

**NEW
FORCES
AT
WORK
IN REFINING**

**Industry Views of Critical Business
and Operations Trends**

**D.J. Peterson and
Sergej Mahnovski**

Prepared for the
National Energy Technology Laboratory
United States Department of Energy

**RAND
SCIENCE AND TECHNOLOGY**

The research described in this report was conducted by RAND Science and Technology for the National Energy Technology Laboratory, the United States Department of Energy.

Library of Congress Cataloging-in-Publication Data

Peterson, D. J.

New forces at work in refining : industry views of critical business and operations trends / D.J. Peterson, Sergej Mahnovski.

p. cm.

“MR-1707.”

ISBN 0-8330-3436-7 (Pbk.)

1. Petroleum industry and trade—United States. 2. Petroleum—Refining—United States. I. Mahnovski, Sergej. II. Title.

HD9565.P349 2003

338.4766553'0973—dc21

2003013082

RAND is a nonprofit institution that helps improve policy and decisionmaking through research and analysis. RAND® is a registered trademark. RAND's publications do not necessarily reflect the opinions or policies of its research sponsors.

© Copyright 2003 RAND

All rights reserved. No part of this book may be reproduced in any form by any electronic or mechanical means (including photocopying, recording, or information storage and retrieval) without permission in writing from RAND.

Published 2003 by RAND

1700 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138

1200 South Hayes Street, Arlington, VA 22202-5050

201 North Craig Street, Suite 202, Pittsburgh, PA 15213-1516

RAND URL: <http://www.rand.org/>

To order RAND documents or to obtain additional information, contact
Distribution Services: Telephone: (310) 451-7002; Fax: (310) 451-6915; Email:
order@rand.org

This report presents an overview of how the U.S. refining industry views its future. The findings were derived from discussions with representatives of 40 refining firms, technologies and services providers, research institutions, and other organizations who were selected for their prominent positions in the industry and their ability to think broadly and creatively about current market, management, operations, and policy issues.

The study was commissioned by the Fossil Energy Liquid Fuels Program of the U.S. Department of Energy's National Energy Technology Laboratory. This report is intended to

- aid federal officials in understanding the most important market, management, and regulatory trends impacting refining firms and their operations currently and over the coming decade
- assist decisionmakers in enhancing the effectiveness of federal programs and policies to promote dependable, affordable, and environmentally sound refined products supply.

Other agencies should benefit from the results reported: the U.S. Environmental Protection Agency, the White House Office of Science and Technology Policy, the Department of Justice, the Federal Trade Commission, the Department of Homeland Security, and the Department of Defense. The report will also help refining industry executives, researchers, and stakeholders obtain a broad view and understanding of key trends pertinent to their operations. While refining operations share many technologies and processes, the industry is highly competitive and communication among firms is limited. Thus, industry decisionmakers can benefit from their colleagues' experiences and forward-looking perspectives presented herein.

This research builds on several previous RAND technology studies:

- D. J. Peterson, Tom LaTourrette, and James T. Bartis, *New Forces at Work in Mining: Industry Views of Critical Technologies*, MR-1324-OSTP, RAND, 2001, available at <http://www.rand.org/publications/MR/MR1324/>
- Susan Resetar, *Technology Forces at Work: Profiles of Environmental Research and Development at DuPont, Intel, Monsanto, and Xerox*, MR-1068-OSTP, RAND, 1999, available at <http://www.rand.org/publications/MR/MR1068/>
- Steven W. Popper, Caroline S. Wagner, and Eric V. Larson, *New Forces at Work: Industry Views Critical Technologies*, MR-1008-OSTP, RAND, 1998, available at <http://www.rand.org/publications/MR/MR1008/>.

