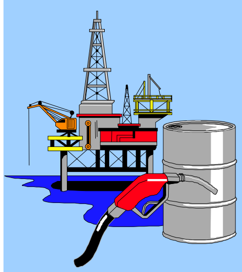
Technology Roadmap for the Petroleum Industry

DRAFT

February 2000



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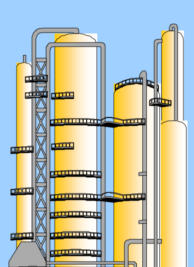
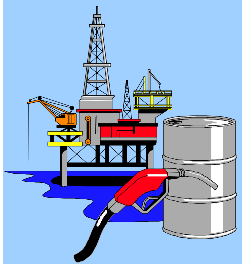
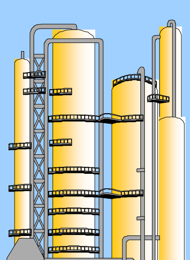
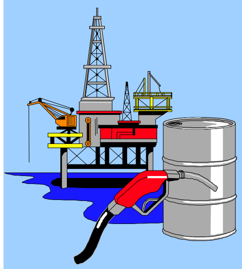








1 Overview

Challenges on the Horizon

Petroleum is the single largest source of energy for United States. On average, every citizen in the U.S. consumes about 20 pounds of petroleum per day. Petroleum is critical to the U.S. economy and quality of life, providing fuels for transportation, heating and industrial uses. Petroleum is the primary source of raw materials for the chemical industry, which relies on petrochemicals to produce a myriad of consumer goods, from paints to plastics. In 1996 the refining industry had over 90,000 employees, and nearly 2 million people were employed in service stations. Revenues from refining and refined products represent a significant contribution to the U.S. gross domestic product.

In the 21st century, the petroleum industry must prepare to address many important challenges. Major forces for change include: continuing concern for the environment; governmental regulation and policy; higher consumer expectations for fuels and fuel delivery systems; and global competition. In many cases, technology research and development will be needed to meet these challenges and maintain the health and profitability of the industry.

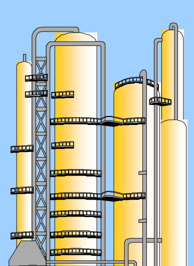
Key Drivers Affecting the Industry

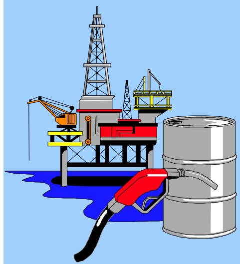
- Environmental regulations
- Increasing cleanliness of fuels
- Globalization
- Increasing yields from crudes of decreasing quality
- Uncertainty about future consumer fuels of choice
- Pressure to reduce emissions of CO_2
- Attaining adequate profit margins
- Proactively dealing with public scrutiny, environment, global warming and other issues

The life-cycle effect of petroleum fuels on the environment continues to be a cause for concern. The industry is unique in that both the processes used to refine petroleum as well as the products generated (e.g., fuels) are subject to government regulation. The combination of regulations to reformulate fuels and reduce emissions from refinery operations make petroleum refining one of the most heavily regulated industries in the United States. As cash flows are diverted to ensure compliance with regulation, the direction of technological development, as well as profitability, is often impacted.

Consumers also have a tremendous influence on markets and demand for petroleum products. Increasingly, consumers are demanding fuels that are safe, less polluting, inexpensive, and provide high performance. They also desire means of fuel delivery that are quick, convenient, and environmentally sound. Advances in technology may be needed to ensure fuels as well as fuel delivery systems meet consumer expectations.

Global competition and low profit margins have led to joint ventures, mergers, and restructuring throughout the industry. The number of refineries has declined dramatically since the 1980s, with those remaining operating at higher capacity and with greater efficiency. Refineries have had to deal with the economic impacts of changing crude prices, crude quality variability, and low marketing and transport margins, while meeting increased demand for refined products. The industry must continue to find





ways to balance the demand for better and more products with the desire for increased profitability and capital productivity. Strategically-driven investments in R&D and new technologies represent one way to help drive the industry toward a higher level of financial performance.

Industry Response

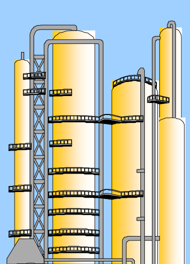
In preparing to respond to these challenges, the petroleum industry, through the American Petroleum Institute (API) and the National Petrochemical and Refiners Association (NPRA), has developed *Technology Vision 2020: A Technology Vision for the U.S. Petroleum Industry* [API 1999a]. This technology vision for the industry builds on two National Petroleum Council (NPC) reports published in 1995 [NPC 1995a, NPC 1995b], which discuss future issues for the oil and gas industry, and the research needed to strengthen the industry over the next two decades.

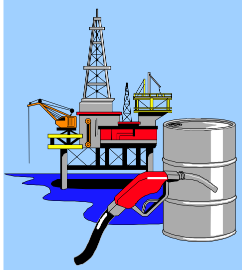
Technology Vision 2020 describes the role of the industry in today's economy, identifies major goals for the future, and outlines broad technology needs. To support some of the pre-competitive R&D needed to meet future industry goals, the vision advocates cooperation among the petroleum industry, the U.S. Department of Energy, the national laboratories, and academia. Government-industry collaboration and effective use of the scientific capabilities of the national laboratory system can leverage scarce funds for research and help to ensure that technology advances are identified and made.

The driving force behind the vision is API's Technology Committee, which is charged with identifying the technical areas of greatest concern to the industry and developing a technology roadmap to address those concerns. In 1999, API took a major step to better define research needs through a technology roadmap workshop held in Chicago, Illinois [API 1999b]. Attendees included participants from six major oil companies, API, and NPRA, along with representatives from the national laboratories, academia, and consulting firms serving the industry. The dialog at this workshop provided insights on the characteristics of the ideal refinery, attainable goals, barriers to overcome, and priority research areas.

The results of the workshop, along with *Technology Vision 2020*, provide the foundation for this technology roadmap. The goals and research priorities outlined in the roadmap will form the basis for making new research investments by government and industry. Hopefully it will stimulate new government-industry partnerships that will further serve to strengthen the industry, while providing benefits to the nation in terms of energy efficiency and environmental performance.

The technology roadmap is a dynamic working document for the API Technology Committee. Expectations are that it will be re-evaluated periodically to ensure that research priorities remain relevant to the needs of both the petroleum industry and its customers.



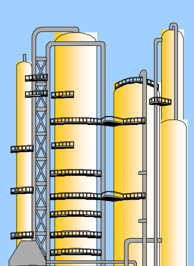


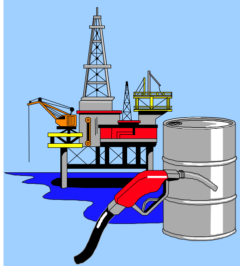
2 A Vision for the Future

By 2020, it is envisioned that the petroleum industry will exhibit a number of desirable characteristics that represent continuous improvements to current practices. These relate to the efficient use of energy as a fuel and feedstock in refining processes, the environmental performance of refineries and fuel delivery systems, and the reliability and safety of plant equipment.

The vision of the industry for the future is summarized as follows [API 1999a, API 1999b]:

> The petroleum industry of the future will be environmentally sound, energy-efficient, safe and simpler to operate. It will be completely automated, operate with minimal inventory, and use processes that are fundamentally well-understood. Over the long term, it will be sustainable, viable, and profitable, with complete synergy between refineries and product consumers.
>
> To improve ***energy and process efficiency***, the industry will strive to use cost-effective technology with lower energy-intensity. Refineries will integrate state-of-the-art technology (e.g., separations, catalysts, sensors and controls, biotechnology) to leap-frog current refinery practice and bring efficiency to new levels. The result will be a highly efficient, flexible refinery that can produce a wider range of products from crudes of variable quality as well as non-conventional feedstocks.
>
> Refineries will take advantage of deregulation of utilities to improve their ability to generate (or cogenerate) electricity on-site, and potentially sell electricity back to the grid. Overall this will reduce the amount of energy required for process heat and power, and improve profitability. There will be increasing use of less energy-intensive biological processes (e.g., bioprocessing of crude, biotreatment of wastewater, bioremediation of soil and groundwater).
>
> Improvements in consumer fuel use efficiency will be driven by regulation, competitive forces and desired performance requirements. Optimization of engines and fuels as a single entity will result in better efficiency in both gasoline and diesel engines. New sources of energy for transportation (e.g., fuel cells for cars) will continue to be developed and implemented.
>
> To improve ***environmental performance***, the industry will strive for lower emissions, with no harm to human health or the environment. The





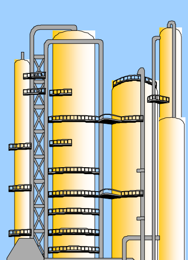
manufacture, storage, and delivery of fuels will be subject to engineering controls to avoid exposure, and sophisticated sensor technology to immediately detect, avoid, and correct releases to the environment. Emissions from engine exhaust and fuel evaporation will be reduced through a combination of regulation and better science and engineering of vehicles, transport systems, and fuel formulations.

A holistic approach, including life-cycle analysis from cradle to grave, will be used to minimize pollution from refining, distribution, retail, and transportation. Environmental rules will hopefully evolve through risk-based, prioritized approaches toward environmental concerns.

New structural ***materials and inspection technology*** will reduce the cost of maintenance, increase plant safety, and extend the useful life of equipment. Inspection technology will be global, on-stream, non-invasive, and in some cases, operated remotely. Equipment will be highly instrumented to monitor structural integrity, and the industry will have no containment boundary releases that significantly impact safety, health or the environment.

In future, the ***refinery distribution system and retail delivery services*** will be flexible to handle various feedstocks and a variety of fuels for conventional and emerging alternative-fueled transportation. Service stations will be larger, more convenient and have higher throughput. Fueling processes and underground storage systems will be improved to reduce potential impacts on the environment and human health. For example, automated fuel dispensing systems will enable consumers to obtain fuel quickly and conveniently.

With this vision in mind, the industry has come together to outline specific goals and the technology research that will be needed to work toward the objectives described above. The technology roadmap which follows is a summary of those efforts.



3 Energy Efficiency and Process Improvement

Current Situation

Petroleum refining is the most energy-intensive manufacturing industry in the United States. According to the most recent Manufacturing Energy Consumption Survey (MECs) conducted by the U.S. Department of Energy, the U.S. petroleum refining industry consumed 6.3 quads (quadrillion Btu, or 10^{15} Btu) of energy in 1994 (excluding electricity generating and transmission losses incurred by the generating utility) [DOE 1997]. As shown in Figure 1, the industry uses a diversity of fuel sources, and relies heavily on refining process by-products for energy. These include refinery gas (sometimes referred to as "still" gas, a component of crude oil and product of distillation, cracking and other refinery processes), petroleum coke, and other oil-based by-products. Typically about 65 percent of the energy consumed by the industry for heat and power is obtained from by-product fuels.

