Conoco and the Vapor Recovery Project

Using Innovation to Preserve Autonomy

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Keywords
cleaner production
closing the loop
maximum available control technology (MACT)
oil and gas industry
pollution prevention
zero emissions

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Volume 3, Number 1

Summary

We describe Conoco's closed-loop approach to reducing undesirable emissions through vapor recovery at some of its natural gas production facilities near Corpus Christi, Texas. In response to the U.S. Clean Air Act Amendments of 1990 (CAAA), Conoco developed a technological solution that routed emissions from the facilities to fuel scrubbers and condensers to capture usable product and hazardous air pollutants. Usable product was sold. Nonsalable emissions were routed to on-site equipment as fuel. The new technology was designed without power needs because electricity was not available. In completing these modifications, a closed system (approaching zero emissions) for these facilities was achieved. This innovation saved and earned money for the firm and allowed Conoco to retain its autonomy in these operations.

The solution was so effective that the air quality permits under the CAAA were not required for these production facilities, for a total out-of-pocket cost of $560,000 (plus earned revenue). The firm saved $2,535,000 in initial and $1,359,000 in annual permit costs and fees. The technology recovered $210,000/yr worth of vent gas as on-site fuel and 3,633 barrels/yr of saleable condensate valued at $58,128/yr. At the same time, it reduced its division environmental impact by 884 tons/year of nitrogen oxides, 2,366 tons/yr of volatile organic compounds, and 495 tons/yr of other hazardous air pollutants. Payout of this $560,000 investment was less than 2 years.

Introduction

Increasingly, businesses are adopting strategies that advance the societal goal of sustainable development by reducing the environmental impact of industrial products and manufacturing processes (Hart 1997). These activities, understood through the lens of what is being called industrial ecology (Frosch and Gallopollus 1989; Graedel and Allenby 1995) represent a transition from command and control, end-of-pipe systems to more closed-loop, life-cycle-oriented environmental management systems (Sharfman et al. 1997). Socolow (1994) suggests that the industrial ecology transition can be understood through six perspectives, which range from an examination of industrial activities on the long-term habitability of the planet to a reconceptualization of the role of the firm and farm. Although still mired in the early stages of this transition, consistent with Socolow (1994) a growing number of industries have begun to actively engage their creative energies toward the development and adoption of organizational and technological systems that consume fewer resources, reduce waste, enhance productivity, and create new market opportunities. All of this transition is taking place in the midst of a plethora of differing environmental regulations. The role of regulation in such change in general and toward environmental innovation in particular is still open to debate. To date, little research exists that investigates the relative importance of market-driven and government regulatory actions in stimulating technological innovation of environmentally benign products—particularly innovation that surpasses regulatory compliance (Alm 1992; Florida 1996).

What makes the role of regulation even more important in innovation is that environmental regulations often act as technology standards by forcing firms to use particular technological approaches to meeting the standards. By doing so, such standards limit a firm's flexibility in reducing emissions. During the prepromulgation phase, however, firms face different choices and greater flexibility in how they will respond to regulation. The opportunity to "innovate their way out" of environmental regulatory oversight creates a strong incentive to seek creative ways to reduce or eliminate emissions (see Norberg-Bohm 1997, 11; Ashford 1993, 297).

This paper examines the effects of regulation on the adoption of a specific "green" technological innovation. We have chosen this topic because of the ongoing debate about the value of government intervention in environmental matters and because the literature that exists on the subject is not conclusive (see Rothwell 1992). The research on the relationship of environmental regulation and technological innovation that has occurred (e.g., Ashford and Heaton 1983; OECD 1985) only shows a weak, slightly negative effect (OTA 1994). Stewart and Wibberly (1980, 120) argued that the reason for the lack of clear findings in research on the regulation/innovation linkage is that only "highly aggregated measures of innovative output" have been used.

In this article, we describe the development of Conoco's closed-loop approach to vapor recovery at some of its natural gas production facilities near Corpus Christi, Texas. In response to the strictures of the U.S. Clean Air Act Amendments (CAAA) of 1990, Conoco personnel developed a technological solution to the problem of air emissions from the production batteries. By installing aromatic recovery units (ARUs) and rerouting flash gas (vaporized natural gas and other emissions) from facility separators and glycol flash tanks, a closed system (approaching zero emissions) for the glycol dehydrators and separator flash gas was achieved. This innovation was significant because it saved and made money for the company, presented the business unit as a leader in the company, and most important, preserved Conoco's operating autonomy.

We have organized the rest of this article as follows: First, we present an overview of Conoco and then present the regulatory context for the effort, specifically a summary of the CAAA of 1990. We then describe the development of technological innovation itself, the business benefits achieved by the innovation, as well as the environmental benefits. We conclude the case study with a discussion of what we believe can be learned from the effort. We developed this case study from data collected from interviews with key informants from the company, internal (proprietary) company documents, and publicly available materials. The activities described in the case took place between 1990 and 1995. The research for the case was completed between 1996 and 1998.

Company Background

The company that is today called Conoco was founded in 1875.[1] In 1981, it became a wholly owned subsidiary of the large chemical company, DuPont. In 1998 DuPont began the process of spinning Conoco off as an independent concern. This was accomplished partially through an initial public offering of stock as well as by giving current DuPont shareholders shares in the newly independent Conoco. The spinoff will be completed in 1999.

Conoco is organized into two basic units: "upstream" and "downstream" plus a relatively small corporate group. The upstream unit explores for, develops, and produces crude oil and natural gas and processes natural gas to recover high-value liquids. The company produces approximately 445,000 barrels (70.7 million liters) of petroleum liquids and 1.3 billion cubic feet (36.8 million cubic meters) of gas per day, mainly from the United States, the Gulf of Mexico, the North Sea, Dubai, and Indonesia. In 1994, Conoco also began producing crude oil in Russia and is currently exploring for new reserves of oil and gas in more than 30 countries on six continents, including Venezuela and the Asia Pacific region. Conoco is the eighth largest firm in the world in terms of the production of petroleum liquids (e.g., crude oil) and the eleventh largest in production of natural gas.

