BASED ON RELEASE REDUCTION AND EXPOSURE REDUCTION

	Release Reduction Option				Exposure Reduction Option		
Rank	Description	#[a]	*(tons/yr)*	*Rank*	*Description*	#[a]	Benzene Expos. Red'n (%)
1	Blowdown System Upgrade	7A	5,096	1	Barge Loading	9	55
2	Barge Loading	9	768	2	Opt 5d & Sec. Seal on Fixed Tanks	5e	20
3	Quarterly LDAR (500 ppm)	11c	706	3	Sec. Seals—Gasoline Tanks	5a	18
4	Opt 5d & Sec. Seal on Fixed Tanks	5e	592	3	Sec. Seals—Gas/Distillate Tanks	5b	18
5	Opt 5c & Floaters on Fixed Tanks	5d	592	3	Sec. Seals—Floating Roof Tanks	5c	18
6	Sec. Seals—Floating Roof Tanks	5c	541	3	Opt 5c & Floaters on Fixed Tanks	5d	18
7	Soils Control	6	530	7	Blowdown System Upgrade	7A	11
8	Quarterly LDAR (10,000 ppm)	11b	511	8	Drainage System Upgrade	7B	5
9	Sec. Seals—Gas/Distillate Tanks	5b	482	8	Treatment Plant Upgrade	7C	5
10	Sec. Seals—Gasoline Tanks	5a	475	10	Quarterly LDAR (10,000 ppm)	11b	3
11	Install FCU ESP	3b	442	10	Quarterly LDAR (500 ppm)	11c	3
12	Annual LDAR (10,000 ppm)	11a	320	12	Annual LDAR (10,000 ppm)	11a	2
13	Replace FCU Cyclones	3a	245	12	Eliminate Coker Blowdown Pond	4	2
14	Eliminate Coker Blowdown Pond	4	130	14	Reroute Desalter	1	1
15	Drainage System Upgrade	7b	113	15	Sour Water System Improvements	10	0
16	Modify Sampling System	8	63	15	Replace FCU Cyclones	3a	0
17	Treatment Plant Upgrade	7c	58	15	Install FCU ESP	3b	0
18	Reroute Desalter	1	52	15	Soils Control	6	0
19	Sour Water System Improvements	10	18	15	Modify Sampling System	8	0

[a]# refers to project numbers from Table V.

ish gradually in terms of release reduction. When compared to the exposure reduction results, all of the highest ranked release reduction options—blowdown system upgrade, barge loading controls, quarterly LDAR program (500 ppm), and double seals on tanks—also rank at the top in terms of exposure reduction.

c. Cost. It is interesting to compare the exposure reduction and release reduction results with the ranking based on cost, shown in Table XII. In terms of annualized costs, modifying the sampling hardware and procedure is the best option, costing three times less than its closest competitor. When evaluating the options, using a single cost criterion alone is not as useful as comparing the cost ranking results with the results based on exposure reduction and release reduction. Modifying sampling ranked high with respect to cost but near the bottom with respect to these other criteria. On the other hand, two options that rank high with regard to exposure reduction and release reduction (secondary seals and quarterly LDAR 500 ppm) also rank well with respect to costs. Barge loading and blowdown system upgrade, which rank near the top from the exposure reduction and release reduction perspective, rank near the bottom from the cost perspective. Based on these three single criterion rankings, the secondary seals and quarterly LDAR options look promising, and, if sufficient funding is available, barge loading and the blowdown system upgrade may be promising as well.

4. Multiple-Criteria Ranking

In some cases, a more integrated multiple-criteria process is desired to help with option selection. For example, the importance attributed to each criterion may be in dispute, and a systematic process may be needed to enable the decision makers to resolve these differences. The study team considered a number of multiple-criteria decision-making techniques for ranking options. The three approaches given greatest attention were (1) the analytical hierarchy process or AHP (Saaty, 1988, 1990); (2) the Kepner–Tregoe approach (Kepner and Tregoe, 1979, 1981), which Amoco has used in reviewing selected corporate decisions; and (3) computation of alternative equivalents (Stokey and Zeckhauser, 1978), which a member of the Peer Review Committee suggested. Ultimately, the study team selected AHP as the ranking methodology since it has proven useful in making decisions involving a large number of diverse criteria and options. As its name implies, AHP devotes a great deal of attention to the process by which the decision is made. Since the Amoco/EPA project involved a diversity of viewpoints at the federal, state, and industrial levels, a systematic process was needed for reaching a consensus or for identifying where and to what extent viewpoints differed. AHP provides such a framework. AHP proceeds by using group discussion to identify criteria, organize them into a hierarchy that embodies relationships

TABLE XII

SINGLE CRITERION RANKINGS BASED ON ANNUALIZED COST AND NET ANNUAL CASH FLOW

	Release Reduction Option				Net Cost Option		
Rank	*Description*	*#*[a]	Annualized[b] Cost $M	Rank	Description	#[a]	Net Annual Cash Flow[c] $M
1	Modify Sampling System	8	27	1	Quarterly LDAR (10,000 ppm)	11b	(4)[d]
2	Sec. Seals—Gasoline Tanks	5a	90	2	Annual LDAR (10,000 ppm)	11a	(2)
3	Annual LDAR (10,000 ppm)	5b	112	3	Quarterly LDAR (500 ppm)	11c	(1)
4	Sec. Seals—Gas/Distillate Tanks	11a	92	4	Sec. Seals—Gasoline tanks	5a	<(1)
5	Quarterly LDAR (10,000 ppm)	11b	138	5	Modify Sampling system	8	5
6	Sec. Seals—Floating Roof Tanks	11c	195	6	Sec. Seals—Gas/Distillate Tanks	5b	10
7	Quarterly LDAR (500 ppm)	5c	155	7	Soils Control	6	17
8	Sour Water System Improvements	10	199	8	Sec. Seals—Floating Roof Tanks	5c	30
9	Soils Control	6	203	9	Sour Water System Improvements	10	110
10	Reroute Desalter	1	329	10	Reroute Desalter	1	131
11	Eliminate Coker Blowdown Pond	4	632	11	Opt 5c Floaters on Fixed Roof Tanks	5d	242
12	Opt 5c & Floaters on Fixed Roof Tanks	5d	637	12	Eliminate Coker Blowdown Pond	4	246
13	Opt 5d & Sec. Seal on Fixed Roof Tanks	5e	698	13	Opt 5d & Sec. Seal on Roof Tanks	5e	281
14	Barge Loading	9	1,608	14	Barge Loading	9	568
15	Blowdown System Upgrade	7A	1,630	15	Blowdown System Upgrade	7A	734
16	Replace FCU Cyclones	3a	3,029	16	Replace FCU Cyclones	3a	1,158
17	Install FCU ESP	3b	3,583	17	Install ESP FCU	3b	1,548
18	Drainage System Upgrade	7B	5,941	18	Drainage System Upgrade	7B	2,467
19	Treatment Plant Upgrade	7C	7,403	19	Treatment Plant Upgrade	7C	3,120

[a]# refers to project numbers in Table V.