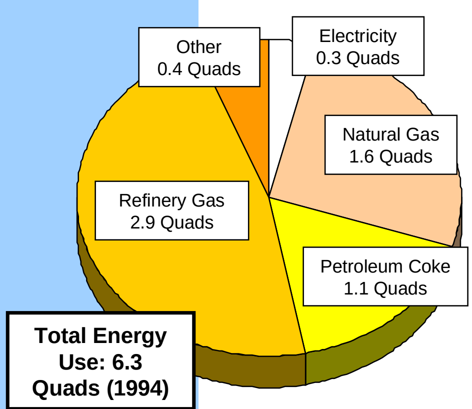
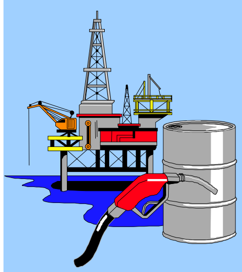


Figure 1. Distribution of Energy Use in U.S. Petroleum Refineries

Refineries use crude oil to manufacture a wide variety of fuels for transportation and heating. They also manufacture a number of non-fuel products, such as lubricating oils, wax, asphalt, and petrochemical feedstocks (e.g., ethylene, propylene). Any energy source (e.g., petroleum, natural gas) that is used to manufacture non-energy products is considered an *energy feedstock*. Of the 6.3 quadrillion Btus used by refineries in 1994, about 38 percent was in the form of energy feedstocks used to manufacture non-fuel products [DOE 1997].

Petroleum refineries generate a considerable amount of electricity on-site. In 1994, U.S. refineries met over 40 percent of electricity requirements with on-site generation. Nearly all of this electricity was from cogeneration units, which also generate steam for process heating.

Energy consumption in the refinery is dominated by a few processes which are not necessarily the most energy-intensive, but have the greatest throughput. For example, atmospheric and vacuum distillation account for 35-40 percent of total process energy consumed in the refinery, primarily because every barrel of crude must be subjected to an initial separation by distillation. Another example is hydrotreating, which is used to remove sulfur, nitrogen, and metal contaminants from feeds and products and accounts for about 19 percent of energy consumption. Many refinery streams must be hydrotreated prior to entering downstream refining units to reduce sulfur and catalyst poisoning and achieve the before and after desired product quality [DOE 1998].

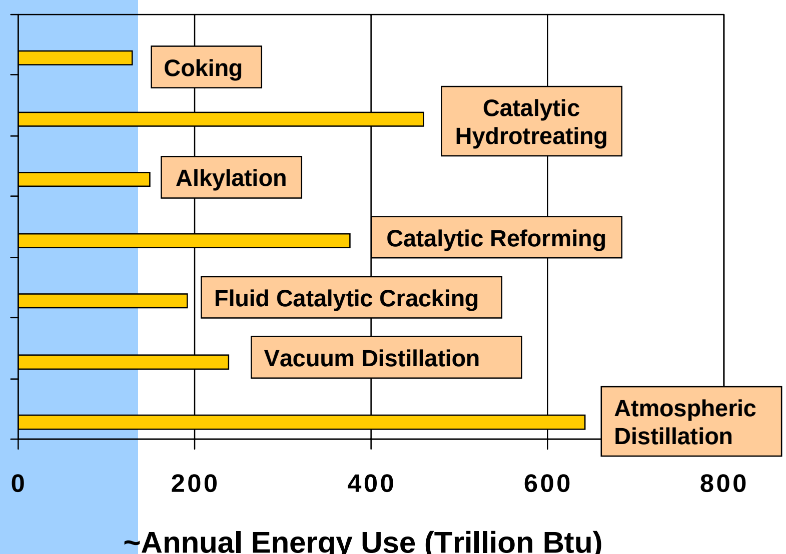


Some processes are energy-intensive, but produce excess steam or hydrogen which can be exported to other processes. Prime examples are fluid catalytic cracking and catalytic reforming. Relative energy use for heat and power among the major refinery processes (excluding steam or hydrogen produced) is shown in Figure 2 [DOE 1998].

Over the last twenty years the industry has reduced its energy consumption (Btu/barrel of crude) by nearly 30 percent. This has been accomplished through conservation measures, consolidation of capacity, shut downs of older, smaller, inefficient facilities, and continued improvements in technology. Substantial technological progress has been made, for example, in development of catalysts (e.g., multi-functional catalytic cracking catalysts) which have greater intrinsic activity, higher yields, and more tolerance to poisoning – all of which impact the energy required for processing.

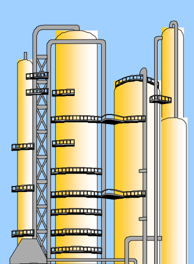
Refineries have also made increasing use of practices that improve overall energy efficiency, such as plant heat integration, recovery of waste heat, and implementation of improved housekeeping and maintenance programs. These activities continue to result in incremental improvements in energy efficiency throughout the U.S. refinery system.

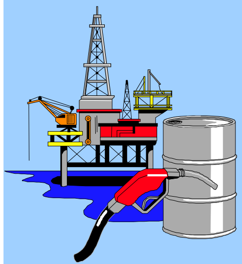
Figure 2. Relative Energy Use of Major Refinery Processes



In recent years, energy intensity has remained relatively constant. However, the cost of energy for heat and power still accounts for as much as 40 percent of operating costs in the refinery. When faced with high environmental costs and low margins, refiners will increasingly look to improvements in energy efficiency to lower costs and increase profitability. Advances in technology will remain a viable option for improving the way energy is used, particularly for very energy-intensive processes.

In the distribution, delivery and retail end of the industry, energy is consumed in the form of fuels for transportation of refined products and in power used for heating and lighting facilities. Improvements to this consumption can potentially come from engines and vehicles with better mile/gallon performance; and improvements in retail station construction, sizing, supply logistics, and lighting.





Future Characteristics: Energy Use and Refining Processes

Ideally, by 2020 the petroleum industry would exhibit a number of desirable characteristics that are significant improvements over current practice. In general, refineries in the future would optimize energy use through more efficient heat exchange and heat integration, better controls, and adopting energy-saving approaches to very energy-intensive process units (e.g., furnaces, distillation towers). Technology to eliminate or substantially reduce fouling would reduce expensive maintenance and down time requirements. Effective integration of controls and practices to increase energy efficiency (e.g., pipe insulation) would result in higher levels of energy optimization. Refineries would maximize their ability to produce energy on-site by increasing the use of cogeneration to generate both heat and power, and in some cases would be producing electricity for sale back to the local grid. In many cases, high efficiency turbines and steam generators would be used to achieve a high thermal efficiency in cogeneration and power generation systems.

Future Characteristics

Energy Efficiency

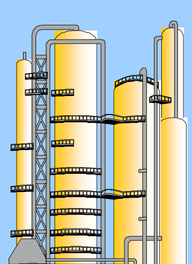
- Energy use is optimized throughout the refinery complex
- Energy efficiency and process controls are integrated
- Fouling of heat exchangers is essentially eliminated
- Innovative heat exchangers are in place (all helical, vertical, no baffles)
- Use of cogeneration in refineries is optimized, and refineries are power producers
- Use of very energy-intensive processes (e.g., distillation, furnaces) is minimized
- Source of heat loss (e.g., in pipes) are easily indentified through monitoring
- Containment vessels are energy efficient

Processing

- Processes have optimum flexibility for dealing with variable crude quality
- Plants are tightly controlled, and rely on intelligent controls
- Plants are fully automated, lab-free, maintenance free, and operated in JIT format (minimal inventory)
- More bioscience is used in processing
- Effective, well-understood process models are in place
- Solid phase catalysts are replaced with ionic liquids
- New processes are in place to handle new fuels and fuel requirements

Processes in the future would be characterized by a high degree of flexibility for handling crudes of variable quality, as well as entirely new feedstocks. Refineries would be tightly controlled to increase performance and efficiency, and require less maintenance and laboratory services. Costs would be minimized by operating with minimal inventory using completely automated processes where possible.

Plant engineers would be able to rely on demonstrated, reliable process models to optimize plant performance. Many new processes would be in place to accommodate new fuels and new fuel requirements, and existing processes would be replaced with alternatives that are more energy efficient and environmentally sound (e.g., ionic liquids in place of solid phase catalysts).



Performance Targets

To strive for the ideal refinery in 2020, the industry has identified broad performance targets for energy efficiency and process improvement. There are two central themes underlying these goals: (1) to identify, develop and implement entirely new technology and practices to replace currently used inefficient, energy-intensive technology, and (2) to improve the energy efficiency of existing technology and practices, where possible.

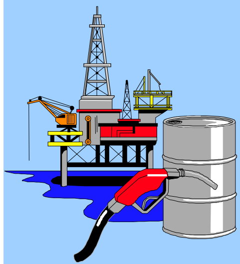
Performance Targets for Energy Efficiency and Process Improvement

- ❖ Identify routes that, if implemented, would reduce processing energy used in U.S. refineries today by 10% (about 320 trillion Btus)
- ❖ Improve efficiency of conventional technology by 10% (e.g., 92% thermal efficiency in furnaces)
- ❖ Achieve 20% improvement in energy efficiency in selected energy-intensive unit operations
- ❖ Improve yields towards 100% of raw material utilization (e.g., crude feedstocks)

Replacing conventional energy-intensive separation processes, for example, could have a major impact on energy consumption in the industry. Distillation processes account for up to 40 percent of all the processing energy consumed in the refinery. Currently, every single barrel of crude oil must be subjected to an initial separation stage using distillation. The thermal efficiency of distillation processes is typically very low, and replacing even a small portion of distillation capacity could have a substantial impact on energy use.

In addition to separations, alternative, less energy-intensive methods for converting crude fractions to the desired products could have a large energy impact. Hydrotreatment, which is used to remove sulfur and other contaminants, and cracking or coking processes are potential candidates. Existing processes could also be improved through redesign, or incorporation of practices that improve heat transfer or reduce process heating requirements (e.g., heat integration, waste heat recovery, better monitoring and maintenance practices).

Energy benefits can also be achieved by improving process yields (the percent of product obtained from the feedstock). The objective is to obtain more product and less byproduct or waste than is currently obtained, using the same or less process energy. Potential routes for improving yields are new, more selective catalysts, better chemical pathways for conversion of hydrocarbons, and the use of bioprocessing.



Technical, Institutional and Market Barriers: Energy Efficiency and Process Improvements

There are a number of barriers inhibiting improvements in energy efficiency and petroleum refining processes. These range from technical limitations imposed by current technologies, to institutional factors such as regulation or business practices.

Technical Barriers

In refineries, an imposing barrier to improving ***energy efficiency*** is the intrinsic inefficiency of refining processes. For example, during the refining of crude fractions, hydrogen is repeatedly added and removed. Cracking and coking processes, which break large, heavy hydrocarbons into smaller molecules, require the input of hydrogen. Other processes, such as catalytic reforming, produce hydrogen along with aromatic hydrocarbons. If hydrogen is not generated in sufficient quantity as a byproduct of processing, then it must be produced independently, at a high energy cost.

Key Technical Barriers: Energy Efficiency

Technology Efficiency Limits

- ❖ Intrinsic inefficiencies in refining
- ❖ Inefficiency of current separation technology
- ❖ Limited fuel conversion efficiencies
- ❖ Lack of novel heat integration systems

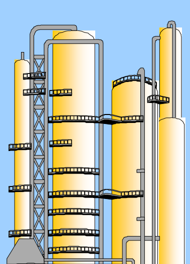
Fouling

- ❖ Lack of cost effective, predictive fouling/corrosion technologies
- ❖ Poor understanding of fouling mechanisms

The refinery complex also relies on a large number of distillation columns (nearly every unit operation requires distillation for product recovery or purification) which typically operate at low efficiencies due to thermodynamic and other restraints. The low efficiency of separation technologies used throughout refining drives high energy consumption in the industry.