The upstream business unit is organized geographically,[2] with the major units being Africa/

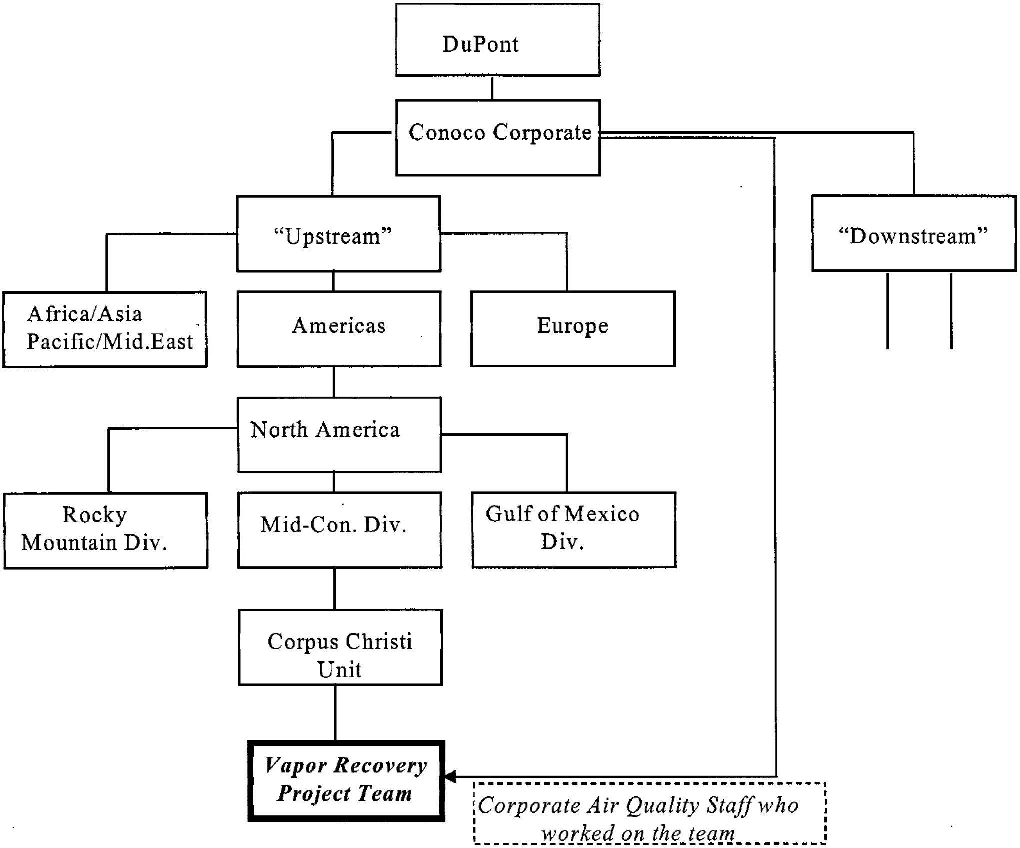

Figure 1 Simplified organization chart for Conoco, showing vapor recovery project team.

Asia Pacific/Middle East, the Americas, and Europe. The Americas unit is split into U.S. and non-U.S. components. The U.S. component is further subdivided into three major groups: the Gulf of Mexico area, the mid-continent area, and the Rocky Mountain area.

The downstream part of the business refines crude oil and other feedstock into petroleum products, trades in crude oil and products, and distributes and markets petroleum products. This unit is also organized along the same geographic basis as the upstream unit. The corporate unit, located in Houston, houses the office of the CEO, financial services, information services, safety/health/environment, new business development, and the usual corporate support functions. We have included as figure 1 a simplified organizational chart of Conoco that also indicates where the team that completed the innovation we describe in this paper fits in the overall firm.

Conoco's refineries—four in the United States, one in England, and shares of one in Germany and two in the Czech Republic—process over 730,000 barrels of feedstock per day. Through a joint venture, the company is constructing a refinery in Malaysia.

Gasoline, diesel, and motor oils under the Conoco¤ , Jet¤ , and Seca¤ brand names are sold through about 7,000 retail outlets in the United States, Europe, and the Asia Pacific region. In 1995, the company gained an interest in a Turkish distribution company that now has about 780 stations. Conoco also manufactures a wide range of industrial lubricants and specialty products. It is the world's leading supplier of graphite coke, a premium product used to make electrodes for the steel-making industry. Conoco's total refined product sales amount to almost 1 million barrels a day.

In addition to expanding its upstream and downstream operations into new areas, Conoco is selectively broadening its activities within the global energy business. In 1995, the company established Conoco Global Power to pursue emerging opportunities in power generation markets.

All of the above activities take place in the context of Conoco's commitment to the environment, which the firm refers to as a core value (Conoco 1999). As one can see from Conoco's Environmental Policy Statement (see Appendix 1), the company has made a major commitment to conducting its business in an environmentally responsible way in harmony with the business needs of the firm.

As we mentioned, at the time of the case study, Conoco was still a wholly owned subsidiary of DuPont. As such, DuPont's environmental policies influenced the actions that Conoco took. DuPont has goals that state "We will drive toward zero waste generation at the source.... We will drive toward zero emissions" (DuPont 1997, 1). Although these statements are goals, not specific objectives, they still provided an overarching framework in Conoco within which decisions with environmental consequences were made and provided incentives for Conoco to share the same goals.

Conoco's internal culture shapes the way it does business. The firm has been a fierce competitor both as an independent firm and as a unit of DuPont. The firm's mission statement sums up this attitude: "Our vision is to be recognized around the world as a truly great, integrated, international energy company that gets to the future first" (Conoco 1999).

The keyword in that statement is *first*. This is a company that wants to win. As the firm puts it, they see themselves as a "dynamic pacesetter in the industry" and "a swift, nimble, focused, aggressive competitor" (Conoco 1999). This is also a company that has a very well-defined way of doing business. Since its early days as Marland (later Continental) Oil Company, the firm has prided itself on going its own way. A good example of this is that the firm went as far as developing in the 1950s its own geophysical seismic exploration technology called Vibroseis¤ rather than using existing technology. It is this independence of spirit and operation that frames the way the company approached the innovation in the case we describe below.

Regulatory Context

The energy industry faces a wide variety of regulatory pressures,[3] ranging from those imposed by the Occupational Safety and Health Administration, to those of the Equal Employment Opportunity Commission, and to various state and local zoning regulations. On November 15, 1990, President Bush signed the U.S. CAA Amendments (CAAA) into law. With the passage of this far-reaching set of regulations,[4] the regulatory pressure on the energy industry changed markedly. Although implementation of this massive legislation would carry through the year 2010, a sweeping new permit program would be in place by November 15, 1994 (Title V of the CAAA).

Prior to 1990, approximately 35 states had implemented air quality permit systems. With the 1990 CAAA, the permit program is still administered by the states. If a state's system does not satisfy the requirements of the CAAA, however, permits could then be issued by the United States Environmental Protection Agency (EPA) directly. Either way, the CAAA permit program requires companies to provide information about which pollutants are being released, indicates how much may be released, and delineates what kinds of steps the source's owner or operator is taking to reduce pollution, including plans to monitor (measure) the pollution. It was hoped that under the new regulations the permit system would be helpful to businesses covered by more than one part of the law. Because information about all of a firm's air pollution would then be in one place, regulatory compliance should be less confusing. The claim was also made that the permit system would simplify and clarify businesses' obligations for cleaning up air pollution and, over time, should reduce compliance paperwork. For instance, a refinery might be covered by the acid deposition ("acid rain"), hazardous air pollutant, and photochemical smog portions of the CAAA. With the CAAA, the detailed information required by all these separate sections would now be in one place—on the permit. The combined listing would make a firm's requirements clearer, so compliance should be easier. Firms also should know more precisely what was expected of them.

