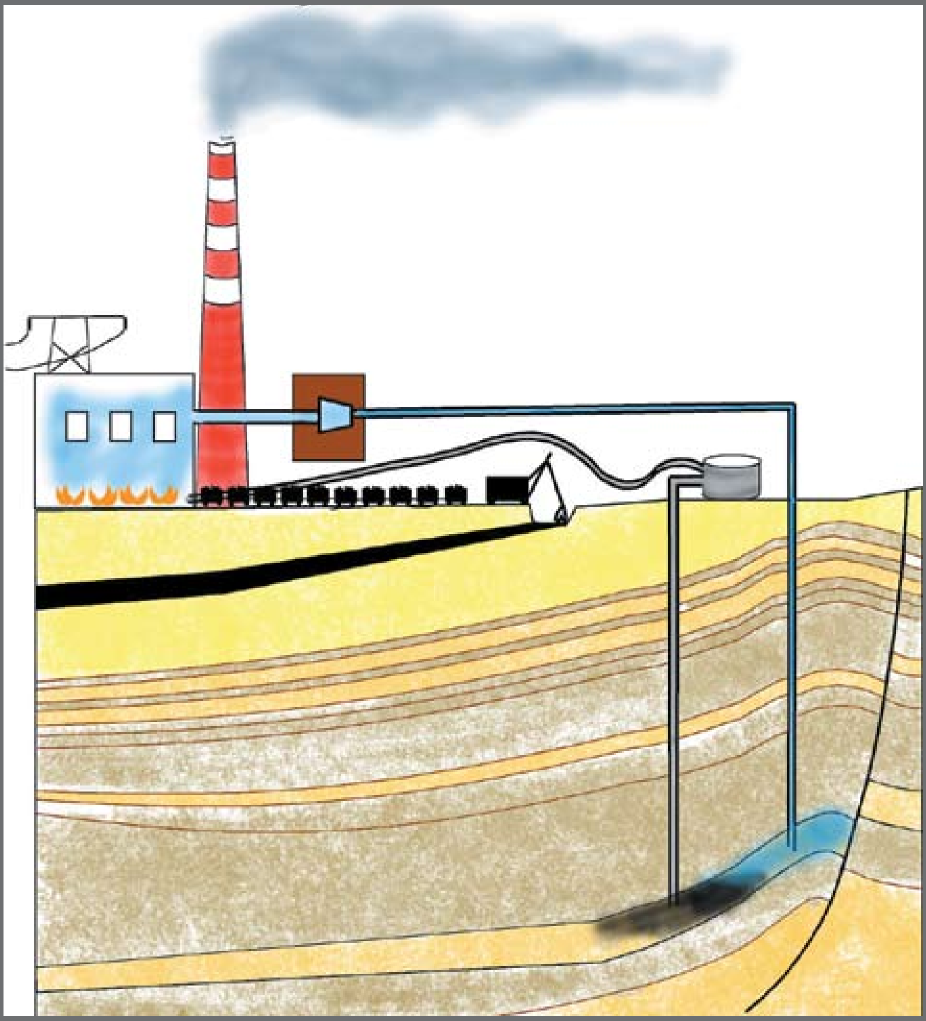
Creating a Carbon Capture and Storage Industry in Texas



Lyndon B. Johnson School of Public Affairs
The University of Texas at Austin
Policy Research Project Report

154

Lyndon B. Johnson School of Public Affairs
Policy Research Project Report
Number 154

Creating a Carbon Capture and Storage Industry in Texas

Project directed by

David Eaton, Ph.D.

Ian Duncan, Ph.D.

A report by the
Policy Research Project on Texas Energy Policy
February 2007

The LBJ School of Public Affairs publishes a wide range of public policy issue titles. For order information and book availability call 512-471-4218 or write to: Office of Communications, Lyndon B. Johnson School of Public Affairs, The University of Texas at Austin, Box Y, Austin, TX 78713-8925. Information is also available online at www.utexas.edu/lbj/pubs/.

Library of Congress Control No.: 2006934159
ISBN-10: 0-89940-767-6
ISBN-13: 978-0-89940-767-8

Printed in the U.S.A.

Cover design by Doug Marshall
LBJ School Communications Office

Policy Research Project Participants

Students

Spencer Bytheway, B.A. (International Studies), Brigham Young University

John Thomas Coleman, P.E., B.S. (Civil Engineering), University of Arkansas-Fayetteville

Clifton T. Cottrell, (Political Science), University of the Ozarks

Michael James Hoffman, B.S. (Anthropology), University of Utah

Kate M. Larsen, B.A. (Biology), Stanford University

Charles V. Stern, B.A. (History and Political Science), Southwestern University

Cyrus Tashakkori, B.A. (Science and Public Policy), University of North Carolina at Asheville

Project Directors

David J. Eaton, Ph.D., Bess Harris Jones Centennial Professor of Natural Resource Policy Studies, Lyndon B Johnson School of Public Affairs, The University of Texas at Austin

Ian Duncan, Ph.D., Associate Director, Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin

Table of Contents

List of Tables

List of Figures

List of Acronyms

API	American Petroleum Institute
Bbl	barrel
Bmt	billion metric tons
BEG	Bureau of Economic Geology at the University of Texas
CCX	Chicago Climate Exchange
CO	carbon monoxide
CO_2	carbon dioxide
COE	cost of electricity
DEA	diethanolamine
DOE	U.S. Department of Energy
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
ERC	emission reduction credit
EUETS	European Union Emissions Trading Scheme
GCCC	Gulf Coast Carbon Center
H_2	hydrogen
HVL	highly volatile liquid
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IMPLAN	Impact Analysis for Planning
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
kWh	kilowatt-hour
Mcf	million cubic feet
MDEA	methyldiethanolamine
MEA	monoethanol amine
MMBtu	million British thermal units

MMP	minimum miscibility pressure
MPa	megapascal
MW	megawatt
NETL	National Energy Technology Laboratory
NEPA	National Environmental Policy Act
NGCC	natural gas combined cycle
NOx	nitrous oxides
NPV	net present value
NSR	New Source Review
OIP	oil in place
OOIP	original oil in place
OPG	Ontario Power Generation
PC	pulverized coal
PEIS	Programmatic Environmental Impact Statement
ppm	parts per million
psi	pounds per square inch
RCRA	Resource Conservation and Recovery Act
SAM	Social Accounting Matrix
SDWA	Safe Drinking Water Act
SO_2	sulfur dioxide
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality
TNRC	Texas Natural Resources Code
TRC	Texas Railroad Commission
TWC	Texas Water Code
UIC	underground injection control
USDOT	U.S. Department of Transportation
USDW	underground sources of drinking water
WAG	water alternating with gas

Foreword

The Lyndon B. Johnson School of Public Affairs has established interdisciplinary research on policy problems as the core of its educational program. A major part of this program is the nine-month policy research project (PRP), in the course of which two or more faculty members from different disciplines direct the research of graduate students of diverse backgrounds on a policy issue of concern to a government or nonprofit agency. This "client orientation" brings the students face to face with administrators, legislators, and other officials active in the policy process and demonstrates that research in a policy environment demands special talents. It also illuminates the occasional difficulties of relating research findings to the world of political realities.

This policy research project is concerned with actions Texas can take to remove carbon dioxide (CO_2), a greenhouse gas, from the atmosphere through capture and storage underground. This project examines the potential barriers to a solution to the problem of global warming by capturing CO_2 from the smokestacks of stationary sources and piping it to oil fields where it can be used to enhance oil recovery as a prelude to long-term sequestration. This report examines the science, engineering, law, economics, and policy of carbon capture and storage. It concludes that carbon capture and storage industries are feasible but face barriers that can be overcome through government policies. The PRP report closes with a detailed case study of removing CO_2 from an oil refinery near Houston, Texas, and piping it 25 miles to be injected to enhance oil production.

The curriculum of the LBJ School is intended not only to develop effective public servants but also to produce research that will enlighten and inform those already engaged in the policy process. The project that resulted in this report has helped to accomplish the first task; it is our hope that the report itself will contribute to the second. Neither the LBJ School nor The University of Texas at Austin necessarily endorses the views or findings of this report.

James Steinberg
Dean

Acknowledgments and Disclaimer

This project would not have been possible without the support of five key people and the PRP is thankful for their involvement: Charles Christopher, Jay Banner, Bob Inman, Bill Fisher, and John Butler. Charles Christopher, Ph.D., Director of the BP Climate Group in Texas, first suggested this study and facilitated the initial support through the Gulf Coast Carbon Center. Jay Banner, Ph.D., Director of the Environmental Science Institute at The University of Texas at Austin (UT/Austin), convened faculty throughout UT/Austin to discuss a response to Dr. Christopher's challenge; Dr. Duncan and Dr. Eaton co-developed this course as a result. Admiral Bob Inman, Lyndon B. Johnson Centennial Chair in National Policy and Interim Dean of the LBJ School, was willing to initiate this project with the largest single contribution of financial support. Bill Fisher, Ph.D., Dean of the John A. and Katherine G. Jackson School of Geosciences, supported the project with a key contribution of matching funds through Ian Duncan, Ph.D. of the Bureau of Economic Geology and he contributed personally when he spoke to the class about the future of fossil fuels. John Butler, Ph.D., Director of the Institute of Creativity and Capital (IC^2) at UT/Austin contributed the final piece of funding that allowed the project to proceed.

This report was drafted as a group effort by students in the PRP class, including Spencer Bytheway, John Thomas Coleman, Clifton Cottrell, Michael James Hoffman, Kate M. Larsen, Charles V. Stern, and Cyrus Tashakkori. David Eaton and Ian Duncan provided guidance and supervision to the class and David Eaton edited the report.

The PRP research benefited from advice and guidance from a number of faculty and research staff at UT/Austin. Sue Hovorca, Ph.D., Research Scientist at the Bureau of Economic Geology, encouraged the faculty and students to stay practical and focus on how to move a Texas carbon capture and storage industry forward. Larry Lake, Ph.D., W. A. "Monty" Moncrief Centennial Chair in Petroleum Engineering at the Department of Petroleum and Geoscience Engineering, gave generously of his time to help the class understand enhanced oil recovery and contributed useful comments that improved the draft report. Mark Holtz, Ph.D., from the Bureau of Economic Geology and Steve Bryant Assistant Professor of Petroleum and Geoscience Engineering helped explain the scientific and technical details related to the case study. Bob Loucks and Romulo Briceno of the Bureau of Economic Geology provided information on oil leases and royalties. Gary Rochelle, Ph.D., Carol and Henry Groppe Professor in Chemical Engineering, discussed methods for separating CO_2 from stationary source flue gas with the class. Chandler Stolp, Ph.D., Associate Professor at the LBJ School of Public Affairs, contributed insights to class members on economic modeling and IMPLAN. Gürcan Gülen, Ph.D., Senior Energy Economist at the Bureau of Economic Geology, provided the class with important background on the Texas electricity regulatory system.

Speakers from private business and organizations conveyed important background information on energy policy and the energy industry to the PRP class. The class would like to thank Jim Marston, Director of the Austin Office of Environmental Defense; Bertrand Collomb, Chairman of Lafarge; and David Burns, Manager of Business Development at Praxair, Inc.

Professionals in private organizations and business contributed to the study through their expertise and advice. We acknowledge Jon Hockenyos and Travis James of TxP Consulting and Michael Bomba of Bomba Associates for their help on IMPLAN input/output analyses and taxation questions. The class appreciated Bill Townsend of BlueSource, LLC, for his help with carbon emission credits.

Civil servants from a number of Texas state agencies provided helpful guidance and comments on many key study topics. For example, the class recognizes Fernando de Leon and Doug Johnson from the Texas Railroad Commission for their help with regulatory issues and Miguel Pavon of the staff of the Border Information Center of the Texas Water Development Board for help with geographic information systems.

The class is thankful to Lucy Neighbors and Lori O'Neal of UT/Austin staff who supported the development of this project and this report. This report was edited while the editor resided in Ferienhof Möller, Germany and the project is thankful to Anette and Hans Möller for the peace and quiet of their farm.

None of the sponsoring units, including the LBJ School of Public Affairs, the John. A. and Katherine G. Jackson School of Geosciences, the Institute for Creativity and Capital – IC^2 Institute, the Gulf Coast Carbon Center or The University of Texas at Austin endorses the views or findings of this report. Any omissions or errors are the sole responsibility of the authors and editors of this report.

Executive Summary

Carbon dioxide (CO_2), a product of burning fossil fuels, is considered by many of the world's climatologists to be a greenhouse gas that contributes to the warming of the earth. Increasing levels of CO_2 in the atmosphere have prompted many nations to adopt limits on emissions to inhibit increases in CO_2 levels. Emissions limits are just one strategy for controlling CO_2. Another approach is to remove CO_2 from the atmosphere and store it underground. This so-called "geologic sequestration" is a viable option that can both reduce greenhouse gas accumulation in the atmosphere and use CO_2 to enhance oil recovery (EOR). This report examines how to enhance oil recovery in the Gulf Coast region through geologic sequestration of CO_2.

Since the early 1970s oil producers in the Texas Permian Basin have used CO_2 enhanced oil recovery to extract oil from reservoirs. After primary pumping and water flooding as a secondary treatment, enhanced oil recovery involves injecting pressurized CO_2 into a reservoir to move more oil to the surface for recovery. The addition of CO_2 to an oil reservoir during enhanced oil recovery increases the volume of recoverable oil. Using this process in the Gulf Coast, oil producers could recover billions of barrels of oil that otherwise would not be produced, increasing domestic oil production and revenue. Potential Gulf Coast reservoirs are in close proximity to CO_2 emitting sources such as power plants, refineries, and other stationary sources. CO_2, now a waste residual of sources in the region, could instead be captured and transported for enhanced oil recovery to become a valuable resource for Texas.

Two characteristics make the Gulf Coast a prime site for geologic sequestration: sources for CO_2 emissions and a substantial capacity to store CO_2 in underground oil reservoirs and geological formations. Geologic sequestration involves injecting and trapping captured CO_2 in underground reservoirs for storage. The technology used for capturing CO_2 at emitting sources is a mature technology; projects worldwide have explored the various techniques and costs associated with carbon capture. Given the substantial costs associated with CO_2 capture and transmission, Texas may want to consider research, tax or royalty subsidies, loan programs, or other public sector initiatives to facilitate carbon capture and storage.

This study includes a case study that illustrates how such a Texas carbon capture and storage industry could work to benefit the companies that invest in it, the citizens of the State of Texas, and the world. The process starts with CO_2 capture from a Texas City refinery, transport to a nearby oil reservoir, and injection for enhanced oil recovery. The case documents how even a small project can produce significant volumes of new oil, substantial profits for oil producers, significant tax revenues for the State of Texas and local governments, create new employment, and reduce CO_2 in the atmosphere. The case study concludes that the oil produced from the reservoir can produce a profit after paying for CO_2 capture, transmission, and injection infrastructure. Such a system also has the potential to remove CO_2 from the atmosphere by sequestering large volumes underground.

The combination of energy-related profits driving CO_2 sequestration represents a target of opportunity for Texas. Despite the decline of domestic oil production, Texas remains in the forefront of the world's energy industry, with a high concentration of successful corporations, advanced research facilities, and experienced workers. With a developed carbon capture and storage industry in position, Texas can remain a source of innovation in the oil industry while creating thousands of jobs, expanding private sector benefits, and providing state revenues, while serving the public's interest in preventing the venting of greenhouse gases into the atmosphere.

Introduction

Texas leads the nation in energy production and consumption, which puts it as a state in first place in the production of carbon dioxide (CO_2).[1] As greenhouse gas limits are developed across the world as part of the Kyoto Agreement, emissions trading mechanisms in place in Europe and the Northeastern United States may cause money to flow to areas where carbon can be effectively sequestered. Texas has the potential to develop systems to capture industrial CO_2 emissions to enhance oil recovery (EOR) and store large volumes underground.

For decades, Texas oil companies have used naturally occurring CO_2 piped from sources in Colorado to inject into existing oil wells in West Texas to recover deep stores of oil. Due to the maturity of Texas oil reserves, oil production in other areas of Texas has begun to decline, whereas states like Mississippi have increased production through investment in CO_2 EOR. CO_2 from natural deposits is in limited supply and is known to be insufficient to satisfy demand in West Texas. If Texas wants to tap the more than 5.7 billion barrels of oil recoverable by CO_2 EOR outside of West Texas, corporations could develop projects to capture man-made CO_2 and build the infrastructure necessary to perform EOR.[2] Such EOR projects could enhance significantly Texas' economic performance.

There is broad scientific consensus among the world's climatologists that anthropocentric greenhouse gas (GHG) emissions are leading to a warming of the earth.[3] Climate models indicate that increased global surface and ocean temperatures could contribute to increased storm activity and severity, higher sea elevations, flooding of coastal areas, droughts, and displaced agriculture, among other effects.[4] The potential threats presented by global warming have fueled interest in mitigating GHG emissions, particularly CO_2.[5]

Since the early 1800s, CO_2 concentrations in the atmosphere have increased more than 33 percent, and the rate is accelerating steadily.[6] In 2003, across the world 6.8 billion tons of fossil fuel-based carbon was burned, producing approximately 25 billion metric tons (Bmt) of CO_2.[7] The U.S. share amounted to 5.8 Bmt CO_2, just under a quarter of the world total.[8] Texas contributed roughly 0.7 Bmt CO_2, or 12 percent of the U.S. total.[9]

While CO_2 is considered a residual of burning carbon, markets for the gas can turn a waste stream into a valuable production input for petroleum extraction.[10] The process of enhanced oil recovery takes excess CO_2, compresses it and floods it through wells into mature oil fields, saturating the field and oil and facilitating new production. The expected incremental oil production is on the order of an additional 10 percent of the original oil from the field; in some cases the increased production yield has been as much as 20 percent.[11]

Most CO_2 currently being used in EOR in Texas' Permian Basin is harvested from high-purity, naturally-occurring deposits and pumped via pipeline into oil production wells. A smaller number of oil fields use waste-stream CO_2 from industrial sources such as fertilizer plants and natural gas processing facilities. These existing projects provide data on CO_2 EOR costs and regulations.[12] CO_2 from point sources in the Texas' Gulf Coast could provide a reliable, steady stream of CO_2 for use in EOR. Any enhanced oil recovery project could provide billions of gallons of oil to American markets, profits to the firms that produce the oil, new employment, and hundreds of millions of dollars in tax revenue for the State of Texas. With the development of pipelines to transport CO_2 from point sources for use in EOR, the same infrastructure needed to capture and transport CO_2 for EOR would allow for permanent sequestration of CO_2 in geological formations. Such CO_2 mitigation could become valuable to Texas when international CO_2 trading links to Texas, or in the event that state or national carbon trading programs are created.

The science and engineering aspects of CO_2 sequestration and enhanced oil recovery are well understood. Texas has all the elements needed for development of a successful integrated EOR and CO_2 sequestration industry. Texas is in a unique position as the largest state producer of CO_2, with the largest state potential for CO_2-based EOR production in the country and an enormous capacity for geologic sequestration with the co-benefit of enhanced oil recovery. This report outlines a Texas-specific plan to help focus private investment in profitable options as well as help identify and overcome potential barriers to private investment and ensure Texas remains the leader in this field.

Notes

[1] USEPA, *State GHG Inventories.* Online. Available: http://yosemite.epa.gov/oar%5Cglobalwarming.nsf/content/EmissionsStateGHGInventories.html#TX. Accessed: April 17, 2006.

[2] Bureau of Economic Geology, The University of Texas at Austin, *Technical Summary: Optimal Geological Environments for Carbon Dioxide Disposal in Brine Formations (Saline Aquifers) in the United States* (August 1999, pp. 39-41). Online. Available: http://www.beg.utexas.edu/environqlty/abndnhydrores/co2text.pdf. Accessed: October 27, 2005.

[3] Sandia National Laboratories, *Energy and National Security,* Conference Report (2003). Online. Available: http://www.sandia.gov. Accessed: September 3, 2005.

[4] Ibid.

[5] Ibid.

[6] Dale Simbeck, "CO_2 Capture Economics," Pew Center on Global Climate Change and the National Commission on Energy Policy, Contributing Paper from workshop proceedings, "The 10-50 Solution: Technologies and Policies for a Low-Carbon Future," 2005.

[7] Ibid.

[8] Ibid.

[9] U.S. Department of Energy, Energy Information Administration, *World Carbon Dioxide Emissions from the Consumption and Flaring of Fossil Fuels,* International Energy Annual 2003. Online. Available: http://www.eia.doe.gov/emeu/iea/carbon.html. Accessed: September 3, 2005.

[10] Class presentation by Ian Duncan, Bureau of Economic Geology, The University of Texas at Austin, "Texas Energy Policy," at the Lyndon B. Johnson School of Public Affairs, Austin, Texas, November 4, 2005.

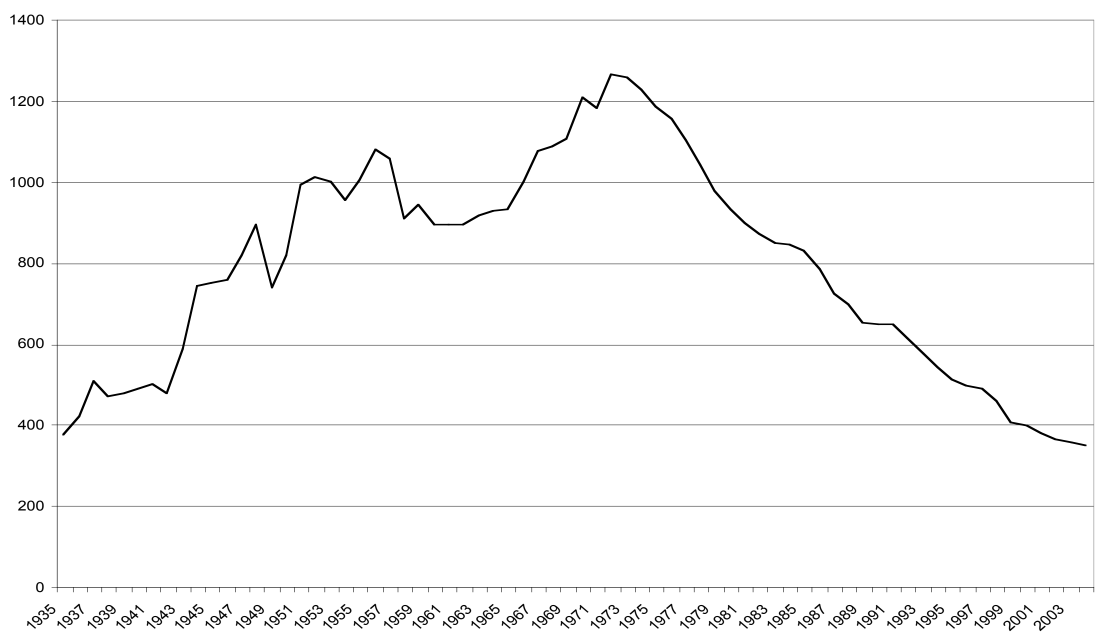
[11] Ibid.

[12] Ibid.

Chapter 1. Enhanced Oil Recovery

Since the discovery of oil at Spindletop in 1901, oil production has played an important role in the economy of Texas as an engine for economic development and a source of tax revenues garnered from production.[1] As technology improved and additional fields were discovered, Texas oil production increased for almost three-quarters of a century, peaking in 1972 at 1.26 billion barrels a year.[2] Since 1972, however, oil production has declined steadily due to gradual exhaustion of oil recovered through traditional primary and secondary methods (see Figure 1.1).[3] By 2004, oil production had slipped 72 percent to 349 million barrels.[4] Declining oil production translates to declining oil industry contributions to the Texas economy and represents a lost revenue stream to the state. While a significant discovery of new Texas reservoirs is unlikely, the declining production trend could be slowed by technological improvements, such as the adoption of enhanced oil recovery (EOR) methods in the Gulf Coast region and in East Texas.

Figure 1.1
Annual Oil Production in Texas (in Millions of Barrels)



Adapted from: Railroad Commission of Texas, *Oil Production and Well Counts (1935-2003)*. Online. Available: http://www.rrc.state.tx.us/divisions/og/information-data/stats/ogisopwc.html. Accessed: November 26, 2005.

Carbon dioxide can be used as a liquid solvent to enhance oil recovery. During the initial or primary stage of recovery, the natural pressure in an oil reservoir, aided by pumps, allows the removal of about 10 percent of the oil in place.[5] When primary recovery is exhausted, secondary recovery techniques assist in the extraction of additional oil. The secondary phase consists of injecting pressurized water into the reservoir to displace oil and force it to the surface. Secondary techniques allow for total oil in-place recovery of between 20 and 40 percent.[6] During a tertiary stage of recovery, pressurized CO_2 can be injected into the reservoir to displace and extract additional oil, a method known as CO_2 enhanced oil recovery. EOR techniques can further boost total recovery to about 30 to 60 percent.[7] The marginal incremental production from CO_2 EOR can vary between 1 and 29 percent of oil in place (OIP), with a median estimate on the order of 10 percent OIP.[8]

EOR is a well-developed technology and has been used worldwide. CO_2 has been injected into depleted oilfields to enhance oil recovery in the Permian Basin in West Texas since 1972, where oil companies have paid to pipe CO_2 from natural reservoirs in the surrounding region.[9] Nationwide in 1998, 43 million metric tons of CO_2 were used for EOR at 67 sites.[10] Using these same techniques, CO_2 can be piped from anthropogenic (human origin) sources in the Gulf Coast region and East Texas to neighboring oilfields. If there were ever to be sufficiently high oil prices and sufficiently low CO_2 costs, revenues from EOR ventures could pay for the costs of carbon capture, creating additional revenue streams for oil extraction companies, carbon capturing entities, and even the State of Texas through taxation and royalties.

Enhanced Oil Recovery in Texas

The Gulf Coast contains a combination of factors that provide opportunities for effective EOR. Oil reservoirs that could benefit from CO_2 injection are located near potential CO_2 sources. There are an abundance of CO_2 emitting sources in the region, such as electricity generation stations, refineries, and industrial sites. For example, in one seven-county area in the Texas Gulf Coast region, 32 million tons of CO_2 were emitted in 1996 from power plants alone. More than 100 chemical plants and refineries emit additional CO_2 in the area.[11] Other anthropogenic CO_2 sources, such as natural gas-fired power plants and chemical plants, could provide CO_2 to augment oil production from other reservoirs.

EOR using CO_2 can increase the potential for oil production in Texas, as an estimated 80 percent of all oilfields could benefit from EOR.[12] The US Department of Energy (DOE) identified 16 billion barrels of onshore stranded oil in the Gulf Coast region (including parts of Texas, Louisiana, and Mississippi) that could be recovered by CO_2 EOR.[13] Such a resource represents almost nine times the total U.S. oil production in 2005.[14] An estimated 1,700 such reservoirs are found in Texas within 90 miles of major coal-fired power plants, and from these reservoirs an estimated 8 billion barrels of oil could be extracted via CO_2 EOR.[15] The Bureau of Economic Geology (BEG), a research facility at The University of Texas at Austin, estimates that EOR could increase oil production in the Texas Gulf Coast alone by at least 5.7 billion barrels.[16] Extensive enhanced oil recovery possibilities also exist in East Texas.[17]

Enhanced oil recovery represents a step towards CO_2 sequestration because the EOR provides a rationale for injecting CO_2 into old wells to aid in harvesting oil that could not be obtained by traditional methods. After recovering the available oil from a site, much of the same infrastructure can be used for carbon storage. Using EOR as an initial approach to geologic sequestration would create three types of infrastructure for sequestration: carbon removal and concentration technologies, CO_2 pipelines and compressors, and CO_2 injection methods. If and when national carbon emission policies tighten or sufficient capture or trading incentives make non-EOR sequestration profitable, Texas could sustain an industry that stores CO_2 underground. When a depleted oil field is filled to capacity with CO_2, deeper injection wells can be drilled in the same area, allowing the continued use of the carbon capture and pipeline structure already in place to store carbon in greater quantities in the vast sandstone and brine formations below the ground.

Economic Considerations

The incremental installation costs of EOR itself (once the CO_2 is captured and transported to the site) are limited to the well-drilling costs. Drilling costs for injection wells have been estimated at $840 per meter, or about $1,536,000 for a well of 6,000 feet.[18] The operating costs of EOR include pumping, separating the oil from the CO_2, and then recompressing and recycling the CO_2. These costs, along with basic monitoring costs, have been estimated on a per barrel basis. The costs differ in accordance to well depth as follows: for wells 800-1,500 meters deep, costs are estimated to be around $3.89 per barrel. Wells 1,500-2,500 meters deep are estimated to cost about $4.87 per barrel, and wells deeper than 2,500 meters are estimated to cost $5.83 per barrel.[19] Costs of CO_2 capture and transport vary by source and distance. One source estimates the cost of capturing CO_2 from electricity generating plants in Texas and transporting it through 100 miles of pipeline to a reservoir at $23 to $60 per ton of CO_2.[20] The costs and methods of CO_2 capture and transport are discussed in greater detail elsewhere in this report.

One analyst has estimated that EOR using anthropogenic CO_2 would be profitable if oil prices were over $20 per barrel and CO_2 prices were less than $34 per ton.[21] Estimated average costs of capture and transportation lie between $22 and $28 per ton.[22] Oil prices have climbed significantly above the $20 range. The most recent contracted oil price average for the U.S. as of this writing was $58.82.[23] Oil prices have demonstrated volatile tendencies, but they seem unlikely to drop below $20 in the foreseeable future. The cost of CO_2 in areas distant from natural CO_2 reservoirs will depend on capture and transport prices, discussed elsewhere in this report.