Fouling of heat exchange equipment also represents a major problem for refiners. Fouling reduces thermal efficiency and heat transfer capacity, resulting in significant increases in energy use. Fouling creates an economic burden through increased energy costs, lost productivity, unscheduled plant shut downs, and increased maintenance of equipment. Fouling is difficult to prevent, as the mechanisms which lead to fouling are not well understood. Tools for predicting and monitoring fouling conditions are limited, but becoming available. Their true effectiveness is still unknown.

Technical barriers that limit ***process improvement*** fall into several key categories – process engineering, sensing and measurement, and process modeling. An imposing barrier to implementing better processes is that there are simply not enough alternatives to the conventional way of refining crude. Alternatives are needed, for example, to replace processes requiring severe operating conditions (e.g., very high temperatures and pressures, cryogenics, acid catalysts). Processes operating at ambient conditions, such as bioprocesses, could be candidates but are currently not well-developed.



Accurate sensing and measurement techniques are essential for effective control and monitoring of processes. The greatest limitation in this area is the inability to rapidly, precisely, and accurately obtain the composition of feeds and products, and then process that information in a control loop. Having this information would enable plant engineers to adjust conditions to maximize yields, and consequently energy requirements.

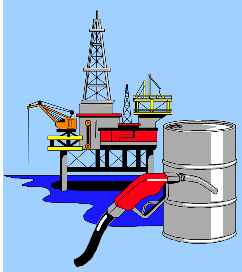
> **Key Technical Barriers:**
> **Process Improvement**
>
> ***Process Engineering***
>
> - Lack of alternative processes
> - Inadequate selectivity of current catalyst systems
> - Poor understanding of biocatalytic processes
>
> ***Sensing and Measurement***
>
> - Inability to rapidly/accurately obtain composition of feeds and products
> - Lack of real-time chemical composition analyzers and non-intrusive sensors
> - Lack of remote sensors for plant monitoring
>
> ***Process Modeling***
>
> - Lack of models to extrapolate beyond data
> - Incomplete models for refining processes
> - No capability to link composition to physical properties and emissions

Composition sensing is dependent on effective chemical composition analyzers and sensors, which are currently inadequate for non-intrusive, real-time applications.

There is currently a lack of process models based on first principles that would allow process designers to extrapolate beyond the scope of available data, which limits design optimization. In general, models that comprehensively describe petroleum refining processes are limited or incomplete. The purpose of process models is to estimate and predict performance, and without this capability, process engineers must make "guesses" about how process improvements will affect performance. When millions of dollars of product are at stake daily, this is usually too risky a proposition. The alternative is to conduct experiments to try and determine the end results of proposed design changes – often an expensive and time-consuming process.

Institutional and Other Barriers

The regulatory environment, cost and risk of developing new technology, and lack of long-term commitment to fundamental research (e.g., catalysis, process optimization) are all seen as barriers to improving both energy efficiency and processes. Energy efficiency is not usually a business driver, and is difficult to justify as an investment when capital recovery is too long. Exacerbating this problem is the uncertainty of future product requirements, which may be affected by both consumer demand for performance and regulatory mandates.

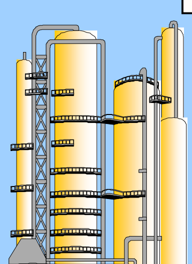


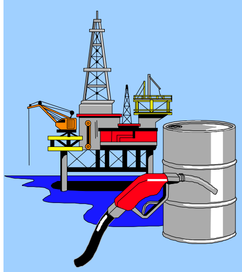
Research and Development Needs

Research and development needed to overcome the major barriers to increasing energy efficiency and improving processes is shown in Figures 3 and 4. R&D is categorized as top and high priority, and aligned by time frame for expected results. Arrows describe the main relationships between research.

Figure 3. Research Needs for Energy Efficiency

Priority	Near-Term (0-3Years)	Mid-Term (by 2010)	Long-Term (by 2020)
TOP	Develop new methods for fouling mitigation, with focus on 2 high profile unit operations.	Develop several anti-fouling coatings for equipment operating at > 500 oC.	Identify and develop alternatives for distillation beyond membranes (entirely new low-energy separation technologies)
	Devise measurement techniques to detect the on-set of fouling in 90% of heat exchangers.	Conduct field verification tests of fouling variables and prevention methods.	
	Develop membranes for hydrocarbon separations, to achieve 20% efficiency improvement	Design new, more energy efficient equipment that combines mass and heat transfer and catalysis (e.g., catalytic distillation).	
		Increase fuel conversion efficiency through research on at least 2 alternative technologies that utilize waste streams.	
HIGH	Investigate and categorize 60% of mechanisms leading to fouling in heat exchangers.	Explore mechanisms of the interactive effects of fouling and corrosion.	Design novel heat exchangers to reduce fouling and other reliability problems.
	Identify and develop innovative technology for recovery of low-level waste heat.		





Energy is a major part of operating costs in refineries, second only to the cost of crude. The use of energy is directly related to the thermal efficiency of process heating equipment, as well as process design, operation and control. Improvements in the way energy is converted to process heat, for example, can increase **energy efficiency**. A major impact area in process heating is the mitigation of fouling in heat exchangers (see Table 1). Fouling reduces heat transfer efficiency, resulting in an increase in expenditures for energy and equipment maintenance. Fouling of heat exchangers used in refining of crude oils is a well-documented problem. Various estimates put the cost of process-side fouling in petroleum refineries in the United States at about $2 billion a year. An Exxon study in 1981 showed that for a typical refinery with a capacity of 100,000 bbl/d, fouling-related costs were about $12 million per year, of which about one third was for added energy [Exxon 1981]. A major share of the cost penalty occurs in the crude pre-heat train. A study by Argonne in 1998 showed that fouling of the pre-heat train increased energy consumption by about 12,000 Btu/bbl after one year of operation without cleaning [ANL 1998]. This represents about a 10 percent increase in the amount of energy used per barrel of crude for atmospheric distillation [DOE 1998].

Table 1. High Priority R&D Topics for Energy Efficiency and Process Improvement

Topic	Importance to Industry	Energy Savings Potential	Likelihood of Short Term Success	Potential Competitive Issue
Fouling Mitigation in Heat Exchangers	High	High	Low	Low
Improved Real-time Process Measurements	High	Medium	Medium	Low
Improved Fuel Conversion Efficiency	Medium	Medium	Medium	Medium

In petroleum refining, the complexity of crude composition makes it particularly difficult to develop a generalized fouling mitigation method. Important research goals are developing an understanding of the threshold conditions of fouling with the chemical composition of crude, and using this knowledge to determine the effectiveness of mitigation methods for various crude blending processes (see Figure 3). Thermal stability and solubility characteristics of asphaltenes, with and without fouling precursors such as iron or sulfur compounds, are two key issues. Iron can be either a part of crude feed stocks or a corrosion product. High concentration of naphthenic acid in the crude, for example, has been shown to cause corrosion products, leading to a high fouling rate. Unit operations of greatest interest include the crude oil pre-heat train, and efficient feed heat exchange for hydrotreating and reforming processes.

Topics Areas of Practical Interest in Fouling

- ❖ Role of iron/iron sulfides in hydrocarbon stream fouling
- ❖ Role of asphaltenes and non-asphaltenes in fouling
- ❖ Impact of crude oil components in blending
- ❖ Impact of oilfield chemicals on fouling (silica, calcium)
- ❖ Chemical cleaning (solvents and surfactants)

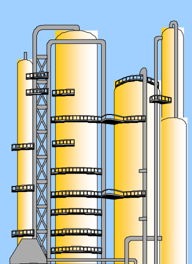
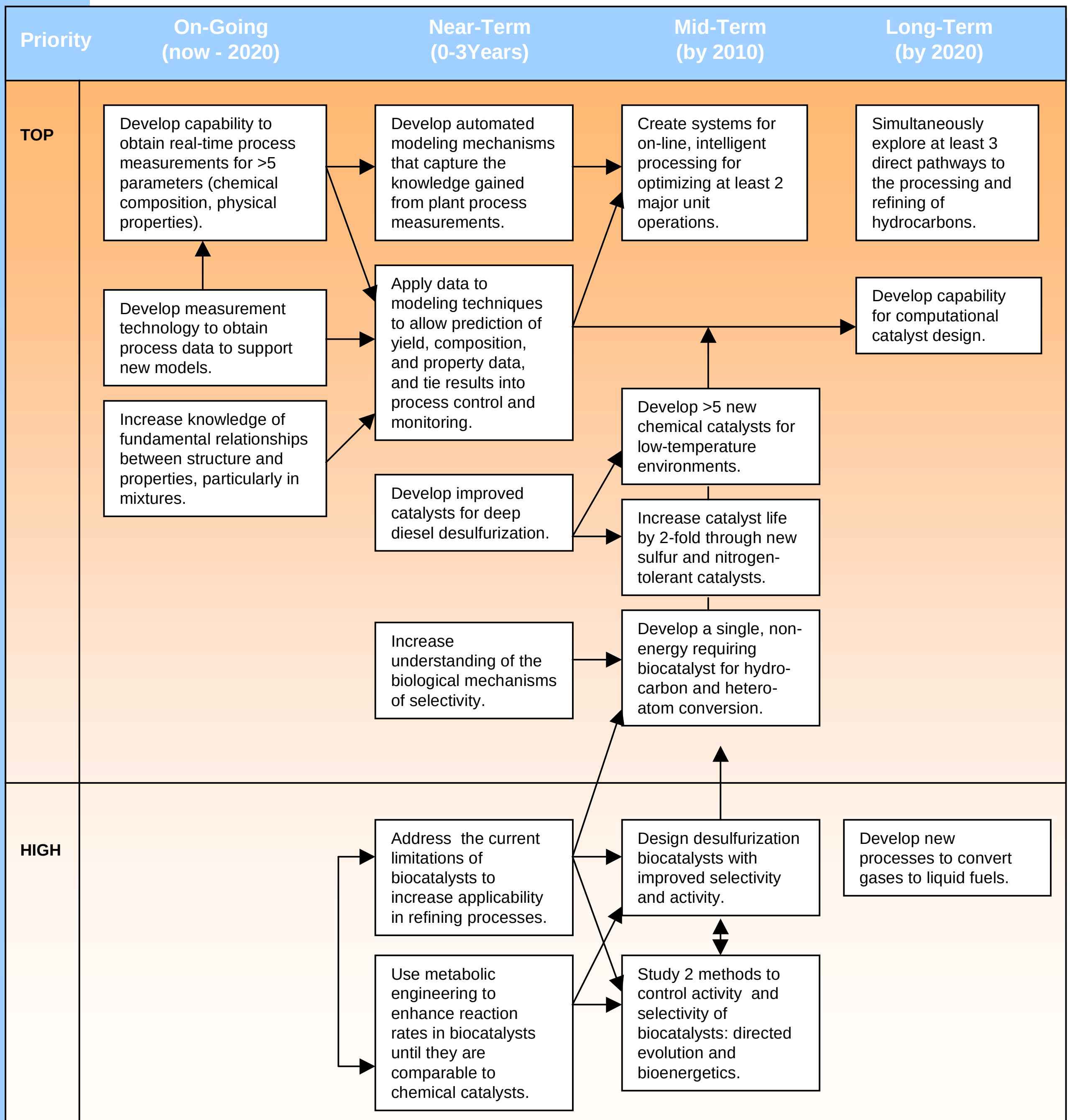


Figure 4. Research Needs for Process Improvement



Another priority research area is development and use of equipment that combines mass and heat transfer mechanisms and catalysis to achieve the desired results more efficiently. An example of this is catalytic distillation, which is currently used in the production of fuel additives such as methyl-tert-butyl-ether (MTBE) and tertiary-amyl-methyl-ether (TAME). Catalytic distillation reduces energy use by using the heat of reaction to drive the distillation process, eliminating the need for separate energy input. It is a single-stage process, and in the case of ethers, provides higher product yields and less processing time when compared with the conventional process.