There is a cost to the permitting process. Organizations seeking permits have to pay permit fees much as car owners pay for car registrations. The permit costs are based on a variety of factors, including the extent of emissions and size of the facility.

The 1990 CAAA gave important new enforcement powers to the EPA. Prior to the 1990 Amendments, it was difficult for EPA to penalize a company for violating the standards. Under the old system, the only way the EPA could enforce the regulations was through a court's order—even for a minor infraction. The 1990 law enabled EPA to fine violators directly. Other parts of the 1990 law increased penalties for violating the Act and brought the CAA's enforcement powers in line with other environmental laws.

Not all of the features of the 1990 CAAA were enforcement- or permit-oriented. The 1990 Amendments had some features designed to clean up air pollution as efficiently and inexpensively as possible, while giving targeted businesses some flexibility in their choices as to the best way to achieve pollution cleanup goals. These new, more flexible programs were called market or market-based approaches. One example comes from the acid rain cleanup program (Subchapter IV-A), which offers utilities choices as to how they reach their pollution reduction goals and includes pollution allowances that can be traded, bought, and sold. The 1990 Amendments also provide some limited economic incentives for cleaning up pollution. For instance, gasoline refiners can get emission "credits" if they produce cleaner gasoline than required. These credits can used against those times when the refiner exceeds permitted emission levels.

The Amendments also gave the EPA the right to specify exactly how to reduce pollutant releases, but, wherever possible, companies were supposed to have the flexibility to choose how they meet requirements. Even though firms were supposed to have flexibility in meeting the standards, one of the essential features of the Amendments was that "[s]ources are to use Maximum Available Control Technology (MACT) to reduce pollutant releases" (EPA 1997). In practice, MACT requirements were understood as meaning that the main choice firms had was whether to implement MACT according to the EPA's definition or find something better.

Another essential element of the 1990 CAAA was its emphasis on the reduction of smog and acid rain. These emphases were particularly important for the energy industry because of two of its most common sets of emissions—volatile organic compounds (VOCs) and nitrogen oxides (NO_x). VOCs are thought to be important smog-forming chemicals, whereas NO_x is believed to be an important component of acid rain. With the added emphasis placed on these two families of chemicals by the CAAA, the energy industry was under particular scrutiny in reducing its emissions of these compounds.

The 1990 CAAA also stepped up enforcement of regulations requiring nationwide reductions in ozone-depleting chemicals (ODCs). Although chlorofluorocarbons (CFCs) are considered the most important of the ODCs, several of the commonly occurring compounds in natural gas (methane, hexane, etc.) are also under scrutiny for possible tighter regulation. As such, the energy industry faced even tighter restrictions on its emissions of these common compounds.

In summary, the passage of the 1990 CAAA created a very different regulatory climate in the United States in terms of air quality, particularly for the energy industry. For the first time, the industry faced a uniform approach to air quality management that included specific targets and sanctions if those targets were not met. The challenge for the industry then was finding ways to meet the requirements of the law without affecting costs any more than necessary.

Using Technology to Respond to the CAAA

The Corpus Christi Unit (CCU) of Conoco consists of 87 oil and gas production/storage tank batteries and other production facilities throughout Texas and Louisiana. It has a daily production average of 7,100 barrels of oil and 153 million cubic feet (mmcf) of natural gas.[5] These production facilities serve as separation and processing centers for the 1,061 producing oil and gas wells within the division. Process equipment at a typical production tank battery (see figure 2) includes one or more of the following: multistage pressure reducers, "knockout" drums, flash gas tanks, production and test separators designed to gravity separate immiscible produced fluids (e.g., light oils such as kerosene); heater treater and chemical-electric separators used in the treatment and further separation of emulsified oils; storage tanks for both produced oil and water; glycol injection into gas lines to prevent methane hydrate formation; "glycol," diethylene, or triethylene glycol, dehydrators designed to remove water vapor from natural gas prior to sale; and various engines, primarily driving compressors, ranging in size from 100 to 1,000 horsepower. All of the above types of equipment are potential sources of toxic air pollutants, the quantity of which is directly related to equipment size, produced fluid composition, and facility throughput.

On April 22nd of 1990 (Earth Day), Conoco announced nine voluntary environmental initiatives designed to demonstrate the company's environmental concern and commitment. The first of these nine initiatives was a one-third reduction of toxic air emissions by the end of 1993. This goal was further defined in each of the business units to include specific reduction targets for VOCs and toxic air pollutants (benzene, ethylbenzene, xylene, toluene, and n-hexane).

Recognizing the importance of continuous environmental improvement reflected in Conoco's voluntary environmental initiatives and the potential cost implications of the CAAA, an interdisciplinary team of engineering, operations, and environmental personnel was formed by the Mid-Continent (Mid-Con) Upstream Division senior management to evaluate the impact of the new CAAA on CCU operations. The team was also asked to look for cost-effective, proactive opportunities to decrease emissions and minimize environmental impact.

The first task at hand was completion of a computerized air emission inventory for all CCU facilities and a determination of how many sites exceeded the air emission thresholds of Title V of the CAA. The team completed this task in the fall of 1993. Sixteen facilities were found to exceed CAAA Title III and V emission thresholds.

The next step was to define the cost and manpower implications of the CAAA for these 16 facilities. The high cost of obtaining and maintaining Title V permits and the limited manpower available to comply with the numerous stipulations of each permit made the team focus on decreasing facility emissions below CAAA Title V permit limits. Detailed analysis of each facility's major emission sources revealed significant potential for recovery of hydrocarbons nor-