[b]Includes only direct and indirect costs.

[c]Includes both direct and indirect costs, and revenues from recovered materials.

[d]Numbers in parenthesis represent positive cash flow.

among the criteria, and establish priorities (i.e., criteria weights) with respect to an overall goal. AHP has been used in a wide variety of complex decisions. Examples include use by DOE to prioritize hazardous waste remedial efforts at federal energy facilities; use by the Regional Advisory Committee of the National Health Care Management Center to identify problem areas for research affecting health care in the United States; and use for setting priorities in development of a transportation system for the Sudan.

B. Analytical Hierarchy Process

AHP analysis involves five steps. First, identify the overall goal and the important decision criteria. For this project, the goal was to select the most effective pollution prevention options for the refinery.

Second, organize the criteria into a hierarchical structure based on the relationships among criteria and the project objective.

Third, establish the relative significance (weight) of each criterion. This usually is accomplished via a set of pairwise comparisons among the different criteria. In each pairwise comparison, two criteria on the same hierarchical level are directly compared. The decision maker (in this case, the study team) establishes the importance of one criteria relative to the other. All unique pairs of criteria at each level of the hierarchy are compared via such pairwise comparisons until all possible combinations have been compared. AHP then translates the pairwise comparison results into a relative weight for each criterion.

Fourth, evaluate each option within the context of the proposed hierarchy. Overall scores are determined for each option based on its performance on the criteria in the hierarchy. A comparative ranking of options among themselves is thereby established.

Fifth, adjust and/or revise the hierarchy based on information acquired during the preceding steps in the decision-making process. Using sensitivity analyses, decision makers can review the overall contributions of specific criteria and judgments to the final decision; how changes in criteria weights affect outcomes; or how changes in the hierarchical structure influence the decision. This review may lead to altered judgments and/or a revised hierarchy.

1. Identification of Ranking Criteria

An initial list of criteria was generated from the project workplan (Amoco/EPA, 1990) and two brainstorming sessions at the Williamsburg workshop (Amoco/EPA, 1991d). The project workplan provided overall perspective for criteria selection. Criteria identified at the Williamsburg workshop provided a "base" list that was refined at subsequent study team meetings. Initial criteria lists, which were broad in scope, were made more specific as the study team gained knowledge about the characteristics of the options and the availability of data.

Through a process of elimination and refinement, the following criteria were ultimately selected for ranking options based on quantitative (and sometimes qualitative) assessment of the following characteristics:

- *Risk.* Relative benzene exposure reduction.
- *Technical characteristics.* Release reduction (mass); status in pollution prevention management hierarchy (e.g., source reduction versus treatment); transferability of option to other refineries or industries; timeliness of option implementation; secondary emissions.
- *Cost factors.* Resources utilization (raw materials and utilities); capital, operating, and maintenance costs; effects of option implementation on potential remedial, product, and catastrophic liabilities.

2. *Development of Hierarchy and Criteria Weights*

Hierarchy structure was developed in parallel with refining the criteria list. The study team identified relationships among criteria and constructed a hierarchy to represent these relationships. Within the hierarchical structure, each level is influenced only by the next higher level and can influence only the next lower level. To rank options, each criterion on the hierarchy must be assigned a relative weight. Developing weights involved two steps. First, study team members completed a survey of pairwise comparisons for each set of criteria on the hierarchy. Second, the study team convened an all-day session to review survey results and to revise criteria weights and the hierarchy structure.

3. *AHP Ranking Results*

Table XIII presents the results of the AHP ranking using the hierarchy and criteria weights developed by the study team. There appear to be three distinct groupings of options: most preferred, least preferred, and a middle ground where no strong preference exists for one choice over another. Two major factors influenced the overall ranking of options: exposure reduction and cost. Technical characteristics determine the rankings within the mid- and low-performance groups.

Reductions in barge loading emissions, which achieves a 55% benzene exposure reduction, receives a ranking score more than two times greater than the next best option. The second group of options, which related to installing secondary seals or upgrading the blowdown system and annual LDAR, achieve significant exposure reductions. The 8 lowest ranked options all have minor or no impact on the benzene exposure to the surrounding human population.

TABLE XIII
AHP RANKING USING WORKGROUP WEIGHTS

Rank	Option: Description	Option: #[a]	Score
1	Barge Loading	9	100
2	Sec. Seals—Floating Roof Tanks	5c	43
2	Opt 5d & Sec. Seal on Fixed Tanks	5e	43
2	Sec. Seals—Gas/Distillate Tanks	5b	43
2	Sec. Seals—Gasoline Tanks	5a	43
6	Opt 5c & Floaters on Fixed Tanks	5d	40
7	Blowdown System Upgrade	7a	29
8	Quarterly LDAR (500 ppm)	11c	19
9	Quarterly LDAR (10,000 ppm)	11b	18
10	Annual LDAR (10,000 ppm)	11a	16
11	Drainage System Upgrade	7b	13
12	Treatment Plant Upgrade	7c	12
12	Eliminate Coker Blowdown Pond	4	12
14	Reroute Desalter	1	11
14	Soils Control	6	11
14	Modify Sampling System	8	11
17	Sour Water System Improvements	10	10
18	Replace FCU Cyclones	3a	5
18	Install FCU ESP	3b	5

[a]# refers to project numbers in Table V.

AHP analyses were conducted to compare the results obtained using the criteria weights proposed by Amoco with the results using weights proposed by EPA/Commonwealth of Virginia team members. This analysis suggests how the options might be ranked from an industry outlook as compared with the ranking from a regulator's viewpoint. Despite differences in perspective, the results show that reducing barge loading emissions is the preferred choice for both groups. In addition, while other options change order, the readjustments are minor. Workgroup members from Amoco assigned nearly equal weights to all three criteria, while EPA/Virginia members assigned the highest weight to risk reduction, next highest weight to technical factors, and the lowest weight to cost.