Other priority research areas that impact energy use include the need to improve fuel conversion efficiency, and development of more effective, alternative separation processes to distillation. Fuel conversion efficiency could be improved through the development of technologies that use waste streams as fuel, such as fuel cells that use propane or fuel gas, or new concepts such as pulse combustion fuel cells. Membranes that are capable of efficiently separating hydrocarbons are needed, as well as entirely new, low-energy alternatives to distillation that go beyond membranes.

In **process improvement**, the most important research area is developing the capability for real-time process measurements. A primary objective is the capability to rapidly, precisely, and accurately obtain information on the composition of feeds and products, and be able to interpret this information for use in process optimization. This will require the development of on-line, real-time chemical composition analyzers that can performin refinery operating environments. To support this capability, research is needed to devise measurement technologies that will obtain the data needed for computational methods for process design as well as control. Data obtained through real-time measure-ments can be used to develop on-line intelligent processing systems, which have been identified as a high priority. Data will also support the development of automated modeling mechanisms and predictive modeling techniques, which can provide a means to capture knowledge gained from operating experience and apply it to process optimization, design and control. Research to better understand the fundamental relationships between structure and properties, particularly in mixtures, will be needed to support both model design and interpretation. Figure 5 illustrates the critical links between R&D in these areas.

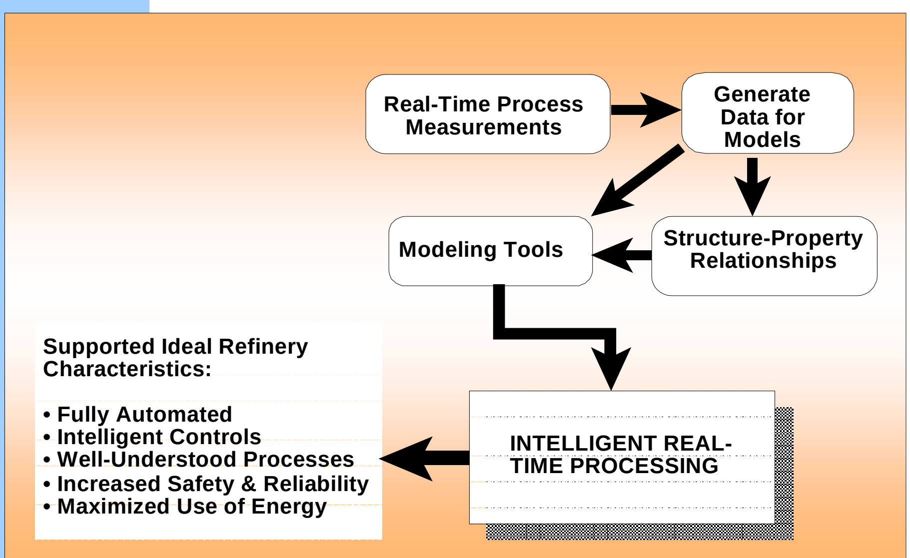
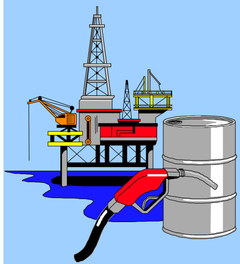


Figure 5. R&D Links for Intelligent Real-Time Processing



Catalysis has been identified as a priority research area for improving a number of processes. The primary area of interest is catalysts that achieve the desired results in low temperature environments, with potential reductions in process heat requirements. Desulfurization catalysts are another priority research area, as are catalysts that are highly resistant to poisoning by sulfur and nitrogen. As crude quality continues to decrease, along with more stringent specifications on sulfur content in fuels, the availability of effective, long-life desulfurization catalysts will become increasingly critical.

Robust biocatalysts that can operate in severe refining environments are a high priority. Research is needed to overcome the sensitivities inherent in the current generation of biocatalysts, and to increase the reaction rates and selectivity of biocatalysts. Particular areas of interest include the conversion and upgrading of hydrocarbon streams, and removal of heteroatoms (e.g., nitrogen, sulfur). Research is needed to study the biological mechanisms of these catalysts with regard to selectivity and activity for specific reactions. Methods for controlling the activity and selectivity of biocatalysts are also needed (e.g., directed evolution, bioenergetics).

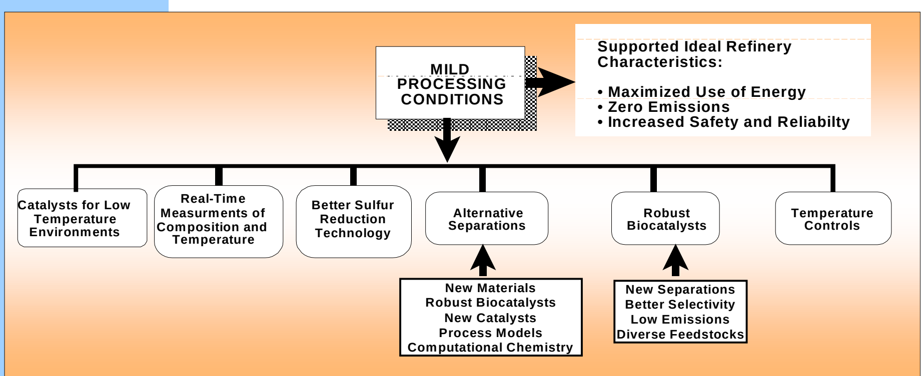
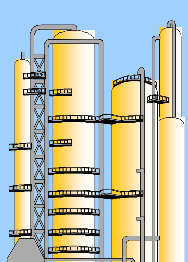


Figure 6. R&D Leading to Mild Processing Conditions

Leap-frog technology is needed to reduce the large amount of energy used in distillation throughout the refinery complex. Alternative separation technologies may be one answer (e.g., membranes, reactive distillation). Another route is bypassing the initial distillation of crude altogether through revolutionary new pathways, such as thermal cracking. Other possibilities include processes that convert gases directly to liquid fuels, or that clean and upgrade the crude in the field, before it enters the refinery.

Many of the technologies and research areas discussed above will support processing of hydrocarbons under milder conditions (temperatures, pressures, less corrosive) than is currently possible. Operation at less severe conditions will lead to lower energy consumption, reduced emissions, and improved safety and reliability (see Figure 6).



4 Environmental Performance

Current Situation

Petroleum products are critical to the economy, providing fuels for transportation as well as industrial and residential heating. As petroleum products are burned in cars, trucks, industrial heaters, utility boilers, and residential heating systems, they create various air emissions. In addition, the manufacturing processes used to produce petroleum products also generate a variety of air emissions and other residuals. Some of these are hazardous and/or toxic chemicals.

Sources of Air Emissions in Refineries

- **combustion emissions** associated with the burning of fuels in the refinery, including fuels used in the generation of electricity,
- **equipment leak emissions** (**fugitive emissions)** released through leaking valves, pumps, or other process devices,
- **process vent emissions (point source emissions)** released from process vents during manufacturing (e.g., venting, chemical reactions),
- **storage tank emissions** released when product is transferred to and from storage tanks, and
- **wastewater system emissions** from tanks, ponds and sewer system drains.

Refineries also produce process wastewater, which consists of surface water runoff, cooling water, process water, and sanitary wastewater. Wastewaters are treated in water treatment facilities and discharged to public water treatment plants or surface waters (under permit). Wastewater that has been contaminated with oil must often be subjected to two or three water treatment steps to remove contaminants prior to discharge to public treatment plants. [DOE 1998]

Both hazardous and non-hazardous wastes and other residuals are produced, recycled, treated, and disposed of during refinery operations. The method of disposal of these residuals depends upon the nature of the residual and applicable regulations. Residuals are generated from many refining processes, from the handling of the petroleum products through wastewater treatment. Overall, refineries recycle about 54 percent of the residuals produced, according to 1995 data. Further, the trend towards increased recycling continued in 1996, with about 60 percent recycling of residuals [API 1997c].

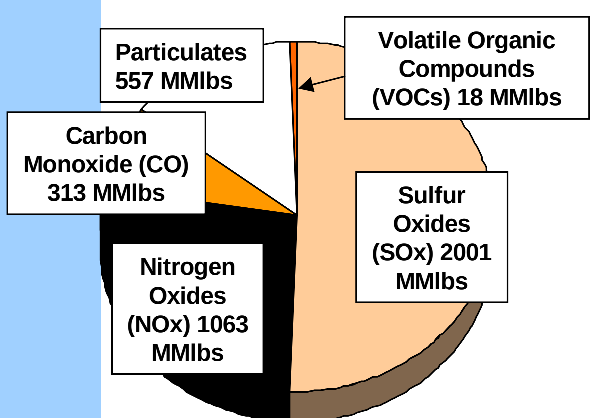
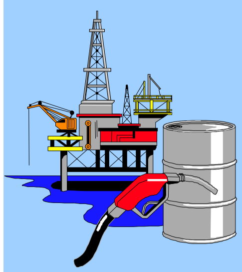


Figure 5. Estimated Air Emissions from Combustion of Fuels in Refineries, 1996

Petroleum refining and the use of refined products are impacted by a number of environmental laws and regulations. Some of the most significant statutes are those that focus on altering the formulation of products (mostly fuels) to reduce air emissions generated by their use. These often require substantial changes in



refinery processes along with large capital investments. Various Federal and state regulations also focus on reducing refinery process emissions to air, land, and water.

Major Air Toxics from Refineries

Toluene	Benzene
Ammonia	MTBE
Methanol	Ethylene
nHexane	Hydrochloric Acid
Propylene	Cyclohexane
Methyl Ethyl Ketone	Ethylbenzene
Xylene	1,2,4-Trimethylbenzene

The cost of controlling emissions to air, land and water is high. Petroleum refiners spent about $5.5 billion in 1995 on environmental compliance [API 1997b]. About 40 percent of this was for capital expenditures; the remainder was for operation and maintenance of equipment for environmental control and abatement.

Residuals from Refineries (1995)

Residual	1000 wet tons
Spent Caustics	988
Biomass	582
Contaminated Soils/Solids	525
Slop Oil Emulsion Solids	225
FCC Catalyst	173
DAF Float	164
Primary Sludges	128
Tank Bottoms	83
Pond Sediments	65

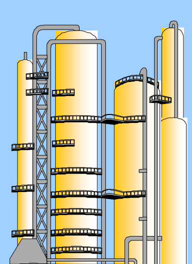
The refining industry participates in a number of public and private initiatives aimed at improving environmental performance. The STEP initiative (Strategies for Today's Environmental Partnership), for example, is a collective environmental strategy supported by the membership of the American Petroleum Institute (API) to improve environmental, health and safety performance [API 1997a]. The National Petroleum Refiners Association sponsors a similar program, Building Environmental Stewardship Tools (BEST) to promote the same principles at refineries that are not API members.