RAND Science and Technology (RAND S&T) conducts research and analysis that helps government and corporate decisionmakers address opportunities and challenges created by scientific innovation and rapid technological change. Its work stretches from emerging energy technologies to global environmental change to still other endeavors seeking a better understanding of the nation's scientific enterprise and how best to nurture it. Focal points of RAND S&T work include energy, the environment, information technology, aerospace issues, technology and economic development, bioethics, advanced materials, and "critical" technologies for industries and occupations.

RAND S&T serves a variety of clients, including federal, state, and local government agencies; foreign governments; foundations; and private organizations. The S&T team has a wide range of expertise and includes physicists and geophysicists; chemists and geochemists; electrical, chemical, mechanical, and information technology engineers; biological and environmental scientists; and economists and other social scientists.

Inquiries regarding RAND Science and Technology may be directed to:

Stephen Rattien, Director
RAND Science and Technology
1200 South Hayes Street
Arlington, VA 22202-5050
Phone: (703) 413-1100 x5219
Email: contact-st@rand.org
Website: www.rand.org/scitech/

CONTENTS

Preface	iii
Figures	ix
Tables	xi
Summary	xiii
Acknowledgments	xxiii
Acronyms	xxv
Glossary	xxvii
Chapter One	
INTRODUCTION: A CRITICAL INFRASTRUCTURE	1
Petroleum Products in the U.S. Economy	1
Change and Challenges in Refining	2
A Critical Infrastructure	5
About the Study	6
Task	6
Purpose	6
How the Study Was Conducted	7
Scope	8
Organization of the Report	11
Chapter Two	
THE REFINING INDUSTRY AND PETROLEUM PRODUCTS	
MARKETS	13
Industry Segments and Business Models	13
Economic Hardship and Restructuring	15
Is the Downstream Enjoying an Economic Recovery?	17
Product Slate	20
Higher-Performance Fuels	21
Regionalization of Products Markets	23

Future Demand	27
Imports	30
Chapter Three	
REFINERY OPERATIONS AND TECHNOLOGIES	35
Current Operations Trends	35
Refinery Production and Capacity	35
Refinery Utilization	42
Current Trends in Technologies	43
Catalysts	43
Instrumentation and Controls	44
Maintenance and Reliability	45
Longer-Term Trends in Technologies and Operations	47
Refinery Processes	47
Cogeneration	48
Hydrogen Production	50
Liquid Fuels for Fuel Cell Vehicles	51
The Environment for Technology Innovation	51
Research and Development Trends	52
Supply of New Technologies and Practices	54
Federal R&D Support	54
Human Capital	56
Chapter Four	
REGULATORY AND FINANCIAL ENVIRONMENT	59
Return on Investment	60
Capital Constraints	64
Regulatory Flexibility	68
Regulatory Uncertainty	70
Implications for Future Product Supplies	73
Industry Views of Policy and Regulation	77
Chapter Five	
THE REFINING INDUSTRY IN A NEW ERA: KEY FINDINGS AND POLICY ISSUES	81
Key Findings	81
Refining Industry Views Are Consistent With Those of Other Industries	81
The United States Has a Sufficient Near-Term Refining Capacity Base	82
The Downstream No Longer Has Substantial Excess Capacity	82
Boutique Fuels Add Complexity and Rigidity to the Supply Chain	83
Market Trends and Volatility Vary Greatly by Region	84

Executives Question the Transition to Ultra-Low-Sulfur Diesel Fuel	85
Refiners See Both Challenges and Opportunities in Regulation	85
Medium- and Long-Term Trends Are Viewed as Highly Uncertain	86
Operating Company Representatives Are Optimistic About Their Future	87
The Downstream Is Not Technology Constrained	88
Industry Leaders Envision a Focused Policy Role for DOE	88
Policy Issues of Importance	89
Near- to Mid-Term Refined Products Supply Balance	89
Long-Term Refined Products Supply Balance	90
Refined Products Imports	90
Regulatory Environment	91
Research	91
Appendix	
A. RAND DISCUSSION PARTICIPANTS	93
B. DISCUSSION PROTOCOL	101
C. PETROLEUM REFINING PROCESSES AND PRODUCTS	103
Bibliography	113