C. REGULATORY REQUIREMENTS AND PROJECT OPTIONS

As indicated in Table X, 8 of the 12 project options would, if implemented, contribute to meeting current or anticipated regulatory and statutory program requirements. Legal requirements dictate that these options or an equivalent be undertaken at the refinery. The characteristics of these 8 options are summarized in Table XIV,

TABLE XIV

REGULATORY REQUIREMENTS OPTIONS

#[a]	Project	Materials	Annual Cost ($MM)	Release Reductn (tons/yr)	Benzene Exposure Red/n (%)	Statutory Program	Expect. Compl. Year
7C	Treatment Plt Upgrade	VOC	7.40	58	5	Benzene NESHAP/nonattainment	1993
7A	B/D Upgrade	VOC	1.63	5,096	11	Benzene NESHAP/nonattainment	1993
11b	Drainage Upgrade	VOC	5.94	113	5	Benzene NESHAP/stormwater	1994
9	Elim. Coker Pond	VOC	0.63	130	2	RCRA/CAA	1994
7B	Sec. Seals Flt Roof	VOC	0.16	541	18	SIP, nonattainment	1994
4	Modify Sampling	VOC/HC	0.03	63	0	MACT or HON	1995
5c	Quarterly LDAR	VOC	0.14	511	3	Ozone nonattainment	1996
8	Barge Loading	VOC	1.61	768	55	MACT, nonattainment	1996
	Total		17.53	7,279	99		

[a]# refers to project numbers in Table V.

listed in order of compliance year. The eight options at an annual cost of $17.5 million achieve a release reduction of 7300 tons per year and a benzene exposure reduction equaling 99% of that associated with all twelve options. The four options *not* required by current or anticipated regulations include soils control, rerouting the desalter effluent, installing an electrostatic precipitator for fines control at the FCU, and the improving the sour water stripper operation.

For purposes of comparison, an analysis was conducted to assess what options might be selected to achieve comparable release reduction and exposure reduction objectives in the absence of the existing regulatory constraints. To avoid double counting in this analysis, a specific alternative was selected for those options involving multiple alternatives. The alternative options selected were 3b for FCU fines recovery, 5c for secondary seals, and 11b for LDAR. The goal in this analysis was to attain the desired environmental targets—release reduction or exposure reduction—at a lesser cost.

The 12 options are ranked in Table XV with respect to cost effectiveness of release reduction, expressed in dollars per ton. The results indicate that five options—11b, Quarterly LDAR; 5c, Secondary Seals on Storage Tanks; 7a, Blowdown System Upgrade; 6, Soils Control; and 8, Modify Sampling—are the most cost effective with regard to release reduction. Taken together, these five options attain a release reduction of 6700 tons of hydrocarbons and hazardous solid waste per year at an annual cost of $2.2 million. Note that while soils control is a good pollution prevention option since it prevents the generation of hazardous waste, it

TABLE XV
COST-EFFECTIVE RELEASE REDUCTION RANKING

#[a]	Project	Annual Cost ($MM)	Cumul. Annual ($MM)	Release Reductn (tons/yr)	Cumul. Rel. Redn (tons/yr)	Cost Effect ($/ton)	Cumul. Cost Effect ($/ton)
11b	Quarterly LDAR	0.14	0.14	511	511	270	270
5c	Sec. Seals Flt Roof	0.16	0.29	541	1,052	287	276
7A	B/D Upgrade	1.63	1.92	5,096	6,148	320	313
6	Soils Control	0.20	2.13	530	6,678	383	319
8	Modify Sampling	0.03	2.15	63	6,741	429	319
9	Barge Loading	1.61	3.76	768	7,509	2,094	500
4	Elim. Coker Pond	0.63	4.39	130	7,639	4,862	575
1	Reroute Desalter	0.33	4.72	52	7,691	6,279	614
3b	Install FCU ESP	3.58	8.31	442	8,133	8,106	1022
10	Sour Water Improvement	0.20	8.50	18	8,151	11,056	1043
7B	Drainage Upgrade	5.94	14.44	113	8,263	52,810	1748
7C	Treatment Plt Upgrade	7.40	21.84	58	8,321	127,586	2625
	Total	21.84		8,321		2,625	

[a]# refers to project numbers in Table V.

TABLE XVI
COST-EFFECTIVE BENZENE EXPOSURE REDUCTION RANKING

#[a]	Project	Annual Cost ($MM)	Cumul. Cost ($MM)	Benzene Exposure Red'n (%)	Cost-Effective Exposure Red. ($M/% exp. red.)
5c	Sec. Seals Flt Roof	0.16	0.16	18	9
9	Barge Loading	1.61	1.76	55	29
11b	Quarterly LDAR	0.14	1.90	3	46
7A	B/D Upgrade	1.63	3.53	11	148
4	Elim. Coker Pond	0.63	4.16	2	316
1	Reroute Desalter	0.33	4.49	1	329
7B	Drainage Upgrade	5.94	10.43	5	1,188
7C	Treatment Plt Upgrade	7.40	17.83	5	1,480
10	Sour Water Improvement	0.20	18.03	0	
6	Soils Control	0.20	18.23	0	
3b	Install FCU ESP	3.58	21.82	0	
8	Modify Sampling	0.03	21.84	0	
	Total	21.84		100	

[a]# refers to project numbers in Table V.

does not reduce air emissions. When compared to the full set of regulatory requirement options, the cost-effective options attain more than 90% of the release reduction at less than 15% of the annual cost. Adding barge loading emissions to the five most cost-effective options achieves 103% of the required tonnage reduction for a little over 20% of the annual cost of the set of options required by regulations. Of this group of six, all options except soils control are required for compliance with current or anticipated regulations.

A similar analysis is shown for exposure reduction in Table XVI. In this case, six options—5c, Secondary Seals on Storage Tanks; 9, Barge Loading; 11b, Quarterly LDAR; 7a, Blowdown System Upgrade; 4, Eliminate Coker Pond; and 1, Reroute Desalter—are much more cost effective than the next two options in terms of benzene exposure reduction. The six options collectively attain 90% benzene exposure reduction of the full set of eight regulatory requirements at about 20% of the annual cost. Four options achieve no reduction in benzene exposure.