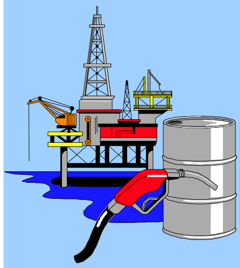
Major Federal Regulations Affecting the Petroleum Industry

- Clean Air Act of 1970 (CAA) and regulations
- Clean Air Act Amendments of 1990 (CAAA) and regulations thereunder
- Resource Conservation and Recovery Act (RCRA)
- Clean Water Act (CWA)
- Safe Drinking Water Act (SDWA)
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)
- OSHA Health Standards and Process Safety Management Rules
- Emergency Planning and Community Right-to-Know (EPCRA)
- 1990 Oil Pollution Act and Spill Prevention Control and Countermeasure Plans

Many refineries also participated in the Environmental Protection Agency's 33/50 program to reduce air toxics, and some are actively involved with other government environmental initiatives (e.g., Green Lights Program).

Refineries have also been working to increase recycling, reduce pollution and decrease releases of toxic chemicals. Approximately 40 percent of refineries conduct pollution prevention activities at their facilities [EPA 1995a]. In addition, total releases of toxic chemicals from refineries (counting only those included in the Toxic Release Inventory since 1988) have declined by 26 percent since 1988 [API 1997a].





Global climate change and potential reductions in greenhouse gas emissions are also receiving a great deal of attention, although there are still questions about the extent of climate change, and whether the U.S. will sign the Kyoto treaty. Voluntary reduction programs continue to be a possibility on the horizon.

Future Characteristics: Environmental Performance

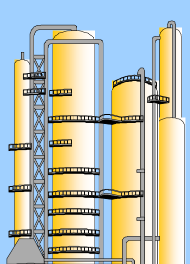
Ideally, by 2020, the U.S. petroleum industry would like to be recognized as a model of continuous improvement in environmental performance, while successfully balancing efforts to meet consumer demands for safe, high performance fuels. The industry would move toward minimizing environmental impacts through a combination of improved decision-making and process optimization.

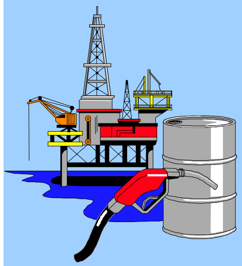
Future Characteristics: Environmental Performance

- ❖ Means to address environmental concerns are integrated with production
- ❖ Products are totally contained, from refinery to consumer (no toxic leaks)
- ❖ Environmental impacts on society are minimized (work toward zero emissions)
- ❖ Processes will handle poor quality feeds with minimal environmental impact
- ❖ Environmental decisions will be risk-based, using sound scientific methods
- ❖ Refinery configurations will be flexible to handle poorer quality feedstocks and alternate feedstocks, with minimal environmental impacts
- ❖ Monitoring and sensing will greatly improved, with automated control to correct and eliminate emissions
- ❖ Storage tanks will be leak-free

Environmental concerns would be integrated into the production side of the refinery (e.g., balancing sulfur in the refinery, from crude to products). To accomplish this effectively, a systems approach would be employed which relies on collaboration between producers, users, and regulators. Data would be available to enable decision-makers and regulators to better understand the actual impacts of the production and use of petroleum products on the environment and human health, and thus make regulatory and control decisions based on quantified risks. The technological, economic, and political concerns of all stakeholders would be balanced in this process. Verified, risk-based models would be in place to support regulatory decisions. The environmental aspects of poorer quality feedstocks, as well as alternative feedstocks, would be incorporated in the decision-making process and reflected in refinery processing configurations.

To support continuous improvements in environmental performance, better monitoring and sensing systems would be in place to optimize control of process variables, monitor emissions as they arise, and activate effective controls to correct the situation. Refineries would move toward minimal impacts on society (e.g., cleaner waste water, lower emissions), using the least costly technology available. Storage tanks would be designed to eliminate leaks, and products would be totally contained, from the refinery all the way to the consumer.





Performance Targets

The industry has identified a number of broad targets for environmental performance that are in line with the industry's vision for 2020. Specific targets focus on reducing emissions to air, land and water; using risk-based standards; and establishing a sound, flexible approach for improving environmental performance.

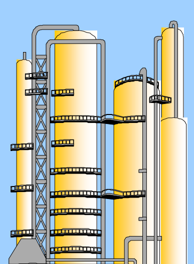
Performance Targets for Environmental Performance

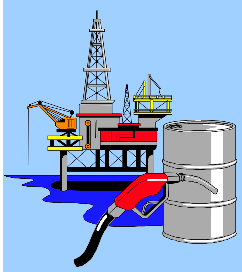
- ❖ Attain a leadership position in emission standards
- ❖ Offset contamination of public waterways from leaks - reduce incidents by 75%
- ❖ Publish an industry report in 2000 and report every 5 years on improvements
- ❖ Identify and implement economical routes to zero discharges
- ❖ Match environmental performance with risk-based standards
- ❖ Continually improve the tools for risk evaluation
- ❖ Reduce wastewater flow, solid wastes, and emissions to air from stationary and mobile sources
- ❖ Establish (by 2000) quantitative targets for reductions, using a risk-based approach
- ❖ Reduce the number of events (spills)
- ❖ Reduce the amount of oil in wastewater

An overarching goal is to reduce generation of wastewater and solid waste from petroleum refining, and to reduce air emissions from both stationary and mobile sources. Other targets include reducing the amount of and potential for events that results in spills, and reducing the amount of oil present in wastewater. Meeting the goals for reductions in waste and emissions will result in many benefits for the industry as well as the nation. Reducing waste generation will avoid potential environmental impacts on land and water, while reducing the costs and energy consumption associated with waste handling, treatment and transportation. When processes are redesigned to mitigate production of waste or undesirable byproducts, yields may be increased, which optimizes consumption of energy feedstocks. Reducing air emissions from process heaters, boilers, and from fugitive sources will decrease potential impacts on air quality. Effective control of fugitive air emissions could facilitate recovery of valuable products worth millions of dollars and representing trillions of BTUs of energy feedstocks every year.

By the end of the year 2000, the industry hopes to effectively establish quantitative targets for reductions in emissions, wastes and wasterwaters, using a risk-based approach. As risk-based quantitative targets are established, the industry can work more definitively toward meeting specific goals. The goal is to establish a mutally cooperative process to reduce emissions, rather than being driven by regulation. An important part of this effort over the next decade will be continually improving the tools by which risk-based evaluation is done. To evaluate progress, industry proposes to publish a report in 2000 on environmental performance, and to report every 5 years thereafter, including incremental improvements.

Ultimately, refiners should be able to take a flexible approach to meeting and establishing environmental goals, while balancing increasing demand for high performance products. This could mean a variety of solutions from process redesign to end-of-pipe monitoring and control.





Technical and Institutional Barriers: Environmental Performance

Technical Barriers

Technical as well as institutional barriers impact how the petroleum industry addresses environmental concerns. While some of these cannot be addressed by research, technological advances may have a significant influence on whether they remain barriers over the next two decades.

Key Technical Barriers: Environmental Performance

Risk Assessment

- Lack of toxicology database to support risk assessment
- No inexpensive means for evaluating toxicity

Site Remediation

- No cost-effective technology for MTBE clean-up
- No leak-proof delivery systems at service stations
- Lack of good methods for leak detection from tanks

Emissions to Air

- Inability to cheaply and effectively detect leaks at refineries
- Poor understanding of sources of emissions
- Insufficient data and modeling for ozone formation
- Inadequate methods for NOX and SOX removal
- Inability to cost-effectively control combustion and fugitive emissions

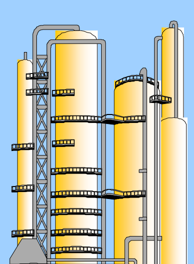
Wastewater

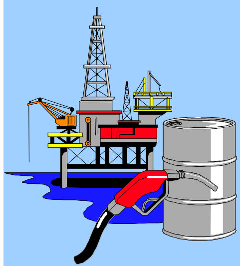
- Inadequate knowledge about what components in wastewater kill aquatic organisms
- High cost of water recycle, and handling corrosives from

A key barrier is the way that risk assessments of environmental and health impacts are currently made. At present the science behind risk assessment is not strong, and accepted levels of risk are seriously lacking. One reason is the lack of a toxicology database that supports credible risk assessment. Creating a comprehensive toxicology database requires an inexpensive, expedient means for evaluating toxicity, which currently is not available.

Effectively performing site remediation continues to be a challenge. There are currently no cost-effective technologies for cleaning up MTBE, and future remediation of sites containing MTBE will pose considerable economic burdens. The lack of good methods for leak detection from underground storage tanks, and lack of leak-proof fuel delivery systems at distribution sites (service stations) exacerbates the problem of both site contamination and remediation.

Current sensing capabilities place some limits on the ability to control and reduce air emissions. Cost-effective reliable means for detecting leaks in pipes, valves, and equipment in the refinery (e.g., those that give rise to fugitive emissions) are currently not available. Effective sensing systems for such leaks could enable control and/or elimination of many sources of fugitive emissions altogether.





The lack of information and scientific understanding concerning some air emissions makes it more difficult to devise means to control emissions. The sources of some emissions are poorly understood, and data for predicting sources of emissions is limited. Data, for example, are lacking on emission factors as well as the chemistry associated with the formation of very small particulates (PM 2.5) from combustion of fuels or other refinery processes.   Sources and formation of ozone is another area where knowledge is lacking. Currently available data and models are not sufficient for use as tools in predicting the impacts of transportation, for example, in specific regions. For some air emissions, current technology for mitigation and control is simply not cost-effective and or sufficient to meet some projected targets (e.g., NOX and SOX control).

Key challenges for control and reduction of wastewater are the costs involved in water recycle, as well as dealing with the corrosion problems (e.g., salts) that may arise from water reuse. Some wastewater streams represent very dilute solutions, which make it very difficult and costly to separate undesirable constituents. Understanding of the wastewater constituents in general, and their specific impacts on aquatic life, is limited. As more is understood about the actual effects of wastewater constituents on ecosystems, processes can be designed to cost-effectively reduce those impacts.

Institutional Barriers

The data, models, and processes currently supporting the development of regulations inhibits the industry from taking a more effective approach to improvements in environmental performance. A key barrier is that the models currently in use to determine impacts and facilitate the regulatory process are inadequate and out-dated. The result is models that produce results that exaggerate the impact of refineries.

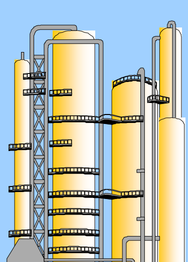
Key Institutional Barriers:
Environmental Performance

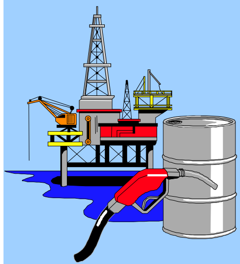
Regulatory Issues

- Models are based on overly conservative assumptions
- Inadequate collaboration between industry and regulatory agencies
- Models used for development of regulations are out-dated.

Agencies that rely on these models or other out-dated means for developing regulations sometimes create goals for compliance that are too high to reach. Such regulations may be difficult to comply with, and often divert costs toward end-of-pipe controls rather than long-term solutions to mitigate emissions at the origin.

Part of the problem is that during the regulatory process, industry and regulatory agencies are not collaborating to the extent needed to ensure regulations are based on verifiable, quantified risks. Contributing to the problem is that funding for research (both public and private) to increase understanding of environmental issues and collect the needed date is increasingly scarce.