Using an economic model employed by the Texas Comptroller, the Railroad Commission of Texas estimated the potential profits from producing the $5.7 billion barrels of oil projected by BEG as recoverable in Texas outside the Permian Basin. At $30 per barrel, 5.7 billion barrels would have a wellhead value of $171 billion. The model predicts that this production would generate $26 billion in taxes, $498 billion in economic activity, and 3.3 million jobs.[24] If National Energy Technology Laboratory estimates that a comprehensive Gulf Coast EOR project would have a lifetime of about 25 years are accurate,[25] this production would generate an average of $1.04 billion in state taxes, 132,000 jobs, and $19.92 billion in economic activity per year.[26] These figures may be perceived as unreasonably high because they are based on such a large quantity of oil. By way of comparison, total U.S. crude production in 2004 was less than 3.9 billion barrels.[27] The case study in Chapter 7 documents the costs and benefits from one specific project to capture CO_2 from a refinery waste stream and inject in an oil reservoir for EOR 25 miles away.

In addition to immediate economic benefits, extensive EOR would create an infrastructure that could be used to sequester CO_2 underground permanently, thus offering a partial solution to the challenge of greenhouse gas accumulation in the atmosphere. Some of the policy elements needed to assure the sustainability of sequestration are discussed in the case study as well.

Notes

[1] Arthur M. Johnson, "The Early Texas Oil Industry: Pipelines and the Birth of an Integrated Oil Industry, 1901-1911," *Journal of Southern History*, vol. 32, no. 4 (November 1966), p. 519. Online. Available: http://www.jstor.org. Accessed: December 19, 2005.

[2] Railroad Commission of Texas, *Oil Production and Well Counts (1935-2003).* Online. Available: http://www.rrc.state.tx.us/divisions/og/information-data/stats/ogisopwc.html. Accessed: November 26, 2005.

[3] Richard A. Kerr, "The Next Oil Crisis Looms Large-and Perhaps Close," *Science*, Vol. 281, No. 5380 (August 21, 1998), pp. 1128-1130. Online. Available: http://www.sciencemag.org. Accessed: December 19, 2005.

[4] Railroad Commission of Texas, *Oil Production and Well Counts* (online).

[5] U.S. Department of Energy (DOE), Office of Fossil Energy, *Enhanced Oil Recovery/ CO_2 Injection* (updated July 6, 2005). Online. Available: http://www.fe.doe.gov/programs/oilgas/eor/. Accessed: November 25, 2005.

[6] Ibid.

[7] Ibid.

[8] Class presentation by Larry Lake, Professor, Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, at the Lyndon B. Johnson School of Public Affairs, Austin, Texas, November 2005.

[9] DOE*, Enhanced Oil Recovery* (online).

[10] Howard J. Herzog, "What Future for Carbon Capture and Sequestration," *Environmental Science and Technology,* vol. 37, no. 7 (April 1 2001), p. 150A. Online. Available: http://pubs3.acs.org. Accessed: December 19, 2005.

[11] S. D. Hovorka, C. Doughty, P.R. Knox, C.T. Green, K. Pruess, and S.M. Benson., *Evaluation of Brine-Bearing Sand of the Frio Formation, Upper Texas Gulf Coast for Geological Sequestration of CO_2* (p. 2). Online. Available: http://www.beg.utexas.edu/environqlty/pdfs/hovorka-netl01.pdf. Accessed: October 27, 2005.

[12] Sally M. Benson, "Carbon Dioxide Capture and Storage in Underground Geologic Formations," paper presented at the conference "The 10-50 Solution: Technologies and Policies for a Low-Carbon Future," at the Pew Center on Global Climate Change and the National Commission on Energy Policy, p. 5. Online. Available: http://wwwpewclimate.org. Accessed: December 19, 2005.

[13] DOE, *Enhanced Oil Recovery* (online).

[14] U.S. Department of Energy, Energy Information Administration, *Crude Oil Production* (2005). Online. Available: http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm. Accessed: April 17, 2006.

[15]Mark H. Holtz, Peter K. Nance, and Robert J. Finley, "Reduction of Greenhouse Gas Emissions," *Environmental Geosciences,* vol. 8, no. 3 (September 2001), pp. 196-197. Online. Available: http://weblinks1.epnet.com. Accessed: December 19, 2005.

[16] Michael L. Williams, *RRC Commissioner Williams Hosts* CO_2 *Reduction Conference: Focus on Capturing* CO_2 *from Industrial Facilities for Use in Oil Production* (April 4, 2005). Online. Available: http://www.rrc.state.tx.us/news-releases/2005/050404mlw.html. Accessed: November 26, 2005.

[17] Bureau of Economic Geology, The University of Texas at Austin, *Technical Summary: Optimal Geological Environments for Carbon Dioxide Disposal in Brine Formations (Saline Aquifers) in the United States* (August 1999, pp. 39-41). Online. Available: http://www.beg.utexas.edu/environqlty/abndnhydrores/co2text.pdf. Accessed: October 27, 2005.

[18] Kay Damen, Andre Faaij, Frank van Bergen, John Gale, and Erik Lysen., "Identification of Early Opportunities for CO_2 Sequestration—Worldwide Screening for CO_2-EOR and CO_2-ECBM Projects," *Energy,* vol. 30, no. 10 (July 2005), p. 1945. Online. Available: http://www.sciencedirect.com. Accessed: December 19, 2005.

[19] Ibid.

[20] Mark H. Holtz, Peter K. Nance, and Robert J. Finley, *Reduction of Greenhouse Gas Emissions through Underground* CO_2 *Sequestration in Texas Oil and Gas Reservoirs* (August 1999, p. 49). Online. Available: http://www.beg.utexas.edu/environqlty/abndnhydrores/co2text.pdf. Accessed: November 28, 2005.

[21] Holtz, Nance, and Finley, "Reduction of Greenhouse Gas Emissions," p. 197.

[22] Ibid.

[23] U.S. Department of Energy, Energy Information Administration, *This Week in Petroleum* (April 18, 2006). Online. Available: http://tonto.eia.doe.gov/oog/info/twip/twip_crude.html. Accessed: April 18, 2006.

[24] Williams, *RRC Commissioner Williams Hosts* CO_2 *Reduction Conference* (online).

[25] U.S. Department of Energy, National Energy Technology Laboratory, *Regional Carbon Sequestration Partnerships Review Meeting.* Online. Available: http://www.netl.doe.gov/publications/proceedings/05/RCSP/pdf/PhaseI-SECARB.pdf. Accessed: December 18, 2005.

[26] Williams, *RRC Commissioner Williams Hosts* CO_2 *Reduction Conference* (online).

[27] U.S. Department of Energy, Energy Information Administration, *Crude Oil Production and Crude Oil Well Productivity, 1954-2004*. Online. Available: http://www.eia.doe.gov. Accessed: March 31, 2006.

Chapter 2. Sequestration

A series of scientific reports have identified carbon dioxide (CO_2) as a greenhouse gas associated with increasing global temperatures.[1,2] The international community has responded by planning reductions of CO_2 releases by developed nations and the capture of CO_2 to remove it from the atmosphere.[3] This chapter describes and explores one of the methods for sequestering CO_2 from the atmosphere, by pumping and storing it deep underground.

CO_2 emissions from human, or anthropogenic, sources have increased during the period following the industrial revolution, as illustrated by atmospheric CO_2 measured from ice core samples and direct atmospheric observation. Atmospheric CO_2 in the mid-1800s has been estimated at 287 parts per million (ppm). The current concentration is about 382 ppm. If emissions continue at the current rate, CO_2 concentrations in the atmosphere are predicted to reach 573 ppm by the year 2100.[4]

Various scientific reports identify CO_2 as a greenhouse gas that tends to trap heat in the atmosphere that otherwise would escape, thus contributing to global warming trends.[5] Anthropogenic CO_2 has been identified as one of the major contributing agents to this warming, accounting for 60 percent of the known causes of global warming, according to one report.[6] Another report claims that the global rate of climate change during the next century is expected to be greater than at any time during the last ten millennia.[7] A third report cites current CO_2 induced climate changes, including increased flooding, glacial and permafrost melt and sea level rise.[8] With an atmospheric lifetime of 50-200 years, CO_2 emissions could have a long-term warming effect; CO_2 emitted today may contribute to greenhouse warming for the next 50-200 years.[9]

International organizations have proposed a number of policy alternatives to slow greenhouse gas accumulation and subsequent global warming, such as alternative energy sources, more efficient fossil fuel technologies, and carbon sequestration. This chapter focuses on underground carbon storage methods and the possibilities for sequestration in Texas.

Sequestration Methods

There are three main methods of sequestering carbon from the atmosphere: terrestrial, ocean, and geologic sequestration. Terrestrial sequestration absorbs CO_2 in soils and biomass. Ocean sequestration involves injecting CO_2 deep into the ocean. Geologic sequestration involves storing CO_2 in sedimentary structures underground. Although this section provides a brief overview of terrestrial and ocean options, the focus is geologic sequestration.

Terrestrial sequestration seeks to take CO_2 out of the atmosphere by fixing it in plants. Plants absorb atmospheric carbon through photosynthesis and lock it in the soil. Researchers have provided many suggestions for increasing agricultural plants' rate of conversion of atmospheric CO_2 to soil carbon, such as low-impact tilling techniques that reduce the amount of organic material removed from the soil.[10] Much of the carbon captured by agricultural plants is consumed in the resulting food products. One study documented that maize sequesters carbon in soil at a rate of 184 grams per square meter per year when cultivated with low impact tilling methods, even assuming full consumption.[11] Another study suggests, however, that nearly all CO_2 captured by agricultural sequestration will eventually escape to the atmosphere.[12]

Because forest vegetation effectively fixes carbon, expansion of forested land is another sequestration alternative. Recent research has improved the techniques used to measure terrestrial sequestration.[13] A recent study cautions that estimates of the capacity of forests to store carbon may be overly optimistic because forests tend to occupy areas with low soil nutrients and moisture, which hinder their ability to fix carbon.[14] Another study indicates that forest sequestration efforts may offset carbon released by land use and biomass extraction, but is unlikely to reduce atmospheric CO_2 levels.[15]

The world's oceans act as a natural sink, absorbing atmospheric CO_2 and potentially converting it to a carbonate form that would remove it from atmospheric circulation. One sequestration option is to inject liquefied CO_2 deep into the ocean either by ship or via pipelines along the ocean floor. This option faces technical challenges as well as potential environmental impacts. The injection of CO_2 could change the acid-base balance in the area near the injection source, and many marine organisms are sensitive to such changes.[16] Questions have also been raised about the permanence of ocean sequestration. One study estimated that on the order of 85 percent of the CO_2 pumped underwater would remain permanently sequestered.[17] A less optimistic study suggests that all CO_2 injected into the ocean may leak back into the atmosphere over a period of 300 years.[18]

Geologic sequestration involves the transport of CO_2 from point sources and injection underground in oil and gas fields, coal beds, sandstone sediments, or saline formations. All four formations are abundant in Texas. This study focuses on oilfields and saline formations, which often are present at the same location at different depths. Vast brine formations underlie many of the partially depleted oilfields of the Gulf Coast region.[19]

Geologic Sequestration in Texas

The Gulf Coast contains potential CO_2 sources and storage sites located close to one another, a combination of factors that provide opportunities for effective CO_2 sequestration. Appropriate potential storage sites are plentiful along the Gulf, such as the Frio and Jasper brine formations, which extend along the entire Texas Gulf Coast at depths between 800 and 2,400 meters. In addition, the porous sediment is thick, more than 500 meters,[20] so CO_2 pumped underground may stay there. An estimated 8 billion barrels of oil could be recovered in Texas via CO_2 EOR.[21] There are an abundance of CO_2 emitting sources in the region, such as electricity generation stations, refineries, and industrial sites. For example, in one seven-county area in the Texas Gulf Coast region, 32 million tons of CO_2 were emitted in 1996 from power plants alone. More than 100 chemical plants and refineries emit additional CO_2 in the area.[22]

Enhanced oil recovery projects using captured CO_2 would provide the technical experience and infrastructure needed to engage in long-term carbon sequestration. After recovering the available oil from a site, much of the same infrastructure can be used for larger scale carbon storage. When the depleted oil field is filled to capacity with CO_2, a deeper injection well can be drilled in the same area, allowing the continued use of the carbon capture and pipeline structure already in place. Carbon can then be stored in greater quantities in the vast sandstone and brine formations below. The Frio and Jasper brine formations in the Gulf Coast region may be suited for large scale sequestration as advocated by the Gulf Coast Carbon Center (GCCC) Frio Brine Project that has tested sequestration in the Frio formation. The experiment demonstrated that CO_2 can be stored securely and predictably in the region.[23]

Safety issues related to carbon sequestration are well understood and sequestered CO_2 poses only limited risks. Carbon should be stored in secure formations below the water table to prevent the contamination of water resources. Care should be taken in the selection and maintenance of injection sites, so as to limit the dangers of sudden leakage. Carbon dioxide is not toxic unless levels exceed 10,000 parts per million or 1 percent of the total air volume; breathing lower concentrations causes no harm to humans.[24] A sudden, massive leak in an inhabited area could pose risks because CO_2 is heavier than air, so it would tend to accumulate near ground level, placing persons in the immediate vicinity in danger of suffocation.[25] This concern is relatively minor because injection wells (which comprise the most likely leakage points) are rarely sited in residential areas.

Of practical concern is the issue of permanence: will injected CO_2 stay underground? For carbon capture and sequestration to be effective, CO_2 must remain underground. The Bureau of Economic Geology (BEG) at The University of Texas at Austin has conducted modeling to simulate the flow of CO_2 over time. Given a 30 percent porosity level for the sediment in which the carbon is injected, BEG predicted that the CO_2 would migrate about 200 meters from the injection well and remain there, assuming no change in geologic conditions.[26] As oil and gas reservoirs have demonstrated an ability to contain pressurized fluids over long periods of geologic time, it is reasonable to test whether pressurized liquid CO_2 can be sequestered in underground structures. Care must be taken, however, to secure old wells that were drilled into the reservoir, the locations of which are not always well-documented. Some formations will require detailed geologic analysis. The porous sedimentary layer into which the CO_2 is injected should be overlaid by an impermeable rock layer. The presence of faults or other potential breeches could compromise permanence. Because CO_2 is buoyant in brine, it may migrate from the injection point if the overlying layer is not level. As noted above, CO_2 changes the acid-base (pH) balance of saltwater, making it more acidic, so well seals should be made resistant to this increased acidity to ensure permanent sequestration.

Depending on the salinity, temperature, and pressure in a saline formation, much of the injected CO_2 may dissolve into the brine.[27] As the brine becomes saturated with CO_2,

CO_2 droplets become trapped among water pores through a process called capillary trapping.[28] Geologists have argued that most of the carbon will become embedded in the rock over time.[29] Thus, with time, the importance of monitoring and the integrity of the sealing mechanisms may decline.

Estimates of the capacity of saltwater formations to absorb CO_2 lie between 300 and 10,000 billion tons worldwide.[30] Sequestration efforts in Texas could serve as a model for projects in similar formations elsewhere.

Economic Considerations

Costs of CO_2 capture vary by the source. Sequestered CO_2 from a power plant waste stream are estimated to be between $30 and $70 per ton. Transport costs are estimated at $1 to $3 per ton for every 100 km of pipeline. The cost of sequestration without EOR is estimated at between $1 and $15 per ton.[31]

Under some conditions, carbon sequestration can be cost-effective when compared to its release as a gas. For example, under a sufficiently high carbon emission tax, it would be cheaper for emitting companies to sequester carbon than to emit and pay the tax. Norway's $50 per ton tax on carbon emissions prompted Statoil to sequester carbon emitted from its facility on the Sleipner field in a geologic formation under the North Sea. The company spent less to sequester the carbon than it would have paid as a carbon tax, recovering its investment in one and a half years.[32]

Sequestration could also be profitable under some carbon trading systems, such as the one proposed in the Kyoto Protocol. Under such a system, firms that discharge CO_2 in areas that are less suited for sequestration could pay emitters in areas better suited to store carbon for them, thus reducing the amount of emitted carbon for which they are responsible. One study has estimated that trading CO_2 is an economically attractive alternative to country-specific solutions, reducing the projected costs of Kyoto compliance from $120 billion to $11-54 billion.[33] Texas, with abundant potential storage sites in close proximity to emission sources, would be a plausible beneficiary of such a trading program, especially if the capture and transportation infrastructure were already in place due to EOR ventures. Using EOR as a first step to geologic sequestration will ensure that the infrastructure for sequestration is in place if and when national carbon emission policies tighten or sufficient capture or trading incentives make non-EOR sequestration profitable.

When evaluating the prospects of sequestration beyond EOR, it is important to consider public attitudes towards global warming and sequestration, as well as their willingness to pay for capture and storage. A nationwide survey conducted by MIT and Cambridge researchers explored the attitudes of Americans towards global warming. Environmental concerns ranked 13th among the 22 choices given respondents. Global warming ranked sixth among environmental concerns. The study found that only 4 percent of respondents had heard of carbon capture and sequestration.[34] Participants were asked how much they would be willing to pay per month to "solve global warming." The average response was about \$6.50. These results point to the need for public education to accompany any publicly funded sequestration agenda.

Economics profoundly affect the feasibility of CO_2 sequestration. The most costly and problematic element of the sequestration process is the capture of CO_2 from power plants and industry, as explored in the next chapter.

Notes

[1] John Houghton, *Global Warming: The Complete Briefing*, 2nd ed. (Cambridge: Cambridge University Press, 1997). Online. Available: http://books.google.com. Accessed: December 19, 2005.

[2] Stefan Rahmstorf and Andrey Ganopolski, “Long-Term Global Warming Scenarios Computed with an Efficient Coupled Climate Model,” *Climatic Change,* vol. 43, no. 2 (October 1999), pp. 353-367. Online. Available: http://www.springerlink.com. Accessed: December 19, 2005.

[3] United Nations Framework Convention on Climate Change, *Kyoto Protocol to the United Nations Framework Convention on Climate Change.* Online. Available: http://unfccc.int/resource/docs/convkp/kpeng.html. Accessed: November 12, 2005.

[4] Pierre Friedlingstein and Susan Solomon, “Contributions of Past and Present Human Generations to Committed Warming Caused by Carbon Dioxide,” *Proceedings of the National Academy of Sciences of the United States of America,* vol. 102, no. 31 (August 2, 2005), pp. 10834-10835. Online. Available: http://www.pnas.org. Accessed: December 19, 2005.

[5] Houghton, *Global Warming*, p. 22.

[6] Friedlingstein and Solomon, *Contributions of Past and Present*, p. 10832.

[7] U.S. Department of Energy, *The Climate Change Action Plan* (October 1993). Online. Available: http://gcrio.gcrio.org/USCCAP/toc.html. Accessed: October 25, 2005.

[8] United Nations Environment Programme, *Climate Change.* Online. Available: http://hq.unep.org/themes/climatechange. Accessed: October 25, 2005.

[9] Curt M. White, Brian R. Strazisar, Evan J. Granite, James S. Hoffman, and Henry W. Pennline, “Separation and Capture of CO_2 from Large Stationary Sources and Sequestration in Geological Formations—Coalbeds and Deep Saline Aquifers,” *Journal of the Air and Waste Management Association,* vol. 53, no. 6 (June 2003), p. 646. Online. Available: http://weblinks3.epnet.com. Accessed: December 19, 2005.

[10] U.M Sainju, W.F. Whitehead, and B.P Singh, “Carbon Accumulation in Cotton, Sorghum, and Underlying Soil as Influenced by Tillage, Cover Crops, and Nitrogen Fertilization,” *Plant and Soil,* vol. 273, no. 1-2 (June 2005), pp. 219-234. Online. Available: http://www.springerlink.com. Accessed: December 19, 2005.

[11] Steven E. Hollinger, Carl J. Bernacchi, and Tilden P. Meyers, “Carbon Budget of Mature No-till Ecosystem in North Central Region of the United States,” *Agricultural and Forest Meteorology,* vol. 130, no. 1-2 (May 24, 2005), pp. 59-61. Online. Available: http://www.sciencedirect.com. Accessed: December 19, 2005.

[12] Gregg Marland, Kristy Fruit, and Roger Sedjo, “Accounting for Sequestered Carbon: The Question of Permanence,” *Environmental Science and Policy,* vol. 4, no. 6 (December 2001), pp. 259-268. Online. Available: http://sciencedirect.com. Accessed: December 19, 2005.

[13] Sandra Brown, Timothy Pearson, Dana Slaymaker, Stephen Ambagis, Nathan Moore, Darrell Novelo, and Wilber Sabido, “Creating a Virtual Tropical Forest from Three-dimensional Aerial Imagery to Estimate Carbon Stocks,” *Ecological Applications,* vol. 15, no. 3 (June 2005), pp. 1083-1095. Online. Available: http://www.esajournals.org. Accessed: December 19, 2005.

[14] Ram Oren, David S. Ellsworth, Kurt H. Johnson, Nathan Phillips, Brent E. Ewers, Chris Maier, Karina V. R. Schafer, Heather McCarthy, George Hendrey, Steven G. McNulty and Gabriel G. Katul, “Soil Fertility Limits Carbon Sequestration by Forest Ecosystems in a CO_2-Enriched Atmosphere,” *Nature*, vol. 411 (May 24, 2001), pp. 469-472. Online. Available: http://www.nature.com. Accessed: December 19, 2005.

[15] D.S. Schimel, J.I. House, P. Bousquet, P. Ciais, P. Peylin, B.H. Braswell, M.J. Apps, D. Baker, J. Canadell, W. Cramer, A.S. Denning, C.B. Field, P. Friedlingstein, C. Goodale, M. Heinmann, R.A. Houghton, J.M. Melillo, B. Moore III, D. Murdiyarso, I. Noble, S.W. Pacala, I.C. Prentice, M.R. Raupach, P.J. Rayner, R.J. Scholes, W.L. Steffen, and C. Wirth, “Recent Patterns and Mechanisms of Carbon Exchange by Terrestrial Ecosystems,” *Nature,* vol. 414, no. 6860 (November 2001), pp. 169-172. Online. Available: http://www.nature.com. Accessed: December 19, 2005.

[16] Brad A. Seibel and Patrick J. Walsh, “Potential Impacts of CO_2 Injection on Deep-Sea Biota,” *Science,* vol. 294. no. 5541 (October 12, 2001). Online. Available: http://www.sciencemag.org. Accessed: December 19, 2005.

[17] L.D. Danny Harvey, “Impact of Deep-ocean Carbon Sequestration on Atmospheric CO_2 and on Surface-water Chemistry,” *Geophysical Research Letters,* vol. 30, no. 5 (March 2003), pp. 1237-1240. Online. Available: http://www.agu.org. Accessed: December 19, 2005.

[18] Howard Herzog, Ken Caldeira, and John Reilly, “An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage,” *Climatic Change,* vol. 59, no. 3 (August 2003), p. 302. Online. Available: http://www.springerlink.com. Accessed: December 19, 2005.

[19] Bureau of Economic Geology, The University of Texas at Austin, *Technical Summary: Optimal Geological Environments for Carbon Dioxide Disposal in Brine Formations (Saline Aquifers) in the United States* (pp. 39-41). Online. Available: http://www.beg.utexas.edu/environqlty/co2seq/finalreport.pdf. Accessed: October 27, 2005.

[20] Ibid.

[21] Mark H. Holtz, Peter K. Nance, and Robert J. Finley, *Reduction of Greenhouse Gas Emissions through Underground CO_2 Sequestration in Texas Oil and Gas Reservoirs* (August 1999, p. iii). Online. Available: http://www.beg.utexas.edu/environqlty/abndnhydrores/co2text.pdf. Accessed: October 27, 2005.

[22] Susan D. Hovorka, C.A. Doughty, Paul R. Knox, C.T. Green, K. Pruess, and S.M. Benson, *Evaluation of Brine-Bearing Sand of the Frio Formation, Upper Texas Gulf Coast for Geological Sequestration of* CO_2 (p. 2). Online. Available: http://www.beg.utexas.edu/environqlty/pdfs/hovorka-netl01.pdf. Accessed: October 27, 2005.

[23] Paul R. Knox, Jeffery G. Paine, and Susan D. Hovorka, *Optimal Geological Environments for Carbon Dioxide Disposal in Brine Formations (Saline Aquifers) in the United States—Pilot Experiment in the Frio Formation, Houston Area* (April 2003). Online. Available: http://www.beg.utexas.edu/environqlty/co2seq/pubs_presentations/Frio_draftea4_03.pdf. Accessed: October 25, 2005.

[24] Sally M. Benson, "Carbon Dioxide Capture and Storage in Underground Geologic Formations," paper presented at conference "The 10-50 Solution: Technologies and Policies for a Low-Carbon Future," at the Pew Center on Global Climate Change and the National Commission on Energy Policy, p. 9. Online. Available: http://wwwpewclimate.org. Accessed: December 19, 2005.

[25] Howard J. Herzog, "What Future for Carbon Capture and Sequestration," *Environmental Science and Technology,* vol. 37, no. 7 (April 1, 2001), p. 151 A. Online. Available: http://pubs3.acs.org. Accessed: December 19, 2005.

[26] Knox, Paine and Hovorka, *Optimal Geological Environments* (online).

[27] BEG, *Technical Summary*, p. 28

[28] Mark H. Holtz, *Optimization of* CO_2 *Sequestered as a Residual Phase in Brine-Saturated Formations*, Online. Available: http://www.beg.utexas.edu/environqlty/co2seq/pubs_presentations/holtz_poster.pdf. Accessed: October 28, 2005.

[29] W.D. Gunter, E.H. Perkins, and Ian Hutcheon, "Aquifer Disposal of Acid Gases: Modelling of Water-rock Reactions for Trapping of Acid Wastes," *Applied Geochemistry*, vol. 15, no. 8 (September 1, 2000), p. 1090. Online. Available: http://www.sciencedirect.com. Accessed: December 19, 2005.

[30] Benson, "Carbon Dioxide Capture and Storage," p. 8.

[31]Kay Damen, Andre Faaij, Frank van Bergen, John Gale, and Erik Lysen, "Identification of Early Opportunities for CO_2 Sequestration—Worldwide Screening for CO2-EOR and CO2-ECBM Projects," *Energy,* vol. 30, no. 10 (July 2005), p. 1932. Online. Available: http://www.sciencedirect.com. Accessed: December 19, 2005.

[32] Herzog, "What Future for Carbon Capture and Sequestration?" p. 151 A.

[33] Jules Pretty and Andrew Ball, *Agricultural Influences on Carbon Emissions and Sequestration: A Review of Evidence and the Emerging Trading Options*, March 2001. Online. Available: http://www2.essex.ac.uk/ces/ResearchProgrammes/CESOccasionalPapers/CSEQPaperFINAL.pdf. Accessed: October 28, 2005.

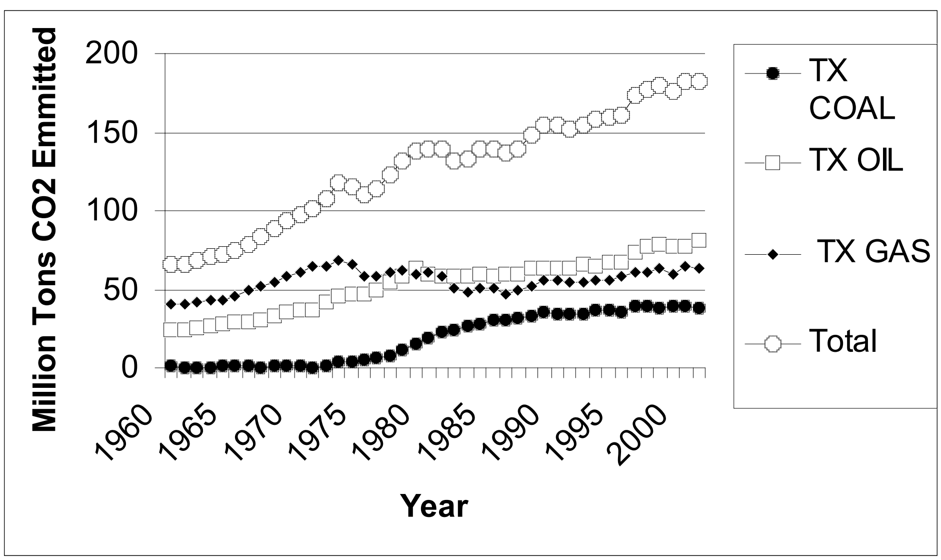
[34] Tom Curry, David M. Reiner, Stephen Ansolabehere, and Howard J. Herzog, *How Aware is the Public of Carbon Capture and Storage?* Online. Available: http://sequestration.mit.edu/pdf/GHGT7_paper137_ Curry.pdf. Accessed: October 28, 2005.

Chapter 3. Carbon Capture

The cost of CO_2 separation from air emissions represents a key variable in any business plan to capture and store CO_2 for EOR or sequestration. If the capture costs of anthropogenic CO_2 are low, a firm can realize a profit using the CO_2 as an EOR resource.

Most CO_2 currently being used in EOR in Alaska and Texas' Permian Basin is harvested from high-purity naturally-occurring deposits and pumped via pipeline into oil production wells. A smaller number of oil fields use waste streams of CO_2 from industrial sources such as fertilizer plants and natural gas processing facilities. Analysts have proposed the use of CO_2 for EOR in the Texas' Gulf Coast region.[1] Estimated CO_2 costs for use in EOR are about $0.65 per million cubic feet (Mcf) from natural domes, $1/Mcf from natural gas processing, and $3/Mcf from power plant flue gas.[2] These estimates do not include the cost of CO_2 pipeline, transportation, or injections. One available CO_2 source is capture from power plants or other point sources. The Texas Gulf Coast region has an abundance of power plants, refineries, and other industries releasing CO_2 in close proximity to mature oil fields (see Figure 3.1).