The regulatory requirements shown in Table XIV have been or will be developed using administrative procedures. The regulatory development process includes review and comment opportunities for the public and for industry organizations. It is not the intent of the analysis presented here to assess critically all of those regulatory requirements, since the level of evaluative detail here is considerably less. The results presented here merely indicate the possibility that when the collective requirements of the regulations imposed on a given facility are taken into account, granting the industrial organization greater flexibility in how to achieve the designated standards may enable a facility to attain standards at a significantly reduced cost. The cost effectiveness of various pollution prevention or regulatory options varies widely from location to location. In this case, most of the benefits required can be achieved at a fraction of the cost of all the options.

D. Summary of Ranking Results

The scores achieved by each pollution prevention option under each of the ranking methods are summarized in Table XVII. disregarding minor differences between option scores, the scores achieved under each method are grouped into high, medium, or low categories. The absence of a ranking score under a particular ranking method indicates that option received a low score for that method.

Those options (or alternatives) that received at least a high or medium score under all but one of the rankings are marked with an asterisk (*). These include all five double seal alternatives, blowdown system upgrade, barge loading controls, and the two quarterly LDAR alternatives. By virtue of their favorable ranking under a variety of perspectives, the study team concluded that these four options show the most promise among the twelve different options considered. Note that all four options in this group are required by current or anticipated regulations, and that the blowdown system upgrade is ranked high on release reduction but low on cost ranking.

Three options that fare next best across the ranking protocols are annual LDAR, modification of sampling systems, and soils control. Several options ranked consistently low and were thus least preferred. These included (3a) replacing the FCU cyclones, (7b) the drainage system upgrade, and (7c) the treatment plant upgrade. None of these received a medium or high score. Just above this group, a third tier included options 1, 2, 3b, 4, and 10. The matrix below separates the options into four preference categories.

1. Most Preferred
   - 5 Install Secondary Seals
   - 7A Upgrade Blowdown System
   - 9 Reduce Barge Loading Losses
   - 11b,c Quarterly LDAR Program
2. Next Most Preferred
   - 11a Annual LDAR Program
   - 8 Sampling Systems Mod.
   - 6 Soils Control
3. Next Least Preferred
   - 1 Reroute Desalter
   - 3b Install FCU ESP

TABLE XVII

OPTION SCORES BY RANKING TECHNIQUE

#[a]	Option	Release Reduction	Exposure Reduction	Cost	Cost-Effective Rel Red'n	Cost-Effective Exp Red'n	AHP
1	Reroute Desalter				M	M	
3a	Replace FCU Cyclones						
3b	Install FCU ESP	M			M		
4	Elim. Coker Pond				M	M	
5a	Sec. Seals Gasoline Tks*[b]	M	M	M	H	H	M
5b	S. Seals—Gas/Dist. Tks*	M	M	M	H	H	M
5c	Sec. Seals—All FltRf Tks*	M	M	M	H	H	M
5d	Opt 5c & Flt on Fix Tk*	M	M		H	H	M
5e	Opt 5d & S. Seal Fix Tk*	M	M		H	H	M
6	Soils Control	M		M	H		
7A	B/D Upgrade*	H	M		H	M	M
7B	Drainage Upgrade						
7C	Treatment Plt Upgrade						
8	Modify Sampling			H	H		M
9	Barge Loading*	M	H		M	H	H
10	Sour Water Improvement			M	M		
11a	Ann. LDAR (10,000 ppm)			M	H	H	M
11b	Quart LDAR (10,000 ppm)*	M		M	H	H	M
11c	Quart LDAR (500 ppm)*	M		M	H	H	M

Note: All options were ranked high (H), medium (M), or low (L). Blank space denotes low (L).

[a]# refers to project numbers in Table V.

[b]Asterisk (*) denotes projects ranked high or medium with only one low ranking.

   4 Eliminate Coker Pond
   10 Sour Water Improvements
4. Least Preferred
   3a Replace FCU Cyclone
   7B Drainage System Upgrade
   7C Treatment Plant Upgrade

IX. Implementation of Selected Options: Obstacles and Incentives

The preceding material has identified and ranked a number of technology options that can reduce, eliminate, or change releases from the Yorktown refinery. This section first generally examines obstacles and incentives to implementing pollution reduction initiatives, and then considers specific issues that might apply to implementing five highly ranked options at the Yorktown refinery. The end of this section identifies several general trends gleaned from the specific examination of Yorktown.

A. Background

The Yorktown refinery has operated under state and federal regulations for some 35 years. During this time the standards to be met have changed dramatically. Since the early 1970s, when media-specific environmental regulation began, Amoco's environmental investments have focused on meeting regulatory requirements as they were developed. Thus, investments were made in advanced wastewater treatment in 1974–1976 to comply with Clean Water Act requirements by July 1, 1977. The refinery also improved its sulfur plant to ensure compliance with Clean Air Act requirements. An MTBE unit was built in 1985 to help the refinery meet lead phasedown requirements. A sludge processing unit to handle RCRA listed wastes was constructed in 1987 to allow closure of previously used landfarms. Other facilities were built to meet lower gasoline vapor pressure requirements.

Today, new tanks are replacing surface impoundments previously used to store wastewater. The coke yard is being renovated to reduce windblown dust particles and to minimize potential groundwater and stormwater contamination. Underground sewer systems in the tankfields are being redesigned to meet new benzene waste NESHAP requirements and stormwater regulations. Amoco has funded research at the University of Waterloo in Canada to help identify the mechanism of dioxin formation in catalytic reforming systems. Simultaneously, a multimedia sampling program for dioxins was completed at Yorktown. At the refinery, equipment believed to be responsible for producing dioxins was taken out of service as soon as it could be identified, and an alternative catalyst regeneration process was implemented.

Until quite recently, there was little integrated management of these multiple regulatory requirements because (1) the regulations themselves did not recognize the potential value of such integration, (2) sufficient information about multimedia releases was not available, and (3) relatively short compliance time frames did not allow time for more integrated analysis.

B. Obstacles

There are at least three major obstacles to doing anything different than regulations require (such as earlier implementation, better control, control of more sources, and so on) require: (1) limited resources, (2) poor economic return, and (3) regulatory disincentives.