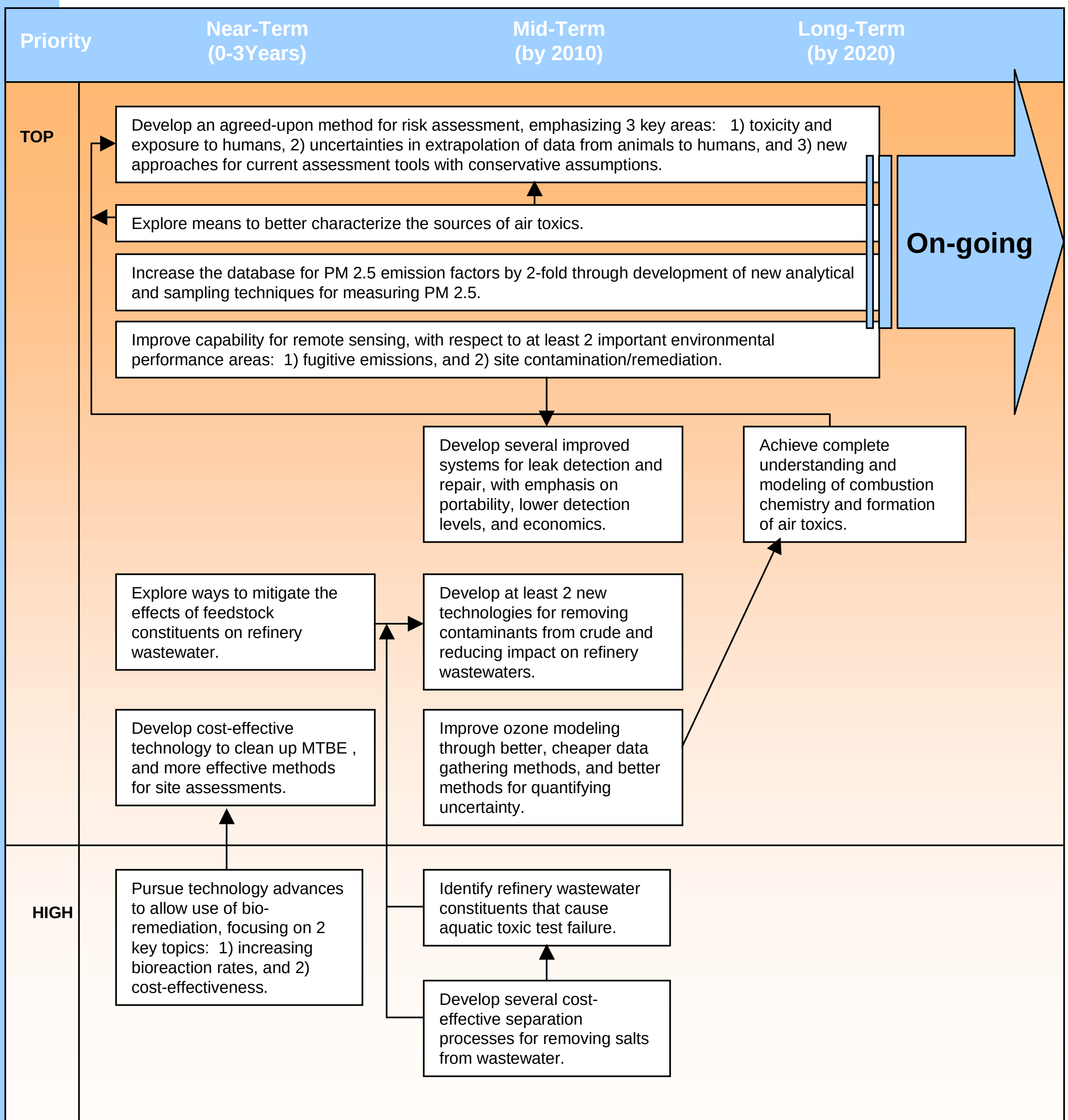


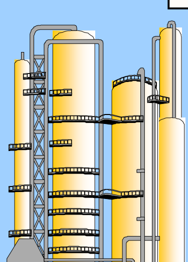


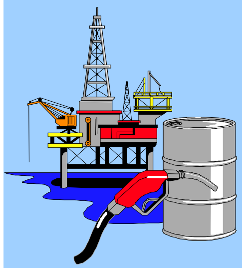
Research and Development Needs

Research and development can help overcome some of the most critical barriers to achieving continuous improvements in environmental performance (see Figure 6).

Figure 6. Research and Development Needs for Environmental Performance





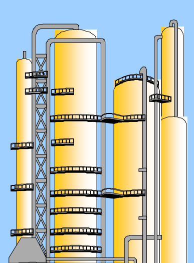


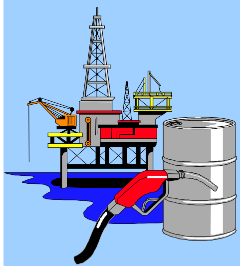
The impact of petroleum fuels on the environment continues to be a major concern, particularly the effects of toxic components released to air, land and water. Key research topics aimed at continuous improvements in environmental performance are shown in Table 2. **Risk-based methods** are needed to guide the regulatory process as well as compliance. The most important elements of research to develop risk-based analysis and assessment are developing data on toxicity and exposure to humans; and reducing the uncertainties in extrapolating animal data to fit human conditions. Research to improve understanding and prediction of combustion chemistry and formation of air toxics, including primary sources, will be integral to efforts in risk-based analysis. This includes modeling and data collection related to ozone formation. Overall improvements are needed in air quality models, including the ability to handle multiple pollutants, multiple regions, and annual average standards. Along with this research should come a comprehensive review of currently used assessment tools with respect to conservative assumptions, accompanied by the development of data or approaches to replace such assumptions with more valid ones that are universally accepted by government and industry. Risk-based analysis and assessment activities should be conducted in cooperation with EPA (residual risk), CRC, and the API air modeling task force.

Table 2. High Priority R&D Topics for Environmental Performance

Topic	Importance to Industry	Energy Savings Potential	Likelihood of Short Term Success	Potential Competitive Issue
Agreed-upon Method for Risk Analysis/Assessment	High	Low	Low	Low
Improved System for Leak Detection and Repair	High	Medium	High	Low
Cost-Effective Technology for MTBE Clean-Up	High	Medium	High	Medium
Database for PM 2.5 Emission Factors	High	High	High	Low

Improved systems for **leak detection and repair** are a critical area of research, particularly to achieve goals for mitigation and control of volatile hydrocarbons and air toxics. Remote sensing technology that is portable and cost-effective is most desirable. Research should be conducted in concert with instrument vendors, universities and government laboratories (NASA, DOE labs). One possible future technology is the use of satellite techniques for detecting hydrocarbon releases remotely from space. An increasing number of satellite systems, having the capability to obtain high resolution spectral data over a wide range of wavelengths ("hyperspectral remote sensing"), are expected to be launched into orbit in the near future. Recent airborne studies sponsored by the Geosat Committee Inc., a consortium of petroleum companies and others who use remote sensing, have demonstrated that these techniques can facilitate environmental assessments of sites with hydrocarbon contamination. As these systems become more widespread, information on hydrocarbon emissions from processing and



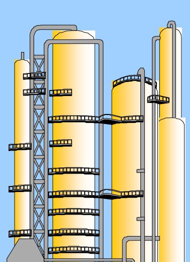


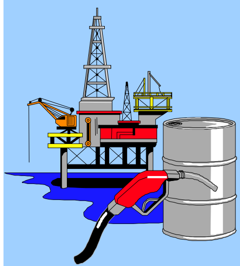
storage areas can be collected more easily and more comprehensively. Earlier detection and repair of leaks will not only decrease the direct loss of product, but also decrease the amount of energy and expense required to bring the product to market by avoiding costly cleanup operations.

Research to increase available data on particulates (PM 2.5) is needed to facilitate reductions in air emissions as well a help guide the regulatory process through better air quality data. New sampling and analytical techniques are needed to facilitate data collection and interpretation. A number of organizations could contribute to this effort, notably API, CRC, EPA, DOE and its laboratories, state agencies, and universities.

In the area of wastewater management, a priority need is research to reduce or eliminate the effects of the feedstock (crude and its components) on refinery wastewater. Contamination from feeds include metals, sulfur, nitrogen, oil, and various organic compounds, some of which are toxic or hazardous. Process waters that come in contact with oils must sometimes undergo multiple water treatment steps before they can be discharged and/or effectively recycled. One possibility is developing new technologies that remove contaminants from crude, which could help to mitigate contamination further downstream. To enable greater potential for cost-effective recycle of refinery wastewaters, research is needed to develop new separation processes that remove salts, which constitute a potential source of corrosion in process equipment.

Site remediation continues to be a challenge, with clean-up of MTBE becoming an area of increasing concern. Designing new, cost-effective methods for cleaning up MTBE-contaminated sites is a high priority, along with more effective methods for assessing site contamination. Bio-remediation is a potential solution for site clean-up. To make this a more viable solution, research is needed to increase bioreaction rates, and to develop cost-effective systems that may be suitable for large-scale operations. Technology advances are needed for both bioremediation and phytoremediation systems that are conducted *in situ*. The multi-disciplinary nature of this work will require expertise in micro-biology, combined with chemistry and chemical engineering. A collaborative activity is envisioned using universities and national laboratories.





5 Inspection and Containment Boundary Integrity

Current Situation

Inspection methodologies play a critical role in the overall energy, economic, safety, reliability and environmental performance of the U.S. petroleum industry. Effective inspection of equipment is vital to the construction and safe operation of distillation equipment, furnaces, heat exchange systems, reactors, storage vessels, piping systems, and a host of other unit operations. Testing and monitoring of equipment integrity, particularly while it remains in service, is essential to plant safety and optimum reliability as it pertains to energy efficiency.

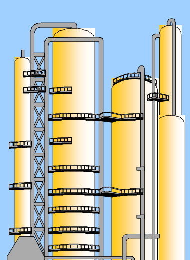
Many of the currently available inspection technologies are intrusive or destructive, and must be used when equipment is in 'shut-down' mode, rather than providing on-line information about equipment integrity. For example, traditional strength testing of metals is destructive, and involves taking a sample and testing it to its point of failure. To prevent catastrophic failures, inspection of equipment operating in high temperature or corrosive environments (heat exchangers, storage tanks, reactor vessels) typically requires shut down of the process on a regular basis. Abnormal operating conditions such as equipment start-up and shut-down also tends to increase vulnerability. In the absence of global inspection technologies, material evaluation often occurs locally. It is therefore necessary for the operator to use good engineering judgement to identify the most likely locations for material degradation. Failures also occur in places where inspection is difficult to conduct (pipe supports, gaskets, under insulation).

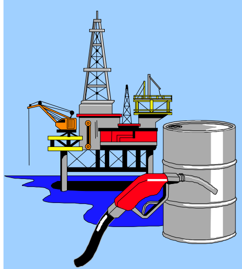
Future Characteristics: Inspection and Monitoring of Equipment

Ideally, by 2020, refineries would be significantly safer, more energy efficient and more reliable. Refineries would be highly instrumented to ensure structural integrity of equipment, and would be monitored using global, on-line non-invasive inspection techniques. These techniques would allow for immediate detection of loss of containment, and provide early warnings for corrosion and potential flaws in structural integrity. Inspection would be conducted automatically, without people, and would provide complete knowledge of equipment conditions at all times.