FIGURES

2.1. Operating Costs and Margins for Mid-Size and Large U.S. Refiners, 1979–2001	18
2.2. U.S. Refining Industry Product Slate	20
2.3. Major Refineries and Refined-Products Pipelines	24
2.4. U.S. Gasoline Requirements, January 2003	26
2.5. One Company’s View of Potential Gasoline Demand	29
2.6. U.S. Net Imports of Crude Oil and Intermediate and Finished Petroleum Products, 1970-2002	31
3.1. Principal Refinery Processes and Outputs	36
3.2. U.S. Crude Distillation Capacity and Input at Operable Refineries, 1970–2002	37
3.3. U.S. Refineries and Capacity Utilization, 1950–2002	37
3.4. Company R&D Spending in the United States, 1985 and 1988	53
C.1. Range of Products in Light and Heavy Crude Oils Prior to Refining and the Market Demand for Refined Products	104

TABLES

1.1. The U.S. Refining Industry at a Glance, 2002	2
2.1. Summary of Major Fuel Specifications	22

THIS STUDY

In 2001, RAND was requested by the National Energy Technology Laboratory within the U.S. Department of Energy's (DOE's) Office of Fossil Energy to conduct a series of in-depth discussions with key members of the U.S. petroleum refining industry. The objective was to obtain a close-up and high-level understanding of the issues industry leaders considered critical to the success of their current operations as well as those likely to be significant in the years ahead. This information is intended to aid DOE and other federal decision-makers in the development of policies concerning refining technology research and development, refined products markets, and environmental protection.

In 2002, RAND researchers met with and led structured discussions with 72 representatives from 40 organizations across a broad spectrum of the refining industry. Organizations represented included 18 operating companies (the companies that actually produce refined products—e.g., refiners) and 10 firms that provide refineries with process technologies, equipment, and services. The information gathered from these two groups comprises the bulk of the views presented in this report and answers several questions:

- How do trends in markets, operations, technology, and the regulatory climate affect refining firms and their operations?
- How is the refining industry responding to these opportunities and challenges?
- What issues and trends merit attention from DOE given its mandate to promote dependable, affordable, and environmentally sound energy for the future?

Participating refiners in the RAND sample represented a broad spectrum of the petroleum refining industry with operations in all regions of the United States.

They included both very large and small firms manufacturing a diverse slate of products. The sample of refining technology and services suppliers also spanned a range of specialties and sizes.

REFINING INDUSTRY AND PETROLEUM PRODUCTS MARKETS

The demand for refined products—transportation fuels in particular—has been rising steadily over the past two decades. In 2000–2002, consumption of refined petroleum products in the United States peaked at an all-time high of 19.7 million barrels per day. The Energy Information Administration (EIA) projects that, based on current trends, consumption of petroleum products in the United States could increase by 47 percent between 2001 and 2025, or 1.6 percent annually.

As demand for petroleum products has grown, their quality and performance have changed substantially as a result of environmental regulations and motor vehicle performance requirements. Over the next several years, the industry will be upgrading its facilities to produce ultra-low-sulfur gasoline and diesel fuel; to phase out methyl tertiary butyl ether (MTBE) as a gasoline additive; to blend in ethanol as an oxygenate; and to reduce the environmental impacts of plant operations. Another impact of regulations is the proliferation of transportation fuels. Many local markets have “boutique fuel” specifications that add complexity and rigidity to the market, and have the potential to increase upward price pressures.

The 1990s were widely viewed by the industry as a period of unprecedented economic volatility and hardship, characterized by poor profit margins as a result of substantial excess capacity, the increasing cost of compliance with environmental regulations, and unfavorable crude oil price trends. At the same time, the refining industry in the United States has been dramatically changed by corporate restructuring and consolidation.