1. Limited Resources

Doing something over and above actual regulatory requirements often means expending resources either earlier or in greater amounts than otherwise planned. Corporate resources are constantly being prioritized to meet competing demands. Environmental projects that go beyond meeting legal requirements compete with other investments for limited technical manpower and capital. In the refining part of Amoco's business, these competing requirements include the following: (1) sustaining investments to replace worn-out equipment and keep facilities operable; (2) energy conservation programs to reduce manufacturing costs, which coincidentally reduce emissions from combustion sources; (3) safety programs to improve worker safety and meet new OSHA requirements; (4) product reformulations to improve quality and to meet new federal requirements; (5) development of new manufacturing catalysts and processes; and (6) modifications and improvements to existing processes to increase productivity. Therefore, all projects that are not absolutely required for compliance with laws and regulations are evaluated on a profitability basis, and compared with all other investments.

Once investments have been made, they tend to have long operating lives. Most refineries in this country are more than 40 years old. If the investment solves the problem of concern adequately, there is no incentive to address the same problem again later. In this project, the existing end-of-pipe water treatment plant was found to do an excellent job cleaning process water. Discharge quantities are normally well below permitted values. Because waterborne pollutants are handled effectively and the treatment plant has ample capacity, there was little incentive to spend limited project resources developing other ways to reduce or manage the same pollutants.

Compliance with existing and pending regulations consumes substantial manpower. Doing more requires technically trained manpower to invent, evaluate, design, engineer, construct, and start up new equipment or programs. Although Amoco's environmental staff at the refinery has increased by more than 100% in the last two years, staff time is fully committed to understanding and complying with current regulatory requirements. These have typically short-term deadlines and severe penalties for failure; they, therefore, receive top priority in allocating staff time.

2. *Return on Investment*

Corporate investments are made to earn an adequate return on invested capital for shareholders, ensure economic stability and growth of the corporation, and provide employment for workers. Many of the options identified for the pollution prevention project were found to be uneconomic. That is, the value of the recovered hydrocarbons was simply insufficient to pay for the capital and operating cost of the recovery equipment. Two exceptions were adding secondary seals to gasoline storage tanks and instituting an LDAR program to reduce fugitive emissions. The fact that most of these options are not profitable is not surprising for two reasons: First, product or emission recovery projects that provide positive economic return are probably already implemented for economic reasons; and second, projects that do not have economic returns have already been dropped from consideration.

Amoco's project evaluation approach has usually viewed environmental projects in the limited context of meeting specific regulatory requirements within a fixed time frame. The Yorktown project suggests that a broader, longer term view might reveal some incentives for release reductions beyond meeting current legal requirements. For example, cogeneration of electricity is typically evaluated on the basis of the cost to generate versus the cost to buy steam and power. The lower cost option is usually the option selected.

But cogeneration is also a potential means to capture energy value from VOC emissions that might otherwise require separate investments for recovery, treatment, or destruction facilities. Viewed on a broader geographic basis, cogeneration frequently results in a net reduction in criteria pollutant emissions by replacing low-efficiency power generation with higher efficiency cogeneration. Thus, cogeneration potentially combines emissions control with improved efficiency while avoiding additional treatment and disposal costs.

3. *Regulatory Disincentives*

Exceeding regulatory requirements could use scarce resources to reduce current emissions without providing any "credit" for these reductions (Levin, 1990).

Many regulatory programs define a baseline period, and measure progress or changes from that base. The need for a Prevention of Significant Deterioration (PSD) Review for an air permit starts with emissions present in August 1977. The 33/50 voluntary reduction program sets 1988 as a base year from which to measure progress. The early reductions provisions of the Clean Air Act Amendments of 1990 use 1987 as a base year. Reducing emissions before required reduces a company's baseline emissions and makes achieving future regulatory targets more difficult and costly, because the most cost-effective reduction would have already been made. Those companies that have made minimal emission reductions are indirectly rewarded because when required to reduce, they can do so more economically than a "more progressive" company that has already made substantial reductions.

a. Clean Air Act Limits. Since 1977, amendments to the Clean Air Act have discouraged industry from making voluntary improvements to a facility because doing so may compromise the facility's future ability to expand or modify processes. Federal and state air regulations generally do not allow "banking" of emission reductions that could be credited toward future facility modifications. In cases where banking programs do exist, significant time restrictions have been imposed on them.

There has been considerable debate on the value, benefits, costs, and administrative procedures for emissions banking (Liroff, 1986). This project has not attempted to resolve these complex issues. It simply points out that from an industrial perspective, the inadequacies of existing banking systems present a disincentive to voluntary emissions reductions. In this context, since most of the options being considered are required by current or anticipated regulations, the concept of banking would involve early implementation of projects.

Most facility modifications require an air quality permit for construction. The time required to obtain this permit could be reduced from a typical 12–18 months to 2–6 months by using eligible emission reduction credits to offset new emissions from the proposed modifications.

Under the 1990 Amendments to the Clean Air Act, this disincentive for voluntary reductions persists. The act requires the refining industry to construct major new facilities to produce reformulated fuels. Since these new facilities must also obtain construction permits, they will, in effect, consume many of the offsets available for other possible changes. It will be increasingly difficult to obtain offsets to modify or expand facilities. One bright spot, although not directly applicable to this situation: On March 29, 1993, the Chicago Board of Trade offered sulfur dioxide emissions as a new tradable commodity. Under a sealed bid system \$21.4 million was paid for the right to emit 150,000 tons of sulfur dioxide from electrical utility smokestacks. Amoco has begun discussions with the Environmental Defense Fund to explore a similar concept for VOCs and NO_x as a way to provide incentives to refineries to reduce their emissions.

b. Clean Water Act Limits. A facility that makes voluntary reductions in its waterborne pollutants may find its permit limits permanently changed to these lower values. Indeed, several EPA representatives have commented informally that data from this project showed the refinery is doing such a good job meeting water permit limits most of the time, that it may be appropriate to lower these limits. This approach fails to recognize that equipment failures and operating upsets can occur, causing significant excursions above normal performance. Since the facility is required to meet permit limits under all conditions (or face potential penalties), an operating margin is essential for continuous compliance.

c. RCRA Limits. Regulations governing hazardous wastes under the Resource Conservation and Recovery Act require the toxicity characteristic (TC) test to determine if a substance is hazardous. Once a substance has failed this test and is deemed hazardous, the generator has little economic incentive to spend resources reducing toxicity or mobility of the waste. The waste must still meet the same treatment, storage, and disposal requirements as if the waste still posed the same degree of hazard. There is no credit in terms of reduced regulatory burden for improving waste characteristics. A number of other RCRA-related obstacles have been identified in a recent presentation by Byers (Byers, 1991).