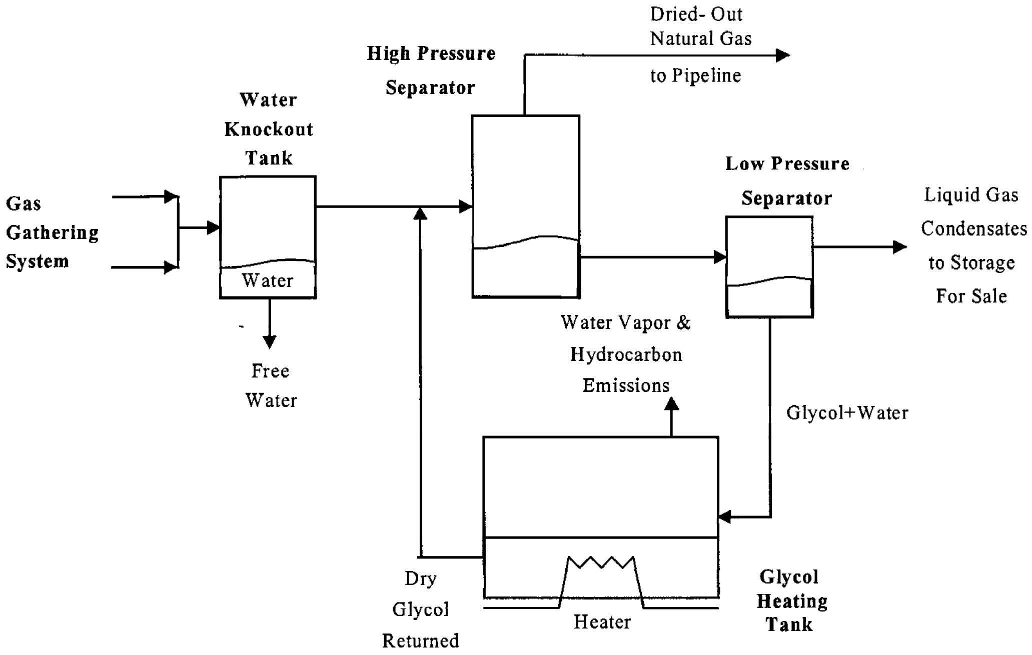

Figure 2 Basic configuration of a natural gas production facility.

mally vented to the atmosphere. Capture and reuse of these hydrocarbons would dramatically decrease divisionwide emissions of VOCs and five other hazardous air pollutants. This would also result in the recovery of significant amounts of lost revenue. It was critical for the team to find good solutions to these emissions problems. Without company-implemented solutions, the firm might be subject to the uncertainties of maximum achievable control technology mentioned above, something the firm desperately wanted to avoid. Even though the upstream MACT standards were not to be put in place until 1998, it was still a major concern for the team. Jim Phelan, then an environmental supervisor and one of the team's leaders, said that (Phelan 1997)

> Given the potential cost implications (of MACT) we began looking for cost effective, proactive opportunities to decrease emissions and minimize environmental impact. MACT standards have very specific air pollution control technology, monitoring, reporting and recordkeeping requirements. We were very concerned not only with the capital investment related to control technology, but also with the cost of monitoring, reporting and recordkeeping. The man hours involved in establishing and maintaining compliance were, in our opinion, going to be very high.
>
> As a company and an industry, competition and the struggle to be cost effective was at an all time high. We were very lean from a manpower standpoint and capital was not available. We simply did not know how we were going to meet all of these requirements given the business climate that we were in then and still are in today. We had to find a better solution to these upcoming regulatory requirements.

The Challenges

The team faced many important challenges in addressing the CAAA. First and foremost, Conoco's existing approach to air emission controls used to reduce emissions needed to be protected under a "federally enforceable" document (such as a state permit or exemption) to avoid the CAAA Title V permit requirements. Monitoring was also required to ensure whatever system was implemented kept emissions below levels that would trigger Title V obligations. State air permits, like Title V permits, are costly and time consuming.

The challenge for the team was to find an alternate means of establishing that the facilities were below state enforceable emission limits. A strategy of formal registration as exempt for the production facilities (which would include acceptable monitoring for each control device) was developed. The team and BDR Technology (an engineering consulting firm) personnel worked together to solidify this strategy, and through various meetings with state regulatory personnel, eventually gained approval for this approach. BDR Technology staff kept division environmental personnel informed on the latest developments under Title V and served as a resource for technical questions during this process.

The next key challenge was that all emission reduction modifications and formal standard exemption registrations had to be completed prior to EPA's approval of the State Title V permit program—November 15, 1994. Division personnel had 9 months to complete modifications at 16 facilities plus prepare and submit lengthy registration applications for 15 facilities.

Finally, consistent with the Earth Day initiative, the team was given the goal to achieve a reduction of 2,196 tons/year of VOC emissions and 463 tons/year of hazardous air pollutants at 11 facilities without increasing the electrical load at each facility. This latter requirement arose because the local electric company could not supply additional power over the existing distribution system. Primary sources of these emissions were separator flash gas, generated as the liquid hydrocarbons' drop in pressure through each successive stage of separation and VOCs liberated from glycol dehydration systems (flash tanks and reboiler still columns). In addition, the hazardous air pollutants consisted of compounds such as benzene, toluene, and xylene from storage tanks with no controls and from compressors emitting NO_x.

What Should Be Done?

The first essential issue in implementing solutions to the emissions problems at the 15 facilities was the cost of the controls and of the permitting. Jim Phelan (1997) described the challenge in the following way:

> We began by looking at the cost of controls under Title III and the cost of permitting under Title V . . . Based on our initial emission inventories in 1993, we had 16 production facilities or tank batteries which would be major sources under both Title V and Title III. Initial capital costs for emission controls were estimated at $124,000–$140,000 per facility. Annual operating and compliance costs to maintain these controls and comply with the administrative requirements of each facility's Title V permit was estimated at $33,000–$66,000. At an initial potential capital cost of $2.5 million plus annual operating and compliance cost of approximately $1.0 million, we were in a big hurry to find a better solution. Given our manpower situation in the field and office, we simply did not know how we would keep up with the numerous requirements which would apply to each of these 16 facilities.
>
> Another, perhaps more important concern was the loss of operational flexibility which would result from having to obtain Title V permits. These permits would include specific restrictions which would limit our ability to quickly change our operation as we explored and developed a given area. The exploration and production business is an ever-changing world. In this particular area of South Texas we had a drilling program which included on the order of 60 development wells per year. The producing sands in this area were very tight, requiring fracturing to enhance flow. The average life of a given producing zone after the initial fracture was 1–3 years before declining to a point where compression was required to maintain production. We typically contracted 5–6 rigs to complete the drilling of these 60 wells, drilling and completing an average 10,000 foot well in 30–45 days. A given facility may receive production from 4–5 or more new wells

> per year. Thus production rates of oil/condensate and natural gas are constantly fluctuating as new wells come on line and existing wells begin to decline. The tendency for a facility in an area being actively developed is an increasing rate of production. Air emissions from an exploration and production battery are very directly related to production rate of oil/condensate and natural gas. Air permit restrictions limit growth of a facility, which would include physical growth/construction of new equipment and growth or increase in production rate. A facility modification or increase in production rate resulting from a new well would not be allowed until a construction permit and operating permit modification were obtained. Permit modifications taking as long as 6 months or more are typical and we feared even longer delays for Title V permit modifications. These types of delays are costly and thus were a very very large concern for us; we had to maintain operational flexibility to be competitive.

Relatively soon after the team began analyzing the facilities, however, it became clear that a large percentage of the emissions was saleable product. Again Jim Phelan remarked (Phelan 1997):

> In completing the air emission inventory we basically discovered the approach we could take to cost effectively comply with these new regulations and maintain flexibility in our operation. Most of the emissions from each facility were hydrocarbons which were recoverable. We initially did not know what we were going to do with these hydrocarbon emissions but there was potential to recover value. What we hoped was that we could invest capital to capture these hydrocarbon emissions and use or sell them, offsetting the capital investment and at the same time reducing emissions to a point where we could exempt each facility from both Titles III and V.