- The sector has become less vertically integrated as management has sought to focus on core competencies. Most vertically integrated “majors” have scaled back, shut down, or spun off their process technology development divisions. Many also have shed refineries and retail outlets. This trend has led to the emergence of new business models and large independent refining firms and marketers.
- Operations within firms have become more autonomous. In the past, vertically integrated oil companies often managed downstream operations as a means to “monetize” crude oil production operations. That is, downstream refining operations often were subsidized or financed by the upstream. Today, U.S. refining and marketing operations are generally managed as

stand-alone business units accountable for their own profit and loss performance. Disaggregation of business units, combined with new management practices, has focused attention on obtaining greater returns from existing capital, avoiding unnecessary investment, and cutting costs.

- A wave of mergers, acquisitions, joint venture alliances, and selective divestitures started in 1998. The aim was cutting costs, gaining economies of scale, increasing returns on investment, and boosting profitability. In 2002, 58 firms were engaged in refining in the United States, down from 189 firms in 1981.

Consolidation and restructuring appear to have had the salutary effect executives intended. EIA data indicates that mid- and large-size refiners reduced per-barrel operating costs by one-third. This enabled them to gradually recover their profit margins, despite burdens such as mandated regulatory investment. In 2001, profit margins were the highest since the EIA started tracking industry performance in 1979.

KEY FINDINGS

Several key findings emerged from the industry leaders' discussions with RAND.

The United States has a sufficient near-term refining capacity base.

In contrast to industry warnings of chronic, widespread shortages issued in the late 1990s, no executives in the RAND discussions said a fundamental imbalance in supply and demand in the United States was imminent. The slowdown in the global economy has dampened demand pressures both in the United States and abroad, while refiners in recent years have added capacity through selective investments and productivity enhancements—efforts facilitated by corporate restructuring and consolidation. Meanwhile, the availability of imports, especially from the Caribbean, Canada, and Europe, continues to add liquidity to the supply environment.

Substantial excess capacity no longer exists in the downstream segment.

Between 1985 and 2000, average refinery utilization increased from 78 to over 92 percent. This higher rate is expected to hold in the foreseeable future. For operating companies, the elimination of excess capacity represents a significant business accomplishment: Low profits in the 1980s and 1990s were blamed in part on overcapacity in the sector. Since the mid-1990s, economic performance industry-wide has recovered and reached record levels in 2001. On the other

hand, for consumers, the elimination of spare downstream capacity generates upward pressure on prices at the pump and produces short-term market vulnerabilities. Disruptions in refinery operations resulting from scheduled maintenance and overhauls or unscheduled breakdowns are more likely to lead to acute (i.e., measured in weeks) supply shortfalls and price spikes. Indeed, industry leaders warned that this was likely to occur. While the RAND discussants saw high and low capacity utilization rates as unsustainable for operating companies, they did not identify a balance point that was ideal for both producers and consumers.

Market trends and potential volatility vary greatly by region.

Industry representatives emphasized the regional character of U.S. markets. This point was brought out in reference to refiners' regional business strategies, the constraints imposed by refinery locations, pipeline infrastructure, and "boutique" fuel specifications. Market volatility and potential supply shortfalls, should they occur, are most likely to be of regional, not national, scope. The Gulf Coast, Eastern Seaboard, and Southeast are seen as the least-vulnerable regions because of the concentration of refineries and pipelines there and the greater accessibility of imports. The West Coast and Midwest were frequently cited as regions of concern because of regional environmental regulations and the lack of easily accessible alternative supplies, among other issues.

Regulations are a concern.

Operating company representatives who spoke with RAND were uniformly proud about their past accomplishments in promoting worker health and safety at their facilities and improving the environmental performance of their facilities and products. Some, however, saw current and future regulations as a threat to refiners' bottom line and their ability to meet demand in a reliable manner. Accordingly, changes were recommended to resolve concerns about return on investment, capital availability, and regulatory flexibility and uncertainty.

The leaders addressed three regulatory concerns at length, all of them related to environmental protection.