C. General Observations on Five Highly Ranked Options

Five highly ranked options were identified by the project:

1. Reduce barge loading emissions.
2. Install secondary seals on storage tanks.
3. Upgrade blowdown systems.
4. Remove soils from sewers.
5. Institute LDAR program.

Specific barriers and incentives for each option are reviewed in the remainder of this section. Table XVIII summarizes the obstacles and incentives for each option discussed. Three themes reappear: First, there is no workable banking system for emissions reductions. Thus, early reductions will frequently "disappear," because they are no longer available to meet pending or anticipated regulatory programs. Also, a facility making such reductions is put at a disadvantage compared to its competition that elects not to make such reductions. Subsequent reductions become increasingly expensive. In effect, the current system "rewards" those who

TABLE XVIII
SUMMARY OF OBSTACLES AND INCENTIVES FOR FIVE POLLUTION PREVENTION OPTIONS

Option	Obstacles	Incentives
1. Reduce Barge Loading Emissions	Safety Regulatory authority Regulatory requirements Permitting Equipment availability	Product recovery Benzene exposure reduction
2. Secondary Seals on Tanks	Tank availability Regulatory requirements No emission banking	Known technology Modest cost Product recovery Benzene exposure reduction Low administrative burden Ability to identify proper sources
3. Upgrade Blowdown Stacks	Engineering complexity Regulatory requirements No emission banking	Benzene exposure reduction
4. Reduce Soil Intrusion	None	Reduced disposal cost and liability Improved treatment plant operation Low administrative burden Modest cost
5. Institute LDAR Program	Manpower Limits No emission banking	Effectiveness Modest cost Low administrative burden Regulatory requirements Timeliness

do little, by leaving them with emissions that are more easily reduced. Similarly, it "punishes" those who do more, since subsequent reductions are usually more difficult and expensive.

Second, few of the projects identified and analyzed in this project offered significant economic incentives. This type of facility is characterized by high mass recoveries (>99%) as an integral part of normal process operations and business practices. Most product or emission recovery projects that have positive economics have already been implemented. For many of the options identified in the project, the cost of further source reduction, recovery, or treating of emissions far exceeded the potential revenue to be gained from material recovered.

Finally, for many of the projects considered, the implementation time required does not match mandated compliance deadlines. Typical refining industry projects take 2 or 3 years to complete under the best of circumstances.

Because the study team initially selected projects that appeared achievable with current technology, we cannot assess the incentives or obstacles for innovative technical solutions. There is no question that inventing, testing, designing, constructing, and starting up new technology takes significantly longer than using standard, well-proven, commercially demonstrated approaches. Many of these issues were addressed in a recent report by the Technology Innovation and Economics Committee of the National Advisory Council for Environmental Policy and Technology (TIE/NACEPT, 1991).

1. Reduce Barge Loading Emissions

Barge loading losses total 800 tons/year of hydrocarbons, including 15 tons/year of benzene. These occur in the York River, around the marine tanker dock and loading facility. The dock extends more than one-half mile into the river from shore. The proposed control scheme would move hydrocarbon vapors emitted during the loading process to an on-shore vapor recovery system or flare. If materials are recovered, they can be recycled to the refinery for redistillation and use in products.

a. Incentives

(i) Potential Revenue. A vapor recovery system for Yorktown's marine loading losses could provide potential revenues of $160,000 per year. No such revenue could be realized if product is flared rather than recovered. Although the potential for some income is an incentive, it is not sufficient in this case to justify this $4.7 million investment. If all the recovered vapors were salable as gasoline, the cost for this incremental gasoline would be more than $6/gallon.

(ii) Benzene Exposure Reduction. Dispersion modeling clearly showed that reduced barge loading emissions had the largest single influence on reducing potential benzene exposure at a nearby residence.

b. Obstacles

(i) Potential Safety Problems. Marine vapor recovery systems collect and move hydrocarbon vapors in a closed system. The safety considerations of this option are slightly different than those of routine hydrocarbon processing, due to the introduction of air into the recovery system. There is always a concern and potential for buildup of air in a recovery system, producing an explosive air/hydrocarbon mixture. For the system considered for Yorktown, safety control hardware represents nearly $1.5 million of the total $4.7 million estimated capital cost.

(ii) Engineering Complexity. Significant engineering details remain to be resolved for an installation at Yorktown. A major concern at this time is how to move hydrocarbons the long distance (approximately 3000 feet) from the dock to an on-shore blower or compressor. Resolving these details while ensuring safe design and operation takes more time than typical compliance deadlines normally

provide. A more ideal solution to marine loading emissions would consider unconventional approaches such as working with barge companies to jointly develop workable, economic ship-board systems. However, solutions involving second- or third-party participation take even more time than single-party answers.

(iii) Regulatory Authority. Process systems dealing with marine vapor recovery must receive U.S. Coast Guard approval before operation. The EPA is required to establish standards for such systems under the Clean Air Act (Title I and III). It is not clear to the regulated community who will have final authority for approval. What may be considered a state-of-the-art system today may not meet tomorrow's regulatory requirements.

(iv) Regulatory Requirements. Title I of the Clean Air Act requires the EPA to establish requirements for marine vapor loading losses to ozone nonattainment areas. Title III of the same act requires control of this emission source to regulate hazardous air pollutants. Standards will therefore be established in the relatively near future for this type of equipment. Until regulatory standards are developed and approved, it will be difficult to construct "acceptable" vapor recovery facilities.

(v) Permitting. A flare for vapor treatment will require an additional air emission permit. If criteria pollutant emissions from burning the recovered vapor exceed PSD levels, an extensive air quality study, and possible control of offsetting emissions, would be required. The permit process could take significant time and technical resources.

(vi) Equipment Availability. A very limited number of suppliers have equipment and control systems with Coast Guard approval. These designs may not have been tested and approved under all conditions. Once marine vapor control becomes mandatory, equipment demand may exceed supply, leading to extended delivery times and higher costs.