Figure 3.1
Texas Industrial CO_2 Emissions, 1960-2001



Adapted from: U.S. Department of Energy, Energy Information Administration, *State Energy Data 2001*. Online. Available: http://www.eia.doe.gov/emeu/states/sep_use/total/csv/use_csv.html. Accessed: October 23, 2005.

The Bureau of Economic Geology (BEG) at The University of Texas at Austin estimated that in this region there are 3 billion barrels of oil recoverable within 30 miles of candidate power plants, 6 billion barrels within 60 miles, and 8 billion within 90 miles.[3]

CO_2 from point sources in the Texas' Gulf Coast could provide a reliable, steady stream of CO_2 for use in EOR. Even a single EOR operation could provide millions of gallons of oil to American markets and hundreds of millions of dollars in tax revenue for the State of Texas over decades.

If pipelines were to be developed to transport CO_2 from point sources for use in EOR, the same infrastructure needed to capture and transport CO_2 for EOR would allow for permanent sequestration of CO_2 in geological formations. Such CO_2 mitigation could become valuable to Texas if an international CO_2 trading market were to develop.

There is an abundance of information on the capture of CO_2 from industrial flue gas sources from existing projects and academic analysis. Dozens of projects worldwide have explored the various techniques of capturing carbon and have estimated costs of capture.[4] CO_2 capture technology is a mature technology. While modest reductions in capture costs are attainable in the near-term, dramatic cost reductions will only be achieved through breakthrough technology.[5] There are two main types of CO_2 capture technology: chemical absorption and physical absorption, as discussed below.

Chemical Absorption

Most coal-fired power production facilities burn pulverized coal (PC) and use the resulting heat to produce electricity. These plants emit a flue gas containing much of the burned carbon in the source fuel as CO_2. On average, flue gas is 15 percent CO_2 by volume, largely due to the high concentration of nitrogen in the air used for combustion.[6] Plants that burn natural gas as a fuel source emit a flue gas that is around 7 percent CO_2 by volume.[7]

One carbon capturing technology involves chemical absorption or "scrubbing" of CO_2 from flue gas. The flue gas is bubbled through a solution of water and amines such as monoethanol amine (MEA), diethanolamine (DEA), or methyldiethanolamine (MDEA), and the solution absorbs the CO_2. The rich amines are pumped away and heated, producing regular amines and CO_2 gas. These techniques (see Table 3.1) have been used for decades on a small scale, such as in submarines and spacecraft.[8]

Table 3.1
Basic Formula for Coal Oxidation (Combustion) and CO_2 Capture with MEA

Coal + Air → CO_2 + Flue gas + Heat[a]
$C_{135}H_{96}O_9NS$ (Coal)[a] + $66O_2$ → $135CO_2 + 2H_2O + NO_2 + SO_2$ + Heat
Flue gas + Amine → CO_2-Rich Amine + other products
$135CO_2 + 135(CH_2)_2OHNH_2 + 2H_2O + NO_2 + SO_2$→ $135(CH_2)_2OHNH_2\text{-}CO_2 + 2H_2 + 2H_2O + NO_2 + SO_2$
CO_2-Rich Amine + Heat → CO_2 + Amine[b]
$135(CH_2)_2OHNH_2\text{-}CO_2$ + Heat → $135(CH_2)_2OHNH_2 + 135CO_2$

Adapted from: Formula for coal from Chemical Land 21, *Chemical Land 21.* Online. Available: http://www.chemicalland21.com. Accessed: November 7, 2005. Formula for ethanolamine from Opentopia, *Encyclopedia*. Online. Available: http://encycl.opentopia.com/E/ET/ETH. Accessed: December 1, 2005.

[a] Basic formula for combustion.

[b] This formula describes the process by which the CO_2-rich amine is heated, releasing pure CO_2.

Post-combustion chemical absorption of CO_2 is usually considered for existing boilers using natural gas, which has a relatively low nitrogen oxides (NO_x) and sulfur dioxide (SO_2) content in the flue gas, or in coal fired boilers that have NO_x and SO_2 removal systems. Current water-based amine solvent-capture systems are energy intensive due to the large volume of water needed in these systems to offset the corrosion and air flow problems created by the use of amines. The large steam requirements of the amine stripper used to recycle the amines and release the CO_2, combined with the energy required to compress the CO_2 in order to deliver it by pipeline, can lead to an estimated increase of 25 to 30 percent in the energy requirements compared with similar plants without capture.[9]

Water-based amine solvent-capture systems also can scrub CO_2 from refinery flue gases. Scrubbing CO_2 from the flue gas of a natural gas refinery requires roughly 20 percent increase in capital costs resulting from the need to scrub a larger volume of gas with a 7 percent concentration of CO_2 versus the 15 percent concentration of CO_2 in the PC flue gas.[10]

Some analysts believe that there is a high likelihood of improved CO_2 capture technology and solvents with a corresponding reduction in capture cost.[11] For example, pilot studies have tested new solvent and heat recovery technologies that can reduce the energy requirement of CO_2 capture from PC by around 20 percent, and from natural gas by around 10 percent.[12]

CO_2 capture with current technology costs roughly \$49 per ton of CO_2, though price can fluctuate due to location specific factors, such as the cost of the fuel that is being used to produce heat needed for water-based amine solvent-capture systems.[13,14] Near-term improvements could reduce the incremental cost of chemical absorption carbon capture to \$34 to \$42 per ton of CO_2.[15]

Physical Absorption

Pre-combustion physical absorption of CO_2 is an alternative to chemical absorption from post-combustion flue gas. Gasification systems can use coal, petrol coke, biomass, or even trash as a fuel source. Such so-called Integrated Gasification Combined Cycle (IGCC) systems gasify coal under high temperatures and limited oxygen to produce a synthesis gas. Natural Gas Combined Cycle systems (NGCC) can use similar gasification processes, with natural gas as the feedstock. The resulting synthesis gas, or syngas, consists of carbon monoxide (CO) and hydrogen (H_2). Catalysts and steam are then used to form a mixture of H_2 and CO_2. Later, various solvents can be used under high pressure and low temperature to bond with the CO_2, separating it from the H_2 (see equation below).

$C_{135}H_{96}O_9NS$ (Coal) + $65O_2$ + Heat $\rightarrow$ 135CO + $48H_2$ (Syngas) + NO_2 + SO_2 + Heat

Some analysts believe that gasification systems represent the most cost-effective and sustainable fossil-fuel power production technology for the coming decades.[16] The technology has operated successfully in dozens of sites worldwide, including five plants between 250 and 350 Megawatts (MW).[17] The Energy Policy Act of 2005 created incentives for IGCC plant production.[18] As the technology has the backing of a wide array of supporters, including environmental groups, coal producers, and electric utilities,[19] pre-combustion techniques for carbon-capture may become more prevalent in coming decades. The current incremental cost of capturing carbon through IGCC is around \$26 per ton CO_2, with costs of \$18 per ton CO_2 expected within a decade.[20]

Another form of physical capture of CO_2 involves combusting fossil fuels in pure oxygen instead of air, which is mostly nitrogen by volume. Without the nitrogen, the concentration of CO_2 in the flue gas would be much higher, making capture much more efficient. However, new materials must be developed in order to develop gasifiers that can withstand the extremely high temperatures at which combustion occurs in pure oxygen.[21]

Carbon capture technology has yet to be tested on a large scale, as there remain barriers to implementation at this stage. For example, the capital cost of IGCC or oxygen combustion technology and the high cost of pure oxygen provides a significant economic barrier, as discussed below.

Cost Comparison of Capture: IGCC, NGCC, versus PC

Key cost factors of CO_2 capture are heat rate, energy required for capture, and capital costs of the capture technology. Due to the energy requirements of carbon capture, more CO_2 is produced in generating the same amount of electricity than without carbon capture.[22] Current technology can capture 90 percent of CO_2 from industrial flue gas or syngas.[23] A comparison of the relative costs of CO_2 capture from PC, IGCC, and NGCC illustrates the relevant cost considerations of carbon capture (see Table 3.2).

Table 3.2
Cost Comparison for Capture Plants, 2000

	Energy Requirement, kWh/T CO_2[a]	**Capture Cost, $/T CO_2[b]**
Pulverized Coal	317	49
Integrated Gasification Combined Cycle	194	26
Natural Gas Combined Cycle	354	49

Adapted from: Jeremy David and Howard Herzog, *Cost of Carbon Capture* (Cambridge, Mass.: Massachusetts Institute of Technology, 2000). Online. Available: http://www.netl.doe.gov. Accessed: September 23, 2005.

[a] Calculations are based on plants operating 18 hours per day, a discount rate of 15 percent per year, fuel cost of $1.24/MMBtu for coal and $2.93/MMBtu for natural gas, and CO_2 capture efficiency of 90 percent. Unit represents the energy required in kilowatt hours per ton of CO_2 captured.

[b] Unit represents the cost of capture for one ton of CO_2.

Capital costs associated with PC or IGCC plants fitted with carbon capturing technology are more than double the cost of a NGCC plant with carbon capture. The cost of carbon capture with PC plants are the highest of the three, while capture costs for IGCC and NGCC are similar (see Table 3.1). There can be a large degree of variation in capture cost due to the type of fuel, cost of electricity, and other factors that affect capture costs.[24]

Capturing CO_2 with NGCC requires the greatest amount of energy of the three technologies. This is partly due to the low CO_2 content in the flue gas, which is about 3 percent CO_2 by volume. PC requires slightly less energy due to the high content of CO_2 in the post-combustion flue gas. IGCC has the lowest percent CO_2 energy requirement. This is due to the relatively small volume of concentrated CO_2 under high pressure, which lends itself to more economic carbon capture.[25]

Carbon capture at electric power plants increases the cost of electricity (see Table 3.3).[26] One study estimated that electricity production prices would increase from 5.0 cents per kWh without capture to 6.7 cents per kWh with capture at IGCC plants and from 3.3 to 4.9 cents per kWh at NGCC plants. Pulverized coal plants would increase costs by greater than 3 cent per kWh increase, from 4.4 to 7.7 cents per kWh.[27]

Table 3.3
Cost of Electricity Production with Carbon Capture

	Cost of Electricity Production without Carbon Capture (cents per kWh)	Cost of Electricity Production with Carbon Capture (cents per kWh)
Pulverized Coal	4.4	7.7
Integrated Gasification Combined Cycle	5.0	6.7
Natural Gas Combined Cycle	3.3	4.9

Adapted from: Jeremy David and Howard Herzog, *Cost of Carbon Capture* (Cambridge, Mass.: Massachusetts Institute of Technology, 2000). Online. Available: http://www.netl.doe.gov. Accessed: September 23, 2005.

CO_2 capture cost calculations sometimes reflect peak-time electricity prices.[28] However, CO_2 scrubbing could be restricted to off-peak hours, when electricity prices are lower. Thus, actual incremental costs for capturing CO_2 could be lower than the projections cited above.[29] Also, integrating CO_2 capture into an existing plant will not be as efficient as building a new plant with CO_2 capture, as existing steam sources would need to be diverted or a new turbine installed to generate steam, options that are less than optimal.[30]

Conclusion

Implementing CO_2 capture in the Texas Gulf Coast region is a feasible and attractive approach to enhancing oil production in the state. Building new IGCC plants or retrofitting existing plants with IGCC requires considerable capital investment but will offer relatively low capture costs, energy requirements, and fuel flexibility. CO_2 capture with PC is more expensive, though most of the capital costs have already been sunk on existing PC plants. NGCC offers the lowest capital costs and the high capture costs and energy requirements due to the relatively low volume of CO_2 in the flue gas. Thus it seems that chemical absorption of CO_2 from PC flue gases may be a reasonable choice for near-term carbon capture in the Texas Gulf Coast. In the long term, improving technologies and shifting to IGCC systems would make more economical and efficient carbon capture possible.

Notes

[1] Class presentation by Charles Christopher, BP Americas, “Overview of Climate Change and the Role of CO_2,” at the Lyndon B. Johnson School of Public Affairs, Austin, Texas, November 4, 2005.

[2] Ibid.

[3] Texas Bureau of Economic Geology, The University of Texas at Austin, *Reduction of Greenhouse Gas Emissions through Underground CO_2 Sequestration in Texas Oil and Gas Reservoirs* (1999). Online. Available: http://www.beg.utexas.edu. Accessed: October 23, 2005.

[4] Arthur Lee, “CO_2 Capture Project’s Policies and Incentives Study,” IEA CSLF Workshop on Legal Regulatory Issues, July 12-13, 2004. Online. Available: http://www.iea.org/textbase/work/2004/storing_carbon/Lee.pdf. Accessed: December 5, 2005.

[5] Jeremy David and Howard Herzog, *Cost of Carbon Capture* (Cambridge, Mass.: Massachusetts Institute of Technology, 2000). Online. Available: http://www.netl.doe.gov. Accessed: October 23, 2005.

[6] Dale Simbeck, “CO_2 Capture Economics,” Paper prepared for “The 10-50 Solution: Technologies and Policies for a Low-Carbon Future,” Pew Center on Global Climate Change and the National Commission on Energy Policy, Washington, D.C., March 25-26, 2004.

[7] Interview by Cyrus Tashakkori with Gary T. Rochelle, Groppe Professor of Chemical Engineering, Department of Chemical Engineering, The University of Texas at Austin, November 18, 2005.

[8] M.L. Gray, Y. Soong, K.J. Champagne, H.W. Pennline, J. Baltrus, R.W. Stevens, Jr., R. Khatri, and S.S.C. Chuang, “Capture of Carbon Dioxide by Solid Amine Sorbents,” *International Journal of Environmental Technology and Management*, vol. 4, nos. 1-2 (2004), pp. 82-88. Online. Available: http://www.netl.doe.gov/osta/techpapers/2003-118.pdf. Accessed: November 28, 2005.

[9] Simbeck, “CO_2 Capture Economics,” p. 2.

[10] Rochelle interview, November 18, 2005.

[11] Norifumi Matsumiya, Masaaki Teramoto, Satoshi Kitada, Nobuaki Ohnishi, and Hideto Matsuvama, “Evaluation of energy consumption for separation of CO_2 in flue gas by hollow fiber facilitated transport membrane module with permeation of amine solution,” *Separation and Purification Technology*, vol. 46, iss. 1-2 (November, 2005), pp. 26- 32.

[12] Ibid.

[13] David and Herzog, *Cost of Carbon Capture* (online).

[14] Rochelle interview, November 18, 2005.

[15] Soren Anderson and Richard Newell, “Prospects for Carbon Capture and Storage Technologies,” *Annual Review of Environment and Resources*, vol. 29 (Nov. 2004), pp. 109-142.

[16] William G. Ropsenberg, Dwight C. Alpern, and Michael R. Walker, "Deploying IGCC in This Decade With 3Party Covenant Financing," Energy Technology Innovation Project Discussion Paper, 2004-07 (Cambridge, Mass.: Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, July 2004). Online. Available: http://www.ksg.harvard.edu/bcsia/enrp. Accessed: October 23, 2005.

[17] Ibid.

[18] U.S. Senate, *Energy Policy Act of 2005*, Public Law 109-58, 109th Congress, 1st session (2005).

[19] Class presentation by Ian Duncan, Bureau of Economic Geology, The University of Texas at Austin, "Texas Energy Policy," at the Lyndon B. Johnson School of Public Affairs, Austin, Texas, November 4, 2005.

[20] David and Herzog, *Cost of Carbon Capture* (online).

[21] Simbeck, "CO_2 Capture Economics," p. 2.

[22] Ibid.

[23] David and Herzog, *Cost of Carbon Capture* (online).

[24] Paul Freund and John Davison, "General overview of costs," IEA Greenhouse Gas R&D Programme, GL52 7RZ, U.K. Online. Available: http://arch.rivm.nl/env/int/ipcc/docs/css2002/ccs02-06.pdf. Accessed: October 27, 2005.

[25] David and Herzog, *Cost of Carbon Capture* (online).

[26] Ibid.

[27] Ibid.

[28] Interview by Cyrus Tashakkori with Ian Duncan, Director, Bureau of Economic Geology, The University of Texas at Austin, November 10, 2005.

[29] Ibid.

[30] Rochelle interview, November 18, 2005.

Chapter 4. Transport

Once CO_2 is captured at a source, the next step is to move it to an oil field for use in EOR or geological sequestration. The design and construction of a regional pipeline system would be a challenge for any industry seeking to use CO_2 for EOR in East Texas and the Gulf Coast. Such a pipeline system could bring CO_2 from a stationary point source of capture to the well head site for injection. One design issue would be how to assure the pipeline is as accessible as possible to many large point sources of CO_2 and to many mature fields appropriate for EOR. A pipeline design also might take into account potential CO_2 sources and sinks for future use in carbon sequestration.

Any regional pipeline system should provide access to major CO_2 producers and consumers. Its design should also facilitate a future transition from medium-term EOR (30-year life) to long-term sequestration of CO_2. Pipeline use for EOR will likely involve capture of CO_2 at major refineries, power plants, or other point sources and transport of the pressurized gas to depleted oil fields where it can be utilized in the EOR process. Several existing projects throughout the world utilize both natural and captured anthropogenic CO_2 for EOR activities. Long-term use of the regional pipeline system will include CO_2 transportation to potential sites that qualify for use in long-term carbon sequestration. It may include an expanded number of sources participating in CO_2 capture, such as coal-fired power plants, oil refineries, ammonia or other chemical plants, metal processing facilities, or cement manufacturers.

Given the inherent uncertainty regarding the geographic location of potential future active sources and sinks, a regional system that acts as a "mother-line" to local-level connections could provide maximum coverage and efficiency, while minimizing the costs associated with incorporating the line. East Texas and the Gulf Coast region are well-suited for a pipeline, given the relative proximity of CO_2 producers to both potential EOR oil fields and potential carbon sequestration sites.

Existing CO_2 Transportation Systems

Millions of tons of CO_2 are transported every year onshore by long-distance, high-pressure pipelines in the U.S. The West Texas petroleum industry uses this type of pipeline for EOR activities and has demonstrated the effectiveness of this technology. Transport of CO_2 by pipeline is a proven technology that has been utilized in 72 CO_2-based EOR projects in the United States.[1] Other means of CO_2 transportation, used mainly by the food and beverage industries, include rail transport, motorized transport and sea transport. The advantage of pipeline transportation of CO_2 is that it can deliver a constant and steady flow of gas without the need for intermediate storage along a distribution route. Pipeline transportation of CO_2 can be "cost-effective and reliable when large quantities of CO_2 are to be transported."[2]

One recently constructed pipeline system connecting an anthropogenic CO_2 source to an EOR project is the Weyburn Enhanced Oil Recovery Project between North Dakota in the U.S. and Saskatchewan in Canada. This project utilizes a 205-mile pipeline to transport more than 5,000 tons of CO_2 per day from the Dakota Gasification Company Synfuels Plant in North Dakota to the Weyburn Oil Field in Saskatchewan, Canada. The pipeline was constructed at a cost of $100 million and includes segments of both 12-inch and 14-inch diameter pipes. It has two existing compression stations, with an additional compression station planned to provide CO_2 for another buyer in Canada interested in connecting to the pipeline system and using the CO_2 for EOR.[3] The difficulties encountered during the design and implementation of the Weyburn Project pipeline infrastructure could be comparable to those of a regional pipeline system in East Texas and the Gulf Coast. A Gulf Coast CO_2 transportation system would be used both for EOR projects and geologic CO_2 sequestration.

The International Energy Agency (IEA), along with a consortium of international corporations, government sponsors, and research partners, hopes to demonstrate the economic and technical feasibility of CO_2 sequestration for both EOR activities and long-term storage by studying the effectiveness of the Weyburn Project.[4] The project began in 1997 when EnCana Energy announced plans to utilize CO_2 transported by pipeline from a coal gasification facility in North Dakota to begin EOR activities at the Weyburn oil field.[5] The pipeline transports over 5,000 tons CO_2 per day to the Weyburn facilities in order to recover an estimated 130 million additional barrels of oil from the reservoir.[6] The injection and storage of CO_2 is monitored continually to verify the movement of the underground gas and to ensure permanent storage. The project will provide valuable insight into the behavior of CO_2 in underground formations, the effectiveness of new technologies, and the cost-effectiveness of using CO_2 for EOR.

Pipeline Design Considerations

For CO_2 to be transported in a pipeline it must be in a "supercritical" phase, which occurs at temperatures greater than -60º Celsius (C) and at a pressure higher than 7.38 Megapascals (Mpa).[7] This pressure is roughly equivalent to 1070 pounds per square inch (psi), or about 73 times the standard atmospheric pressure at sea level of 14.7 psi. In a supercritical phase the CO_2 has density and flow properties comparable to a liquid. The pipeline system must maintain the CO_2 within the appropriate temperature and pressure range to sustain the supercritical phase. Given the ambient temperatures of East Texas and the Gulf Coast region, a potential to dip below -60º C is unlikely. Unless CO_2 is repressurized in compression stations along the pipeline, the pressure of the CO_2 within the pipeline could decrease over long distances, relative to the distance traveled and the diameter of the pipeline. Under normal conditions, the supercritical CO_2 may need to be recompressed in any pipelines longer than 90 miles, depending on the diameter of the pipe and the initial pressure.[8] As a rule of thumb, the narrower the pipe, the more frequently the supercritical CO_2 must be recompressed.[9] A CO_2 pipeline should be constructed to handle pressures of between 7.5-12 MPa, and it should be able to withstand pressures of up to 14 MPa.

Pipelines that transport carbon dioxide must conform to three sets of U.S. and Texas regulations, as listed in Table 4.1. A CO_2 pipeline would be regulated as a medium for transport of both a hazardous liquid and a gas, and so would be subject to two separate U.S. Department of Transportation sets of rules. The parallel Texas pipeline regulations are managed by the Texas Railroad Commission.[10]

Table 4.1
Potential Pipeline Regulations for CO_2 Transmission in Texas' Gulf Coast

Description	Regulation
Transportation of Hazardous Liquids by Pipeline	U.S. Department of Transportation (DOT) Code 49 CFR195
Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards	U.S. DOT Code 49 CFR 192
Pipeline Safety Regulations	Texas Administrative Code Title 16, Part 1, Chapter 8

Adapted from: U.S. Office of Pipeline Safety, *Code of Federal Regulations, Title 49, Volume 3, Part 192*. Online. Available: http://ops.dot.gov/regs/1999/part192.htm. Accessed: November 26, 2005; U.S. Office of Pipeline Safety, *Code of Federal Regulations, Title 49, Volume 3, Part 195*. Online. Available: http://ops.dot.gov/regs/1999/part195.htm. Accessed: November 26, 2005; and Office of the Texas Secretary of State, *Texas Administrative Code, Title 16, Part 1, Chapter 8*. Online. Available: http://info.sos.state.tx.us/pls/pub/readtac$ext.ViewTAC?tac_view=4&ti=16&pt=1&ch=8. Accessed: November 26, 2005.

Any regional pipeline system in East Texas and the Gulf Coast region would be subject to diverse local, state and federal regulatory oversight in the process of its design and construction. Although pipeline transport of CO_2 is not a new activity in Texas, certain aspects of the capture, transport and injection/sequestration process may tread on new regulatory territory. The Weyburn pipeline adhered to the regulatory structure of at least three different bodies, so coordination among those agencies and the Dakota Gasification Company was vital to the timely progression of the project. A CO_2 pipeline system used for EOR and sequestration in Texas must comply with all applicable regulations and monitoring requirements of the Texas Railroad Commission, the Texas Commission of Environmental Quality, and the U.S. Department of Transportation (USDOT).

USDOT regulation entitled "Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards" (U.S. DOT Code 49 CFR 192) regulates the minimum wall thickness, corrosion control systems, and other physical design factors of CO_2 pipelines. It also establishes safety standards for compressor stations including emergency shutdown and pressure-limiting devices.[11] The "Transportation of Hazardous Liquids by Pipeline" regulations (U.S. DOT Code 49, CFR 195) establish requirements for incident reporting, pipeline location, welding specifications, valve specifications, pipeline pressure testing requirements, maintenance requirements, and public education requirements.[12] CO_2 pipeline regulations in Texas, established in the Texas Administrative Code (TAC) Title 16, Part 1, Chapter 8 titled "Pipeline Safety Regulations," require Pipeline Integrity Assessments and Management Plans for all CO_2 pipelines. The TAC also mandates corrosion control specifications, public education programs, and prohibits the location of CO_2 or other hazardous liquids pipelines within 1,000 feet of a public school.[13] If the pipeline were to connect to a similar project in Louisiana, a partnership between the Texas state agencies and the Louisiana Department of Natural Resources, which regulates pipelines in the state, would need to be formed to facilitate the establishment of a new regulatory structure.[14]

Once a design has been developed for a regional pipeline system, the question of who will pay to construct and operate the pipeline system becomes a key subject. The potential revenue generated by the EOR activities throughout the region may be an incentive for investment into such a system. For example, in the Gulf Coast region, large and medium-sized petroleum companies that maintain onshore operations in East Texas and the Gulf Coast stand to gain from a regional CO_2 pipeline system in the form of increased yields from previously depleted oil fields that can benefit from EOR technologies.[15] In this case, either the oil producers or the large point sources of CO_2 (such as refineries, power plants, or other industrial facilities) could invest in a CO_2 pipeline infrastructure. An economic incentive may not yet exist for any of these markets to develop a CO_2 pipeline due to the high cost of carbon capture at the source. The transportation costs of CO_2 and the investment in necessary infrastructure are a small part of the total cost of the capture, transport, and injection/storage process.[16]

There has yet to be a published industry study of any specific pipelines used for the East Texas or Gulf Coast oil fields estimating the specific costs of constructing and operating a CO_2 pipeline. There does exist in the literature a wealth of information on the costs of natural gas pipelines, which some analysts consider to be similar.[17] Specific equations have been developed for calculating expected pipeline costs (materials, labor, right-of-way, and miscellaneous costs) based on a pipeline's length and diameter.[18] The appropriate pipeline diameter would be chosen based upon the flow rate of CO_2 passing through the pipeline and the physical attributes (density, viscosity, temperature, pressure) of the gas during transport. Costs of pipeline construction can range between $0.5 and $1 million per mile, depending upon proximity to large metropolitan areas, contour of the land to be traversed, costly river or other barrier crossings, and type of soil.[19] For example, the Weyburn Project pipeline, with 205 miles of 12-inch and 14-inch pipeline, cost $100 million, or roughly $0.5 million per mile.[20]

Safety Concerns and Public Reaction to CO_2 Pipelines

The development of any CO_2 pipeline may face public resistance due to the prospect of long-term, long-distance transport of a gas which has health risks associated with high concentrations of the gas in a confined area. Carbon dioxide is not flammable or poisonous, but at concentrations higher than 10 percent it can cause severe injury or death due to asphyxiation. As a result, strict regulatory and monitoring measures exist to reduce the risks of technical failures along the pipeline. The overall safety record of CO_2

pipelines in the EOR industry indicates that the rate of leakage is lower than that of natural gas or other hazardous pipelines.[21] According to the Office of Pipeline Safety, over an 11-year period (1990-2001) there were ten reported incidents for CO_2 pipelines.[22] The Canyon Reef Carriers pipeline, one of the first major CO_2 pipelines used for EOR in West Texas, recorded only five malfunctions between 1972 and 1984, none of them involving injuries.[23]

Safety technologies including odor additives, line-monitoring systems, and emergency response mechanisms can reduce the risk of a major CO_2 leak.[24] Dissemination of relevant information regarding existing CO_2 pipeline systems and their respective safety records could help a project with community cooperation. Weyburn Project officials conducted a public relations campaign before pipeline construction to inform affected community members of the potential impacts of the pipeline and to coordinate reclamation efforts. According to published reports, the project's pre-emptive public involvement allowed the right-of-way process to proceed with little resistance from affected property owners, and no condemnation of land was necessary.[25] The Weyburn example of an active public information campaign to address the health and safety concerns of nearby residents can help a project limit costly construction delays.

Several policy measures could be adopted at the state level that would facilitate the construction of a CO_2 pipeline. The use of existing pipeline right-of-ways could be granted to projects that propose the construction of new CO_2 pipelines for use in EOR or sequestration. The cost of new equipment associated with anthropogenic CO_2-based EOR could be given state tax breaks to offset the initial capital-intensive investment. The state regulations concerning CO_2 capture, transport, and injection could be re-evaluated given the special circumstances of EOR and sequestration. The permitting process associated with each step of the EOR process could also be streamlined to minimize costs and delays.

The costs and potential benefits of a CO_2-based EOR project in the Texas Gulf Coast could be demonstrated by evaluating a specific case study. The capture of CO_2, the transport of CO_2 to an oil field, and the injection of CO_2 for EOR would each have a range of costs for both capital and operating expenses. The potential revenues from the increased oil production using EOR could be estimated using a conservative price per barrel of oil. The difference between overall costs and revenues for the case study could be used in a more in-depth analysis of the economic feasibility of implementing a CO_2-based EOR project in the Texas Gulf Coast. Such a case study is developed in Chapter 7.

Notes

[1] Gunter Moritis, "EOR Weathers Low Oil Prices," *Oil & Gas Journal*, vol. 98, iss. 12 (2000), p. 42.

[2] Rickard Svensson, Mikael Odenberger, Filip Johnsson, and Lars Strömberg, "Transportation Systems for CO_2—Applications for Carbon Capture and Storage," *Energy Conversion and Management,* vol. 45, iss. 15-16 (2004), p. 2350.

[3] IEA Greenhouse Gas R & D Programme, *Weyburn Enhanced Oil Recovery Details*. Online. Available: http://www.co2captureandstorage.info/project_specific.php4?project_id=70. Accessed: October 5, 2005.

[4] Ibid.

[5] Ibid.