- A few participants were particularly concerned about MTBE phase-out and its replacement with ethanol as a gasoline blending component, arguing that it may lead to shortages. Most, however, did not consider this a critical supply issue and suggested the industry would comply with the transition in a timely manner in California and elsewhere, as required. Nearly all par-

ticipants, however, questioned ethanol blending in terms of its macroeconomic costs and environmental and public health benefits.

- New Source Review rules governing facility air pollution emissions, as they existed and were enforced in early 2002, were criticized by nearly all discussants. Some saw rules on “routine maintenance, replacement and repair,” for example, as adding excessive uncertainty to the permitting process and having a chilling effect on investment for capacity increases and upgrades for regulatory compliance. After the RAND discussions, the U.S. Environmental Protection Agency (EPA) issued a proposed rule that would exclude from NSR permitting many plant modifications deemed “routine.” This rule appeared to address concerns raised by the refining industry.
- Discussants raised a number of concerns regarding the introduction of ultra-low sulfur diesel fuel (ULSD) in 2006, such as potential contamination and downgrading of ULSD stocks outside the refinery gate. Participants in the RAND discussions generally saw supply problems as a transition issue that could have local price impacts, but likely would be quickly mitigated and corrected. In a worst-case scenario, a few participants mentioned that a temporary rules waiver might become necessary, even if it penalized those who complied on time. Speaking about their own firms’ plans (more than three years ahead of scheduled implementation), no operating company executives suggested that they would be exiting the diesel market. Smaller firms in particular, stated or implied that they would remain in the market and meet the sulfur limit in a timely manner.

Refiners see both challenges and opportunities in regulation.

A countervailing theme was that environmental improvement was part of the normal—even welcomed—evolution of the refining industry. The variation in discussants’ views on regulation was issue-, region-, and even refinery-specific and was said to depend largely on how they affect one’s business. Regulations, it was observed, also can create business opportunities for refiners and their suppliers. Local (boutique) fuel formulations, which can favor some refiners while deterring others, were cited as an example. Refiners in California, the state with the most stringent regulations, enjoy the highest profit margins, observed several discussants. In sum, although regulation was a prominent discussion theme, no clear consensus emerged on ways to improve the overall regulatory climate or specific rules.

Longer-term trends are highly uncertain.

RAND discussants reported that the industry is extremely preoccupied with current regulatory compliance and business restructuring challenges, making

longer-term planning difficult. In the medium term, out to 2010–2012, most industry leaders anticipate a gradual phase-out of MTBE nationwide. After ULSD implementation, most expect additional clean fuels initiatives to come into force, including further reductions in fuel sulfur content to “near-zero” levels.

They also expect demand for petroleum products to grow at the brisk rates seen in the 1990s and as predicted by the Energy Information Administration. Without the cushion of excess capacity, however, leaders questioned the industry’s ability to keep up with demand, and they doubted imports would be sufficient to fill the expected supply gap. They cited market disincentives, logistical barriers, and stringent fuel specifications—a marked departure from EIA forecasts. Of note, a few refiners are contemplating the potential for a significant easing of demand, perhaps as soon as 2010, prompted by the introduction of highly efficient motor vehicles. Such thinking may create pressure to minimize increases in capacity and other investment in plant and equipment in the mid term, thus contributing to higher and more volatile prices and better profit margins.

Looking to the longer term, beyond 2012, discussants did not foresee the emergence of fundamentally different ultra-clean fuels, such as oxygenates, compressed natural gas, and synthetic liquid fuels derived from natural gas—except as blending components or in niche applications. Most asserted that their industry was well situated to provide a petroleum-based energy source for fuel cell vehicles. They did not, however, express a clear view about how the refinery of the future might be configured to produce such a fuel.

Operating company representatives are optimistic about their future.