2. *Install Secondary Seals on Storage Tanks*

Vapor losses from tanks account for an estimated 600 tons/year of VOC emissions, including 10 tons/year of benzene. Systems that reduce these losses could recover 500–600 tons/year of VOCs.

a. *Incentives*

(i) Known Technical Solutions. Secondary seal technology is well developed. Although there are several alternative systems, most are well tested in commercial service.

(ii) Modest Cost. The "average" tank can probably be equipped with a secondary seal system for $20,000. Crude oil tanks would cost significantly more because they are significantly larger. The total cost for sealing a specific number of tanks is a multiple of the single-tank cost. There are no significant economies of scale.

(iii) Reduced Releases, Product Recovery. Vapors that remain in the tank can be recovered as product, provided their recovery does not violate product vapor pressure limits. Since the more volatile compounds typically concentrate in emissions, their recovery may require removing some butane, a light hydrocarbon normally added to gasoline for vapor pressure control. Where butane can be sold or consumed, recovery should not present a serious problem. But in some refineries, excess butane is a low-valued product and cannot be sold economically.

(iv) Reduced Benzene Exposure. Dispersion modeling work showed that storage tank emissions have a measurable influence on exposure, although less than barge loading losses. Thus, reducing these emissions has a modest, direct, and positive impact by reducing potential exposure to surrounding areas.

(v) Minimal Administrative Burden. In the Commonwealth of Virginia, installing a secondary seal on a tank reduces emissions and would not constitute a significant modification to an existing emission source. Thus, no permit action would be required, other than notification of local Air Pollution Control District authorities.

(vi) Opportunity to Identify Proper Sources. While there are more than 80 tanks in the refinery, gasoline storage tanks are responsible for nearly 80% of tank fugitive emissions. At this time, industry is able to select for control those sources that offer the most benefits. This provides the ability to target maintenance and capital spending on a specific subset of tanks.

b. Obstacles

(i) Tank Availability for Maintenance. Each year, 5–10 tanks from the 80 tanks on-site are removed from service, emptied, inspected, and repaired. For safety reasons, secondary seals can only be installed when the tank is empty and hydrocarbon free. Tank availability constrains the implementation of secondary seals, since piping connections among processing units and tankage is fixed, and spare tankage is available for a limited number of variations to the normal product market demands, refinery operations, and crude availability schedule. It would take approximately 10 years for all tanks in the refinery to be available for maintenance and modification work.

(ii) Regulatory Requirements. The Clean Air Act Amendments of 1990 require the application of MACT on certain refinery equipment items. Precise definition of MACT standards for storage tanks has not been completed. Absent a firm definition of requirements, there is a reluctance to commit resources to construct what may be ruled an unacceptable control system. Further, depending on the outcome of current EPA discussions regarding averaging emissions from different sources, it may be more cost effective to overcontrol some emission sources, while undercontrolling others. Thus, it may be advantageous to overcontrol tank emissions and have less control on other fugitive sources.

(iii) Emissions Reduction Banking. As discussed earlier, the lack of a workable hydrocarbon emissions banking program is a disincentive for more rapid implementation.

3. Upgrade Blowdown Stacks

Two blowdown stacks handle process releases during emergency and upset conditions. A third stack handles vent gases released during the cooling cycle at the coker. Emission estimates show these are the largest single-point sources for hydrocarbon releases in the refinery (5200 tons/year), including an estimated 32 tons/year of benzene. The engineering solution considered to control these emissions involves collecting blowdown vent gases in a common system and treating them in one or more new flares(s).

A number of other possible solutions that involved recovery of heat content, cogeneration, or sale to an adjacent Virginia Electric Power Company generating plant were considered in the early stages of this study. Many have been evaluated during the last 10 years by Amoco as part of its energy conservation programs. All had been previously rejected on the basis of difficult, time-consuming contract negotiations, and uncertain, unpredictable energy prices.

a. Incentives

(i) Reduced Off-Site Exposure. Dispersion showed that blowdown stacks contribute to potential off-site exposure to about the same extent that storage tank emissions do. Reducing these releases will also provide a modest reduction in exposure potential.

b. Obstacles

(i) Engineering Complexity. Flare systems are notoriously difficult to size and design because they are required to handle a wide variety of upset conditions. Flare siting and sizing requires that the load be well defined. But definition depends heavily on which scenarios should be included in the system design basis. For ex-

ample, a new flare must typically handle the emergency releases from connected process units which may occur as a result of a storm-induced power failure. Should this same system also be capable of handling simultaneous releases from several different units? Should it be designed to handle releases that might result from a simultaneous power failure in one area of the plant and a fire in a different area?

Each scenario requires detailed analysis of system component size, cost, radiation released, impact on the surrounding ground area, etc. Most analyses require detailed information on existing systems. For older facilities, this is sometimes difficult to locate. Plot space limitations add to the complexity. These issues require substantial engineering time before final design, engineering, and construction can begin. Typical "compliance" deadlines do not normally recognize this time requirement.

(ii) Regulatory Requirements. Clean Air Act amendments may require modification of existing equipment such as atmospheric relief valves. These modifications could affect flare system size and design. Because of the difficult engineering work required to design this type of system, there is a reluctance to conduct detailed studies until regulatory requirements are defined well enough to minimize rework.

(iii) Emissions Reduction Banking. As previously discussed, there is no credit for emissions removed from blowdown stacks against future potential emissions that may occur from facility modifications.

4. Reduce Soil Intrusion into Drainage System

Sampling analysis during this project identified more than 1000 tons/year of soil entering the refinery's underground drainage system. Once there, the solid tends to become oil coated, deposit as sludge in the oil/water separator, and must be handled as listed hazardous waste. At Yorktown, most hazardous waste sludges are recycled to the refinery's coker where hydrocarbons are converted into usable liquid and solid products. A small amount of soil components remains in the coke product.

Engineering solutions to reduce soil intrusion to the drainage system include (1) using a road sweeper to collect soil and catalyst fines from roadways and process areas before they are blown or washed into the drainage system, and (2) modifying sewer box designs, particularly in earthen areas such as the tank field, to keep soil from entering with water runoff.

a. Incentives

(i) Coker Capacity. Reducing solid wastes generated and sent to the coker would initially improve the coke quality and yield of other higher valued prod-

ucts. However, the refinery currently sends some wastes off-site for proper disposal including some tank bottoms and some oil/water separator sludge. It is likely that coker sludge processing capacity made available by reducing soil load would be used to handle other solid wastes. Thus there would be little or no long-term impact on coke quality or other product yields.