[6] K. Brown, W. Jaxrawi, R. Moberg, M. Wilson, *Role of Enhanced Oil Recovery in Carbon Sequestration: The Weyburn Monitoring Project, a Case Study* (p. 2). Online. Available: http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/2a1.pdf. Accessed: October 18, 2005.

[7] Svensson, Odenberger, Johnsson, and Strömberg, "Transportation Systems for CO_2," p. 2346.

[8] Gemma Heddle, Howard Herzog, and Michael Klett, *The Economics of CO_2 Storage* (Massachusetts Institute of Technology, Laboratory for Energy and the Environment, August 2003, p. 17). Online. Available: http://sequestration.mit.edu/pdf/LFEE_2003-003_RP.pdf. Accessed: October 28, 2005.

[9] Ibid., p. 17.

[10] Railroad Commission of Texas, *Railroad Commission of Texas Rules*. Online. Available: http://www.rrc.state.tx.us/rules/rule.html. Accessed: December 13, 2005.

[11] U.S. Office of Pipeline Safety, *Code of Federal Regulations, Title 49, Volume 3, Part 192*. Online. Available: http://ops.dot.gov/regs/1999/part192.htm. Accessed: November 26, 2005.

[12] U.S. Office of Pipeline Safety, *Code of Federal Regulations, Title 49, Volume 3, Part 195*. Online. Available: http://ops.dot.gov/regs/1999/part195.htm. Accessed: November 26, 2005.

[13] Office of the Texas Secretary of State, *Texas Administrative Code, Title 16, Part 1, Chapter 8*. Online. Available: http://info.sos.state.tx.us/pls/pub/readtac$ext.ViewTAC?tac_view=4&ti=16&pt=1&ch=8. Accessed: November 26, 2005.

[14] Louisiana Department of Natural Resources, Office of Conservation, Pipeline Division, Pipeline Safety Section, *Hazardous Liquids and Gas Transmission*. Online. Available: http://dnr.louisiana.gov/CONS/CONSERPI/Safety/pi-hazliquids.ssi. Accessed: December 13, 2005.

[15] Class Presentation by Ian Duncan, Bureau of Economic Geology, at the Lyndon B. Johnson School of Public Affairs, October 4, 2005.

[16] Heddle, Herzog, and Klett, "The Economics of CO_2 Storage," pp. 17-42.

[17] Ibid., p. 26.

[18] Sean McCoy, "Geological Storage of CO_2: Pipeline Cost Model Economics Summary" (Pittsburgh, Penn.: Carnegie Mellon University, July 15, 2005), p. 2.

[19] Heddle, Herzog, and Klett, "The Economics of CO_2 Storage," pp. 17-22.

[20] IEA Greenhouse Gas R & D Programme, *Weyburn Enhanced Oil Recovery Details* (online).

[21] Svensson, Odenberger, Johnsson, and Strömberg, "Transportation Systems for CO_2," p. 2347.

[22] J. Barrie, K. Brown, P.R. Hatcher, and H.U. Schellhase, "Carbon Dioxide Pipelines: A Preliminary Review of Design and Risks" (University of Regina, Saskatchewan, Canada, p. 2). Online. Available: http://uregina.ca/ghgt7/PDF/papers/peer/126.pdf. Accessed: November 23, 2005.

[23] Heddle, Herzog, and Klett, "The Economics of CO_2 Storage," p. 17.

[24] Barrie, Brown, Hatcher, and Schellhase, "Carbon Dioxide Pipelines: A Preliminary Review of Design and Risks," pp. 1-6.

[25] Stan Stelter, *Reclaiming the Land Covering North Dakota's CO_2 Pipeline* (Basin Electric Power Cooperative, 2004). Online. Available: http://www.basinelectric.com/NewsCenter/News/FeaturedArticles/Reclaiming_the_land_.html. Accessed: December 2, 2005.

Chapter 5. Monitoring and Verification

Monitoring and verification are essential mechanisms for enhanced oil recovery and carbon sequestration. Although a potential exists to store CO_2 in a number of mediums (including terrestrial ecosystems, ocean ecosystems, geologic formations, and coal formations), this chapter focuses on issues pertaining to the monitoring and verification of CO_2 in geologic formations.

A firm that seeks to store CO_2 underground has three reasons to monitor. It is useful to monitor the CO_2 injected underground to measure the quantity and ensure the integrity of the injection well. A second purpose of monitoring concerns the process of long-term CO_2 storage, or injecting CO_2 into the deep geologic formations in which it is to be stored permanently, to reduce the effects of climate change. The sequestered CO_2 could then potentially be used for carbon credits and trading in a carbon market. In order for sequestration to be legitimate, the CO_2 will need to be monitored while it is being injected to determine the volume of CO_2 that remains stored. A third type of monitoring examines the CO_2 plume, so as to assure the reservoir integrity over an extended period of time. Any stored CO_2 has the potential for future release through leakage or migration. Therefore monitoring should examine cap rock integrity and plume movement to ensure that there are no negative effects on public health, safety, or the environment.

"Verification" is useful for carbon sequestration because even after CO_2 has been injected, its stability in situ is a requirement for any potential CO_2 storage credits regulated by a governing body, such as the Chicago Climate Exchange. Verification would determine officially the amount of CO_2 sequestered so as to allow credits to be recognized and traded in a market. Although some nations already permit CO_2 credit registration, internationally accepted standard protocols do not exist for verification. Monitoring and verification are necessary components for ensuring the accurate measurement and integrity of carbon dioxide storage.

Current Requirements

Monitoring CO_2 injection for EOR is currently required by the State of Texas. These requirements evolved out of the Environmental Protection Agency's (EPA) Underground Injection Control (UIC) requirements. An injection authorization, a Class II permit, is obtained by submitting an application to the Texas Railroad Commission's (TRC) Environmental Services Section and paying the proper fee.[1] The application requires documentation showing the injection well will not pollute any freshwater sources or endanger existing oil, gas, or geothermal resources. To do this the applicant must provide adequate geologic information, specifications for casing and cementing, and an evaluation of the performance of CO_2 injection on all wells within one-fourth of a mile of the well in question.[2] The review requires mechanical integrity testing of each well by equalizing casing and tubing pressure and then testing the tubing to ensure the pressure is stabilized.[3] After the applicant submits a permit request the TRC has a minimum of 45 days to review it, a process that can be extended if the appropriate information is not included or if the application is protested.[4] Monthly surface injection pressure monitoring is also required after the permit is filed, which is then compiled into an annual report and sent to both the TRC's Austin headquarters and the TRC district office closest to the well. The TRC district office is also expected to perform periodic field inspections of the well to ensure compliance.[5]

As of 2006 there are no existing federal, state, or international requirements for monitoring the movement of fluids within geologic formations for the purposes of carbon sequestration. There are no federal requirements for monitoring in overlying zones to detect leakage, with the exception of specific Class I Hazardous wells.[6] Although the Intergovernmental Panel on Climate Change (IPCC) has identified specific technologies for monitoring and verification, international CO_2 sequestration regulations do not exist.[7] Some individual countries have developed their own requirements for sequestration. For example, Norway may be the most advanced nation in the field of CO_2 monitoring. Every year Norway publishes information on captured and stored amounts of CO_2, based on seismic methods, monitoring reservoirs, and the amounts of CO_2 that escapes to the atmosphere during the injection process. No physical leakage has been detected from carbon storage underground, although projects continuously monitor to reduce uncertainties.

Monitoring CO_2 Underground

Much of the existing monitoring technology was developed in the oil and gas industry and can be applied when monitoring geologic formations (see Table 5.1). For example, standard methods exist for measuring injection rates and pressures, subsurface distribution of CO_2, injection well integrity and local environmental effects. These practices are being tested at many pilot projects around the world including, the Frio project in Texas,[8] the Weyburn project in Canada,[9] the Sleipner project in the North Sea,[10] and the Salah project in Algeria.[11] These studies have allowed the comparison of diverse monitoring and verification technologies and a better understanding of CO_2 behavior.

Table 5.1
Summary of Direct and Indirect Techniques that can be used to Monitor CO_2 Storage Projects

Measurement Technique	Measurement Parameters	Example Applications
Introduced and natural tracers	Travel time Partitioning of CO_2 into brine or oil Identification sources of CO_2	Tracing movement of CO_2 in the storage formation Quantifying solubility trapping Tracing Leakage
Water Composition	CO_2 Trace elements Salinity	Quantifying CO_2 -water-rock interactions Detecting leakage into shallow groundwater aquifers
Subsurface pressure	Formation pressure Annulus pressure Groundwater aquifer pressure	Control of formation pressure below fracture gradient Leakage out of the storage formation
Well logs	Brine salinity Sonic velocity CO_2 saturation	Tracking CO_2 movement in and above storage formation
Time-lapse 3D seismic imaging	Seismic amplitude attenuation P and S wave velocity Reflection horizons	Tracking CO_2 movement in and above storage formation
Vertical seismic profiling and crosswell seismic imaging	Seismic amplitude attenuation P and S wave velocity Reflection horizons	Detecting detailed distribution of CO_2 in the storage formation Detection leakage through faults and fractures
Passive seismic monitoring	Location, magnitude and source characteristics of seismic events	Development of microfractures in formation or cap rock CO_2 migration
Electrical and electromagnetic techniques	Formation conductivity Electromagnetic induction	Tracking movement of CO_2 in and above the storage formation
Time-lapse gravity measurements	Density changes caused by fluid displacement	Detect CO_2 movement in or above storage formation CO_2 mass balance in the subsurface
Land surface deformation	Tilt Vertical and horizontal displacement using interferometry and GPS	Detect geomechanical effects on storage formation and cap rock Locate CO_2 migration pathways
Visible and infrared imaging from satellite or planes	Hyperspectral imaging of land surface	Detect vegetative stress
CO_2 land surface flux monitoring using flux chambers or eddycovariance	CO_2 fluxes between the land surface and atmosphere	Detect, locate, and quantify CO_2 releases
Soil gas sampling	Soil gas composition Isotopic analysis of CO_2	Detect elevated levels of CO_2 Identify source of elevated soil gas CO_2 Evaluate ecosystem impacts

Source: Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage* (September 2005, p. 236). Online. Available: http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/SRCCS_WholeReport.pdf. Accessed: October 23, 2005.

These field tests helped the IPCC develop two monitoring "packages," which are associated with four distinct phases that make up the life cycle of a carbon sequestration project (see Tables 5.2 and 5.3).[12] The two monitoring packages are designated as basic and enhanced. The basic package includes seismic tests, microseismicity, wellhead pressure, and injection rate monitoring. The enhanced package adds periodic well logging and surface CO_2 flux monitoring.[13] The duration of testing assumes 30 years of injection and 20 years of long-term monitoring when used for EOR sites.[14] The four phases consist of pre-operation, operation, closure, and post-closure.[15] The primary characteristic of the pre-operation phase is establishing the monitoring baseline. This baseline is determined by evaluating the existing characteristics of the chosen site, so changes can be identified once the CO_2 injection begins. The operation phase is defined by the injection of the CO_2 and plume monitoring. The closure phase occurs once CO_2 injection has stopped and the wells are closed and abandoned. The post-closure phase includes the completion of all records pertaining to the site and the transition to the regulatory agency that will be responsible for the verification of the injected CO_2.

Table 5.2
Life Cycle of a Storage Project

Phase	Characteristics	Time Line
Pre-Operation	Site Characterization Risk Assessment Establish monitoring baseline	0-5 Years
Operation	Verify injection rates Track location of plume Ensure safe operations Detect and prevent environmental impacts	5-35 Years
Closure	CO_2 injection stops Surface facilities removed; wells abandoned Confirm long-term security of storage project	35-55 Years
Post-Closure	Completed records given to regulatory authorities Monitoring needed only if long-term storage security not established	85- ∞ Years

Adapted from: Presentation by Sally Benson, Deputy Director, Lawrence Berkley National Lab, "Carbon Dioxide Capture and Storage in Deep Geological Formations: A Solution to Global Warming?" at the 13th Annual David S. Snypes/Clemson Hydrogeology Symposium, Clemson University, Clemson, S.C., April 14, 2005.

Table 5.3
Components of Monitoring Packages

Monitoring	Basic Package	Enhanced Package
Pre-Operational	Well logs Wellhead pressure Formation pressure Injection and production rate testing Seismic survey Atmosphere CO_2 monitoring	Gravity survey Electromagnetic survey CO_2 flux monitoring Pressure and water quality above the storage formation
Operational	Wellhead pressure Injection and production rates Wellhead atmospheric CO_2 monitoring Microseismicity Seismic surveys	Well logs Gravity survey Electromagnetic survey Continuous CO_2 flux monitoring at 10 stations Pressure and water quality above the storage formation
Closure	Seismic survey	Gravity survey Electromagnetic survey Continuous CO_2 flux monitoring at 10 stations Pressure and water quality above the storage formation Wellhead pressure monitoring for five years, after which time the wells will be abandoned

Adapted from: Presentation by Sally Benson, Deputy Director, Lawrence Berkley National Lab, "Carbon Dioxide Capture and Storage in Deep Geological Formations: A Solution to Global Warming?" at the 13th Annual David S. Snypes/Clemson Hydrogeology Symposium, Clemson University, Clemson, S.C., April 14, 2005.

Monitoring and Verification Uncertainties

The primary uncertainties for CO_2 disposal in geologic formations relate to the rate at which CO_2 can be buried underground, the available storage capacity, the utilization of subsurface space and available storage capacity, the presence of a cap rock of low permeability, and the potential for CO_2 leakage through imperfect confinement, which may be natural or induced.[16] The uncertainties vary depending on the type and characteristics of the projects. The probabilities of physical leakage are estimated to be small and risks are mainly associated with leakage from casings of abandoned wells. CO_2 injected into a formation can escape through abandoned well bores, faults, and fractures. The possibility of failure exists due to incomplete knowledge of subsurface conditions or corrosion resistance of materials used in injection wells. The limited industry experience regarding the rate of physical leakage from different storages media means that accidental releases could occur over decades or even centuries. The uncertainties are the reason why the verification process is so essential to the integrity of carbon capture and storage and why so much research focuses in this area. Standard protocols and regulatory oversight are a prerequisite to legitimacy and safety in the carbon capture and storage industry.

Conclusions

According to a study performed for the International Energy Agency Greenhouse Gas R&D Program, Texas could play a major role in carbon sequestration because its Gulf Coast region has been identified as an ideal location for CO_2 storage and Texas has experience with CO_2 sequestration projects.[17] However, neither Texas nor U.S. monitoring regulations have been formalized, nor is there sufficient experience with monitoring to allow conclusions regarding physical leakage rates. It will be a challenge for proponents of carbon capture and storage to develop a sequestration industry that simultaneously develops testing, monitoring, and verification systems providing quality assurance. Some of the regulatory implications are discussed in the next chapter.

Notes

[1] Railroad Commission of Texas, *Underground Injection Control Seminar.* Online. Available: http://www.rrc.state.tx.us/divisions/og/uic/manual/HTML/man-chp1.htm. Accessed: December 6, 2005.

[2] Ibid.

[3] Ibid.

[4] Ibid.

[5] Ibid.

[6] U.S. Department of Energy, Technology Roadmap and Program Plan 2005, *Developing the Technology Base and Infrastructure to Enable Sequestration as a Greenhouse Gas Mitigation Option.* Online. Available: http://www.netl.doe.gov/coal/Carbon%20Sequestration/eis/index.html. Accessed: November 17, 2005.

[7] Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage* (September 2005, Chapter 5). Online. Available: http://www.ipcc.ch/activity/ccsspm.pdf. Accessed: November 12, 2005.

[8] Presentation by Sally Benson, Deputy Director, Lawrence Berkley National Lab, "Carbon Dioxide Capture and Storage in Deep Geological Formations: A Solution to Global Warming?" at the 13th Annual David S. Snypes/Clemson Hydrogeology Symposium, Clemson University, Clemson, S.C., April 14, 2005.

[9] Ibid.

[10] Ibid.

[11] Ibid.

[12] Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage* (online).

[13] Ibid.

[14] Ibid.

[15] Ibid.

[16] Gulf Coast Carbon Center, Bureau of Economic Geology, *Carbon Dioxide Sequestration in Geologic Media,Regional Evaluation and Modeling of Opportunities in the Gulf Coast*. Online. Available: http://www.beg.utexas.edu/environqlty/co2seq/fieldexperiment.htm. Accessed: October 5, 2005.

[17] Sally Benson, Mike Hoversten, Erika Gasperikova and Michael Haines, "Monitoring Protocols and Life Cycle Costs for Geologic Storage of Carbon Dioxide" (unpublished paper presented to the International Conference of Greenhouse Gas Control Technologies, Vancouver, Canada, September 5-9, 2004, pp. 1-5). Online. Available: http://uregina.ca/ghgt7/PDF/papers/nonpeer/410.pdf. Accessed: November 15, 2005.

Chapter 6. Legal and Regulatory Issues

Regulatory issues will play an important role in developing any carbon capture and storage initiative in Texas. Currently there are federal and state guidelines that regulate the use of CO_2 in enhanced oil recovery, but carbon sequestration *per se* is largely unregulated. Developing standards that allow for the capture and safe storage of high concentrations of CO_2 along with effective storage monitoring would facilitate the implementation of sequestration.

Many countries in the world already allocate money to research and development of greenhouse gas management technologies, including CO_2 capture and storage. Scientific panels, such as the Intergovernmental Panel on Climate Change (IPCC), continue to study and explain the effects of greenhouse gases.[1] A number of governments have established incentives to encourage oil companies and others in the petrochemical industry to combine EOR with CO_2 mitigation.[2] This combination could play a significant role in future U.S. oil production, considering that 88 percent of the additions to the U.S. proved reserves of crude oil over the last 30 years are due to reserve growth. This means that 88 percent of new domestic crude oil was actually produced from old reservoirs instead of coming about through new discoveries.[3]

The U.S. government has recognized the benefits of limiting greenhouse gas emissions and is encouraging voluntary reductions, but has not developed sequestration regulations. In Texas there is ample experience with EOR such as the projects in the Permian Basin of west Texas. Policies for CO_2 injection pertaining to EOR exist, but Texas has yet to develop procedures to manage CO_2 storage in geologic formations. This section discusses existing regulations concerning EOR and those aspects of the CO_2 storage process that will require regulatory oversight.

International Activity

Although some countries have promulgated financial incentives for research and development to improve the cost-effectiveness of deploying CO_2 capture and storage technology, few have developed a strategy that includes CO_2 capture and storage policies for national energy or climate change. However, the issues of CO_2 capture and storage are garnering a significant level of attention around the world. In its Electricity Act of 2003, the Netherlands established a tax exemption worth US$31-50 million in the first year (increasing every year by between US$31 and 37 million) to support renewable energy, energy efficiency and climate-neutral electricity, including CO_2 capture and storage.[4] The Norwegian government has adopted a strategy to increase natural gas-fired power production, which includes potential participation by the government in the development and operation of an infrastructure for CO_2 storage, including preparations for use of CO_2 for EOR and for geologic sequestration.[5]

The IPCC includes experts from many groups in the area of CO_2 capture and storage, including academia and industry, and has released numerous reports related to climate change, such as the IPCC Special Report on CO_2 Capture and Storage issued in September 2005.[6] The report assesses current information related to climate change, and how CO_2 storage in geologic formations can help to mitigate that change.[7] In 2003 the U.S. government and IPCC began a forum for information exchange and potential collaboration on CO_2 capture and storage projects among nations. Sixteen nations have signed the charter and expect to participate in developing legal, regulatory, and financial information from surveys of such developments among the members.[8]

CO_2 Regulations and Activity in the United States

The U.S. is encouraging industries to commit to voluntary levels of greenhouse gas emission reductions by reforming section 1605(b) of the federal Energy Policy Act to create a voluntary registry program.[9] The proposed revisions to the program would allow companies and organizations to report and register emissions reductions. The U.S. Department of Energy plans to publish guidelines to encourage and guide industry in establishing monitoring and verification processes for CO_2 injections and geologic storage.[10] The U.S. could encourage federal research activities involving CO_2 indirectly through Underground Injection Control (UIC) for CO_2 injection.[11]

Any project that receives federal funding or uses federal resources that could affect the environment significantly is required to undergo a National Environmental Policy Act (NEPA) review.[12] NEPA requires that any federal actions be based on the understanding of environmental consequences and encourages agencies to take actions that protect, restore, and enhance the environment.[13] Review requirements can also be written into regulations for a specific project. For example, NEPA requires that environmental information be available before federal decisions are made on carbon sequestration.[14]

A NEPA review can trigger requirements for a Programmatic Environmental Impact Statement (PEIS), which can have a national or regional focus in an area such as the Gulf Coast.[15] Currently the National Energy Technology Laboratory (NETL) is developing a PEIS for the DOE's Carbon Sequestration Program. This study, which includes the Weyburn Project in North Dakota and Saskatchewan, Canada, will assist in the development of environmental regulations for capture and storage programs within the United States. It will also help to identify environmental impacts on a program-wide basis.[16]

In 1974 Congress gave the EPA the authority, through the Safe Drinking Water Act (SDWA), to control underground injection as a means of protecting underground drinking water sources.[17] The EPA then created the underground injection control program (UIC) to guide states in developing safeguards so that injection wells do not endanger current and future underground sources of drinking water.[18] States have the authority to accept the EPA's definitions or submit their own definition for EPA approval.[19] The main purposes of the EPA regulations are to:

- Identify underground sources of drinking water;
- Define what constitutes endangerment of these sources;

- Direct the states to set up UIC programs to protect these sources;
- Describe the requirements of such programs and permit systems;
- Establish procedures to ensure enforcement of these requirements by the states or by the federal government if the states fail to do so; and
- List construction, permit, operating, monitoring and reporting requirements for specific types of wells.[20]

The EPA groups underground injection into five classes for regulatory control purposes. Each class includes wells with similar functions and construction and operating features so that technical requirements can be applied consistently. Class I wells permit the placement of hazardous and non-hazardous fluids (industrial and municipal wastes) into isolated formations beneath the lowermost underground sources of drinking water.[21] Class I wells are strictly regulated by the federal Resource, Conservation and Recovery Act and the Safe Drinking Water Act because they may inject hazardous waste.[22] Class II wells permit injection of brines and other fluids associated with oil and gas production.[23] Class III wells accept the injection of fluids associated with solution mining of minerals.[24] Class IV wells, for injection of hazardous or radioactive wastes into or above underground sources of drinking water, are banned unless authorized under other statutes for ground water remediation.[25] Class V includes all underground injection not included in Classes I-IV.[26] Class V wells can include injection wells for non-hazardous fluids into or above underground sources of drinking water.[27] They typically include shallow, on-site disposal systems, such as floor and sink drains which discharge directly or indirectly to ground water, dry wells, leach fields, and similar types of drainage wells.[28]

Regulations and Activity in Texas

At the state level, the Texas Railroad Commission (TRC) and the Texas Commission on Environmental Quality (TCEQ) share oversight responsibility for all injection wells.[29] Each organization's responsibility varies depending on the characterization of a specific well.[30] The TRC's authority over oil and gas exploration and production is derived from the Texas Natural Resources Code (TNRC)[31] and the Texas Water Code (TWC).[32] In 1980 the Texas Legislature created the Environmental Services Section within TRC to administer the EPA's UIC program.[33] The Environmental Services Section is responsible for regulation of Class II, III and V wells associated with waste injection, underground storage of hydrocarbons, brine, in-situ combustion of fossil fuels, geothermal resources, heating and agriculture, and EOR.[34] The TCEQ is responsible for regulation of injection wells dealing with deep injection, mineral extraction other than oil and gas, and environmental cleanup in Class I, III, IV, and V wells.[35] In 1982 the EPA approved the TRC definition for Class II injection wells in Texas, which includes injection wells used to dispose of "oil and gas waste," a term that means:

> Waste arising out of or incidental to drilling for or producing of oil, gas, or geothermal resources, waste arising out of or incidental to the underground storage of hydrocarbons other than storage in artificial tanks or containers, or

> waste arising out of or incidental the operation of gasoline plants, natural gas processing plants, or pressure maintenance or repressurizing plants. The term includes but is not limited to salt water, brine, sludge, drilling mud, and other liquid or semi-liquid waste material.[36]

Within this Class II designation there are two important distinctions pertaining to CO_2 injection wells. The first is Rule 9, which allows for the disposal of oil and gas wastes by injection into formations that are not productive of oil.[37] The second is Rule 46, which permits the injection of oil and gas wastes into those formations that are productive of oil.[38] According to the TRC's Compliance Manager, Fernando de Leon, these rules can regulate CO_2 injection.[39]

The use of CO_2 for EOR is regulated by a Class II designation.[40] A Class II permit is obtained by submitting the appropriate application to the Environmental Services Section and paying the proper fee.[41] The permit requires that the applicant provide documentation that the injection well will not pollute any freshwater source or endanger existing oil, gas, or geothermal resources, based on adequate geologic information, specifications for casing and cementing, and an area review of all wells within one quarter of a mile of the well in question.[42] After the permit is submitted the TRC has a minimum of 45 days for review,[43] a process that can be extended if the appropriate information is not included or if the application is protested.[44] Monthly surface injection pressure monitoring is also required, after a permit is granted; these records must then be compiled into an annual report and sent to the TRC headquarters in Austin and the TRC district office closest to the well's location.[45] The district office is also required to perform periodic field inspections of the well to ensure compliance.[46]

It is not yet clear how CO_2 injection wells pertaining to sequestration will be classified. Some analysts argue for a Class II designation, with the rationale that CO_2 injection for EOR is a standard practice and the cost of a more stringent Class I permit would discourage CO_2 storage.[47] Class I designation advocates argue that the assurance that the injected CO_2 will not migrate outside the injection reservoir is worth the cost.[48] According to the TRC's Permitting Manager, Doug Johnson, the primary argument pertaining to CO_2 injection is whether it is intended for storage and reuse or intended for disposal.[49] If storage were the main purpose, the well would be Class II. A disposal well would fall under the Class I category, which would then shift the permitting responsibility to TCEQ.[50] Currently, acid gas wells (for nitrogen oxides and sulfur oxides) intended for disposal fall under Class II;[51] CO_2 sequestration wells could be placed in this category. The first CO_2 sequestration well in the U.S. for research funded by The National Energy and Technology Laboratory with the Bureau of Economic Geology received a permit for a Class V research well and fell under TCEQ regulatory oversight.[52]

Forthcoming Regulations

Even though Texas has experience with EOR and carbon sequestration, many regulations have yet to be formalized. The Gulf Coast region has been cited as a potential location for CO_2 sequestration because of the large number of CO_2-emitting industries, combined with a high concentration of oil resources found within in its thick impermeable underground layer. However, there are a number of obstacles, such as the absence of a dedicated pipeline system to deliver CO_2 from industrial sites to the storage locations. Land acquisition above the storage locations could be complex.

Site monitoring is another hurdle that will have to be regulated. Monitoring techniques are being developed to detect leaks, gauge CO_2 concentration levels in subsurface chambers, and measure CO_2 migration. Well-bore integrity and CO_2 impacts on cement casing of injection wells are also being studied. Current regulations consider the short-term effects of CO_2 use for EOR, but there is still uncertainty as to what effects CO_2 will have during a longer storage period. If casing is compromised, leaks and migration could occur to aquifers or reservoir zones. The following questions remain unanswered: who will assume ownership and liability of the sequestered CO_2? Should governments create sequestration rights comparable to mineral rights or surface rights? Because of the long-term nature of sequestration, will a company assume liability for the sequestered CO_2? What happens if the company goes bankrupt or dissolves? Is it more feasible for the federal or state government or even a specialized institution to assume liability once the CO_2 is injected?

There are possible risks associated with the storage of high CO_2 concentrations. Surface release of high CO_2 concentrations in excess of 10 percent can be harmful to the health of animals.[53] Some analysts have expressed concerns with ground heaving, induced seismic activity, groundwater displacement, and damage to hydrocarbon reservoirs.[54]

Emission Reduction Credits for Carbon Capture and Storage

As the top CO_2 emitting region in the number one emitting country in the world, the Texas Gulf Coast contains large oil fields conducive to the EOR process. It also has existing geologic formations that could be used for large-scale CO_2 sequestration. By establishing the appropriate legal and regulatory framework Texas could position itself as an international leader in EOR and greenhouse gas mitigation. One key regulatory target is to develop rules for Texas carbon capture and storage projects to receive credits that could be used in current or future CO_2 trading systems. Although the U.S. does not currently regulate greenhouse gas emissions, companies who undertake emission reduction projects, or offsets, can receive compensation for doing so. Recent experience in countries that must meet mandatory or voluntary reduction commitments indicates that foreign firms are willing to purchase emissions offsets from American industries. For example, one of the largest greenhouse gas emission credit trades on the CO_2 market resulted when a Canadian energy company purchased emission offsets from U.S. EOR projects.[55]

The concept of emissions offsets originated with the U.S. Clean Air Act of 1977 and the corresponding evolution of the New Source Review (NSR) program to address permitting of facilities in non-attainment areas (regions out of compliance with the National Ambient Air Quality Standards).[56] Under the NSR program, a new major power plant or major modification must offset its air pollutant emissions increases by obtaining credits originating from other sources. Under NSR, an emission offset is a permanent reduction in a source's emissions created by an action taken above and beyond its regulatory requirements.

Offsets are currently used under various mechanisms to reduce greenhouse gas emissions. Mitigation actions, ranging from actual emission reductions, carbon sequestration projects, or avoided emissions, could potentially become offsets under a greenhouse gas mitigation and reduction framework. The Kyoto Protocol to the UN Framework Convention on Climate Change provides mechanisms under which countries may count the purchase of offsets towards their emission reduction commitments.[57] Once an offset has been verified as meeting the requirements for transaction and use under an existing emissions trading program, such as the European Union Emissions Trading Scheme (EUETS), it becomes an emissions reduction credit (ERC). For an offset to qualify as an ERC, the emission reduction must meet five requirements: it must be real, surplus, permanent, verifiable, and enforceable. These basic guidelines create the standard for verifying.