The RAND discussants typically portrayed the refining industry *as a whole* as facing significant financial and operational challenges. These views were rooted in the 1990s, when the downstream (the part of the industry engaged in crude oil refining and refined product distribution and marketing) was characterized by excess capacity, low crude oil prices, high regulatory spending, and weak economic performance. In contrast, the RAND discussants were upbeat in 2002 when sharing their views *about their own firms’* current and future prospects. This suggests that cost-cutting, consolidation, and the adoption of new business strategies, combined with the gradual reduction of excess capacity, have had the corrective effects intended and that the refining industry has entered a new era of enhanced profitability and sustainability. Contrary to the common wisdom in the industry, small and mid-size refiners in particular were sanguine about their business environment and their ability to prosper in it, and they reported making strategic investments in acquiring refineries and upgrading processing to secure their future—despite concerns about some regulations.

The downstream is not technology constrained.

Despite the sharp decline in industry, university, and federal research and development (R&D) in refining, the pace of innovation is viewed as adequate to meet higher-performance fuel production requirements and other challenges facing operating companies in the coming years. Continued incremental improvement in catalysis (the chemical reaction in which petroleum products are broken down with the aid of an agent that is not consumed in the process) is generally seen as one of the most promising areas. The prospects for fundamental downstream innovation are limited, given operating companies' incentives to minimize capital expenditures and preserve their existing capital base. Most refining industry members, except those in academia, are not concerned that DOE funding for refining R&D has been very low and has recently experienced further decreases. They argued that the private sector can manage the R&D process faster and more effectively on its own. They generally were supportive of a federal role in long-term R&D directed at improving knowledge of fundamental phenomena.

Industry leaders envision a focused policy role for DOE.

Government involvement in downstream operations, however well-intentioned, is seen as highly undesirable. Industry does value DOE's information-gathering activities, but participants' general sense was that the agency could apply more resources in the policy arena. They explicitly called for DOE to take a stronger role on refining industry and fuels policy issues by conducting or sponsoring objective scientific and technical research and science-based policy analyses. The objective is to aid decisionmaking on a wide range of market, operations, and regulatory issues, such as ethanol blending, diesel cetane, refined products imports, New Source Review permitting, and the energy supply for fuel cells.

IMPORTANT POLICY ISSUES

In their discussions with RAND, refining industry leaders recommended that DOE assume a more prominent policy role concerning refining and fuels issues. From these discussions RAND has identified a number of priority policy questions that may merit close attention by DOE and other government decision-makers now and in the coming years. Selected questions are presented below.

Near- to Mid-Term Refined Products Supply

- What will be the likely intensity, duration, and regional distribution of price spikes should supplies of on-road diesel not match demand in 2006? What

measures could government take to avoid disruptions? What actions are available to the government to restore supplies and market confidence in the event of supply and price shocks?

- To what extent are regional fuel specifications an efficient solution to local air pollution problems, considering environmental quality, refinery costs, and the effects on competition and market volatility? Are more efficient options available?
- Does ethanol blending increase national energy security? What are the net economic, environmental, and energy independence benefits of ethanol use?
- What physical barriers constrain product movement in the United States and the West Coast market in particular? In what ways do public policies related to infrastructure investment influence market liquidity?

Long-Term Refined Products Supply

- If domestic demand continues to rise over the coming two decades, will U.S. refining capacity or import capability be sufficient to meet the demand?
- What are the costs and benefits of policy options intended to dampen chronic supply and price volatility in key markets?
- Do more stringent environmental standards governing petroleum product content give domestic refiners an advantage relative to foreign refiners? What are the costs and benefits of harmonizing standards with major trading partners?
- What is the potential mid- to long-term impact on petroleum product demand of evolving consumer preferences, use of alternative fuels, and efforts by automakers to implement advanced vehicle technologies?

Refined Products Imports

- If the demand for imports grows, will foreign refiners have the processing capacity and capabilities to service the U.S. market with either intermediate or finished products in a reliable and sustained manner?
- What port security, shipping safety, and environmental protection measures will be required to accommodate an increase in product imports?
- What level of imports of refined products represents an appropriate balance between local supply needs and national energy security priorities?