The old process, shown in figure 2, had worked as follows: the gas, oil, and water streams from high-pressure wells are reduced simultaneously in pressure to achieve gravity separation. Several stages of pressure reduction are needed achieve optimum separation and to get the liquids into storage tanks. Once the liquid hydrocarbon product is separated, it is sold either by truck or by pipeline. Any remaining water is disposed of by means of injection wells. Gas is taken off the pipeline directly from the separator. Fluid from low-pressure wells comes into intermediate- or low-pressure separators, from which gas, liquid hydrocarbon, and water streams are routed to different destinations. The gas goes to a compressor where it is compressed to pipeline pressure. Before Conoco sells the natural gas, it is run through a tower-based, glycol dehydration system. In this system, glycol drips down through several perforated trays in this tower, while gas is passed up through the glycol to collect any moisture remaining in the gas. The resulting "wet" glycol is pumped to a regenerator where the condensate is heated to drive the water out of the glycol. The regenerated glycol is then sent back through the same process.

Although the systems worked reasonably well, problems were discovered. Some of the sources of emissions were leaks in the valves and connections where the gas was being transferred, and thus the company was losing valuable product. In addition, the components of natural gas themselves are greenhouse gases (GHGs) and hence under increased scrutiny from policymakers. At the same time that the company was investigating the implications of Title III and Title V, it was discovered (by the industry) that these regenerators emit many hazardous air pollutants. The glycol had an affinity for the heavier, hazardous air pollutants, such as benzenes, ethyl benzene, xylene, and toluene. When the wet glycol stream was recycled in the regeneration process, the hazardous air pollutants evaporated along with the water.

Once this discovery was made, it was relatively easy to convince Mid-Con Division management of the need to do something. A consensus formed rather quickly that an engineering solution to recover the hydrocarbons was necessary. Management was convinced easily because the team could pinpoint clearly the projected benefits; specifically the firm would avoid any future regulations, no matter how stringent, and, at the same time, would have a rapid payback on the investment. In addition, this innovation was consistent with Conoco's proactive approach to environmental problems and with DuPont's goal of a drive toward zero emissions. The consensus among the Conoco personnel who were interviewed, however, was that the threat of future CAAA regulatory obligations was the principal incentive to begin this initiative.

The challenges that faced the engineers were (1) to capture the flash gas that resulted from the production of natural gas liquids and (2) to capture the hydrocarbons boiled off in the glycol regeneration. In the first case, the production of natural gas includes condensates (e.g., light hydrocarbons), which enter each facility at very high pressure. During processing, this stream is staged down in pressure, ultimately reaching a storage tank. Every time the liquids go through a pressure drop, they generate flash gas. The question became how to capture this gas and then the issue became whether to control it or reuse it. There was the option of burning it, but that would have wasted revenues and generated GHGs. In addition, once Conoco realized that this flash gas was actually usable product, there were legal issues because of the royalty payments now due to the owners of the land where the wells were operating. The firm wanted to find a way to either use the flash gas as fuel or compress it back into the pipeline. Because the sites under study were near the wells and hence scattered and remote, the engineering problem was compounded. Consequently, any new technology had to operate without electricity.

It would be inaccurate to say that the project proceeded completely without impediments. First, because the CAAA amendments had not been fully implemented, and their final form was not known, there was some doubt by personnel outside the team of the need for such extensive retrofitting of the facilities. Further, even though the firm had specific projections, there was skepticism concerning the veracity of the numbers the team had generated—both in terms of the extent of the emissions estimates as well as the potential that technology held for both product recapture and emission reduction. Even though Mid-Con management recognized the problem, along the way it was difficult to get the issue seen as a high enough priority by the various engineering and management personnel whose assistance and approval for specific elements were needed. This difficulty was exacerbated by the relatively low awareness (outside the team) of how the as yet not fully defined CAAA regulations would affect company operations.

The Solutions

In solving the first problem there were some minor difficulties along the way. The large-scale, on-site power sources were already using natural gas from the site as a fuel. The new technology, described below, captured the flash gas from the separators and then routed it to compressors for fuel for the on-site equipment. The compressors, however, did not run well on the even richer gas (in the 1,500 to 1,600 Btu range) that was being captured by the new system. The team had to make some changes, but they were able to adapt standard modifications such as reducing the compression ratio on the engine and retarding spark timing to solve the problems. The new changes increase the amount of equipment to be maintained, and the operators have to "babysit" the compressor engines a little bit more. As Jeff Mitchell (1997), process engineer for the team, put it, however, the extra work was worth it because of the effect that the new technology had on the level of odor emitted by the installations. He said, "In fact, it's been a big benefit because . . . you walk out, you don't smell anything. You don't see any smoke, . . . and so the operators say, 'Heh, that's great.'"

The solution to the second problem, although not brand-new technology, did meet the challenges identified by the team. Jeff Mitchell (1997) described it as follows:

> We put together different technologies . . . we basically just took a finned-tube heat exchanger, put it on an elevation, built a base for it, put that on an elevation and fabricated a chimney for it, to draw a natural draft (of air) up through it, so that we could take the still column vapors . . . and condense them to a liquid. [This

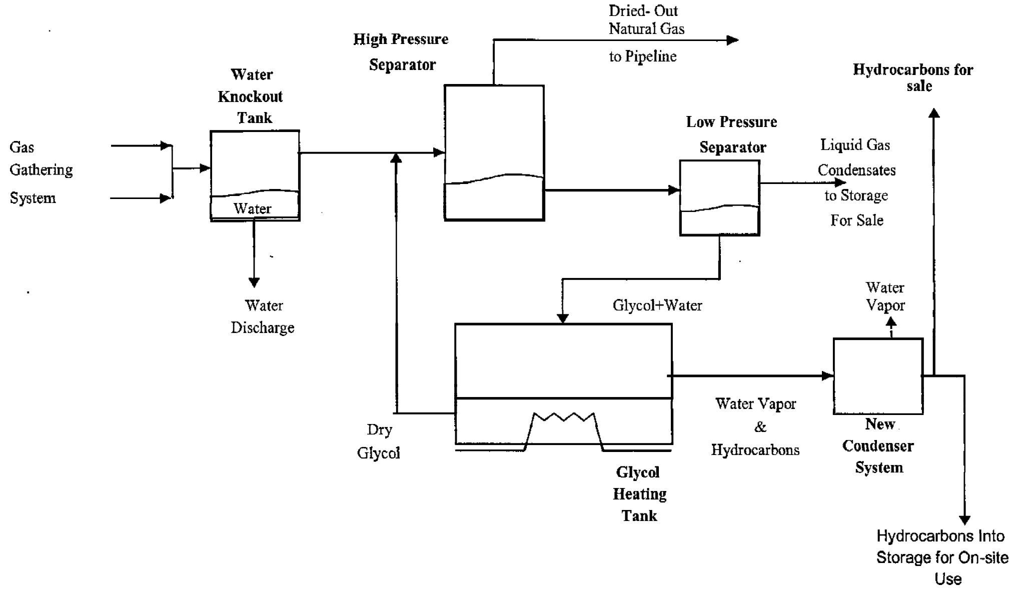

Figure 3 A production facility after the introduction of the new technology.