A greenhouse gas reduction is "real" if it reduces the concentration of greenhouse gases in the atmosphere. An offset must be the result of a specific and identifiable project net of leakage that is measurable and directly attributable to the project and may only be used once. In other words, a reduction cannot be counted as an improvement in the generator's emissions and then traded to another entity for re-use in meeting a compliance obligation.

A reduction must be "surplus," in that the reductions reflect project activities that would not have "happened anyway." A reduction is surplus if it, or the activity that causes it, is not required by existing federal or state regulations, or is in excess of normal, or baseline, operations. "Permanence" refers to the lifespan of the emission reduction. Offsets must remove the claimed emissions in such a way to reduce the reasonable risk that it will be re-emitted to the atmosphere.

An emission reduction is "verifiable" if the quantification methodology is sound, clear and replicable. The raw data required to verify the calculation must be available for validation. An emission reduction is measurable and "enforceable" if the level of emissions in the baseline and the actual level of emissions with the project in place can be quantified with an acceptable level of confidence.

The establishment of offsets as an authorized means of mitigating emissions of greenhouse gases has been a difficult process. The majority of initially planned offset projects involved terrestrial sequestration, the storage of carbon in agricultural land and forests. This posed a challenge in meeting the five requirements listed above. Two potentially serious problems with terrestrial carbon offsets are that there may be carbon leakage and that the reduction may be hard to verify. Leakage refers to the situation in which a carbon sequestration activity (e.g., tree planting) triggers an activity which counteracts the carbon effects of the initial activity (e.g., trees cut in other areas).[58]

These problems, however, may be of less concern for geologic carbon sequestration. Many of the issues with terrestrial sequestration are avoided with the more precise methods used in the capture of CO_2 and injection underground. The real and surplus requirements can be managed with EOR and geologic sequestration. Currently no federal or state regulations exist in Texas that require emission reduction; therefore, any removal of CO_2 for EOR or sequestration purposes is surplus of baseline emissions. Because of the nature of CO_2 removal from emissions sources and the existing technology for monitoring and verifying emissions through transport and injection, carbon storage can meet the verifiable and enforceable requirements. Permanence in CO_2 storage in an underground reservoir is also less problematic than with terrestrial storage. Once the CO_2 has been injected, long-term storage (in excess of 1,000 years) is both likely and can be measured with reasonable certainty. The 2006 IPCC report on carbon capture and storage reported that the fraction of CO_2 retained underground with appropriately selected and managed geological reservoirs is likely to exceed 99 percent over 1,000 years.[59]

Texas CO_2 Credit Experience

Texas firms have already received credit for CO_2 storage that has been traded within international systems. In 2002, a trade totaling 9 million tons of CO_2-equivalent (CO_2e) became the largest publicly announced purchase of greenhouse gas reduction credits in the history of the global market.[60] The transaction consisted of two trades of CO_2e between Blue Source LLC, the leader in aggregation of greenhouse gas reduction offsets, and Ontario Power Generation (OPG).

The reductions were generated through EOR projects in Texas, Mississippi, and Wyoming. Blue Source purchased the rights to these reductions from local projects that replaced CO_2 acquired from natural sources with CO_2 captured from industrial sources. The volume of CO_2e emissions that would have been released to the atmosphere in the absence of Blue Source clients' operations is the volume of CO_2 that is injected into the EOR projects, less related emissions necessary to support the injection operations.

At OPG, CO_2 emission reductions are required to meet a corporate absolute target set voluntarily to stabilize net emissions of greenhouse gases at 1990 levels. OPG annually reports progress towards its target with Canada's Climate Change Voluntary Challenge and Registry. OPG's strategy for managing greenhouse gases is based on avoiding and reducing emissions from OPG facilities and removing CO_2 from the atmosphere. To meet its stabilization target each year from 2001 to 2007, OPG has contracted for forward delivery of emission reduction credits.

This trade demonstrates that geologic sequestration of CO_2 during EOR operations is an attractive source of emission reductions in the United States and North America. The cross-border nature of this trade shows international emissions trading to be a viable reality and an effective environmental solution. Based on the client's costs to sequester CO_2, the price per ton was advantageous, supporting the notion that initial low-cost emission reductions are available to early market movers.

Short and Long-Term Liability

As carbon changes hands from those who produce the emissions to those who capture and ultimately store them, the responsibility for those emissions must also be documented. With credit comes liability. How legal liability for leakage of CO_2 from reservoirs should be assigned or apportioned has not been fully determined through practice or in the literature. As an industry of capture and storage evolves, the shape of the liability system will likely determine the cost-effectiveness of the technology and the attractiveness for new entrants to the market. If liability significantly increases storage costs, the viability of carbon storage as a long-term solution to climate change may be affected.

Liability for certain aspects of the capture and storage process can be handled easily using procedures developed for managing risk in the oil and gas industry, including acid gas injection, enhanced oil recovery, natural gas storage, and carbon dioxide transport.[61] Environmental, health, and safety risks associated with the capture and transport of CO_2 are well documented and successfully managed under existing frameworks. According to some analysts, liability associated with these oil industry operating risks, known as operational liability, should not pose a significant obstacle to carbon capture and storage.

Another source of liability is the risk that CO_2 leakage from reservoirs will escape into the atmosphere, removing the climate benefit of storage. While the permanence of carbon storage is fairly well-documented as indicated above, and the IPCC has found that a well-managed project can achieve 99 percent retention rates, a probability of leakage remains. This climate credit liability could be handled under a greenhouse gas emissions policy.[62] In the case of Blue Source's emissions trade with OPG, Blue Source assumed the long-term climate liability and agreed to replace any potential loss of CO_2 from storage with a like-kind emission reduction from another project or from the original project if it can be shown that the leakage was quantifiable and remedied.[63]

In situ liability, covering the health and environmental risks associated with leakage or movement of the CO_2 once it has been injected into the reservoir, represents the third type of liability and the biggest challenge. Although CO_2 is considered a safe, non-toxic gas at low concentrations, leakage and CO_2 accumulation to high concentrations can be unsafe to humans, animals, and plant life. Leakage and spread of CO_2 underground has the potential to cause environmental or ecosystem damage, such as soil acidification.[64] Although the likelihood of such an event is low, it is not clear what institutional mechanism can account for these risks.

Four stakeholders could take responsibility for the in situ liability: the federal government, a state government, an industry, or a firm.[65] While it seems intuitive that liability should be placed on the firm responsible for storage, this may not be an ideal solution because many different entities can be involved in the process, from the entity who owns the land or subsurface rights to the firm who carries out injection and eventual sealing of the reservoir. As the liability for leakage may exist for as much as 1,000 years, there is no guarantee that these firms will continue to exist. A state or federal government may need to step in to assume liability in order to assure that someone retains contingent liability for these risks. For example, the U.S. government has assumed in situ liability for nuclear power under the Price-Anderson Act of 1957 and for low-level radioactive waste. The effectiveness and incentives created by such programs do not provide a clear indication of the appropriateness of federal or state liability for in situ carbon capture and storage.

There remains much uncertainty about how liability will be addressed for carbon capture and storage. Analogous cases exist in the natural gas sector (relatively low-cost liability) and hazardous waste storage (much more costly). Both may play a role in informing the development of a system for CO_2 . Which path CO_2 storage liability follows will depend on the results of ongoing research into storage and monitoring technology and observation of the precedent set by projects currently underway.

Notes

[1] Intergovernmental Panel on Climate Change (IPCC), *Carbon Dioxide Capture and Storage* (September 2005). Online. Available: http://www.ipcc.ch/activity/ccsspm.pdf. Accessed: November 12, 2005.

[2] David C. Thomas and Sally Benson (Eds.), *Carbon Dioxide for Storage in Deep Geologic Formations—Results From a CO_2 Capture Project,* vol. 1, chap. 1 (January 2005), pp. 17-35.

[3] Michael J. Osborne, "Silver in the Mine: A Long Term Comprehensive Energy Plan for the City of Austin" (Austin, Tex.: Austin Energy Publishing, 2002), p. 44.

[4] Ibid.

[5] Ibid.

[6] IPCC, *Carbon Dioxide Capture and Storage*, Preface (online).

[7] Ibid.

[8] Thomas and Benson, *Carbon Dioxide for Storage in Deep Geologic Formations*, pp. 17-35.

[9] Ibid.

[10] Ibid.

[11] Environmental Protection Agency, *Underground Injection Controls.* Online. Available: http://www.epa.gov/safewater/uic. Accessed: October 20, 2005.

[12] Department of Energy's National Energy and Technology Laboratory, NEPA Presentation (June 15, 2005). Online. Available: http://www.netl.doe.gov/publications/carbon_seq/eis/Presentations/NEPAPres.pdf. Accessed: October 15, 2005.

[13] Ibid.

[14] Ibid.

[15] Ibid.

[16] Ibid.

[17] Environmental Protection Agency, *Safe Drinking Water Act.* Online. Available: http://www.epa.gov/region5/defs/html/sdwa.htm. Accessed: December 6, 2005.

[18] Environmental Protection Agency, *Underground Injection Controls.* Online. Available: http://www.epa.gov/safewater/uic.html. Accessed: October 20, 2005.

[19] Ibid.

[20] Ibid.

[21] Ibid.

[22] Ibid.

[23] Ibid.

[24] Ibid.

[25] Ibid.

[26] Ibid.

[27] Ibid.

[28] Ibid.

[29] Texas Commission on Environmental Quality, *Underground Injection Control Permits and Registrations.* Online. Available: http://www.tceq.state.tx.us/permitting/waste_permits/uic_permits/UIC_Am_I_Regulated.html. Accessed: December 6, 2005.

[30] Ibid.

[31] Texas Natural Resources Code, ch. 81.

[32] Texas Water Code, ch. 27.

[33] Railroad Commission of Texas, *Underground Injection Control Seminar.* Online. Available: http://www.TRC.state.tx.us/divisions/og/uic/manual/HTML/man-chp1.htm. Accessed: December 6, 2005.

[34] Ibid.

[35] Texas Commission on Environmental Quality, *Underground Injection Control Permits and Registrations.* Online. Available: http://www.tceq.state.tx.us/permitting/waste_permits/uic_permits/UIC_Am_I_Regulated.html. Accessed: December 6, 2005.

[36] Texas Water Code, ch. 27, Section 27.002(6).

[37] Railroad Commission of Texas, *Underground Injection Control Seminar* (online).

[38] Ibid.

[39] Interview by John Coleman with Fernando de Leon, Compliance Manager, Injection Wells, Texas Railroad Commission, Austin, Texas, December 5, 2005.

[40] Railroad Commission of Texas, *Underground Injection Control Seminar* (online).

[41] Ibid.

[42] Ibid.

[43] Ibid.

[44] Ibid.

[45] Ibid.

[46] De Leon interview.

[47] Sarah M. Forbes, "Regulatory Barriers for Carbon Capture, Storage and Sequestration," National Energy Technology Laboratory (November 2002). Online. Available: www.netl.doe.gov/coal/Carbon%20 Sequestration/pubs/reg-issues/Capture.PDF. Accessed: October 20, 2005.

[48] Ibid.

[49] Interview by John Coleman with Doug Johnson, Permitting Manager, Injection Wells, Texas Railroad Commission, Austin, Texas, November 2005.

[50] Ibid.

[51] Ibid.

[52] Sarah M. Forbes, "Regulatory Barriers for Carbon Capture, Storage and Sequestration," National Energy Technology Laboratory (November 2002). Online. Available: www.netl.doe.gov/coal/Carbon%20 Sequestration/pubs/reg-issues/Capture.PDF. Accessed: October 20, 2005.

[53] Ibid.

[54] Ibid.

[55] CO2e. *July 2, 2000 Press Release*. Online. Available: http://www.co2e.com/common/faq.asp?intPage ElementID=33924&intCategoryID=29. Accessed: February 15, 2006.

[56] U.S. Environmental Protection Agency. *New Source Review: Non-attainment NSR Program. 40 CFR 51.165.* Available: http://ecfr.gpoaccess.gov/cgi/t/text/textidx?c=ecfr&sid=5f2b25d1de7e11a0da1 dbe1ebd0ce9a1&rgn=div8&view=text&node=40:2.0.1.1.2.6.8.6&idno=40. Accessed: February 15, 2006.

[57] United Nations, "Kyoto Protocol to the United National Framework Convention on Climate Change," *Report of the Conference of the Parties on its Seventh Session, Held in Marrakesh,* FCCC/CP/2001/13/Add.2, January 2002. Online. Available: http://www.ceeindia.org/greenhousegases/ c7.pdf. Accessed: November 25, 2005.

[58] Intergovernmental Panel on Climate Change, *Climate Change Mitigation: A report of Working Group III* (2001). Online. Available: http://www.grida.no/climate/ipcc_tar/wg3/index.htm. Accessed: November 25, 2005.

[59] Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage* (2006). Online. Available: http://www.ipcc.ch/activity/srccs/index.htm. Accessed: January 21, 2006.

[60] CO2e. *July 2, 2000 Press Release*. Online. Available: http://www.co2e.com/common/faq.asp?intPageElementID=33924&intCategoryID=29. Accessed: February 15, 2006.

[61] J. Heinrich, H.J. Herzog,. and D.M. Reiner, "Environmental Assessment of Geologic Storage of CO_2," Paper presented at the Second Annual Conference on Carbon Sequestration, Alexandria, VA, United States Department of Energy, 2003.

[62] H.J. Herzog, K. Caldeira, and J. Reilly, "An Issue of Permanence: Assessing the Effectiveness of Ocean Carbon Sequestration," *Climatic Change*, vol. 59, no. 3 (2003), pp. 293-310.

[63] Interview by Kate Larson with Bill Townsend, Chief Executive Officer, Blue Source, LLP, Salt Lake City, Utah, February 25, 2006.

[64] Sally Benson, "Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geological Formations," Report no. LBNL-51170 (Berkeley, CA: E.O. Lawrence Berkeley National Laboratories, 2002), p. 3.

[65] Mark A. de Figueiredo, David M. Reiner, and Howard J. Herzog, "Framing the Long-Term In Situ Liability Issue for Geologic Carbon Storage in the United States," *Mitigation and Adaptation Strategies for Global Change*, vol. 10 (2005), pp. 647-657.

Chapter 7. Case Study

The potential for enhanced oil recovery (EOR) to develop into a profitable business venture along the Texas Gulf Coast can be explored through a case study of a hypothetical CO_2-based EOR project. This chapter attempts such a case based on a real CO_2 source (the BP Refinery in Texas City, Texas) and a real sink (the Hastings West Frio field in Brazoria County, Texas). This assessment begins with the fact that the BP Refinery produces CO_2 residuals of on the order of one million tons per year[1] that can be captured and pressurized for transport to nearby oil fields. The area within 25 miles of Texas City contains numerous oil fields that demonstrate a high EOR potential based on several characteristics that will be discussed later in the chapter. One of the larger and more accessible fields is the Hastings West Frio Field, which was selected as the CO_2-based EOR site for this study.

The Hastings West Frio Field lies 25 miles to the northeast of the BP Refinery in Texas City, Texas. It is an active field with a steadily declining production rate from primary and secondary recovery.[2] It is estimated to have contained original oil in place (OOIP) of 1,265,296,000 barrels,[3] of which an estimated 50 percent has not been recovered.[4] Based upon previous CO_2-based EOR projects in similar Gulf Coast locations, on the order of 15 percent of the OOIP at the Hastings West Frio site may be recovered through EOR, representing 189,794,400 barrels of recoverable oil.[5]

This chapter is divided into six sections: carbon capture, transport, CO_2-based EOR, costs and benefits of CO_2 storage and EOR, monitoring and verification, and sequestration. Appendix A lists costs and benefits.

Carbon Capture

Amine-based scrubbing using monoethanol amine (MEA) is widely believed to be one of the most cost-effective options for large-scale CO_2 capture from existing stationary sources such as power plants and refineries. Due to the large number of existing point sources of CO_2 in the Texas Gulf Coast region, chemical absorption of CO_2 from flue gases using MEA absorbers represents one choice for near-term carbon capture in this region, as capture technology can be added to existing plants.

For the purpose of this case study, the capital cost estimates of the CO_2 capture plant are interpolations based on a large-scale study of the cost of capturing CO_2 from a pulverized coal power plant flue stack. Since the CO_2 concentration in the PC flue is about twice that of the flue in a steam-reforming hydrogen plant (15 percent vs. 7 percent), the cost of the amine absorbers, storage tanks, and the associated costs (facilities, installation, etc.) are doubled. The project is then scaled down to the 1 million tons per year capture requirements of the project associated with the BP Texas Refinery and the Hastings oil field. The use of MEA capture means that the operator must regenerate the MEA periodically, which requires energy that produces CO_2. Total capitol costs associated with a capture and EOR project of this scale are summarized in Table 7.1.

Table 7.1
Capital Costs Data: Texas City Enhanced Oil Recovery Case Study

Item	Case Study Costs
Capture plant cost	$104,000,000
Compressor cost	$16,000,000
Well reworking	$5,023,567
Recycling plant	$24,219,117
CO_2 pipeline	$3,990,000
Total capital costs	$153,232,684

Sources and notes: The capture plant cost estimate is based on the reference plant discussed in Tables 7.3 and 7.4. The reference plant is designed to capture 415 tons CO_2 per hour and requires a capital expenditure of $233,074,100 (Kevin S. Fisher, Carrie Beitler, Curtis Rueter, Katherin Searcy, Gary Rochelle, and Majeed Jassim, "Integrating MEA Regeneration with CO_2 Compression and Peaking to Reduce CO_2 Capture Costs" Trimeric Corporation and U.S. Department of Energy: National Energy Technology Laboratory. Online. Available: http://www.trimeric-corp.com/Report%20060905.pdf. Accessed: April 20, 2006). The Texas City capture plant will capture 125 tons CO_2 per hour. The cost estimates for the Texas City plant were scaled down from those of the reference plant, using a factor 0.432 (233,074,100 x $[125/415]^{0.7}$ = $100,623022, which accounts for the increasing returns to scale of the larger plant) for CO_2 capture requirements and a factor of 1.2 ($100,623,022 x 1.2 = $120,747,627) to scale for flue gas CO_2 content in a PC plant versus the Texas City natural gas flue. The cost of the compressor was then separated out. The share of the capital cost attributed to the compressor for the Texas City plant was estimated by applying the same scaling discussed above.

The well reworking and recycling plant estimates are based upon a per well injection well conversion cost of $5.00/ft depth plus $35,000 and producer cost of $40,000 for 15 injection wells and 89 production wells from: Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

Based on interviews with carbon capture professionals, it is assumed that construction of the CO_2 capture plant will take two years, and construction of the recycling plant, pipelines, and well reworking will occur in the second year. The distribution of capital costs reflects this assumption, with $60 million expended in the first year, and about $90.5 million in the second year. It is also assumed that the EOR project will require roughly two years of CO_2 injection before a marginal increase in oil production is realized, even though this "delay in production" assumption may be unduly pessimistic. Thus the revenue stream from the EOR does not start until year five.

The base case assumes that the steam reforming hydrogen plant at BP's Texas City refinery would use a new gas fired turbine to produce high pressure steam for generating electricity and to capture CO_2. The CO_2 capture costs based on such an assumption will be much higher than realistic costs, which could be based on available steam from other sources that could be purchased at a reasonable cost most likely below the expense of constructing a new turbine. Part of the reason for this construction assumption is that using a gas fired turbine would produce steam at well over 1,000 pounds per square inch (psi), while the MEA-based CO_2 capture process requires steam that is only 30 psi.[6] Integrating the capture plant into the existing infrastructure of the steam reforming hydrogen plant and diverting steam currently used elsewhere would require more coordination from the refinery than adding a new turbine and producing new steam. Also, burning natural gas to produce steam is expensive, as natural gas (currently ranging from \$6 to \$15/MMBtu)[7,8] is likely to be more expensive than coal, which is priced around \$2/MMBtu.[9]

Transport

After the CO_2 is captured at the BP/Praxair refinery, it must be transported to the Hastings West Frio Oil Field for EOR. This section describes the projected route and the pipeline system. It then discusses right-of-way issues and the permitting and reporting requirements. Finally, the risks associated with a CO_2 pipeline in the Texas City area are addressed.

In order for the CO_2 captured at the BP's Texas City refinery facility to be used in the Hastings West Frio Field, a pipeline would be required to transport it approximately 19 miles to the northwest to the Webster Field, and then west another 5 miles (see Figure 7.1). The pipeline would travel from BP Chemicals Americas Inc. (at 201 Bay Street North, Texas, City, Texas, 77590) westward through Texas City along 25th Street to the intersection of 25th and Galveston Highway 3. It would then follow Highway 3 northwest until reaching the Webster Field. The pipeline would then turn due west, continuing to the Hastings West Frio Field. This route passes northwest through the municipalities of Texas City, Dickinson, and League City in Galveston County, entering Harris County and the city of Webster. After turning west, the pipeline would pass into Pearland in Brazoria County.

Figure 7.1
Proposed Project Site

⌂=Refinery	1=Webster Field	2=Hastings West Frio Field	●=Other Oil Field

Adapted from: Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

The pipeline would pass near or through other oilfields along this route. Most notable among these is Webster Field, which is similar in size and other characteristics to Hastings West Frio.[10] Smaller fields along the route include Gillock, Gillock South, Franks, and Hastings East.[11] While this case study focuses specifically on CO_2 EOR in the Hastings West Frio field, the pipeline could service any of these fields.

Right-of-Way

A series of pipelines are already in place along the route between the refinery and the target fields. While no single pipeline travels the entire distance, pipeline rights-of-way have been obtained and used at every point along the route. The pipelines in place transmit natural gas, crude oil (transmission and gathering), and highly volatile liquid

(HVL) products in pipe sizes that vary from 8.63 to 36 inches. Pipelines along Galveston Highway 3 are operated by Kinder Morgan, BP Pipelines, Teppco Crude and Dow Pipeline. Houston Pipeline operates the natural gas line along 25th Street in Texas City. Several pipelines have been laid between the two fields as well that do not necessarily follow public roads. As of 2006, the Railroad Commission of Texas (TRC) lists all of these pipelines as "in service."[12]

The existence of these pipelines alongside public highways suggests that rights-of-way for a new CO_2 pipeline should be attainable. To qualify for right-of-way along public roads, the operator of the CO_2 pipeline must be considered a "common carrier," meaning that it transports CO_2 "to or for the public for hire," rather than for internal company use.[13] The State of Texas guarantees common carriers the right "to lay, maintain and operate [pipelines] along, across, or under a public stream or highway," on condition that: (a) the pipeline does not hinder traffic; (b) the road is "promptly restored" (at the common carrier's expense); (c) local authorities supervise any required road restoration; and (d) express approval of local authorities is obtained for any part of the pipeline system within 15 feet of improved highway.[14]

Written acceptance of the pipeline operator's responsibilities as a common carrier, filed with the TRC, enables these rights-of-way.[15] Similar rights are guaranteed common carriers along railways and canals in Texas. Because a railway parallels Galveston Highway 3, this adds further right-of-way options. Laying a pipeline along 25th Street in Texas City would require approval of the municipal government, as highway rights-of-way do not extend to "a public street or alley in an incorporated or unincorporated city or town except with express permission of the governing body."[16] As of March 2006, it is not known whether the land between the two oilfields is privately owned, but that is a reasonable assumption. The Texas Natural Resource Code provides common carriers with eminent domain, as long as the carrier assumes all costs due to property alteration and restore property "to its former condition as near as reasonably practicable."[17] Upon request of a property owner, the pipeline operator must provide material safety data sheets (MSDS) for the transported commodity (CO_2 in this case).[18] The existence of pipelines indicates that a company seeking to lay a CO_2 pipe should be able to obtain the right-of-way to do so. As a matter of good practice, pipeline operators check with state agencies overseeing wildlife and historical sites when planning a pipeline project.[19] While no environmental or archaeological conflict is known at this time, the operator should clear the proposed route with the Texas Historical Commission and the Texas Parks and Wildlife Department.

Pipeline Construction

It is possible to transport CO_2 in a pipeline designed for CO_2 or in a pipeline originally created for other commodities. For example, Denbury purchased a Mississippi natural gas pipeline in 2005 and modified it for CO_2 transport.[20] Using a line designed for another commodity would require modifications to counter the corrosive nature of carbonic acid, which inevitably will form in a pipeline as water comes into contact with pressurized CO_2. One source suggests the use of stainless steel pipe for CO_2, especially near potential compressors and valves, which are particularly vulnerable to carbonic acid corrosion.[21] Another option is threading a new pipeline designed for CO_2 through a larger abandoned pipe, thus eliminating costs of digging new trenches and providing additional protection from the elements.

While recognizing these possibilities, this study assumes the laying of a new pipeline for a number of reasons. First, no single line runs the entire length from the BP facility to the oilfields, so any use of existing lines could only present a partial solution. Second, all of the pipelines along the proposed route are described as "in service" in TRC reports. This may or may not mean that they are moving other liquids or gasses, but it would be conservative to assume so. Third, cost estimates for retrofitting an existing line or threading a smaller line through a larger one are not available. Fourth, assessing the possibility and cost of using an existing pipeline would require negotiations with multiple current pipeline operators, efforts beyond the scope of this study. Finally, such arrangements for reuse of an existing pipeline are not likely to be present at other sites that might rely on this case study as a model. Thus, while such options should be considered in an actual CO_2 EOR venture, this study assumes the construction of a new pipeline system.

This study assumes the capture, compression, and injection of 1 million tons of CO_2 per year, or 2,740 tons per day. Such a flow would require an eight-inch pipeline.[22] Estimates for CO_2 pipeline costs vary significantly in the EOR and sequestration literature. For instance, one source suggests a cost of $700 per meter of pipeline,[23] which would yield a total pipeline cost of about $27 million for a 24 mile pipeline based on a larger diameter pipe than this project will require. Much of the uncertainty arises from differences in pipeline size and scale. Models often simulate large-scale projects which require large diameter pipes over long distances. Another source takes pipeline diameter into account, suggesting a cost of 1,040 Euros (€) ($1,235) per kilometer per millimeter of pipeline diameter,[24] which would yield project cost of about $9.7 million. The cost estimate used in this study is based on a model developed by the Kinder Morgan pipeline company specifically to model EOR costs in Texas. Kinder Morgan estimates costs through a formula of $150,000 plus $20,000 per mile per inch of pipeline diameter; thus the model predicts a pipeline cost of $4 million.[25] Because the model was developed and used by a company with considerable experience in the pipeline industry in Texas, it seems to be the most applicable model to the present case.

The Hastings West Frio field could absorb CO_2 for EOR at a rate of 1 million tons per year for over 25 years (see below). If more CO_2 became available from either the BP facility or other carbon emitting sources in the region, a regional pipeline system could be designed to link the various sources and oil fields. If this pipeline was envisioned as a trunk line for a future regional system, a larger pipe might be considered. Such considerations are beyond the scope of this case study.

The compression and transport of CO_2 would require energy. Any permanent CO_2 storage would have to be net of such energy use and CO_2 generations, as discussed below.

Texas law requires that CO_2 transport system components have a corrosion-resistant coating.[26] As mentioned above, the transport of 2,740 tons of CO_2 per day would require an eight-inch pipe. According to one source, transmission of CO_2 requires the gas to be pressurized to 8 Megapascals (1,160 pounds per square inch) for transport.[27] Another source claims that while CO_2 reaches a supercritical state at 7.38 MPa, common practice dictates compression to 10.3 MPa to ensure that the CO_2 remains supercritical.[28] While booster stations providing additional compression would be required for a pipeline longer than 100 km, no additional compression would be necessary for a 24-mile CO_2 pipeline.[29] The compressor would be incorporated into the capture process at the refinery.

Under ideal conditions, pipeline construction could proceed at a rate of as fast as 1.5 km per day.[30] This rate would suggest a minimum construction time allotment of 26 days for the pipeline, although there is no need for such a compressed construction schedule for this case study. Construction of the pipeline and carbon capture systems can occur simultaneously. Because of the much longer construction time requirement of the carbon capture system, pipeline construction should not affect the timing of the overall project.

Permits

Before construction begins on the pipeline, the operator must apply for a permit (Form T-4) and file a report with the TRC detailing its design and use (PS-48).[31,32] Texas law requires the pipeline operator to educate local public emergency officials about the project.[33] State law requires that the pipeline operator provide pipeline schematics and emergency contact information to administrators of any public school within 1,000 feet of the pipeline.[34] In addition to accident reports and a facility response plan, Texas requires that the pipeline operator file an annual report (Form PS-45) detailing carbon dioxide transported and accident data.[35] Texas law requires that the pipeline be inspected at least every five years. The electrical components of the transport system must be inspected six times annually.[36]

Risks

Recent research has suggested that CO_2 transport poses greater risks than hydrocarbon transport due to its odorless quality and its tendency to collect in depressions rather than dissipate like natural gas. The report suggested that any CO_2 transport project undertaken near residential areas be accompanied by significant safety monitoring activities.[37] When CO_2 has been transported to the Hastings West Frio field. The intent is to inject it into the reservoir for enhanced oil recovery (EOR), as discussed below.