- How do differences in environmental standards between the United States and its trading partners governing petroleum product content and plant emissions influence trade in refined products?

The Regulatory Environment

- What alternative regulatory strategies could provide refiners with more operational flexibility without increasing environmental impacts from the production or consumption of petroleum products or generating excessive administrative complexity?
- How are changes in the implementation of New Source Review affecting investments in capacity additions, compliance with new fuels specifications, and net emissions?
- What market-oriented and other regulatory tools can government use more aggressively to give refiners greater incentive to be proactive and innovative in meeting environmental goals?
- Can government establish and enforce performance standards for fuels without dictating the content of the fuels?
- What are the net benefits of longer lead times to plan for new regulations, provide more certainty and stability about regulation, and reduce the costs to refiners?

Research

- What basic or long-range technology research can government support that industry is unlikely to fund itself?
- What is the appropriate role for the refining industry in the federal fuel cell-related initiatives?
- How can government partner better with the refining industry to foster demonstration of new technologies and practices?

ACKNOWLEDGMENTS

The authors wish to thank all the individuals who participated in the RAND refining industry discussions for their time, candor, and good will. The participants are listed in Appendix A.

We extend special thanks to Fred Potter and his team at Hart/IRI Fuels Information Services, who served as consultants and provided guidance and assistance during the discussions and drafting phases of this project. Industry engagement also was facilitated by Bob Slaughter, then General Counsel and Director of Public Policy at the National Petrochemical and Refiners Association, and Ed Murphy, Downstream General Manager at the American Petroleum Institute. Robert L. Hirsch provided key background information and insights regarding trends in operations and management in the refining industry, and he participated in many of the discussions.

A number of people reviewed the manuscript and provided valuable insights on issues and trends in refining and other industry sectors that strengthened our presentation. At RAND, James T. Bartis and Frank Camm provided extensive critical input for which the authors are greatly appreciative. Additional RAND contributors include Keith Crane, Debra Knopman, Parry Norling, Susan Resetar, and Jerry Sollinger. Nancy W. Newkirk and Christopher Ross served as the external peer reviewers and their insights and contextualization were valuable to us.

Greg Kawalkin of the National Energy Technology Laboratory managed this project, and the authors wish to thank him in particular for his sustained interest and support through all its phases.

While the content of the report reflects the observations and opinions of the people interviewed, the authors accept the responsibility for the ways those views are expressed in these pages.

ACRONYMS

CAFE	corporate average fuel economy
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
MTBE	methyl tertiary butyl ether
PPM	parts per million
ROI	return on investment
ULSD	ultra-low-sulfur diesel

Aromatics	A group of hydrocarbons characterized by unsaturated carbon atoms in a ring formation. The group consists of valuable petrochemical species (primarily benzene, toluene, and xylene). In gasoline, aromatics serve to boost octane but they also are known carcinogens.
Barrel	Standard measure of liquid volume used in the oil industry; equal to 42 gallons.
Catalyst	A chemical material used to promote chemical reactions, which itself is not consumed as part of the chemical process. In refining, these are typically solid materials, with the exception of alkylation, where liquid catalysts are used.
Cleaner fuels	A general description of transportation fuels formulated to have reduced environmental and public health impacts. Cleaner fuels include those with ultra-low-sulfur content, lower vapor pressure, and reduced aromatics content.
Coke	A solid, high-carbon residue similar in appearance to coal that is a by-product of refining operations.
Complexity	A measure of a refinery's hardware to process different grades of crude oil inputs. Higher-complexity refineries can handle a wider range of petroleum inputs—most importantly, the heavier crudes that are becoming more prevalent on world markets.
Crude oil	A mixture of hydrocarbon species (molecules of differing patterns and ratios of hydrogen and carbon atoms) that exists in liquid phase in underground reservoirs. Crude oil also contains contaminants such as sulfur, nitrogen, and heavy metals.