> would then] go into a vessel from which we could then pump back to our storage tanks [for use]. We capture water and a little bit of condensate off that. So, it can actually make us some money. The vapors that will not condense are re-routed back to the fire-tube heater where we rigged up a mixing valve and a burner assembly to combust them.
>
> I broke up our dehydration units into three classes: up to 10 million a day cubic feet of gas, up to 20 million, and up to 35 million, and I sat down with a simulation program and calculated what kind of heat exchange tube area I needed to condense this 220 degree vapor, . . . just did the modeling to see what kind of volume we had, and said, all right, I need "x" number of tubes, etc. Then I sketched it up and then we went out to bid. We said, these are three types of (we call them condenser packages) that we want somebody to build for us.

The beauty of this approach was that it was a closed system with no electricity involved. All of this processing occurred in the presence of high-temperature gas coming off the generator and hot ambient site temperatures. See figure 3 for a diagram of the new process.

To address the problem of NO_x produced by the compressor engines, the engines were outfitted with catalytic converters and ratio controllers. The converter decomposes NO_x to nitrogen and oxygen so that the installation can emit it safely. The ratio controllers manage the mixture of natural gas going to the engine, which reduces the overall NO_x level. The catalytic converter then simply decomposes the NO_x as it comes up in the exhaust.

The Business Case

In this particular case, the results from the investment were striking. For a total out-of-pocket equipment investment of $560,000, the team was able to reduce emissions below CAAA permit levels at the 16 facilities within the division that exceeded CAAA Title V limits. This proactive approach resulted in the following savings and earnings;

- Recovery of $210,000/year worth of vent gas for use as fuel and the elimination of two gas recovery compressors saving $35,000/year in operation costs.
- ARU condensation of hydrocarbon liquids from glycol reboiler still columns;

3,633 barrels/year valued at $58,128/year (based on $16.00/barrel).

- Average cost savings per facility of $34,000 in CAAA Title V permit preparation costs. A total one-time cost savings of $510,000 (initial permit costs). This does not include similar costs for permit Amendments, which would be required for future facility modifications.
- Elimination of enhanced monitoring (continuous electronic stack monitoring of air pollutant concentration) on 17 specific sources at an average cost of $105,000/monitor (one-time cost—purchase and installation). A total one-time cost savings of $1,785,000.
- Average annual cost savings of $66,000/facility in monitoring equipment operation and maintenance costs, compliance certification, quarterly data reporting requirements, and recordkeeping. A total annual cost savings of $990,000.
- Elimination of annual air emission fees of $94,801 (under rule 101.27).
- Cost savings achieved through reduction of emissions below CAAA Title III thresholds, thereby eliminating the need for maximum achievable control technology on dehydration systems, storage tanks, and fugitive emission sources at 11 facilities. For these 11 facilities, this equates to savings of $240,000 in capital costs, $158,000/year in operating costs, and $116,000/year in monitoring, inspection, recordkeeping, and reporting costs.

It should be noted that the estimates for permitting were based on estimates using external consultants to complete the process. In addition, the $560,000 cost does not include the time of the team responsible for the project. As such, although the initial costs would be between $100,000 and $200,000 higher if the time of the team was included, the economic results of this innovation are still striking. The savings on permit preparation and annual costs alone more than paid back all of the expenses of the project.

There have been other benefits to the firm as well. The innovative heat exchanger design, emergency liquid flow leg, and pilot flame/fuel mixing system used on division-developed ARUs has been incorporated into the Conoco Specialty Products (CSP) ARU. The reduction in instrumentation and increased reliability have made the CSP patented ARU units more affordable (dropping unit cost from $30,000 to $18,000), effectively doubling the CSP ARU market. These design modifications have been incorporated under CSP's original patent.

Fugitive emission monitoring and repair programs were instituted at nine separate facilities to further reduce hydrocarbon emissions and avoid the cost of smokeless flares as backup for primary emission controls (average cost $20,000/flare).

Reduction of NO_x emissions was necessary at nine facilities involving 11 separate compressor engines totaling 17,000 horsepower. Both catalytic converters and lean burn engines were used to achieve the most economic reduction possible. The team was able to save the cost of a catalytic converter on two separate engines by permanently limiting the output capabilities of the governor to reduce maximum available horsepower. This resulted in a $40,000 cost savings.

By reducing emissions below CAAA and state permit thresholds, the division maintained maximum flexibility to expand operations without 6- to 12-month permit delays and minimized manpower necessary to maintain compliance. Finally, the team was able to eliminate one production facility by rerouting produced fluids to another facility. This solved the emission problem at the first facility and saved the cost of a vapor recovery unit (vapor recovery was in place at the second facility). The number of facilities requiring registration was decreased from 16 to 15, with the attendant cost savings.

The Environmental Case

The environmental achievements from this innovation are striking as well. As a result of implementing the technology at 16 production facilities, the firm reduced its emissions as follows:

- 884 tons/year of NO_x (35.7% division-wide reduction)
- 2,365 tons/year of VOCs (57% division-wide reduction)
- 76.1 tons/year of benzene (74% division-wide reduction)