Enhanced Oil Recovery at Hastings West Frio Field

Site Selection and Characterization

The role of this section is to describe and evaluate factors that could be used to determine whether an existing oil field is suitable for EOR by injection of CO_2. One key factor is whether the field has a recovery potential based on previous conventional and secondary water flooding recovery techniques. A field that has responded well to water flooding may also respond well to tertiary recovery through CO_2 EOR. An existing oil in place not recoverable through primary and secondary recovery should possess physical properties that allow for CO_2 EOR to be effective. Geological properties of the reservoir should meet existing industry criteria to be considered for CO_2 EOR based on thorough geologic and engineering characterization of the reservoir. The necessary properties for CO_2 EOR include high miscibility of the oil, appropriate depth and high permeability of the reservoir, and low reactivity of the geological environment to the injected CO_2.

Oil that mixes with CO_2 under pressure is more mobile and therefore easier to extract. The physical property of oil's miscibility with the CO_2 molecules upon injection occurs at a sufficiently high pressure, known as the minimum miscibility pressure (MMP), or 1070 psi, which occurs at an approximate reservoir depth of 2500 feet, although MMP is a function of more than depth or pressure.[38] The MMP is also affected by the density and viscosity of the oil. Higher densities and viscosities increase the MMP, or increase the pressure necessary to achieve miscibility.[39] Previous injection projects using CO_2 "have focused on oil with densities between 29º and 48º API (degrees on the American Petroleum Institute gravity scale) or about 855-711 kg/m³."[40] These lighter density oils, or the light crude oils, have greater miscibility and therefore higher recovery rates. It is estimated that CO_2 displacement in miscible oil environments can recover roughly 22 percent more oil than conventional and secondary techniques, compared to only 10 percent more by immiscible CO_2 displacement.[41]

The geological environment in and around the oil reservoir affects the rate of oil recovery. Existing CO_2 EOR projects have targeted oil reservoirs at depths between 2,500 and 12,000 feet.[42] Although the CO_2 EOR process can be implemented effectively "in both sandstone and carbonate formations with a variety of permeabilities and thicknesses of hydrocarbon bearing zones,"[43] reservoirs with higher permeabilities, such as sandstones, generally yield higher tertiary recovery rates. Additional considerations include the chemical reactivity of minerals within and surrounding the reservoir, the size of the reservoir and the structure of the reservoir.[44] Table 7.2 lists some of the physical characteristics considered prerequisites for CO_2 EOR.

Table 7.2
Enhanced Oil Recovery Field Selection Criteria

Characteristic	Range of Values for CO2 EOR Sites
Reservoir depth	2,500 – 12,000 feet
Oil API	29º - 48º API
Permeability	Varies
Chemical reactivity of geological formation to CO_2	Low to none

Adapted from: Perry D. Bergman, Edward M. Winter, and Zhong-Ying Chen, "Disposal of Power Plant CO_2 in Depleted Oil and Gas Reservoirs in Texas," *Energy Conversion and Management*, vol. 38, supp., (1997), p. S216; and Kristian Jessen, Anthony Kovscek, and Franklin M. Orr, "Increasing CO_2 Storage in Oil Recovery," *Energy Conversion and Management*, vol. 46 (February 2004), p. 294.

The field in this case study represents a good candidate for the use of CO_2 EOR, as indicated by the data listed in Table 7.3. The existing oil in the Hastings West Frio Field has an API gravity of 31º.[45] The Hastings Field has been classified as being in the top 15 of existing oil fields in the Gulf Coast region of Texas for miscibility of existing oil.[46] The reservoir lies in the highly permeable sandstone formation of the Frio Deep-Seated Salt Domes.[47] The Hastings West Frio reservoir has an average well depth of 6200 feet.[48] CO_2 EOR appears to be a viable option in the field given the existing conditions.

Table 7.3
Oil Field Data: Texas City Enhanced Oil Recovery Case Study

Item	Hastings, W. Frio Field
Field number	39603001
County	Brazoria
Current operator	Texcal Energy LLP
Original Oil in Place (OOIP) (barrels)	1,265,296,000
Average well depth (feet)	6200
API of oil	31º
Estimated recoverable oil with CO_2 EOR (barrels)	215,100,320
Operational injection wells	15
Operational production wells	89
Oil production – 1993 (barrels)	1,200,000
Oil production – 2005 (barrels)	637,452
Unitized	Yes
Permeability	High
Reactivity to CO_2	No known reactivity

Adapted from: Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

Additional Factors

The small- and medium-sized oil companies that have continued operations on the diminishing oil fields in Texas may be discouraged from investing in CO_2 EOR for a number of reasons. EOR represents a high-risk investment for oil companies, as illustrated by the high initial discount rate often applied to such projects during economic analysis, sometimes as high as 25 percent.[49] There are substantial up-front costs of technology and infrastructure for EOR. The timeline of EOR production is not conducive to a rapid payback of the investment, as most EOR projects experience a delay in oil recovery up to 24 months after initial injection[50] and full recovery of the oil may take several years. The profitability of EOR depends not only on future crude oil prices (which have been unpredictable at best) but also on future policy changes that may restrict or prohibit all or part of the activities involved.[51]

Another factor is the negotiation of access to the oil field with the mineral rights owner. The usual practice in Texas is for the owner of the mineral rights to negotiate a lease agreement with an operator who extracts the oil.[52] Under a typical lease, the operator of a CO_2 EOR project would assume all expenses of the operations to extract the oil and in return would receive a conveyance of 7/8 interest in the sale of the extracted oil. The leaser or landowner would receive a 1/8 interest with no obligation to cover any of the operation costs.[53] Assurance of cooperation between the operation of this CO_2 EOR project and the owners of the Hastings West Frio field is beyond the scope of this report.

Permitting Process

In Texas, the injection of CO_2 is regulated under three separate classifications depending on the characteristics of the gas being injected and the use of the injected gas. If the CO_2 that is being injected contains any of a number of chemical compounds regulated as pollutants under federal law (including SO_2, NO_x, trace heavy metals, or other toxics), the injectant would be classified as hazardous Class 1 material and would fall under the oversight of the Texas Commission on Environmental Quality (TCEQ).[54] Under Class 1 regulation it is much more difficult to obtain an underground disposal permit because of the regulatory burdens of hazardous waste disposal under the Federal Resource Conservation and Recovery Act (RCRA). If the injectant has no hazardous compounds in significant quantities, it can be classified as a Class 5 material and is also regulated by TCEQ.[55] Class 5 permitting is more lenient than Class 1 permitting because there is no need to register as a disposal site of hazardous waste under RCRA. If the CO_2 is used for EOR, the permitting process can fall under Class 2, easier than Class 5 permitting. Under Class 2 regulation, the Texas Railroad Commission has jurisdiction, as the recovery of oil becomes the economic activity involved.[56] Since the activities of this case study consist of using CO_2 for EOR, the most appropriate assumption is regulation under Class 2 status established by the TRC.[57]

CO_2 Injection and Recovery

Existing physical infrastructure at oil fields can be adapted for use in CO_2 injection.[58] The Hastings West Frio field currently is utilizing water flooding techniques, so it is not necessary to develop new injection wells. The same well infrastructure and injection techniques can be used in the CO_2 injection process that have been used for secondary production using water flooding. Both the existing injection wells and the existing production wells must be reworked in order to be used for CO_2 flooding. To recycle the CO_2 that escapes with the oil in the recovery process and depressurize it for reinjection, it is necessary to construct a recycling plant.

Recycling CO_2 that escapes from the oil recovery process will require energy and thus the generation of CO_2. Any CO_2 credits would of course be net of any CO_2 generated as part of the capture and storage system, as discussed below.

To adapt the Hastings West Frio field to CO_2 EOR, the existing pattern of injection and production wells could be used. The specific wells to be used would be determined by conducting field tests and surveys. The injection wells currently being used for water flooding at each field may already be adequately spaced for adaptation to CO_2 EOR. Given the high permeability of the geologic formation in which the reservoir exists one injection technique used in West Texas, known as "water alternating gas" (WAG), might be used to achieve maximum recovery of oil.[59] The WAG technique maintains a constant pressure differential within the flood zone of the reservoir which is an important factor in recovering optimal amounts of oil.[60] On the other hand, as the good of this process is to store CO_2 underground, it may be preferable just to flood the reservoir only with CO_2.

The recovery process for CO_2 EOR is an extension of conventional and secondary water-flood recovery techniques. Once at the surface, the CO_2 gas that combined with the oil in the displacement process is separated from the oil, recompressed in the recycling plant, and reinjected into the reservoir.

The current estimate of original oil in place (OOIP) for the Hastings West Frio field is 1,265,296,000 barrels.[61] Based on two existing CO_2 EOR projects, the Little Creek and Quarantine Bay projects in Mississippi, which both have similar geologic formations and utilize comparable recovery techniques, potential recovery would be approximately 15 percent of OOIP.[62] A 15-percent recovery of OOIP equates to 189,794,400 barrels of recoverable oil at the Hastings West Frio field. Based on EOR results from high-permeability sandstone formations,[63] a reasonable assumption for the net application rate of CO_2 would be 3.89 barrels recovered per ton (4.5 mcf/stb) of CO_2 injected. For each barrel of oil recovered, it is necessary to capture, re-pressurize and re-inject 0.114 tons of CO_2 (2 mcf/stb).[64] That equates to approximately 443,460 tons of CO_2 per year recycled in the Hastings West Frio EOR project. The net application rate of CO_2 includes the recycled CO_2.

Using these assumptions, an estimate of initial capital costs and annual operations costs can be made for the hypothetical EOR case. Since the cost estimates are based on the Kinder Morgan Scoping Model that was last updated in 2001, 2 percent annual increases in the capital costs (to 2006) and annual costs (through 25-year life of project) have been added to reflect the rise in costs due to inflation. A complete list of costs for the case study can be found in the "Costs and Benefits" section below.

Economic Considerations

One question facing a private company making a decision as to whether to invest in CO_2 capture and storage is whether it can make a profit in the process. If the company decides to inject CO_2 into an oil-bearing strata for EOR, will the revenue from the marginal oil production exceed the costs of capture, storage, taxes and other expenses? If the company wants to sequester oil in deep-brined strata, will the credits of CO_2 sequestration be more than the cost of CO_2 capture and storage? Such investment decisions are made using a multitude of financial measures. The final discounted benefit in dollar terms must exceed the discounted capital and operating costs. The flow of revenue must yield a profit quickly enough to justify the risk of investing capital compared to the alternative oil and gas investment options available to the firm. The return on invested capital must flow at a rate that exceeds the returns available from those other oil and gas investments that could compete with this CO_2 EOR project.

This process, called capital budgeting, allows a firm to predict the extent to which an investment will generate economic profits or losses. The firm estimates future cash flows and expenses of the project and reduces them into a net present value (NPV) of the investment. The time-horizon of the returns—the number of years before the investment is repaid—can be identified by calculating the NPV in each year and predicting the number of years that would be required before the investment is repaid. Firms can calculate the internal rate of return (IRR) by setting the NPV at the end of the life of the investment equal to zero and calculating a new discount rate. This rate is then compared with the potential returns from the alternative oil and gas investment options available to the firm, so as to assess the relative attractiveness of the project or investment. When all three of these criteria look favorable, companies may choose to invest in a particular project.

Monitoring and Verification

Monitoring and verification are essential mechanisms for assuring a safe and healthy environment and validating the value of stored CO_2 from carbon sequestration. There are three necessary components to the process: injection, plume disposal, and leakage. First, the injection pressure of CO_2 must be watched closely to ensure the mechanical integrity of the well casing to make sure that CO_2 is indeed being infused underground. Second, the CO_2 plume has to be monitored so as to understand the location and movement within the geologic formation. Third, the volume of CO_2 sequestered needs to be verified in order to legitimize the process of carbon trading, and to evaluate what amount, if any, of CO_2 is leaking from the geologic formation.

Monitoring CO_2 injection is currently required to perform enhanced oil recovery. A Class II permit can be obtained by submitting the appropriate application to the TRC's Environmental Services Section and paying the proper fee.[65] The application requires adequate geologic information, specifications for casing and cementing, and perform an area review of all wells within one-quarter of a mile of the well in question[66] to document that the injection well will not pollute any freshwater sources or endanger existing oil, gas, or geothermal resources.[67] The review requires mechanical integrity testing of each well by equalizing casing and tubing pressure and then testing the tubing to insure the pressure is stabilized.[68] After the permit is submitted the TRC has a minimum of 45 days for review, a process that can be extended if the appropriate information is not included or if the application is protested.[69] Monthly surface injection pressure monitoring is also required, which is then compiled into an annual report and sent to both the Austin headquarters of the TRC and the TRC district office closest to the well.[70] The TRC district office is also expected to perform periodic field inspections of the well to ensure compliance.[71] Beyond the costs of these requirements there are also costs associated with the maintenance and operation of each well.

In order for CO_2 sequestration to develop as an industry, short and long-term monitoring techniques will be required in order to verify the amount of CO_2 being sequestered for trading, and to monitor environmental effects on groundwater, air, and local ecosystems. To do this, plume movements will need to be monitored as well as surface measurements to detect possible leaks. There are numerous techniques such as tracers, geochemical processes, infrared spectroscopy, and seismic monitoring. The appropriate model will reflect site specifications. One recent report suggests the use of two monitoring packages, basic and enhanced.[72] The basic package includes seismic tests, microseismicity, wellhead pressure, and injection rate monitoring for thirty years of injection, and an additional twenty years of long-term monitoring[73] and in extended to cost $0.05 per ton CO_2.[74] The enhanced package includes all of the basic monitoring techniques as well as CO_2 flux monitoring and other advanced technologies at a cost of $0.069-0.085 per ton CO_2.[75]

Baseline Case Study Cost and Revenue Streams

The case study, using CO_2 captured at BP's Texas City refinery for EOR at the Hastings West Frio oil field, will have annual cash flows from the marginal increase in oil production at the field due to EOR. It will have annual expenses related to the capture and transportation of the CO_2; maintenance and monitoring of EOR activities; and a large capital investment in pipelines, CO_2 capture equipment, and EOR site equipment.[76] The case study examines the cost and revenue flows over a 25-year period. The annual cash flows are a function of the rate of marginal oil production to CO_2 injection (barrels/ton CO_2), the price per barrel of oil, and the amount of CO_2 captured, which has been set at a million tons per year for this case study. The base case assumptions are outlined in Table 7.4.

Table 7.4
Base Case Assumptions: Texas City/Hastings Case Study

Item	Metric	Value
Market price of oil	$/Bbl	55
Discount rate	%	15
Rate of EOR to CO_2 injection	Bbls/Ton CO_2	3.89
Marginal capture and compression cost	$/Ton CO2	39
CO_2 captured per year	Tons	1,000,000
Severance tax rate	%	2.3
Ad valorem tax rate	%	4.6
Federal tax rate	%	35
Lease Royalties	%	12.5

Source: Authors' assumptions.

The annual costs of such a project include the capture, compression, transportation, and injection of CO_2, as well as maintenance and operations of the pipelines, and taxes.

Table 7.5 outlines the CO_2 capture cost calculations. Current year 2006 tax rates have been applied for the base case. The base case discount or amortization rate is set at 15 percent.

Table 7.5
Annual Costs Data: Calculations and Hastings Case Study Results

Item	Case Study Costs
Capture costs/ year[a]	$30,532,000
Injection costs/year[b]	$2,727,200
Lift costs/year[c]	$429,487
Recycle costs/year[d]	$1,711,696
Pipeline maintenance and operations costs/Year[e]	$25,000
General maintenance and operations[f]	$2,204,629
Severance taxes[g]	$4,920,850
Federal income taxes[h]	$52,084,200

Sources and notes:

[a] These values are calculated in the CO_2 Capture Cost Calculation Summary Table 7.4.

[b] This value assumes $5.41 per bbl. Source: Kay Damen, Andre Faaij, Frank van Bergen, John Gale, and Erik Lysen., "Identification of Early Opportunities for CO_2 Sequestration—Worldwide Screening for CO_2-EOR and CO2-ECBM Projects," *Energy*, vol. 30, no. 10 (July 2005), p. 1945. Online. Available: http://www.sciencedirect.com. Accessed: December 19, 2005.

[c] This value uses $0.10/bbl. Source: "Kinder-Morgan CO_2 Flood Scoping Model Spreadsheet" (2001), from Mark Holtz, Bureau of Economic Geology, The University of Texas at Austin (spreadsheet).

[d] This value uses $0.20/mcf. Source: Ibid.

[e] Gemma Heddle, Howard Herzog, and Michael Klett, "The Economics of CO_2 Storage," Massachusetts Institute of Technology, August 2003, p. 26. Online. Available: http://sequestration.mit.edu/pdf/LFEE_2003-003_RP.pdf. Accessed: November 8, 2005.

[f] This value is calculated using $19,200 per well per year for 15 injection wells and 89 production wells. Source: "Kinder-Morgan CO_2 Flood Scoping Model Spreadsheet" (2001), from Mark Holtz, Bureau of Economic Geology, The University of Texas at Austin (spreadsheet).

[g] Texas Railroad Commission, Oil and Gas Division, *Severance Tax Exemptions and Reductions as Incentives to Increasing Texas Oil and Gas Production*. Online. Available: http://www.rrc.state.tx.us/divisions/og/notices-pubs-swr/notices/ogpn24.html. Accessed: October 23, 2005.

[h] This value is 35 percent of total production. Source: "Kinder-Morgan CO_2 Flood Scoping Model Spreadsheet" (2001), from Mark Holtz, Bureau of Economic Geology, The University of Texas at Austin (spreadsheet).

The capital costs include pipeline construction from the Texas City Refinery to the Hastings West Frio oil field, a CO_2 capture plant, a recycling plant at the oil field, and well reworking at the EOR sites (see Table 7.6). The capital cost estimates of the CO_2 capture plant are based on a large scale study of the cost of capturing CO_2 from a large, pulverized-coal power plant flue stack.[77] Since the CO_2 concentration in the PC flue is about twice that of the flue in a steam reforming hydrogen plant (15 percent vs. 7 percent), the cost of the amine absorbers, storage tanks, and the associated costs (such as facilities and installation) are doubled, resulting in a roughly 20 percent increase in total capital costs.[78] The project is then scaled down to the 1 million tons per year capture requirements of the BP Texas Refinery/Hastings project. The scaling calculations are summarized in Table 7.6.

Table 7.6
CO_2 Capture Cost Calculation Summary

Item	Metric	Value
Annual energy capture cost	MMBtu/year	4,108,433
Hourly energy cost	MMBtu/hour	514
Fuel cost	$/MMBtu	6
Capture energy cost/Ton CO_2	$/Ton CO_2	25
Annual capture energy cost	$/year	24,672,000
Annual capture plant maintenance cost[a]	$/year	3,600,000
MEA reagent and water costs[b]	$/year	2,260,000
Total annual capture cost	$/year	30,532,000
Capture cost/Ton CO_2	$/Ton CO_2	30.53

Sources and notes: The CO_2 capture cost estimate is based on a large-scale simulation of MEA-based CO_2 capture at a PC power plant (referred to here as the reference plant) with MEA-based CO_2 capture conducted by Gary Rochelle, Ph.D., of The University of Texas at Austin, the Trimeric Corporation, and the Platte River Power Authority of Colorado. The reference capture plant uses heat at a rate of 1,705 MMBtu per hour to capture 415 tons of CO_2 per hour. The Texas City capture plant will capture 125 tons CO_2 per hour. The corresponding heat requirement for the Texas City capture plant is estimated to be 514 MMBtu per hour (125/415 x 1705 MMBtu). At 8,000 hours per year, the heat requirement is 4,108,433 MMBtu per year, or 4.108 MMBtu per ton CO_2. (Interview by Cyrus Tashakkori with Gary T. Rochelle, Grobbe Professor of Chemical Engineering, Department of Chemical Engineering, The University of Texas at Austin, March 20, 2006). The base case assumes fuel cost for heat production of 6 dollars per MMBtu (Interview by Michael Hoffman with David Burns, Manager, Business Development, Praxair Inc., Austin, Texas, April 3, 2006).

[a] Annual plant maintenance cost is estimated at 3 percent of the capital cost of the capture plant and compressor (Rochelle interview).

[b] The MEA reagent and water costs were calculated using the $7.5 million annual cost of the reference plant and scaling down for CO_2 per hour using the 125/415 factor (Rochelle interview).

Costs to the EOR Producer

Overall cost can be determined by calculating capital cost and annual cost, and comparing these amounts to expected revenue under an assumed discount rate. The previously detailed base case assumptions that lead to capital and operating costs are detailed in Table 7.3. For the BP refinery and the Hastings-West Frio field case study, construction of the CO_2 capture plant will take two years and construction of the pipeline, the EOR recycling plant, and the reworking of all EOR wells will all take place during the second year, thus the capital costs are budgeted only for these first two years. Capital costs, including the capture plant, compressor, well re-working, and pipeline construction, are estimated to be $60 and $90 million over the first two years, or $138 million in discounted costs.

Annual operating costs make up a significant portion of the total project cost. Because of the construction projects occurring over the first two years, there is no annual operating cost included in the cost estimate for the first two years, only capital cost. Excluding taxes, the annual costs of the project for all other years (including capture, compression, transportation, and injection of CO_2, as well as maintenance and operations of the pipelines) are estimated to be $35 million per year. Total annual and capital cost over a 25 year discounted horizon are calculated to be $349 million.

Revenues to the EOR Producer

Based on the production assumptions in Table 7.3 and including no government subsidies for capital and annual project costs, revenues outpace the previously discussed capital and annual operational expenses after the first two years. Based on previous EOR projects, this case assumes that 17 percent of the oil recoverable in the given field can be produced through CO_2 EOR.[79] Based on this percentage, at the Hastings-West Frio field there are 215 million barrels of oil available for EOR recovery, of which it is possible to recover 97 million barrels over the project's 25 year horizon. This would create 3.89 million barrels of production per year, resulting in revenue of $213.9 million per year. Total revenue with the current assumptions comes out to $4.9 billion over 25 years, or $900 million in present value terms (see Table 7.7).

Table 7.7
Revenue: Hastings Field Enhanced Oil Recovery Case Study

Item	Metric	Case Study Value
Total oil in well	Bbls	1,265,296,000
Available for recovery[a]	Bbls	189,794,400
Recovered per year	Bbls	3,890,000[b]
Total recovered (25 year horizon)	Bbls	97,250,000[c]
Revenue per year	US $	213,950,000[d]
Net Present Value of Revenues	US $	900,160,244

Sources and notes:

[a] This assumes 17 percent of the total oil in the field is available for recovery. Source: Mark Holtz , "Gulf Coast CO_2 Enhanced Oil Recovery Case Studies," Presentation at the Bureau of Economic Geology, The University of Texas at Austin, February 10, 2006.

[b] This value assumes 3.89 bbls/ ton of CO_2 and 1,000,000 tons of CO_2 available per year. Source: Mark Holtz, Vanessa Lopez, Caroline Breton, "Moving Permian Basin Technology to the Gulf Coast: the Geologic Distribution of CO_2 EOR Potential in Gulf Coast Reservoirs," West Texas Geological Society Publ. #05-115, Fall Symposium, October 25-27, 2005, p. 6.

[c] This value is calculated using 3,890,000 bbls/yr x 25 yrs.

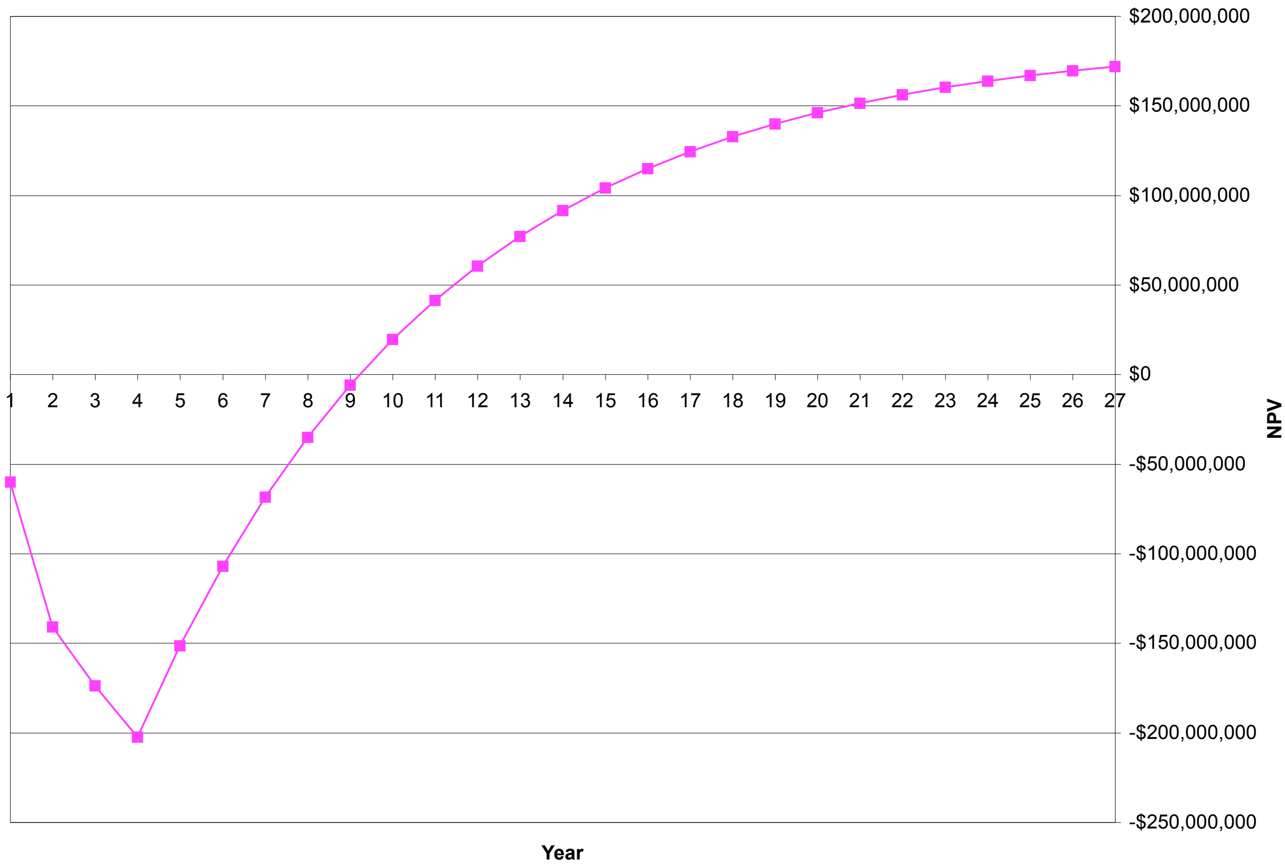
[d] Based on base-case assumption of $55/bbl.

[e] Based on base-case assumption of 15% discount rate over 25 years.

Profits to the EOR Producer

Because of issues related to construction and the amount of time it takes to initially produce oil on an EOR project, profit realized in this case study does not become positive until the fifth year. Annual profit is estimated to be around $150 million per year, or $3.4 billion over the project horizon. Discounting the profit at 15 percent over the 25-year horizon and accounting for all federal, state and local taxes on production and land value, total profit is estimated to be approximately $172 million over the life of the project before any government subsidies are incorporated. Based on this profit and the initial capital costs, the EOR project at Hastings West Frio pays for itself at some point during the ninth year of the project horizon (see Figure 7.2).

Figure 7.2
Net Present Value of Base Case over Time



Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

Local, State, and Federal Government Benefits

Direct taxation benefits to local, state and federal government from oil production are significant, and can be derived based on existing statutes and prediction of oil production. Based on a severance tax rate of 2.3 percent and an ad valorem tax rate of $1 per $100 wellhead value, the state would see a direct increase in annual revenues of several hundred million dollars over the 25-year project horizon. Furthermore, federal tax revenues would also be substantial, and would total in excess of $1 billion over the 25 year project horizon.

Severance taxes are taxes on wellhead production, and would be payable to the state. Currently, the severance tax rate on EOR-produced oil is one-half of the regular severance tax rate (4.6 percent of fair market value) on oil and gas, or 2.3 percent.[80] The exemption currently runs through 2008, and it is reasonable and constructive to assume that it will continue beyond this date. Based on the rate of 2.3 percent, the state can expect approximately $113 million in total direct tax revenue from the project. This revenue stream would coincide with production and thus begin in the fourth year. Texas could also expect to gain significant sales tax revenue from the purchase of equipment relating to the project's infrastructure.

The local ad valorem tax on the carbon capture and storage operator is based on local property tax rates appraisals of property value, as property tax is a revenue source for local governments. In the case of property containing oil and gas reserves, total value of the inventory of oil and gas in reserve is usually based on current projections of future oil prices and a 5.7 year horizon for expected production of a field. Based on this valuation of property, a locality typically taxes a wellhead value at a rate between $1-$2 per $100 of total assessed wellhead value.[81] Any local ad valorem tax rate can vary over a project's life, so it is difficult to predict until production is initiated. However, based on existing rates, it is reasonable assume that approximately 3.95 percent of yearly revenue will be directed to property taxes.[82] This creates direct tax revenue in Brazoria County of approximately $8 million per year, or $211 million in direct tax revenue over the life of the project.

Carbon capture and storage operators will incur federal income tax obligations. Assuming an income tax rate of approximately 35 percent,[83] the federal government could receive $48 million per year, or $1.1 billion in total tax revenue.

Economic Input/Output Analysis

Texas uses economic impact statements to estimate the direct and indirect value of changes in output of a given sector on other sectors of the state economy, often through input/output models. An input/output model is a representation of the flows of economic activity among sectors within a region and can be used to estimate how investments in any sector generate dollar-value changes in the output of various economic sectors.[84] Of these models, one of the most widely used is the MI/REC IMPLAN (Impact Analysis for Planning) system, which projects economic impacts on local and state jurisdictions based on industry multipliers and recent census data. The IMPLAN model was originally developed for the U.S. Forest service in 1993. One reason to use IMPLAN on natural resource related issues is that it provides greater disaggregation of natural resource sectors than do most other input-output models.[85] The results of the IMPLAN calculations include localized economic effects on output, employment, total economic value added, and indirect tax benefits to federal, state and local jurisdictions. Some of these projections for the Hastings-West Frio Case Study are included in Appendix A.