(ii) Reduced Disposal Costs and Liability. Handling more waste with on-site treatment reduces the likelihood of transportation and remediation liabilities associated with off-site disposal or treatment of hazardous wastes. Offsite landfill disposal charges are currently about $250/ton and rising. Incineration costs are about $1500/ton for listed hazardous wastes. Reduced off-site disposal would also decrease transportation-related air emissions.

(iii) Improved Wastewater Treatment Plant Operation. Solids in the drainage system tend to collect and foul some wastewater treatment plant equipment. Reducing solids by removing soil would reduce fouling and maintenance needs.

(iv) Minimal Administrative Burden. Since only internal refinery soils are involved, and no additional emission or release sources are contemplated, it seems likely that no permit action would be required, except notification of the Virginia Department of Waste Management.

(v) Modest Cost. Although costs for this project are nearly equal to or exceed current off-site waste disposal costs, disposal costs are escalating rapidly. Potential future disposal cost savings appear attractive.

b. Obstacles

No obstacles could be identified for this project.

5. Institute a LDAR Program

Process fugitive emissions are about 800 tons/year (including 4 tons/yr of benzene), the second largest source of hydrocarbon emissions at the refinery. A leak detection and repair program involves scheduled inspection of all valves, flanges, pump seals, and other potential leak sources that handle light hydrocarbons, using an organic vapor analyzer to detect leaks. When leaks are found, the inspection team makes an immediate repair attempt and rechecks the component.

If the repair is successful, no further work is necessary. If unsuccessful, a maintenance work order is written for craftsmen to make a second repair attempt within a prescheduled time, usually 15 days. If the second repair is successful, no further work is necessary. If the component cannot be repaired while the equipment is operating, the leak is noted in the maintenance log for repair during the next scheduled shutdown. The EPA has published emission factors for components based on the type of LDAR program used. More frequent inspections have lower emission factors, and therefore lower estimated emissions (EPA, 1985b).

a. Incentives

(i) Effectiveness. Limited testing at Yorktown, which currently has no LDAR program, showed that most of the leaks found could be repaired relatively easily by the inspectors using simple tools (Amoco/EPA, 1991e). Using EPA emission factors, an annual inspection and repair program could reduce estimated emissions by 300 tons/year; a quarterly program could reduce estimated emissions by 500 tons/year.

(ii) Modest Cost. The major cost for an LDAR program is additional manpower. The cost effectiveness is about $275/ton, the second lowest cost per ton of all the options considered. Hydrocarbons recovered have a potential cost of about $0.90 per gallon.

(iii) Low Administrative Burden. The only record keeping is that necessary for adequate internal administration.

(iv) Timeliness. No construction is required, so benefits could be obtained more quickly than with any other option considered.

(v) Regulatory Requirements. LDAR programs are not required in this part of Virginia at the time of the study, but are anticipated to be a part of the MACT requirements of the Clean Air Act Amendments of 1990 and/or the state implementation plan. Similar programs are used in a number of ozone nonattainment areas in other parts of the country. Amoco uses this technique at its Whiting and Texas City refineries. If the Commonwealth of Virginia requirements follow these other programs, no unusual regulatory requirements are expected.

b. Obstacles

(i) Manpower Limitations. As noted earlier, additional manpower would be required for a LDAR program. Initial manpower requirements to start up a new program would probably be higher than final costs.

(ii) Emissions Reduction Banking. Reducing emissions before mandated to do so frequently decreases a facility's baseline emissions. No credit is available for this early decrease, and future emissions reductions become more expensive.

D. FOLLOW-UP TO THE ORIGINAL PROJECT

1. *Implementation Status*

At the time of this writing, the pollution prevention options identified in the study, as well as other projects not related to the study, are in various stages of implementation. Some of the projects have been engineered and installed, some at little cost and others at high costs. The upgrades to the sewer system and wastewater treatment plant to reduce benzene emissions have been completed. This project involved the construction of a new sewer for process wastewater, built completely aboveground, and the replacement of the existing oil/water separator and flotation system with an aboveground closed unit. The project was installed at a capital cost of $29 million compared to the originally estimated $41 million. The underground sewer remains in service, collecting primarily stormwater, so the passive action of the underground sewer system to prevent groundwater contamination is not inhibited by the new construction. Secondary seals are being added to the gasoline tanks on a multiyear schedule. A survey of the refinery has been partially completed to identify and inventory the thousands of small valves and connectors that are the source of "fugitive" air emissions. The formal LDAR program is currently being evaluated.

Some projects were easier to implement than expected, while others are still stymied by the "system." As a result of some innovative refinery process engineering, the refinery was able to completely eliminate the use of the coker cooling pond (rather than just controlling its emissions), achieving twice the emissions reduction at a fraction of the original cost estimate. This is truly one of the noteworthy outcomes of the project. This is a textbook case where, faced with a costly option, the refinery experts teamed up to identify a cost-effective solution that provided the greatest possible environmental benefit—elimination of the emission source entirely. Costly emission controls were avoided. Furthermore, the reduction was accomplished with far fewer resources than originally estimated.

On the other hand, the project that offered the most risk reduction potential—controlling emissions during barge loading—is still on hold. The capital funds commitment remains in the current investment plan, but the engineering awaits the issuance of the regulations that address this emission source. The refinery cannot afford to risk implementing a system to control the emissions that may not comply with a future technology or performance standard.

2. *Subsequent Data Gathering*

One of the project findings was the need for good emissions data for development of both environmental regulations and facility-specific pollution prevention plans. Since testing of blowdown stack emissions proved very difficult during the project, emissions were estimated based on AP-42 emission factors. Subsequent to project completion, Amoco continued to investigate other available sampling and analytical techniques to refine blowdown stack emission estimates. As a result of subsequent testing, VOCs from the blowdown stacks are estimated at 100 tons per year (2% of the 5200 tons/year estimated during the project). Total VOC emissions from the Yorktown refinery area are now estimated to be 2800 tons/year.

While these new data do not change the overall findings of the Yorktown project, they do change the relative effectiveness of the blowdown system upgrade option. These new data are critical to the refinery's ability to set priorities for pollution prevention projects.

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