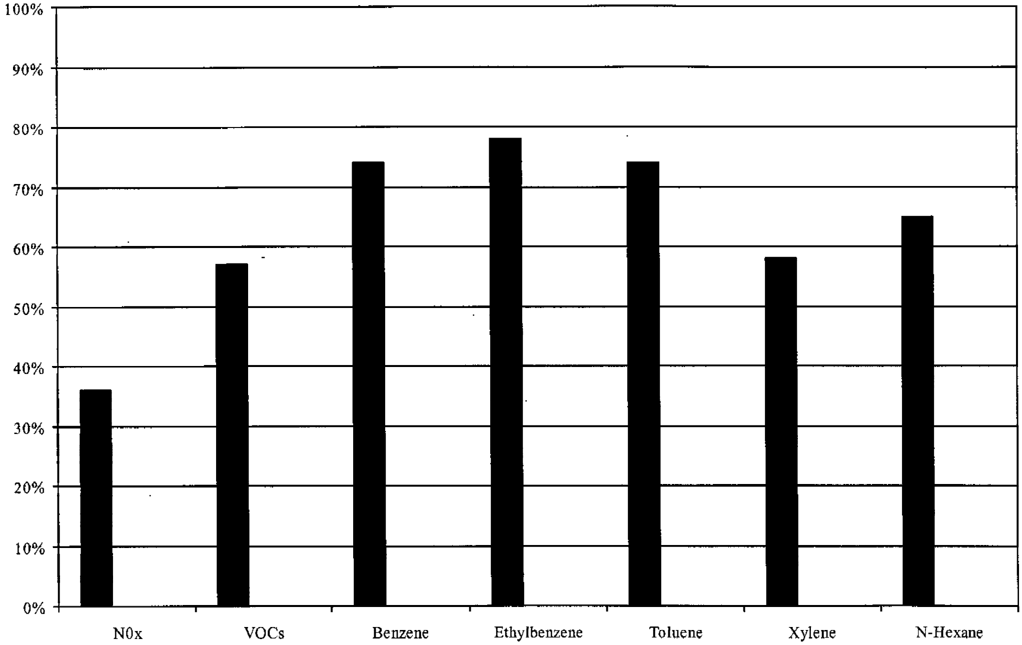

Figure 4 Corpus Christi unit reductions as a percentage of total division reductions.

- 14.6 tons/year of ethylbenzene (78% division-wide reduction)
- 180.1 tons/year of toluene (74% division-wide reduction)
- 204.1 tons/year of xylene (58% division-wide reduction)
- 20.1 tons/year of n-hexane (65% division-wide reduction).

For the division, these emission reductions exceeded the internal goal of a one-third reduction of toxic air emissions. Figure 4 shows the technology's effects as a percentage of division emissions reductions.

There was also an indirect environmental effect from this innovation. Given the remote nature of these facilities, no way to provide additional electrical power for the equipment existed. As such, all of the new technology was added with no increase in the electrical load or any increase in GHGs resulting from that load. Although the on-site engines did generate some additional greenhouse gases from their own combustion processes, which has not been quantified, the amount of GHGs is likely to be much lower than would have been produced by utility-generated electricity.

Discussion

Several important lessons can be gained from Conoco's experience in this case. The case is a powerful example of Socolow's (1994) argument about the interplay of production objectives and environmental objectives (see also Porter and van der Linde 1995). In this instance, the company was losing commercially useful product, emitting materials that could be used for on-site fuel, and emitting several thousand tons of toxic pollutants. By implementing technology that took this set of production facilities to essentially zero emissions, the firm was able to turn pollution into profits by selling the captured product and lowering its own energy costs. In addition, by implementing the closed-loop approach to emission control, the firm was able to save millions of dollars in permit and compliance costs while radically cutting the environmental effects of CCU facilities.

The second key issue has to do with the firm's response to regulation. With its threat of MACT, the CAAA stood to severely constrain Conoco's activities. As we describe above, Conoco values its operating autonomy even more than most firms. Given this likely restraint of the firm's discretion, Conoco used innovation to avoid the pressure of this regulation at the CCU sites while maintaining its operating autonomy. A common perception of the CAAA at the time was that it was going to be a difficult and highly restrictive regulation with which to work. The company was able to develop a solution that removed them from these requirements. In some ways, the severity of the CAAA assisted the firm. Facing the untold difficulties of compliance, the firm was stimulated to find a solution that would remove it from the strictures of the CAA. By going to essentially zero emissions at the CCU facilities, it was able to do so for this part of the firm.

Another important lesson to be learned from this experience is the role that a multidisciplinary team can play in a successful project. The team that completed the innovation described in this case study was composed of environmental, engineering, and operating staff. It was through the interaction of the various functional areas that the solution presented here was developed. From the interviews with the participants, it appears unlikely that the innovation would have occurred or at least been as successful without the input from such a varied group of people. What seemed particularly useful was the ability that team members showed to bring technology (the vapor recovery approach) that was well developed in other areas of chemical engineering into play in this application. The expertise that team members "brought to the table" allowed them to accomplish this knowledge transfer.

One of the most critical lessons learned from this case is the role that educating key personnel outside the team (particularly concerning environmental and regulatory issues) plays in the development of environmental innovations. Throughout this innovation process, there were times when the team met resistance to its plans. In large measure this resistance can be traced to a lack of understanding on the part of individuals outside the team about the severity of the environmental/regulatory problem or the potential compliance cost difficulties that the CAAA was likely to cause. There is also evidence to suggest that initially there was resistance to the project, in part, because some individuals placed a lower level of importance on environmental issues. Educating staff outside of the team concerning both the regulatory burden and the severity of the environmental problems facing the firm and the industry made life a great deal easier for the team.

One of the things that made this education job much easier was upper-management support. Our interviewees suggested that having a division manager who understood the impact of both regulation and environment on the business made both the education and implementation jobs much easier. As the team needed to educate others outside the project, having a supportive division manager gave their efforts a great deal of credibility as well as the "clout" to get done what they needed to do. Further, as the team needed resources or cooperation, the support of upper management increased the likelihood of such resources or cooperation being forthcoming.

This case also demonstrates the gradual transformation of a firm toward a more sustainable form. The transition to sustainability or industrial ecology begins with firms "closing the loop" within their own processes. At present there is no ready prescription for large-scale, comprehensive (sustainable) planning for all industrial enterprises. Rather the present road to sustainability is paved with individual firm actions. Each change in an industrial system is an experiment whose effects on sustainability are not fully known. The idea of technological development as experiment is particularly appropriate with regard to green technological innovation for which large environmental and technological uncertainties make comprehensive planning extremely difficult (see Frosch 1996; Lindblom 1959, 1979). Without leaps forward that reduce the total flow of materials (cf. Socolow 1994) such as we describe in this case, sustainability or industrial ecology will remain an illusive dream.

Conclusion

In this case, Conoco was able to meet several challenges at once. The company was able to address a major set of regulations in such a way as to remove themselves from the requirements. This preserved the firm's operating autonomy while saving them millions of dollars in permitting, monitoring, and compliance costs. The company was also able to approach zero emissions from the production batteries in question. At the same time, the firm was able to recover saleable product while also reducing its on-site fuel costs. The case shows how tightly economic and environmental performances are intertwined and how effectively interdisciplinary teams can confront difficult environmental problems.

Much of Conoco's response to the CAAA regulations was done to preserve the firm's ability to do business as it chose within the law of the land. The innovation in this case preserved operating flexibility in a variety of important ways. First, the innovation freed the firm from the compliance burden that the permitting under the CAAA would have imposed. Not only would this have been costly, but also it would have diverted personnel time that would be better spent on other things. Next, the firm was able to avoid the enormous costs that permitting under the CAAA would likely engender. As a result, resources that would have gone to paying compliance costs could be retained in the firm for other innovations or operations. Next, the firm was free to choose its own technological solutions rather than being handcuffed by the use of MACT. Given Conoco's culture, any infringement on its ability to operate would not be acceptable. As such, the firm became even more highly motivated to find *ways to remove itself as much as possible from the strictures of the* CAAA. In this case, the innovation was as much an effort to retain autonomy as one to save money.