Future Characteristics

- Refineries are highly instrumented and controlled
- Global, on-line, non-invasive inspection is routine
- Immediate detection of loss of containment is possible
- Fouling of heat exchangers is essentially eliminated
- Inspection does not require people, and provides complete knowledge of equipment condition
- Downtime is minimized
- Refineries approach incidents related to loss of containment





Through highly effective inspection techniques, downtime would be minimized and equipment would approach total reliability. Maintenance would be performed according to routines predicted and suggested by regular global inspections and analysis, rather than on empirical or laboratory data. Refineries would continually work toward zero incidents related to loss of containment. Processes in use would be inherently reliable with respect to containment loss through a combination of better design, improved materials, flexibility to accept a wide crude slate, and more effective operating and maintenance practices. Crude flexibility enables improved energy efficiencies. Equipment, maintenance, and inspection in concert would be more reliable, and less likely to result in leaks or structural failures.

Performance Targets

The petroleum industry has identified a number of performance targets for inspection and containment boundary integrity. An overall goal is to be recognized as one of the top U.S. industries in the areas of safety and reliability, based on the Solomon Index. To support this goal the industry will strive to achieve no significant containment boundary releases and eliminate unplanned downtime and slow downs. While safety and energy efficiency are the primary issues, the high cost of incidents as well as equipment maintenance are also major factors. To address the issue of cost, the industry has identified specific targets for reducing capital and operational losses as well as the costs associated with inspection.

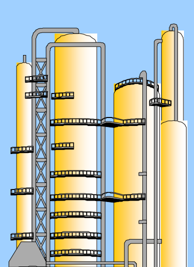
Performance Targets for Inspection & Containment Boundary Integrity

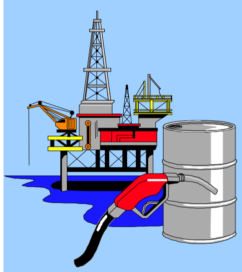
- Reduce capital and operational losses due to abnormal situations by 90%
- Become one of the top industries in safety and reliability
- Strive for zero “unacceptable” unplanned downtime and slow downs throughout the industry
- Reduce labor costs of inspection and support by 75%
- Reduce cost of losses due to breach of containment to less than $0.50/1000 EDC barrels (equivalent distillation capacity)
- Work toward a perfect safety record
- Achieve 75% reduction in safety incidents due to breach

Improving inspection techniques will yield a number of benefits for the industry. Through better inspection methods, plant operators will be better able to predict the health and integrity of equipment while it is in operation. This capability will allow for early warnings of potential system failures, and enable better preventative maintenance and servicing schedules to be followed. The result will be less unplanned downtime, fewer equipment shutdowns, and more efficient operation of equipment – all of which reduce costs for capital, labor and energy. Most important, the potential for catastrophic failures and other significant releases through the containment boundary will be greatly reduced.

Technical Barriers

There are a number of barriers inhibiting improvements in inspection technology. Most of these have to do with the inadequacy of currently available technologies for





monitoring the mechanical and structural integrity and reliability of equipment. The most critical of these is the lack of accurate, reliable, cost-effective sensing instrumentation and technology for global on-stream inspection of equipment. Temperature and insulation creates especially difficult problems for inspection of pressurized vessels. Remote sensors for mechanical integrity, which are highly desirable for ensuring the safety of the plant and personnel, are limited or non-existent for use in refinery settings. Contributing to the problem is that some systems in the plant are physically difficult to inspect with any confidence (e.g., piping that is partially buried and equipment that is lined and/or insulated). The ability to inspect equipment on-line, when it is in operation, is essential to efficient and profitable operation. The alternative is off-line inspection, which usually requires costly shut-downs of critical equipment and processes, and the attendant energy inefficiencies.

The inspection techniques that do exist are often destructive or intrusive, and inadequate for on-line non-destructive evaluation of equipment integrity. Of particular importance is the lack of self-sensing methods to monitor for corrosion and residual stress. Sensing methods for inspection of metals at high temperatures and pressures are also limited.

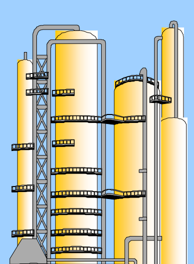
Key Technical Barriers: Inspection & Containment Boundary Integrity

Mechanical Integrity and Reliability

❖ Lack of reliable, cost-effective on-stream global inspection technology
❖ Lack of predictive technology for fouling and corrosion of equipment
❖ Inadequate technology for non-destructive, on-line inspection
❖ Inability to inspect piping with confidence to make global assessments
❖ Poor understanding of the mechanisms of materials degradation
❖ No integrated systems to coordinate sensing, measurement, analysis and corrective responses

Another key barrier which limits the effectiveness of maintaining and operating heat exchange equipment is the lack of cost-effective, reliable methods for predicting the onset of fouling and corrosion (see Section 3 for more on this topic). Failure of this equipment due to fouling and corrosion is a particularly difficult and costly problem in refineries, where such equipment comes into direct contact with crude oil and its higher boiling components. The greatest problems occur in the crude preheat train for atmospheric distillation, where every barrel of oil that enters the refinery is preheated.

Integrated systems that coordinate the results of sensing, measurements, analysis of data, and corrective responses are currently not available. The primary reason is that the software and algorithms needed for analysis of the data have not been developed. While theory for developing the needed algorithms may exist, the data to support validation is often limited or simply not available. Models are lacking for equipment failure modes and reliability analysis, particularly those geared toward the unique conditions of petroleum refining.



There are a number of areas where the fundamental understanding of materials properties and chemical interactions are not well understood, particularly the aging process and what occurs at the surfaces of materials in actual operating environments. In particular there is a significant lack of understanding about the mechanisms of materials degradation, and an inability to determine the life of materials that are in various stages of deterioration. Also, models linking fluid corrosivity to operating conditions, including crude composition, are limited. Without this knowledge, it is difficult to develop with any accuracy models that can predict how materials will perform under given conditions.

Research Needs

Research and development needed to overcome the major barriers to the development and use of better inspection methods is shown in Figure 8. The highest priority research need is the development of global, on-line inspection technology (see Table 3). Global inspection technology offers a step-out opportunity from current methodologies for assessing equipment integrity. Global implies that the inspection occurs at locations remote from the probes. In contrast, conventional inspection methods limit their examinations to the immediate vicinity of the probe. For example, with radiographic (RT) methods, the inspection only occurs at the position of the film. With conventional contact ultrasonics testing (UT), the inspection occurs under the probe or immediately adjacent to it. When using penetrant testing (PT), the inspection only occurs where the dye materials and developer have been applied.

Five critical research areas include ultrasonics for pressure vessels, corrosion under insulation inspection, buried piping inspection, equipment fouling detection, and models for placement of improved corrosion probes. Work is already on-going on some advanced global piping inspection technologies, including long range guided wave ultrasonics and electrical pulsing. Although test results show potential promise for these technologies, additional development is still required for advancement to commercial viability. Originally developed for piping inspection, it appears that these technologies would be applicable for vessel inspection.

Global inspection methods for vessels are equally enticing as piping inspection technologies. A global vessel inspection methodology would provide increased confidence regarding the detection of localized corrosion. With this improved confidence in the inspection, run lengths between maintenance turnarounds and manned vessel entries can be increased. Maintenance turnarounds are usually scheduled in order to make equipment available for inspection. Increased operating run lengths improves energy efficiency by increasing utilization of employed capital equipment. The goal of research in this area would be to deliver a prototype hardware/software system suitable

Figure 8. Research Needs for Inspection & Containment Boundary Integrity

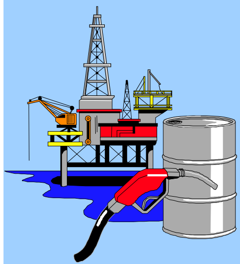
Priority	Near-Term (0-3Years)	Mid-Term (by 2010)	Long-Term (by 2020)
TOP	Develop techniques for rapid, effective inspection of heat exchanger tubes.	Develop technology for reliable, global on-stream inspection of equipment, with focus on 5 critical areas: ultrasonics for pressure vessels, global corrosion-under-insulation inspection, buried pipe, equipment fouling, and placement of improved corrosion probes.	
	Develop the means for global, volumetric inspection of nozzle joints.	Develop >2 methods for monitoring the health of equipment : failure modes and optimized maintenance times.	Develop new methods for *in situ* measurement of residual stress on the most common materials of construction.
		Develop several methods for *in situ* non-destructive evaluation (NDE) of the degradation of materials properties in-service.	
		Reliably quantify corrosion rates and materials deterioration rates using limited data sets.	Reduce corrosion problems by developing a cheap, easy method for testing crude corrosivity.
HIGH		Improve maintenance procedures and failure analysis for high temperature equipment through techniques for on-stream refractory inspection.	Develop smart systems for analysis of equip-ment inspection data.
		Design non-contact sensors and measurement technologies for on-stream inspection of welds.	
		Develop methods for on-stream inspection of air cooler tubes.	

for vessel (and optionally piping) inspection. The technology would provide operators with the confidence of increasing run lengths by offering the capability of detecting localized corrosion while the equipment was still in service. On insulated vessels, it is envisioned that global inspection methods would maximize inspection coverage with minimal insulation removal. Ideally, these inspection methods would be able to detect both internal and external corrosion.

Another high priority is detection, prediction, and prevention of corrosion. Research is needed to develop the capability for reliable quantification of corrosion rates, using only limited data sets. Simple, effective tests to assess the corrosive properties of crude as well as higher boiling components are also needed.

Table 3. High Priority R&D Topics for Inspection and Containment Boundary Integrity

Topic	Importance to Industry	Energy Savings Potential	Potential Competitive Issue	Chances of Funding from Suppliers
Global On-stream Inspection of Equipment	High	High	Low	Medium



6 Fuels and Fuel Delivery

Current Situation

Production and use of transportation fuels have long been associated with concerns about emissions and energy conservation. Historically, these concerns have been addressed independently, rather than as part of an integrated system. For example, emissions concerns have driven the establishment of tailpipe standards for heavy-duty engines and light-duty motor vehicles. Energy concerns have been addressed by government-mandated fuel economy standards for light-duty vehicles, and by consumer demands for lower operating costs for heavy-duty vehicles.

In some cases, steps taken to address emissions concerns can exacerbate energy concerns, and vice versa. For instance, the use of reformulated gasoline (RFG) to reduce vehicle emissions can be detrimental to energy conservation due to increased energy expended in producing and transporting the fuel, and reduced fuel economy that results from its use. Similarly, lowering sulfur levels in gasoline and diesel fuel may reduce tailpipe emissions, but at a cost of increased energy usage in producing these fuels. Optimized strategies for dealing with emissions and energy concerns require integrated approaches that consider complete life-cycle impacts of various fuel, engine, and after-treatment systems.

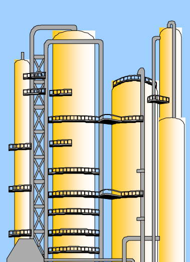
There are also environmental concerns surrounding fuel delivery systems at the retail level (i.e., at the gas pump), as well as potential environmental and safety impacts during transportation of fuels from the refinery to the customer. To date these concerns have been addressed through incremental improvements, such as better valves, or pump handles that reduce or prevent releases of volatile hydrocarbons.