Distillates	Term usually used to group of petroleum products produced in refinery distillation operations that are heavier than gasoline. Distillates include kerosene, jet fuel, diesel fuel, and home heating oil.
Desulfurization	Refinery process of removing sulfur from intermediate and final product streams through chemical reactions and adsorption processes.
Downstream	Segment of the oil industry engaged in crude oil refining and refined product distribution and marketing.
Drivability Index	A composite indicator of fuel quality. The index is designed to measure factors that determine vehicle performance noticeable to a driver, such as hard starting, surging, and stalling.
Ethanol	A two-carbon alcohol, frequently referred to as “grain alcohol,” produced from plant material. Ethanol for blending as a motor fuel in the United States is currently derived primarily from corn.
Feedstock	Input to the refinery process.
Financial Reporting System	U.S. energy company monitoring program maintained by the Department of Energy. Participating companies must be publicly owned and account for at least one percent of U.S. crude oil, natural gas, or natural gas liquids reserves or production, or crude oil refining capacity or refined products sales.
Heavy/light crude	Characterization of a crude oil stock based on its density or boiling range. Heavy crude has a higher carbon-to-hydrogen ratio and require greater refinery complexity to process into finished products.
Hydrocarbons	Compounds containing carbon and hydrogen.
Hydrogen	The lightest of all gases, used in refining as a means to desulfurize petroleum feedstocks or, when added to refining streams, to improve final product quality.
Independent	A refining firm that purchases its crude oil inputs on the open market.
Low-sulfur	In the United States, generally used to describe transportation fuels containing sulfur in concentrations of 500 parts per million or less.

Major	A large vertically integrated oil company that produces both crude oil and refined petroleum products.
Methane	A single-carbon molecule that is the predominant constituent of natural gas. Methane is a by-product of certain refinery processes.
Methyl tertiary butyl ether	An oxygen-bearing compound used as blending agent in gasoline to boost octane levels and improve engine performance and to reduce emissions.
New Source Review	An EPA program requiring pollution-emitting industrial plants—both new plants and existing plants that make major modifications—to obtain a permit that will be issued only if best-technology pollution control measures are included.
Non-return investment	Capital expenditures, typically associated with achieving regulatory compliance or other goals, that do not yield profit enhancement or maximization.
Oxygenate	A blending compound (e.g., alcohols and ethers) containing oxygen that is added to gasoline to improve combustion and reduce carbon monoxide and other smog-forming tailpipe emissions.
Reformulated gasoline	Gasoline specially formulated to reduce emissions of hydrocarbons, aromatics, and other pollutants. Mandated by the federal government to be sold in 10 regions suffering serious ozone pollution, including the West Coast and Midwest.
Renewable fuels standard	Proposed federal requirement that a portion of the U.S. gasoline pool be derived from renewable resources, primarily ethanol. Bills under discussion in 2002–2003 call for five billion gallons of renewables to be included by 2012.
Sour/sweet crude	Characterization of a crude oil stock based on its sulfur content. Sour crude contains higher concentrations of sulfur and requires greater refinery complexity to process into finished products. Sweet crude contains lower concentrations of sulfur. World crude supplies are becoming increasingly sour.
Stranded investment	Capital expenditures on plant and equipment that are rendered redundant or unprofitable as regulations or market conditions change.

Sulfur	A yellowish element that is a natural constituent of crude oil. Sulfur contaminates and degrades catalysts used in refining and in motor vehicle pollution control equipment. At high concentrations, sulfur compounds in tailpipe emissions harm human health and the environment.
Ultra-low-sulfur	A term generally used to describe fuels from which most of the sulfur has been removed. The U.S. government has established a standard of 30 ppm for gasoline for phase-in starting in 2004 and 15 ppm sulfur for on-road diesel fuel starting in 2006.
Upstream	Segment of the oil industry engaged in crude oil exploration, extraction, and gathering.