According to an IMPLAN model using Social Accounting Matrix (SAM) multipliers for Brazoria County and the State of Texas, the total economic output (as a result of the construction of the capture plant, pipeline, and recycling plant for the Hastings project) is estimated to be approximately $246 million in direct, indirect, and induced revenue in all 508 of the model's sectors. Furthermore, construction would result in approximately 2,200 full or part-time jobs, 1,300 of which are expected to be in the oil and gas industry or construction industry (see Appendix A, Tables 1 and 2).

It is difficult to predict with certainty the amount of revenue that will be spent within Texas or in local communities over a horizon of 25 years for a project that is likely to utilize a number of imported products.[86] However, based on existing multipliers for oil and gas industry production, one year's revenue of $213,950,000 would be expected to create $247,907,611 in direct, indirect, and induced economic impacts within the state. Furthermore, the increase in production would be expected to lead to 832 part-time and full-time jobs (231 of those in oil and gas extraction) and a $39 million increase in statewide labor force compensation (see Appendix A, Tables 3 and 4). Assuming that the multipliers and revenue stay somewhat constant over time, these could grow significantly over the project horizon.

Despite the difficulty inherent in economic analysis of an innovative project over an extended time horizon, these numbers indicate that the capital costs invested in plant construction and infrastructure are likely to translate into a significant number of direct, indirect and induced full and part time jobs being created within the Brazoria County area. The oil and gas sector already employs approximately 10,000 people in Brazoria County; additions in employment in this sector will further secure its role within the area's economy.[87] Since the project construction appears to lead to significant employment impacts in the Industrial Construction and Oil and Gas sectors, a carbon capture and storage industry is likely to increase long-term job security for those in the oil and gas sector. In contrast, employment effects derived from one year's production are considerably lower, and may vary over the project's time horizon, depending on factors such as changes in technology. These effects will be of less consequence over time.

The output effects detailed above indicate that both construction and a single year's production will contribute to increases in total value added to final demand in a number of sectors. The highest increases in economic output will be achieved in the oil and natural gas sectors. Other sectors can expect to see significant indirect and induced gains as a result of the increase in investment and production as well. Based on a completed output effects of production from a single year, it appears that over the full project horizon a carbon capture and storage industry is likely to produce positive economic impacts for the region.

Sensitivity Analysis

Once the expense and revenue sources have been identified, a sensitivity analysis can reveal opportunities for policies that will promote investment in a carbon capture and storage industry. As discussed above, the base case assumes a 15 percent discount rate, oil prices at $55 per barrel, and energy costs for CO_2 capture at $6 per million British thermal units (MMbtu). Indeed, Figure 7.5 illustrates the project's IRR of about 25 percent under base case assumptions.

The economic outlook of the Texas City case study is particularly sensitive to changes in the discount rate. Discount rates ranging from 10 percent to 25 percent were examined. The resulting NPV ranges from a low of -$3,276,573 at a 25 percent discount rate to a high of $379,897,631 at a 10 percent discount rate. The time horizon for returns on the investment ranges from 8 years to 27 years. The base case IRR is immune to changes in discount rate, as it is essentially the discount rate at which the NPV would equal zero over the life of the project (see Figure 7.3 and 7.4).

Figure 7.3
Net Present Value-Discount Rate Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

Figure 7.4
Time Horizon-Discount Rate Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

The economic outlook of the case study is sensitive to changes in fuel cost. Fuel costs ranging from $2/MMBtu to $18/MMBtu were examined. The resulting NPV ranges from a low of -$16,003,118 at $18/MMBtu to a high of $234,439,665 at $2/MMBtu. The time horizon ranges from 7 years to 27 years. The IRR ranges from 14 percent to 29 percent (see Figures 7.5, 7.6, and 7.7).

Figure 7.5
Net Present Value-Fuel Cost Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

Figure 7.6
Time Horizon-Fuel Cost Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

Figure 7.7
Internal Rate of Return-Fuel Cost Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

The economic outlook of the case study is also responsive to the price of oil. The oil price was examined in a range of $45/Bbl to $65/Bbl. The NPV ranged from $84,562,013 at $45/Bbl to $259,095,924 at $65/Bbl. The time horizon ranged from 7 years to 12 years, and the IRR ranged from 20 percent to 29 percent (see Figures 7.8, 7.9, and 7.10).

Figure 7.8
Net Present Value-Oil Price Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

Figure 7.9
Time Horizon-Oil Price Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

Figure 7.10
Internal Rate of Return-Oil Price Sensitivity Analysis

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

Three alternate scenarios were explored. The first would involve a doubling of natural gas prices to $12/MMbtu and a long-term increase in oil prices to $65/Bbl. The second doubles natural gas prices to $12/MMbtu while oil prices drop to $50/Bbl. The third case reduces natural gas prices (or the availability of heat from other less-expensive fuel sources) to $2/MMbtu and increases oil prices to $60/Bbl (see Table 7.8).

Table 7.8
Alternative Scenarios and Outcomes

Item	1	2	3
NPV	$165,179,881	$34,279,447	$278,073,142
IRR	23%	17%	31%
Time Horizon	9 years	16 years	7 years

Source: Calculations by authors Cyrus Tashakkori and Charlie Stern.

This analysis indicates that the financial outlook of such a project would look favorable given current trends in the global price of oil. Alternately, the financial attractiveness diminishes slightly due to volatility in natural gas prices. Similar projects using coal rather than natural gas to fuel the capture process can serve to allay concerns over fuel costs and further increase the financial attractiveness of such a project. While the financial attractiveness of this project is sensitive to discount rate, the project remains attractive using reasonable discount rates as high as 15 percent.

Sequestration

Oil production revenues generated from this EOR project are more than enough to cover the capture, transport, and operating costs and yield a profit. The purpose of this section is to determine the viability of using infrastructure developed for EOR to establish a long-term CO_2 storage project at the Hastings West Frio reservoir.

One rationale for state support of EOR projects is the potential for long-term sequestration of CO_2 underground. Without an incentive provided by CO_2 markets, a sequestration industry is unlikely to develop on its own. If the infrastructure costs associated with capturing and transporting CO_2 to appropriate reservoirs are paid for through revenues generated from EOR, sequestration could become profitable at lower CO_2 captures cost rates.

The Hastings field has an area of 20 square miles, is 163 feet thick, and has 30 percent porosity.[88] Based on these values and an assumption of volume/volume replacement of produced oil by CO_2, it is estimated that the storage potential of the Hastings field is 68,725,286 tons of CO_2.[89] This is a low value, as the basic volumetric area vacated by the oil would allow for approximately 680 million tons of CO_2, a 10-fold difference. In other words, the potential for long-term CO_2 storage at Hastings is vast, much larger than necessary to store annual CO_2 emissions from the Texas City refinery for the next century. There would be more than enough space to store the base-case volume of 1 million tons of CO_2 per year from the BP refinery over the next 25 years, for a total of 25 million tons over the life of the sequestration project.

After the end of the EOR phase, the marginal cost of sequestration would include only those operating costs directly involved with capturing and injecting CO_2 for sequestration. This case assumes that capital costs will have been paid for with revenues from EOR. The cost of capturing and sequestering CO_2 in this case is approximately $30.53 per ton.

Carbon Credits

No firm would incur sequestration costs without an incentive, and the only likely future source of incentive would be carbon emission reduction credits. CO_2 credit prices have risen as various actors have developed emission reduction systems. Credits in the EU market in February 2006 ranged from $31 to $32/ton.[90] In regions without established greenhouse gas emission regulations and mandatory trading programs, such as the U.S., prices remain low. The Chicago Climate Exchange, a voluntary trading program, traded credits at approximately $2.00 per ton during this same period.[91] Recent trades of carbon credits for EOR/geologic sequestration in Texas have ranged from $1.00 for voluntary emissions trading programs to $5.00 for mandatory programs.[92]

The process of calculating stored CO_2 volumes for credit is not easy as a manager must first count total emissions stored and then deduct indirect emissions from the capture and storage process. Indirect emissions result from the energy use required for the capture and compression processes. These energy investments in CO_2 separation, transfer, and use from EOR would be subtracted from the total amount stored, because emissions are generated in producing this energy. Once indirect emissions have been subtracted from the total captured volume, the result is the total avoided emissions. Avoided emissions are used to calculate the total number of credits awarded to a project. Over the life of this project, 25 million tons of CO_2 are stored. Indirect emissions represent 41.6 percent of this total or 10.4 million tons. Thus the avoided emissions total 14.6 million tons of CO_2. With a total cost of $30.53 per ton of CO_2 captured, this makes the cost of CO_2 avoided $52.27 per ton (see Table 7.9). Because credits are provided only for CO_2 avoided, it is the cost for CO_2 avoided that is ultimately used to determine whether a sequestration project will be profitable.

Table 7.9
Emissions from Capture and Compression

Capture energy use per ton captured[a]	482 kWh/ton CO_2
Compression energy use per ton captured[b]	111 kWh/ton CO_2
Total energy use per ton captured	593 kWh/ton CO_2
Texas CO_2 emission factor[c]	0.702 tons CO_2/kWh
Total indirect emissions per ton captured[d]	0.416 tons
Total tons CO_2 captured	25,000,000
Total tons CO_2 avoided	14,600,000
Cost CO_2 per ton captured	$30.53
Cost CO_2 per ton avoided[e]	$52.27

Sources and notes:

[a] Interview by Cyrus Tashakkori with Gary T. Rochelle, Grobbe Professor of Chemical Engineering, Department of Chemical Engineering, The University of Texas at Austin, March 20, 2006.

[b] Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage* (September 2005, p. 117). Online. Available: http://www.ipcc.ch/activity/ccsspm.pdf. Accessed: November 12, 2005.

[c] U.S. Department of Energy, Energy Information Administration, *Updated State-level Greenhouse Gas Emission Factors for Electricity Generation, March 2001*. Online. Available: http://tonto.eia.doe.gov/FTPROOT/environment/e-supdoc.pdf. Accessed: April 11, 2006.

[d] Total indirect emissions per ton captured is calculated by multiplying total energy use per ton captured by the Texas-specific electricity generation emission factor for CO_2.

[e] Cost of CO_2 per ton avoided is calculated by calculating the total cost of capturing 25 million tons of CO_2 (25,000,000 x $30.53) and dividing by the total tons avoided (14,600,000).

With current carbon credit prices ranging from $1 to $5 per ton for carbon credits in the U.S., far below the case's CO_2 avoided costs of $52.27 per ton, sequestration without oil production will not be a profitable option. Even though carbon credits have reached the $30-range in Europe, there is little chance of that happening in the U.S. in the foreseeable future. The remaining barriers for creating a profitable sequestration industry once EOR has been developed will be carbon credit prices and the high energy costs associated with carbon capture.

Conclusion

This case study demonstrates the economic and technical feasibility of capturing anthropogenic CO_2 in the Gulf Coast region of Texas and using it to enhance oil recovery and storing it in a depleted oil field over a 25-year period. The technology for such a project exists. Similar carbon storage projects have been conducted successfully. However, there are still many risks that make investors wary. The first set or risks are economic. There is no guarantee what the price of oil and natural gas will be in the near future; uncertainty increases the further into the future one speculates. The significant capital investment that such a project requires means that the long-term financial evaluation of net present value on returns of the investment is subject to risk. If delays occur between initial CO_2 injection and the first oil recovered, the economic return on the investment can appear to shrink quickly. Another set of risks are political. There is no definitive set of regulations specifying how such a project should be conducted and what rules apply to each phase. There is a risk of public opposition if a project is seen as representing a significant threat to human health or to the environment. This uncertainty adds to the calculation of risk that any potential investor will consider when evaluating a CO_2 EOR project.

There are ways to address each risk. Potential policy solutions to the economic risks associated with the project include bond-financing of all or part of the capital investments, tax relief specifically for capital investments for EOR projects with industrial carbon capture or creation of a market for tradable permits of CO_2. A potential policy solution to the political risks associated with the project is the passage of a comprehensive set of regulations delineating all pertinent standards, procedures and authorities related to each step of the project's process from capture to sequestration. Such a set of regulations could include a public information clause stipulating the free flow of information concerning public health and environmental risks associated with the transport and storage of CO_2. The potential benefits that such a project would have for the local and state economy and for the environment could be articulated as clearly as the risks.

The case study also demonstrates the potential that EOR projects represent in laying the foundation in order to facilitate geologic sequestration of CO_2 in the Gulf Coast region of Texas. With the capture plants, pipelines and injection facilities in place, the marginal costs of a regional sequestration program would be reduced, making a carbon capture and storage industry a viable economic option for addressing the problem of climate change.

Notes

[1] Class presentation by Ian Duncan, Associate Director, Bureau of Economic Geology, The University of Texas at Austin, at the Lyndon B. Johnson School of Public Affairs, October 4, 2005.

[2] Railroad Commission of Texas, *Interactive Data.* Online. Available: http://www.rrc.state.tx.us/interactive_data.html. Accessed: March 15, 2006.

[3] Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

[4] Ibid.

[5] Interview by Michael Hoffman with Mark Holtz, Research Associate, Bureau of Economic Geology, The University of Texas at Austin, October 5, 2005.

[6] Interview by Cyrus Tashakkori with Gary T. Rochelle, Grobbe Professor of Chemical Engineering, Department of Chemical Engineering, The University of Texas at Austin, March 20, 2006.

[7] Interview by Michael Hoffman with David Burns, Manager, Business Development, Praxair Inc., Austin, Texas, April 3, 2006.

[8] Rochelle interview.

[9] Ibid.

[10] Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

[11] Railroad Commission of Texas, *RRC Public GIS Map Viewer.* Online. Available: http://gis2.rrc.state.tx.us. Accessed: March 24, 2006.

[12] Ibid. Accessed: February 13, 2006.

[13] Texas Natural Resources Code, Title 3, ch. 111, subchapter A, rules 111.002 and 111.003. *Texas Legislature Online*. Online. Available: http://www.capitol.state.tx.us/statutes/nr.toc.htm. Accessed: March 7, 2006.

[14] Texas Natural Resource Code, Title 3, ch. 111, subchapter B, rule 111.020.

[15] Ibid.

[16] Texas Natural Resource Code, Title 3, ch. 111, subchapter B, rule 111.022.

[17] Texas Natural Resource Code, Title 3, ch. 111, subchapter B, rule 111.021.

[18] Texas Natural Resource Code Title 3, ch. 111, subchapter B, rules 111.019, 111.0191, and 111.0193.

[19] Telephone interview by Spencer Bytheway with Lynn Henrie, Program Manager, Northwest Pipelines, Salt Lake City, Utah, February 10, 2006.

[20] BusinessWire, "Denbury Replaces over 300% of Its Production in 2005, Increases Proved CO_2 Reserves by 74%," *Forbes*. Online. Available: http://www.forbes.com/execpicks/businesswire/feeds/businesswire/2006/01/26/businesswire20060126006004r1.html. Accessed: February 13, 2006.

[21] J. Barrie, K, Brown, P.R. Hatcher, and H.U. Schellhase, "Carbon Dioxide Pipelines: A Preliminary Review of Design and Risks," 7th International Conference on Greenhouse Gas Control Technologies, p. 2. Online. Available: http://uregina.ca/ghgt7/PDF/papers/peer/126.pdf. Accessed: February 7, 2006.

[22] Rena Koinis, "San Andres Scaling Program," Kinder Morgan, Houston, Texas, updated 2001 (Excel model).

[23] Joan M. Ogden, "Modeling Infrastructure for a Fossil Hydrogen Energy System with CO_2 Sequestration" (The Energy Group, Princeton Environmental Institute, p. 4). Online. Available: http://www.princeton.edu/~energy/publications/pdf/2002/Ogden_Kyoto_02.pdf. Accessed: February 14, 2006.

[24] Kay Damen, Andre Faaij, Frank van Bergen, John Gale, and Erik Lysen., "Identification of Early Opportunities for CO_2 Sequestration—Worldwide Screening for CO_2-EOR and CO_2-ECBM Projects," *Energy,* vol. 30, no. 10 (July 2005), p. 1945. Online. Available: http://www.sciencedirect.com. Accessed: December 19, 2005.

[25] Koinis, "San Andres Scaling Program."

[26] Texas Administrative Code, title 16, part 1, ch. 8, subchapter D, rule 8.305. Online. Available: http://info.sos.state.tx.us/pls/pub. Accessed: February 14, 2006.

[27] Joan M. Ogden, "Hydrogen Energy Systems Studies" (U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy, p. 17). Online. Available: http://www.eere.energy.gov/hydrogen andfuelcells/pdfs/26938xx.pd. Accessed: February 7, 2006.

[28] Sam Wong, "CO_2 Compression and Transportation to Storage Reservoir" (The Delphi Group, p. 4). Online. Available: http://www.delphi.ca. Accessed: March 31, 2006.

[29] Ibid.

[30] W. L. Mercer, "Materials Requirements for Pipeline Construction," *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences,* vol. 282, no. 1307 (July 8, 1976) p. 44. Online. Available: http://www.jstor.org. Accessed: March 24, 2006.

[31] Railroad Commission of Texas, *Pipelines*. Online. Available: http://www.rrc.state.tx.us. Accessed: February 14, 2006.

[32] Texas Administrative Code, title 16, part 1, ch. 8, subchapter B, rule 8.115.

[33] Texas Administrative Code, title, 16, part 1, ch. 8, subchapter D, rule 8.310.

[34] Texas Administrative Code, title, 16, part 1, ch. 8, subchapter D, rule 8.315.

[35] Texas Administrative Code, title, 16, part 1, ch. 8, subchapter D, rule 8.301.

[36] Texas Administrative Code, title, 16, part 1, ch. 8, subchapter D, rule 8.305.

[37] Barrie, Brown, Hatcher, and Schellhase, "Carbon Dioxide Pipelines," pp. 1-6.

[38] Perry D. Bergman, Edward M. Winter, and Zhong-Ying Chen, "Disposal of Power Plant CO_2 in Depleted Oil and Gas Reservoirs in Texas," *Energy Conversion and Management*, vol. 38, supp. (1997), p. S216.

[39] Ibid., p. S215.

[40] Kristian Jessen, Anthony Kovscek, and Franklin M. Orr, "Increasing CO_2 Storage in Oil Recovery," *Energy Conversion and Management*, vol. 46 (February 2004), p. 294.

[41] Bergman, Winter, and Chen, "Disposal of Power Plant CO_2," p. S214.

[42] Ibid., p. 294.

[43] Ibid.

[44] Bergman, Winter, and Chen, "Disposal of Power Plant CO_2," pp. S214-S217.

[45] Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

[46] Ibid.

[47] Ibid.

[48] Ibid.

[49] Duncan class presentation.

[50] Kipp Coddington, "Legal, Regulatory and Policy Issues," 10th Annual CO_2 Flooding Conference, Midland, Texas, December 7-8, 2004. Online. Available: http://www.spepb.org/images/pdf/EOR CarbonMgtWorkshop/WednesdayPDFFiles/5-Coddington.pdf. Accessed: November 12, 2005.

[51] Ibid.

[52] Handbook of Texas Online, *Mineral Rights and Royalties*. Online. Available: http://www.tsha. utexas.edu/handbook/online/articles/MM/gym1.html. Accessed: November 12, 2005.

[53] Ibid.

[54] Bergman, Winter, and Chen, "Disposal of Power Plant CO_2" p. S215.

[55] Ibid., p. S215.

[56] Ibid., p. S215.

[57] Ibid., p. S215.

[58] Anthony R. Kovscek and Y. Wang, "Geologic Storage of Carbon Dioxide and Enhanced Oil Recovery: I. Uncertainty Quantification Employing a Streamline Based Proxy for Reservoir Flow Simulation," *Energy Conversion and Management*, vol. 46 (September 2004), p. 1921.

[59] Ibid.

[60] Ibid.

[61] Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

[62] Mark Holtz , "Gulf Coast CO_2 Enhanced Oil Recovery Case Studies," Presentation at the Bureau of Economic Geology, The University of Texas at Austin, February 10, 2006.

[63] Mark Holtz, Vanessa Lopez, and Caroline Breton, "Moving Permian Basin Technology to the Gulf Coast: the Geologic Distribution of CO_2 EOR Potential in Gulf Coast Reservoirs," West Texas Geological Society Publ. #05-115, Fall Symposium, October 25-27, 2005, p. 6.

[64] Ibid.

[65] Railroad Commission of Texas, *Underground Injection Control Seminar.* Online. Available: http://www.TRC.state.tx.us/divisions/og/uic/manual/HTML/man-chp1.htm. Accessed: December 6, 2005.

[66] Ibid.

[67] Ibid.

[68] Ibid.

[69] Ibid.

[70] Ibid.

[71] Ibid.

[72] Intergovernmental Panel on Climate Change (IPCC), *Carbon Dioxide Capture and Storage* (September 2005, p. 259). Online. Available: http://www.ipcc.ch/activity/ccsspm.pdf. Accessed: November 12, 2005.

[73] Ibid.

[74] Ibid.

[75] Ibid.

[76] Rochelle interview.

[77] Kevin S. Fisher, Carrie Beitler, Curtis Rueter, Katherin Searcy, Gary Rochelle, and Majeed Jassim, "Integrating MEA Regeneration with CO_2 Compression and Peaking to Reduce CO_2 Capture Costs," (Trimeric Corporation and U.S. Department of Energy: National Energy Technology Laboratory). Online. Available: http://www.trimeric-corp.com/Report%20060905.pdf. Accessed: April 20, 2006.

[78] Rochelle interview.

[79] Holtz presentation.

[80] Texas Railroad Commission, Oil and Gas Division, *Severance Tax Exemptions and Reductions as Incentives to Increasing Texas Oil and Gas Production*. Online. Available: http://www.rrc.state.tx.us/divisions/og/notices-pubs-swr/notices/ogpn24.html. Accessed: October 23, 2005.

[81] Texas Oil and Gas Association, "A Guide to State and Local Taxation" (Houston, Tex., 2003), p. 45.

[82] Interview by Charlie Stern with Jon Hockenyos, Managing Director, and Travis James, Director, TxP Economic Consultants, Austin, Texas, April 11, 2006.

[83] Tax rate based on "Kinder-Morgan CO_2 Flood Scoping Model Spreadsheet" (2001), from Mark Holtz, Bureau of Economic Geology, The University of Texas at Austin (spreadsheet).

[84] William H. Miernyk, *The Elements of Input-Output Analysis* (New York: Random House, 1965), p. 22.

[85] Alberta H. Charney and Julie Leones, "IMPLAN's Induced Effects Identified Through Multiplier Decomposition," *Journal of Regional Science,* vol. 37, no. 3 (1997), p. 503.

[86] Hockenyos and James interview.

[87] U.S. Census Bureau, *2002 United States Economic Census*. Online. Available: http://www.factfinder.census.gov. Accessed: February 14, 2005.

[88] Bureau of Economic Geology, The University of Texas at Austin, "Reservoir Candidates Spreadsheet" (2005), from Mark Holtz (spreadsheet).

[89] Ibid.

[90] Point Carbon, *Carbon Market Daily,* vol. 2 no. 50 (March 10, 2006). Online. Available: http://www.pointcarbon.com/wimages/CMD20060310a.pdf. Accessed: March 19, 2006.

[91] Chicago Climate Exchange, *CCX Carbon Financial Instruments: February 2006*. Online. Available: http://www.chicagoclimatex.com/trading/stats/monthly/st_0602.html. Accessed: March 19, 2006.

[92] Interview by Kate Larsen with Bill Townsend, Chief Executive Officer, Blue Source, LLP, Salt Lake City, Utah, March 21, 2006.

Chapter 8. Conclusions and Policy Recommendations

Texas is in a unique position to develop a CO_2 geologic storage industry with the co-benefit of enhanced oil recovery, as it is the state which is the largest producer of CO_2 in the U.S. and with the largest potential for CO_2-based EOR production. Despite current high oil prices, both technical and economic barriers exist to CO_2 EOR projects. This report has sought to identify the potential for CO_2 capture and storage and the barriers to development of the industry. This chapter describes some policies that can help overcome barriers that currently hinder projects.

Texas now finds itself on the downward slope of its oil production peak. Declining oil production translates to declining contributions of the oil industry to the Texas economy and represents a lost revenue stream to the state. There is considerable potential for Texas government action to stimulate both EOR and carbon capture, as the state itself could gain by providing incentives for infrastructure development. State assistance with the costs and capital investment as well as short term tax and royalty relief for EOR could induce companies to create a pipeline infrastructure, which in turn could potentially provide jobs and increase oil royalties.

As sequestration of greenhouse gases, especially CO_2, becomes a more viable option for reducing its release to the atmosphere, geologic storage may emerge as the most reliable option. With its abundant potential storage sites in close proximity to emission sources, Texas would be a beneficiary of emissions trading programs, especially if the capture and transportation infrastructure were already in place due to EOR ventures. EOR can facilitate the investment in the infrastructure for geologic sequestration if and when national carbon emission policies tighten or sufficient capture or trading incentives make non-EOR sequestration profitable. If CO_2 trading incentives make non-EOR sequestration profitable, Texas could move rapidly to store CO_2 underground.

Although widespread carbon capture from industrial sources has not been realized in Texas, national emission regulations and trading markets may make capture economical. In the near-term, chemical absorption of CO_2 from PC flue gases may be a feasible choice for carbon capture in the Texas Gulf Coast. In the long-term, improving technologies and shifting to IGCC systems would make more economical and efficient carbon capture possible.

Policy Recommendations

Table 8.1 lists potential actions that federal, Texas, and local governments could take to enhance the likelihood of a carbon capture and storage industry. Each option is discussed below. These options are considered as alternatives for discussion. This report does not endorse or oppose any specific policy option for adoption by federal, Texas, or local governments.

Table 8.1
Policy Options to Assist CO_2 Capture and Storage

Instrument	Option
Federal income tax	Waive income tax until investment reimbursed by oil income; another option would be rapid investment depreciation
Federal CO_2 credits	A federal "credit" could be given for every ton of CO_2 sequestered
Federal incentive	A federal incentive payment could be awarded per ton of CO_2 sequestered
Federal demonstration grant	Demonstration grants to support development of advanced carbon capture and storage technology
Texas Carbon Capture Board	Texas could establish an agency to borrow money that could be lent to entities that wish to invest in carbon capture and storage converting an up-front capital expense to an annual operating expense
Texas resolution of long-term liability	Texas could adopt rules to clarify long-term CO_2 industry liability
Oil reservoir unitization	Texas could require unitization of multiple owner-oil fields to promote CO_2 capture and storage
Royalty relief	Reduction of royalty rates below the current 12 percent
County and local tax relief of ad valorem taxes	Reduction or relief of count or local government ad valorem taxes until investment is repaid by production

Source: Complied by the authors.

Federal Policies

This report has not focused on federal policies towards carbon capture and storage, in part because this field has not been the federal government's comparative advantage. The federal government can use its tax system, its research program and its capacity to develop a carbon credit system to encourage CO_2 capture and storage. The incentives described below are neither novel nor particularly interesting, but they are included for the sake of completeness.

Emissions Trading

It is possible that some day the U.S. federal government could decide to establish a cap on the volume of greenhouse gases that can be emitted from a specific industrial source. This is already taking place in some other nations through the Kyoto Protocol and is being considered by states in the northeastern U.S. as well as California. An emissions trading program would allow industries not in compliance (that exceed the mandatory cap) to buy "credits" from industries that are below the cap. Firms would have an incentive to buy credits if the cost per ton was below the marginal cost of the capital expenditures that it would take to reduce their emissions. The federal government could develop and manage a credit system to encourage CO_2 sequestration, either as a demonstration or as a permanent program.

Incentives

EOR and sequestration could contribute to reducing the country's dependence on foreign sources of energy as well as reducing carbon emissions. To encourage EOR and sequestration the federal government could offer cash incentives to developers that invest in EOR and sequestration.

Demonstration Grant

The federal government could increase the size and scale of research and demonstration grants it already provides to develop and test new technology for carbon capture and storage. Grants could subsidize capital costs associated with retrofitting existing industrial sources with the necessary capture and compression equipment to provide a CO_2 source for EOR and sequestration.

What would federal incentives mean to a carbon capture and storage industry? When the federal government acts, everyone listens: the states, the private sector, and other nations. If the federal government were to encourage carbon capture and storage through any and all of these means, one topic, the "incentives for carbon capture and storage" becomes a legitimate topic of study, practice, and inquiry. These particular four incentives may or may not encourage significant private sector investment, as they represent a "typical" federal response, comparable to ideas used to initiate sulfur oxide controls in the 1970s. It is not easy to say, in retrospect whether U.S. President's Council on Environmental Quality's 1972 legislative report[1] recommending a sulfur oxide initiative can be credited with an causal force behind the eventual widespread adoption of sulfur oxide controls, but there is no doubt that the focus on the topic helped. The implementation of these four ideas related to carbon capture and storage would convey a similar message that the U.S. federal government is serious on its intent to control CO_2 discharges into the atmosphere. States and private industry may re-align their expectations and foreign governments and industries would be likely to be as influenced by such an initiative as they have been by previous U.S. federal government leadership in residuals control.

State Policies

The focus of this report has been on the State of Texas, because of the belief that the state through its legislation and executive agencies has the capacity to help establish a global carbon capture and storage industry through the actions they take to provide incentives to Texas-based investments in moving CO_2 from polluting industries to its reuse in EOR. The policies proposed below are intended to encourage near-term investment by Texas' oil and gas industries in carbon capture and storage.