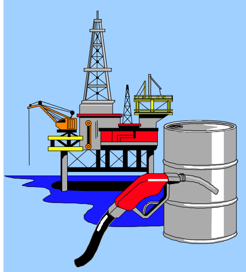
Petroleum products are expected to be a predominant fuel of choice for consumers well into the next century. Their makeup is continually changing, however, to meet new regulatory demands. Other factors influencing fuels include the decreasing quality of available crude feedstocks, and the development of alternative non-petroleum transportation fuels (electricity, biomass).

Future Characteristics

In the future, fuel delivery systems would be safer and easier to use. Retail fuel delivery systems for gasoline and other transportation fuels would be entirely sealed, and totally automated, requiring no human touch for delivery. Distribution systems would support a broad variety of products as well as entirely new fuels.

Petroleum refineries would be highly flexible, producing the fuels demanded by consumers, regardless of feedstock. Fuels might be tailored to maximize chemical end-





use products. There would be a shift toward non-fuel and other products to maximize diversity and profitability, with more refineries operating as integrated fuel/chemical industries. Refineries might be producing liquid hydrocarbon fuels for fuel cell vehicles, as well as other alternative fuels. Fuels produced would be clean-burning, and vehicles would be designed to produce fewer emissions.

Performance Targets

The industry has identified a number of performance targets to improve fuel delivery systems and create the high performance, safe fuels desired by consumers. The industry will strive to effectively balance the need for cleaner products with customer demands for high performance. An important component will be taking steps to prevent the impacts to human health and the environment from fuel exposures and combustion of fuels in vehicles.

Performance Targets for Fuels & Fuel Delivery

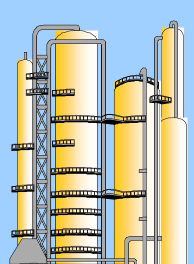
- Reduce emissions from mobile sources
- Create products that are cleaner, satisfy customer needs, and meet performance requirements
- Maintain product quality all the way to the customer
- Reduce expenditures for product quality testing by 75%

Technical Barriers

There are a number of barriers to better fuel delivery and reduced vehicle emissions. In general, there is no integrated, systems approach being taken to develop engine technology with lower mobile source emissions. Further, the industry has little knowledge in advance on how new or reformulated fuels are going to actually perform in advanced technology vehicles (prototypes are not available for testing).

Sulfur tolerant catalysts or other sulfur-tolerant control technologies, which could reduce emissions in vehicle exhaust/tailpipes, have not been successfully developed.   Current technology for control of nitrogen oxides and particulates from diesel-fueled vehicles is also inadequate. Finally, emission controls now in place on vehicles have a tendency to deteriorate.

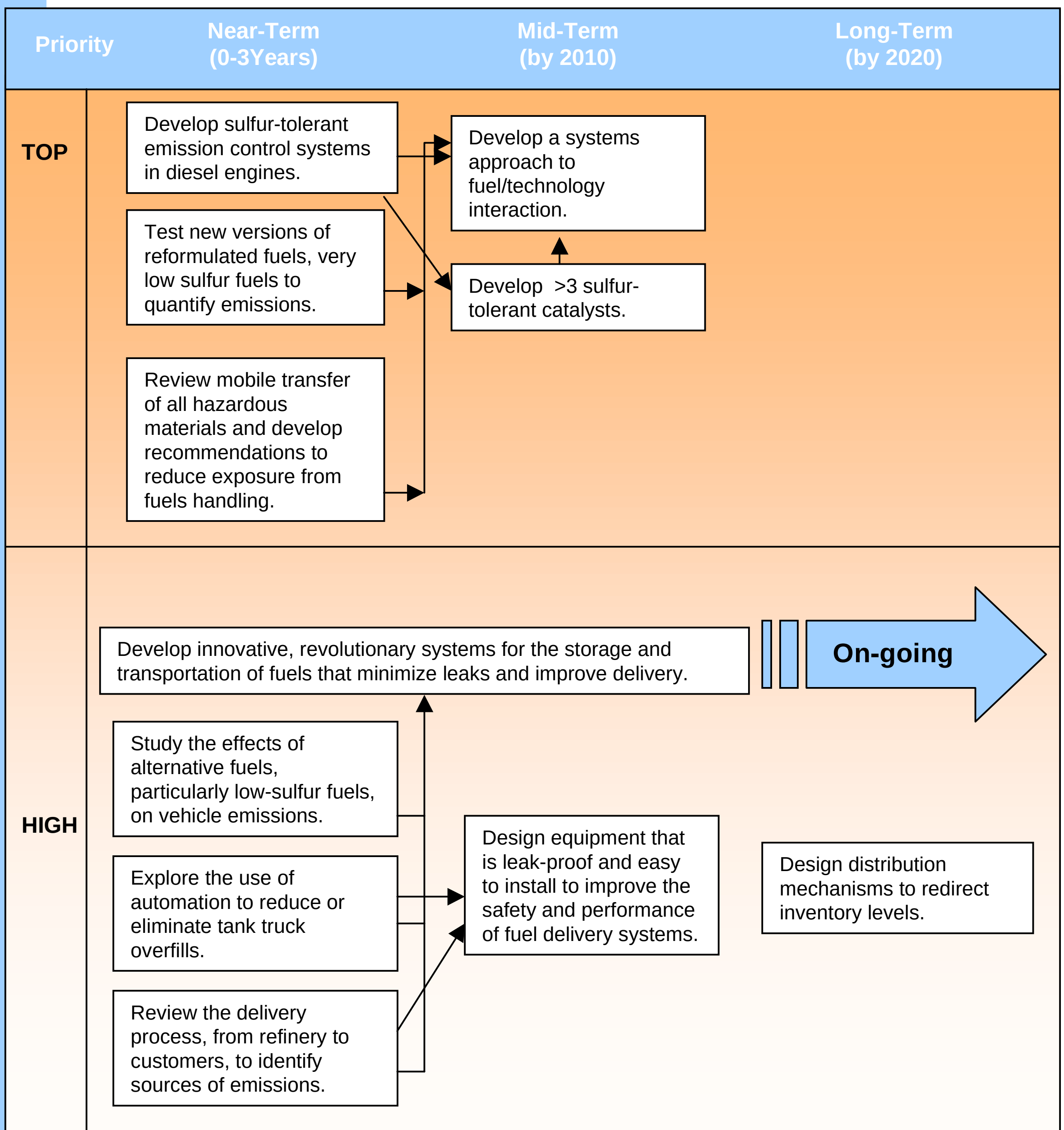
Fuel delivery systems at service stations are not leak-proof, and contribute to emissions of volatiles. The open systems currently in place are sometimes inadequate, and release emissions during refueling of storage tanks.

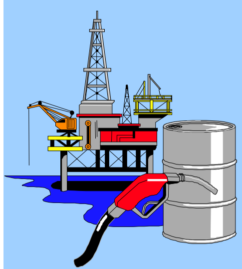


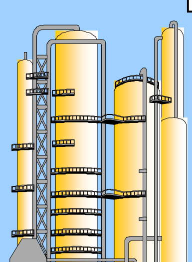
Research and Development Needs

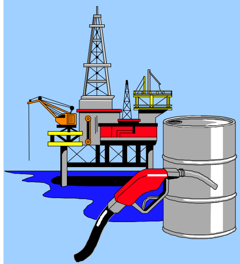
Research and development needed to improve fuel delivery systems and reduce vehicle emissions are shown in Figure 9. R&D is categorized as top and high priority, and aligned by time frame for expected results. Arrows describe the main relationships between research.

Figure 9. Research and Development Needs for Fuels and Fuel Delivery









As discussed earlier, an industry priority is to use an integrated systems approach that combines requirements for fuel efficiency with a desire for reduced emissions (see Table 4). Research is needed to reduce engine exhaust emissions and fuel evaporation emissions. The approach taken may focus on developing better controls, or modifications to fuel specifications. Research is needed to assess how new low-sulfur reformulated fuels will perform in terms of emissions, and alternately, how to reduce emissions from higher sulfur fuels.

Severe sulfur reduction from both gasoline and diesel fuel is generally regarded as producing large emissions benefits -- but at a cost in terms of dollars and energy usage. There is the potential to derive similar emissions benefits from fuels with higher sulfur levels by:

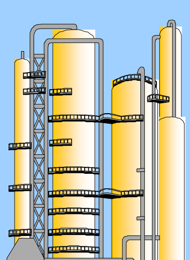
- ❖ Developing sulfur-tolerant emissions control systems, and
- ❖ Developing on-board sulfur-scrubbing technologies

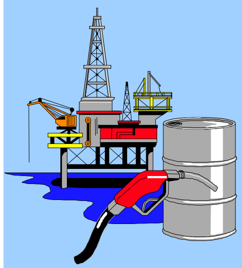
Severe reduction of NO_x emissions under lean conditions remains a major challenge. Some promising technologies involve periodic or continuous injection of a chemical reductant to transform NO_x to N_2. Often, this reductant is the hydrocarbon fuel itself, thereby resulting in an obvious fuel economy penalty. Development of improved reductants, or other NO_x-control technologies, could lead to energy savings.

For improved fuel delivery systems, the ultimate objective is better systems that minimize or eliminate leaks from the storage and delivery of fuels. The current delivery process, from refinery to customer, should be evaluated to identify sources of emissions. New equipment is needed that is leak-proof and easy to install, so that current systems can be retrofitted.

Table 4. High Priority R&D Topics for Fuels and Fuel Delivery

Topic	Importance to Industry	Energy Savings Potential	Likelihood of Short Term Success	Potential Competitive Issue
Systems Approach to Fuel Efficiency/Emissions Reduction and Control	High	High	Low	Low





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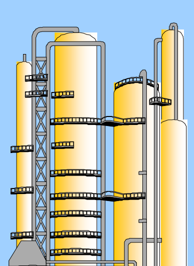

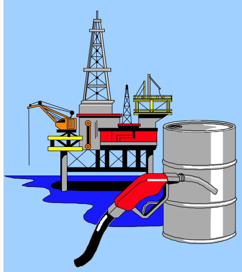

Acknowledgements

The following individuals participated in the workshop that forms the basis for this technology roadmap.

George Birchfield,
Solomon Associates

James Brown,
Exxon Research & Engineering

Ron Chittim
American Petroleum Institute

Mike Clark
BP Amoco

Dave Culler,
Equilon

Vipin Gopal,
Honeywell

Colin Grieves,
BP Amoco

Matt Grossman,
Exxon Research & Engineering

Jeff Hazle
National Petroleum Refiners Assn

S. Kent Hoekman
Chevron Products Company

James Hoffman
Marathon-Ashland LLC

Chia-pin Hsiao
Chevron Research & Technology

Paul Johnson
Arizona State University

Ray Konet
BP Amoco

Bruce Krewinghaus
Equilon

Mark Lozev
Edison Welding Institute

Mani Natarajan
Marathon-Ashland Petroleum Co LLC

C.B. Panchal
Argonne National Laboratory

Jeff Panek
BP Amoco

Mike Petrick
Argonne National Laboratory

A.C. Raptos
Argonne National Laboratory

Peter Redman
BP Amoco

John Reynolds
Equilon

Jim Simnick
BP Amoco

William Steel
Oak Ridge National Laboratory

John Stitzell
MCG Consulting

Dan Vanderzanden

George Vickers
BP Amoco

Dave Wesley

John Wilkinson
Exxon Research & Engineering

Alan Wolf
Exxon Research & Engineering