Acknowledgments

This case analysis was supported under EPA grant #R-824748-01-0, "Regulation and Sustainable Development: The Management of Environmentally Conscious Technological Innovation under Alternative Market Conditions." It should be noted that much of the material for the case study was taken from internal Conoco documents—gratefully used with permission. We wish to thank Rob Anex, Reid Lifset, Teresa Shaft, and two anonymous reviewers for their assistance on this and earlier drafts of this article.

Appendix 1: Glossary

Acid Rain: Rain that has turned acidic because of the presence of sulfur and/or NO_x in the atmosphere.

Aromatic recovery unit (ARU): A partial condenser fed with the water vapor stream from a glycol reboiler. Aromatic hydrocarbons, such as benzene, ethylbenzene, toluene, and xylene, are condensed from the water vapor so that they do not enter the atmosphere.

Barrel: International, standard volume measure for hydrocarbon liquids, 42 U.S. gallons (158 liters).

Benzene: A hydrocarbon composed of six carbons and six hydrogen atoms in a ring structure and considered a hazardous air pollutant.

Catalytic converters: Reactors used for pollution control containing a compound that promotes a chemical change but remains unchanged itself.

Chloroflourocarbons: Hydrocarbon compounds containing chlorine and fluorine atoms (CFCs) that are believed to be very potent ozone-depleting chemicals.

Condensate: Liquid hydrocarbons produced from a gas well.

Ethylbenzene, **Toluene**, and **Xylene**: Hydrocarbon compounds similar to benzene that are also inherent in the natural gas production process.

Emergency liquid flow leg: A device incorporated into the design of a condenser to prevent too high or too low pressure from existing within the unit.

Finned-tube heat exchanger: A tube heat exchange with fins on the outside to facilitate heat exchange.

Flash gas: Gases released when liquid mixtures of hydrocarbons, hydrogen sulfide, dissolved carbon dioxide, and other substances are reduced in pressure through a valve or other orifice.

Fuel scrubber: A vessel in which a light hydrocarbon oil is brought into contact with a fuel gas containing an overly high content of heavier hydrocarbons, to reduce the heating value of the heavier hydrocarbons.

Glycol—Mono-, Di-, or Tri-ethylene glycol: Related to automobile radiator fluid. Absorbs water from hydrocarbon-water mixtures.

Glycol reboiler: A vessel that is fed with a glycol stream that has absorbed water from a hydrocarbon stream elsewhere. The vessel is heated to drive off the absorbed water so that the regenerated glycol can be returned to its absorption use. Otherwise known as a **reboiler still**.

Greenhouse gases: Radiatively active gases that can contribute to warming of the atmosphere, particularly water vapor, methane, and carbon dioxide.

Hazardous air pollutants: Compounds such as hydrogen sulfide that have been designated dangerous for human health under the U.S. Clean Air Act or other regulation.

Heater treater and chemical-electric separators: Equipment facilitating breakdown of water-oil emulsions.

Hydrates: Common name for combinations of hydrocarbons and water formally denoted as clathrates. Can form icelike obstructions in certain conditions in pipelines and equipment.

Immiscible produced fluids: Liquid elements of the oil or natural gas extraction process that cannot be mixed or blended with other fluids.

Lean burn engines: Engines using higher than normal air-fuel ratios to reduce NO_x production.

N-hexane: Another volatile organic compound found in petroleum.

Ozone-depleting chemicals: Substances such as CFCs that destroy stratospheric ozone.

Reboiler pilot systems: Pilot light systems on gas-fired reboilers.

Separator/knockout drum: A vessel fed with a gas/liquid mixture resulting from pressure reduction. Baffles serve to separate the gas and liquid phases so that they can leave separately.

Smog: A photochemical haze caused by the action of solar ultraviolet radiation on an atmosphere polluted with hydrocarbons and NO_x.

Vent gas: Natural gas that would have been discharged to the atmosphere prior to the implementation of stricter air pollution control regulations.

Appendix 2: Conoco Environmental Policy Statement (Conoco,1999)

Our company will conduct business with respect and care for the environments in which we operate. To realize this we will

Minimize the environmental impact of our activities by

- Assessing the environmental sensitivity of potential operating sites and the impact of our operations on the local, regional, and global environments.
- Limiting physical disturbances and employing appropriate reclamation and remediation practices at operating sites.
- Ensuring responsible and efficient use of energy and natural resources.
- Limiting waste generation, discharges and emissions, and handling wastes in a responsible manner.
- Operating in a responsible manner which reduces the risk of spills, leaks, and accidental discharges.
- Maintaining emergency preparedness plans and response capabilities.
- Encouraging life cycle assessments in the development of our products.

Foster open communication on company environmental performance by

- Demonstrating our commitment through environmental excellence.
- Developing dialogue with interested parties to increase knowledge of the effects of our activities.
- Working with government and other interested parties to develop balanced environmental standards and expectations.
- Being responsive to public attitudes and concerns.

Systematically manage environmental performance by

- Addressing environmental concerns in all phases of our activities.
- Developing aligned goals and standards, and ensuring responsibilities are assigned and understood.
- Committing appropriate means and resources to meet stated goals and standards and to comply with applicable laws and regulations.
- Ensuring staff and contractors are trained to carry out their duties responsibly.
- Maintaining a documented environmental management system.
- Utilizing effective performance measures.

- Ensuring that inspections, audits, reviews, and follow-up actions are planned and carried out.
- Encouraging contractors, suppliers, and customers to conduct their business with environmental responsibility.

Continuously improve the total environmental performance of the company through

- Technology innovation and application.
- Organizational development.
- Enhanced understanding.
- Commitment.

Notes

1. This material was taken from the Conoco World Wide Web Page, http://www.conoco.com/about/index.html and is used with permission (accessed last on March 8, 1999).
2. As of this writing, Conoco is undergoing a reorganization as a result of the divestiture from DuPont and the 1998–1999 slump in oil prices. The organizational structure may have changed from this description as a result.
3. Much of the material in this section is taken directly or adapted from "The Plain English Guide To The Clean Air Act" found at http://www.epa.gov/oar/oaqps/peg_caa/pegcaa02.html on the U.S. EPA Web homepage (accessed March 8, 1999).
4. The original U.S. Clean Air Act was passed in 1963, but the national air pollution control program is actually based on the 1970 version of the law. The 1990 Clean Air Act Amendments are the most far-reaching revisions of the 1970 law. The citation for the Amendments is 42 USCA §§7401-7671 q.
5. For the reader who is unfamiliar with the nomenclature and technology of oil and gas production, we have included a glossary of terms as an appendix.

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