Texas Carbon Capture Board

CO_2 capture is a nontraditional and nonessential function for many point sources, such as power plants and refineries. Some uncertainty surrounds the risks and benefits available from capturing CO_2 for EOR. State administered loans and grants could play an important role in mitigating these concerns. Low-interest loans could provide emitting entities sufficient incentive to invest in technology that would provide them with a secondary source of income. To the degree that the state is willing to share some of the risks associated with a carbon capture and storage project, operators may be more likely to invest in capture, compression and transport technology.

The Texas Water Development Board (TWDB), an executive agency responsible for administering state water policy, provides a model that could be followed for administering Texas EOR policy. The TWDB provides oversight, funding, and other assistance for local water development projects. It receives authorization and funding from the Texas Legislature, and is overseen by a Board appointed by the Texas Governor. The Legislature could authorize a new agency, the Texas Carbon Capture Board (TCCB), to perform a similar function with regards to EOR in Texas. The Board could guide local policies and provide state level funding, in the form of grants and loans, and administer policies that would provide incentives for EOR.

The TCCB could borrow funds from the private capital market guaranteed by Texas' state credit rating, Texas' taxation authority, and the assurance that revenue from carbon capture and storage would repay the loans. The TCCB could provide loan funds to appropriate entities that engage in CO_2 capture and storage.

The TCCB would be able to make capital available at much lower rates than the private market based on two assumptions: (a) the cost to Texas to raise capital will be much lower than the private market and (b) the private capital market would provide credit for CO_2 capture, compression, transmission and storage at a high rate because there are risks associated with every element of the process. Even if the TCCB set the rates of its funds at a premium above its costs of capital, the rates would be attractive to industry; risk-sharing by the State of Texas would be welcomed. If the TCCB loaned funds at a premium, the difference in rates could generate the funds needed to support the TCCB, so the net cost of the TCCB's operation to the citizens of the State of Texas could be zero or close to zero.

A TCCB could assist any of the clients of a CO_2 carbon capture and storage industry, as discussed below. With any firms that engage in CO_2 capture, TCCB could provide low interest loans to provide incentives for power plants and other point sources of CO_2 to invest in capture technology. For companies whose business is CO_2 compression, TCCB could provide low interest loans, guaranteed by the state, which could make the risk and cost of barriers less daunting. Like capture technology, CO_2 compressors comprise a significant cost barrier to an EOR project. While oilfield operators may not need much incentive to build a pipeline connecting their field to a nearby trunk line, TCCB could administer grants or loans to create a regional CO_2 pipeline network that would place CO_2 within easy reach of oilfield operators. Since the largest share of the investment for EOR is concentrated in capture and compression, once CO_2 has been transported to an oilfield, injection and recycling operators would respond positively to low-cost capital to invest in the infrastructure required to inject and recycle it.

How likely are TCCB-initiated loans, loan guarantees, or TCCB regional facilitation and planning (for a regional pipeline for example) to midwife a Texas carbon capture and storage industry? The most appropriate parallel is Texas' Water Development Board (TWDB) created in 1957 to provide loans and planning to public and nonprofit water and wastewater systems to enhance water supply, wastewater treatment (water infrastructure) and water conservation in Texas. The TWDB has had a significant impact on the state, as it has been involved in facilitating tens of billions of dollars of new investment in Texas water sector infrastructure. If the TCCB has anything like the influence on carbon capture and storage that the TWDB has had on Texas water infrastructure, it could be one of the Texas Legislature's most visionary decisions.

One of the reasons for the successful of the TWDB is that through the "magic" of state risk-sharing it converts a long-term business risk —one which could "bet" the entire capital of a firm on one investment— into a series of annual payments, using revenues from the project to amortize the state's risk sharing loan. The risk sharing would lead to profit sharing, as income in excess of expenses would compensate the state through taxes and royalties.

The comparison to the TWDB raises the issue of the political viability of loans by the state to assist for-profit oil and gas enterprises. The TWDB is authorized to risk-share only for water supply or wastewater investments of units of government or not-for-profit enterprises.[2] Indeed, some analysts would credit the TWDB support as a reason for the strength of Texas' governmental and nonprofit water and wastewater sub-sectors, including municipal, water district and other not-for-profit district institutions. Whether Texas could provide loan, loan-guarantees or planning assistance to for-profit carbon capture and storage operations is beyond the scope of this report.

Long-Term Liability

One goal of CO_2 capture and storage is that once carbon is sequestered in geologic formations it should remain there for eternity. Because of this time frame, there is concern about who should take responsibility for the sequestered carbon. The State of Texas could share the risk and reduce these concerns by establishing under law the legal liabilities of each of the parties to CO_2 capture and storage once CO_2 has been injected and then monitored for an established length of time. Texas could even assume some of the long-term liabilities for timeframes beyond the current reach of conventional contracts and insurance, such as after a 30-year or a 50-year period. Texas has begun a comparable process through the June 2006 passage of HB 149, which gives the Texas Railroad Commission the right and title to CO_2 captured from any clean coal project in the state.[3]

How important would state acceptance of long-term liability for sequestered CO_2 be for the development of a carbon capture and storage enterprise? Recent research on carbon capture and storage has identified liability risks as a key uncertainty inhibiting investment, even more than the return on investment risks.[4]

Royalty Tax Relief

It is important that a generic royalty regime be created that encourages CO_2 EOR investment while providing fiscal certainty and stability. One possibility would be to use a "Revenue Minus Cost" approach similar to that of the Alberta sands royalty regime in Canada.[5] The royalty is paid in one of two ways, depending on the project's financial status. The deciding factor is the project's payout date. A project has reached payout once its cumulative revenues have exceeded its cumulative costs. In Alberta, the applicable royalty is 1 percent of the project's gross revenue before the payout date. This low rate would recognize the high costs, long lead times and high risks associated with EOR investment. It would prevent undue strain on the developer's financial resources during critical start-up stages of the project. After the payout date, the applicable royalty is the greater of 1 percent of the project's gross revenue or 25 percent of the net revenue for the period. This feature links the royalty payment to the success of the project. A similar structure could be developed in Texas to facilitate EOR and sequestration.

Unitization

Oil fields often have multiple owners. If many separate entities own an oil field collectively, and if all would need to concur before a CO_2 capture and storage project could commence, the diversity of owners could slow the negotiation process for years while trying to reach a contract agreement with the developer. As a means to speed the process and lead to quicker EOR production, the State of Texas could develop a unitization policy that would encourage (or even require) the owners to come together as one body and determine a consistent fee instead of negotiating separate fees for each owner.

How important would a unitization rule be as an incentive to a carbon capture industry? Some analysts have argued that the structure of shared ownership of fields as a key impediment to enhanced oil recovery and carbon sequestration. Whether or not unitization is a key barrier, it will not be easy to achieve through the Texas Legislature. There have been many previous efforts in the Legislature to consider a state unitization policy, but they have failed. Texas remains one of the few states that does not encourage multiple owners of oil and gas reserves to work together to facilitate a joint investment that would benefit all owners, in part because of Texas' respect for the independence and freedom of action of holders of oil and gas reserves.

How important to a carbon capture and storage industry would such a royalty regime be? Farms in Alberta point to the royalty rules as a key factor in their decision to invest (need references). Whether that would be true for Texas firms investment in carbon capture and storage is unknown, but a reduced and certain royalty regime would reduce uncertainty so firms could plan investments on a sustainable basis.

Local Policies

Ad valorem Tax break (County)

Municipalities and counties collect ad valorem taxes on the revenues of emitting entities that could invest in carbon capture technology. Local governments often give tax breaks to provide incentives to companies to invest within their borders. It may be in a local government's interest to encourage a power plant, cement factory or refinery to invest in capital that will result in a new future revenue stream that would provide more in future tax revenues. In such cases, local governments might provide tax relief to encourage investment in capture technology.

How important would ad valorem tax breaks be to firms contemplating carbon capture and storage? It is hard to know how the reduction in ad valorem taxes would affect profitability calculations, as those taxes are but one incremental cost to the firm. However, the cost savings combined with the acknowledgement of local political and administrative support for an investment would be very important. One of the key risks of a carbon sequestration industry is whether the people living adjacent to the carbon capture plane, the pipeline, or the carbon dioxide injection operation are more concerned about the potential risks or the more certain employment, economic and tax repayment benefits. A local decision to offer an ad valorem tax rebate would be a strong signal that the local government welcomes the investment.

Conclusion

While barriers remain for carbon capture and storage, there are ways to address the risks that create uncertainty and promote investment in this potentially lucrative field. One potential policy solution that could be developed is a Texas Carbon Capture Board to establish bond-financing of all or part of the capital investments. To reduce the regulatory uncertainty involved with the injection of an unregulated gas, a comprehensive set of regulations delineating all pertinent standards, procedures and authorities related to each step of the project's process from capture to sequestration would be a necessary first step. Resolving this regulatory uncertainty surrounding long-term storage of CO_2 and reconciliation of liability issues would go a long way to opening the path to development of this important industry. Not only will it bring money to Texas in the form of oil revenues, but it will enhance Texas' constructive contributions to the local and global environment.

Notes

[1] Council on Environmental Quality, *Proposed Legislation, 1972, Executive Office of the President, U.S. Government*, Washington, D.C., 1972.

[2] Texas Government Code §2001.039, Chapter 382, "Water Infrastructure Fund," Amended Effective February 9, 2006.

[3] Texas House Bill 149, 79th Legislature, 3rd called session (2006).

[4] Mark A. de Figueiredo, David M. Reiner, and Howard J. Herzog, "Towards a Long-Term Liability Framework for Geology Carbon Sequestration," Presented at the Second Annual Conference on Carbon Sequestration, Alexandria, VA, May 2003.

[5] Government of Alberta, Department of Energy, *Oil Sands Guidelines (Royalty).* Online. Available: http://www.energy.gov.ab.ca/161.asp. Accessed: May 5, 2005.

Appendix A. IMPLAN Results

The following tables detail the estimated direct, indirect, induced, and total impacts on employment and output caused by the construction of a carbon capture facility and pipeline from the BP refinery in Texas City and the equipping of existing oil wells for EOR at the Hastings-West Frio field, as well as the same consequences from a single year's production from these facilities. The results are derived on a county-specific basis from the MI-REC/IMPLAN (Impact Analysis for Planning) economic analysis software, which was last updated in 2003. While the results of the construction project represent an impact at a specific point in time, the single-year production impacts can be logically extrapolated to continue over the 21-year production horizon for the project, assuming production begins in year 4.

The output matrices (Tables 1 and 2) detail the total dollar value added in direct, indirect, and induced impacts for each sector, as well. For example, Sector 147 (Petrochemical manufacturing) would expect to see total direct, indirect, and induced increases in final demand of $0, $548,000, and $314,000, respectively, because of plant construction totaling $863,000 in this sector. It would also have an increase of $0 in direct revenues, $2.5 million in indirect, and $180,000 in induced impacts, creating approximately $2.7 million as a result of one year's production.

For the employment matrices (Tables 3 and 4), one can determine the effect of the construction on a specific sector by locating it on the matrix. Direct, indirect, induced, as well as combined total employment impacts among all sectors are included. Similar direct, indirect, and induced consequences are computed for the employment effects caused by a year's production of oil. For example, 5.1 jobs would be created in Sector 485 (Commercial machinery and maintenance) as a result of the $150 million in capital costs for the construction project. None of this amount would be expected to be created directly by the construction, but 4.3 jobs would be created indirectly, and 0.8 jobs would be created as a result of the increase in household income. At the same time, one year's production ($213.5 million in oil company revenue) would create approximately 1 job in that same sector.

Table 1.
Output Impact—Plant Construction

	Industry	Direct	Indirect	Induced	Total
1	Oilseed farming	$0	$25	$106	$131
2	Grain farming	0	502	13,889	14,391
3	Vegetable and melon farming	0	545	49,238	49,783
4	Tree nut farming	0	16	4,931	4,947
5	Fruit farming	0	28	3,323	3,351
6	Greenhouse and nursery production	0	13,436	78,810	92,246
7	Tobacco farming	0	0	0	0
8	Cotton farming	0	261	3,233	3,494
9	Sugarcane and sugar beet farming	0	250	1,137	1,388
10	All other crop farming	0	69,406	46,158	115,564
11	Cattle ranching and farming	0	8,391	327,847	336,238
12	Poultry and egg production	0	2,178	129,365	131,543
13	Animal production- except cattle	0	680	25,662	26,342
14	Logging	0	73,253	7,937	81,190
15	Forest nurseries- forest products	0	540	86	626
16	Fishing	0	73	1,670	1,743
17	Hunting and trapping	0	0	17,638	17,638
18	Agriculture and forestry support activ	0	5,159	21,861	27,020
19	Oil and gas extraction	0	978,097	604,820	1,582,916
20	Coal mining	0	7,273	15,823	23,096
21	Iron ore mining	0	0	0	0
22	Copper- nickel- lead- and zinc minin	0	0	0	0
23	Gold- silver- and other metal ore min	0	67	47	114
24	Stone mining and quarrying	0	9,298	578	9,876
25	Sand- gravel- clay- and refractory mi	0	7,349	405	7,755
26	Other nonmetallic mineral mining	0	380	326	707
27	Drilling oil and gas wells	0	3,344	355	3,699
28	Support activities for oil and gas ope	27,015,912	129,508	13,770	27,159,190
29	Support activities for other mining	0	3	3	6
30	Power generation and supply	0	655,374	1,469,286	2,124,660
31	Natural gas distribution	0	123,289	354,255	477,544
32	Water- sewage and other systems	0	21,288	89,681	110,968
33	New residential 1-unit structures- no	0	0	0	0
34	New multifamily housing structures-	0	0	0	0
35	New residential additions and alterat	0	0	0	0
36	New farm housing units and additions	0	0	0	0
37	Manufacturing and industrial buildin	112,520,640	0	0	112,520,640
38	Commercial and institutional buildin	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
39	Highway- street- bridge- and tunnel c	0	0	0	0
40	Water- sewer- and pipeline construct	0	0	0	0
41	Other new construction	0	0	0	0
42	Maintenance and repair of farm and	0	6,545	105,574	112,119
43	Maintenance and repair of nonresiden	0	351,011	253,374	604,385
44	Maintenance and repair of highways-	0	0	0	0
45	Other maintenance and repair constru	0	25,492	66,575	92,067
46	Dog and cat food manufacturing	0	10	14,590	14,600
47	Other animal food manufacturing	0	272	9,907	10,179
48	Flour milling	0	198	15,480	15,678
49	Rice milling	0	35	4,190	4,226
50	Malt manufacturing	0	0	0	0
51	Wet corn milling	0	80	980	1,060
52	Soybean processing	0	8	231	239
53	Other oilseed processing	0	204	2,533	2,738
54	Fats and oils refining and blending	0	175	6,416	6,591
55	Breakfast cereal manufacturing	0	0	0	0
56	Sugar manufacturing	0	466	24,917	25,383
57	Confectionery manufacturing from c	0	4	379	383
58	Confectionery manufacturing from p	0	233	62,185	62,418
59	Nonchocolate confectionery manufac	0	116	10,139	10,255
60	Frozen food manufacturing	0	300	19,019	19,320
61	Fruit and vegetable canning and dryi	0	386	22,865	23,251
62	Fluid milk manufacturing	0	2,050	146,771	148,821
63	Creamery butter manufacturing	0	57	3,804	3,860
64	Cheese manufacturing	0	351	11,258	11,609
65	Dry- condensed- and evaporated dair	0	1,442	63,303	64,745
66	Ice cream and frozen dessert manufac	0	2,118	47,265	49,383
67	Animal- except poultry- slaughtering	0	10,267	363,125	373,392
68	Meat processed from carcasses	0	4,883	294,180	299,063
69	Rendering and meat byproduct proce	0	1,006	6,549	7,555
70	Poultry processing	0	5,021	288,864	293,885
71	Seafood product preparation and pac	0	1,357	27,212	28,569
72	Frozen cakes and other pastries manu	0	34	7,565	7,599
73	Bread and bakery product- except fr	0	4,819	153,138	157,958
74	Cookie and cracker manufacturing	0	85	8,837	8,923
75	Mixes and dough made from purchase	0	232	31,965	32,197
76	Dry pasta manufacturing	0	23	4,757	4,780
77	Tortilla manufacturing	0	57	16,275	16,331
78	Roasted nuts and peanut butter manu	0	115	14,469	14,584

	Industry	Direct	Indirect	Induced	Total
79	Other snack food manufacturing	0	876	120,063	120,939
80	Coffee and tea manufacturing	0	762	32,249	33,011
81	Flavoring syrup and concentrate man	0	3,121	68,814	71,935
82	Mayonnaise- dressing- and sauce man	0	610	21,987	22,597
83	Spice and extract manufacturing	0	289	32,861	33,150
84	All other food manufacturing	0	661	95,552	96,213
85	Soft drink and ice manufacturing	0	1,468	112,531	113,999
86	Breweries	0	476	44,068	44,544
87	Wineries	0	54	5,687	5,741
88	Distilleries	0	86	3,706	3,793
89	Tobacco stemming and redrying	0	0	118	118
90	Cigarette manufacturing	0	0	145	145
91	Other tobacco product manufacturing	0	0	4,426	4,426
92	Fiber- yarn- and thread mills	0	136	513	649
93	Broadwoven fabric mills	0	2,265	8,969	11,234
94	Narrow fabric mills and schiffli embr	0	38	1,097	1,136
95	Nonwoven fabric mills	0	4,231	1,942	6,173
96	Knit fabric mills	0	12	229	240
97	Textile and fabric finishing mills	0	1,396	2,144	3,541
98	Fabric coating mills	0	168	295	463
99	Carpet and rug mills	0	21	94	116
100	Curtain and linen mills	0	124	5,311	5,434
101	Textile bag and canvas mills	0	170	542	712
102	Tire cord and tire fabric mills	0	0	1	1
103	Other miscellaneous textile product m	0	380	862	1,241
104	Sheer hosiery mills	0	0	50	50
105	Other hosiery and sock mills	0	0	40	40
106	Other apparel knitting mills	0	173	1,723	1,895
107	Cut and sew apparel manufacturing	0	1,148	220,088	221,236
108	Accessories and other apparel manufa	0	159	12,762	12,921
109	Leather and hide tanning and finishi	0	1,058	3,559	4,617
110	Footwear manufacturing	0	0	25,029	25,029
111	Other leather product manufacturing	0	582	8,520	9,102
112	Sawmills	0	124,325	14,375	138,700
113	Wood preservation	0	69,146	3,486	72,632
114	Reconstituted wood product manufac	0	33,064	3,345	36,409
115	Veneer and plywood manufacturing	0	96,457	7,533	103,989
116	Engineered wood member and truss m	0	156,173	6,104	162,277
117	Wood windows and door manufactur	0	10,787	13,482	24,270
118	Cut stock- resawing lumber- and plan	0	6,208	804	7,013

	Industry	Direct	Indirect	Induced	Total
119	Other millwork- including flooring	0	72,729	13,485	86,215
120	Wood container and pallet manufactu	0	15,944	16,144	32,089
121	Manufactured home- mobile home- m	0	0	0	0
122	Prefabricated wood building manufac	0	1,319	51	1,371
123	Miscellaneous wood product manufac	0	14,434	9,902	24,336
124	Pulp mills	0	0	0	0
125	Paper and paperboard mills	0	25	36	61
126	Paperboard container manufacturing	0	19,806	16,282	36,088
127	Flexible packaging foil manufacturin	0	0	0	0
128	Surface-coated paperboard manufact	0	73	932	1,004
129	Coated and laminated paper and pack	0	807	1,161	1,968
130	Coated and uncoated paper bag manu	0	640	991	1,631
131	Die-cut paper office supplies manufa	0	19	29	48
132	Envelope manufacturing	0	42	82	123
133	Stationery and related product manuf	0	5	14	18
134	Sanitary paper product manufacturin	0	51	4,033	4,084
135	All other converted paper product ma	0	250	117	367
136	Manifold business forms printing	0	4,073	5,142	9,215
137	Books printing	0	476	2,196	2,672
138	Blankbook and looseleaf binder manu	0	145	424	569
139	Commercial printing	0	58,763	85,529	144,292
140	Tradebinding and related work	0	155	396	550
141	Prepress services	0	2,929	1,845	4,774
142	Petroleum refineries	0	2,066,369	997,198	3,063,567
143	Asphalt paving mixture and block ma	0	184,625	5,820	190,445
144	Asphalt shingle and coating material	0	74,021	16,418	90,440
145	Petroleum lubricating oil and grease	0	28,795	9,759	38,554
146	All other petroleum and coal product	0	4,509	1,031	5,540
147	Petrochemical manufacturing	0	548,792	314,946	863,738
148	Industrial gas manufacturing	0	50,577	35,923	86,500
149	Synthetic dye and pigment manufactu	0	6,531	5,379	11,910
150	Other basic inorganic chemical manu	0	12,022	8,561	20,582
151	Other basic organic chemical manufa	0	43,541	29,104	72,645
152	Plastics material and resin manufactu	0	7,181	5,800	12,981
153	Synthetic rubber manufacturing	0	1,100	746	1,846
154	Cellulosic organic fiber manufacturin	0	0	0	0
155	Noncellulosic organic fiber manufact	0	8	10	18
156	Nitrogenous fertilizer manufacturing	0	7,487	1,969	9,456
157	Phosphatic fertilizer manufacturing	0	14,517	1,177	15,694
158	Fertilizer- mixing only- manufacturin	0	31,101	2,471	33,572

	Industry	Direct	Indirect	Induced	Total
159	Pesticide and other agricultural chem	0	4,063	10,395	14,458
160	Pharmaceutical and medicine manufa	0	223	378,433	378,656
161	Paint and coating manufacturing	0	5,095	956	6,052
162	Adhesive manufacturing	0	25,666	14,782	40,448
163	Soap and other detergent manufactur	0	4,708	34,444	39,153
164	Polish and other sanitation good man	0	9,823	66,667	76,490
165	Surface active agent manufacturing	0	916	248	1,165
166	Toilet preparation manufacturing	0	889	132,122	133,010
167	Printing ink manufacturing	0	3,066	3,887	6,953
168	Explosives manufacturing	0	7,781	293	8,075
169	Custom compounding of purchased re	0	49,174	10,384	59,559
170	Photographic film and chemical manu	0	1,896	5,075	6,970
171	Other miscellaneous chemical produc	0	36,036	32,163	68,199
172	Plastics packaging materials- film an	0	49,625	70,755	120,380
173	Plastics pipe- fittings- and profile sh	0	123,861	30,355	154,216
174	Laminated plastics plate- sheet- and	0	18,771	7,400	26,171
175	Plastics bottle manufacturing	0	4,352	22,368	26,720
176	Resilient floor covering manufacturi	0	5,285	2,107	7,392
177	Plastics plumbing fixtures and all othe	0	583,558	105,477	689,035
178	Foam product manufacturing	0	81,197	68,930	150,128
179	Tire manufacturing	0	52	30	81
180	Rubber and plastics hose and belting	0	1,184	125	1,309
181	Other rubber product manufacturing	0	1,479	623	2,102
182	Vitreous china plumbing fixture man	0	7,468	780	8,248
183	Vitreous china and earthenware artic	0	5	71	76
184	Porcelain electrical supply manufactu	0	31	25	57
185	Brick and structural clay tile manufa	0	142	121	264
186	Ceramic wall and floor tile manufact	0	120	55	175
187	Nonclay refractory manufacturing	0	5	0	5
188	Clay refractory and other structural c	0	115	0	116
189	Glass container manufacturing	0	641	9,542	10,183
190	Glass and glass products- except glas	0	41,323	38,467	79,790
191	Cement manufacturing	0	695	16	710
192	Ready-mix concrete manufacturing	0	265,566	7,122	272,688
193	Concrete block and brick manufactur	0	635	31	665
194	Concrete pipe manufacturing	0	6,592	285	6,877
195	Other concrete product manufacturin	0	15,438	1,096	16,534
196	Lime manufacturing	0	111	10	121
197	Gypsum product manufacturing	0	520	15	535
198	Abrasive product manufacturing	0	908	540	1,448

	Industry	Direct	Indirect	Induced	Total
199	Cut stone and stone product manufac	0	122	45	167
200	Ground or treated minerals and earth	0	47	3	50
201	Mineral wool manufacturing	0	319	280	600
202	Miscellaneous nonmetallic mineral p	0	1,374	405	1,778
203	Iron and steel mills	0	19,416	3,006	22,422
204	Ferroalloy and related product manuf	0	60	6	67
205	Iron- steel pipe and tube from purchas	0	3,117	454	3,571
206	Rolled steel shape manufacturing	0	1,302	198	1,500
207	Steel wire drawing	0	5,017	1,950	6,968
208	Alumina refining	0	433	372	805
209	Primary aluminum production	0	356	60	416
210	Secondary smelting and alloying of	0	42	7	50
211	Aluminum sheet- plate- and foil man	0	392	249	641
212	Aluminum extruded product manufac	0	1,214	194	1,408
213	Other aluminum rolling and drawing	0	393	126	519
214	Primary smelting and refining of cop	0	154	117	271
215	Primary nonferrous metal- except co	0	154	128	282
216	Copper rolling- drawing- and extrudi	0	501	50	551
217	Copper wire- except mechanical- dra	0	7,731	539	8,269
218	Secondary processing of copper	0	0	0	0
219	Nonferrous metal- except copper and	0	179	25	203
220	Secondary processing of other nonfer	0	57	35	92
221	Ferrous metal foundaries	0	636	48	684
222	Aluminum foundries	0	1,040	232	1,272
223	Nonferrous foundries- except alumi	0	382	85	467
224	Iron and steel forging	0	649	163	812
225	Nonferrous forging	0	83	14	97
226	Custom roll forming	0	595	17	612
227	All other forging and stamping	0	507	385	892
228	Cutlery and flatware- except preciou	0	68	692	760
229	Hand and edge tool manufacturing	0	1,685	4,807	6,492
230	Saw blade and handsaw manufacturi	0	33	85	118
231	Kitchen utensil- pot- and pan manufa	0	4	151	155
232	Prefabricated metal buildings and c	0	4,957	313	5,270
233	Fabricated structural metal manufact	0	103,197	1,794	104,991
234	Plate work manufacturing	0	9,001	872	9,874
235	Metal window and door manufacturi	0	37,609	2,183	39,792
236	Sheet metal work manufacturing	0	240,720	4,127	244,847
237	Ornamental and architectural metal	0	22,268	597	22,865
238	Power boiler and heat exchanger man	0	7,658	98	7,756

	Industry	Direct	Indirect	Induced	Total
239	Metal tank- heavy gauge- manufactur	0	2,078	71	2,149
240	Metal can- box- and other container	0	23,729	8,697	32,426
241	Hardware manufacturing	0	8,247	2,989	11,237
242	Spring and wire product manufacturi	0	18,084	8,798	26,882
243	Machine shops	0	114,069	22,434	136,503
244	Turned product and screw- nut- and	0	28,816	5,391	34,208
245	Metal heat treating	0	12,523	1,387	13,911
246	Metal coating and nonprecious engra	0	19,842	2,339	22,182
247	Electroplating- anodizing- and colori	0	34,597	3,739	38,336
248	Metal valve manufacturing	0	600,887	6,404	607,290
249	Ball and roller bearing manufacturing	0	771	460	1,231
250	Small arms manufacturing	0	0	0	0
251	Other ordnance and accessories manu	0	0	0	0
252	Fabricated pipe and pipe fitting manu	0	19,532	1,507	21,039
253	Industrial pattern manufacturing	0	14	3	18
254	Enameled iron and metal sanitary wa	0	3,211	63	3,274
255	Miscellaneous fabricated metal produ	0	1,225	147	1,372
256	Ammunition manufacturing	0	0	1	1
257	Farm machinery and equipment manu	0	2,455	2,903	5,359
258	Lawn and garden equipment manufac	0	3,435	11,198	14,633
259	Construction machinery manufacturi	0	75,127	3,124	78,251
260	Mining machinery and equipment ma	0	550	61	611
261	Oil and gas field machinery and equ	0	246,689	4,672	251,361
262	Sawmill and woodworking machiner	0	487	1,507	1,995
263	Plastics and rubber industry machine	0	4,750	1,172	5,922
264	Paper industry machinery manufactur	0	93	55	148
265	Textile machinery manufacturing	0	28	23	51
266	Printing machinery and equipment m	0	173	176	349
267	Food product machinery manufacturi	0	908	1,424	2,332
268	Semiconductor machinery manufactu	0	382	313	695
269	All other industrial machinery manuf	0	820	2,507	3,327
270	Office machinery manufacturing	0	938	876	1,813
271	Optical instrument and lens manufact	0	577	1,196	1,774
272	Photographic and photocopying equi	0	272	845	1,117
273	Other commercial and service indust	0	2,473	898	3,371
274	Automatic vending- commercial laun	0	1,521	1,077	2,598
275	Air purification equipment manufact	0	399	6	405
276	Industrial and commercial fan and b	0	218	20	239
277	Heating equipment- except warm air	0	0	0	0
278	AC- refrigeration- and forced air heat	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
279	Industrial mold manufacturing	0	311	64	375
280	Metal cutting machine tool manufact	0	399	253	652
281	Metal forming machine tool manufac	0	286	79	365
282	Special tool- die- jig- and fixture ma	0	1,399	642	2,041
283	Cutting tool and machine tool access	0	2,097	798	2,895
284	Rolling mill and other metalworking	0	245	77	322
285	Turbine and turbine generator set uni	0	1,172	1,724	2,896
286	Other engine equipment manufacturi	0	9,736	9,138	18,874
287	Speed changers and mechanical power	0	8,041	2,047	10,088
288	Pump and pumping equipment manuf	0	506	115	620
289	Air and gas compressor manufacturin	0	85	78	162
290	Measuring and dispensing pump man	0	126	2	127
291	Elevator and moving stairway manufa	0	5,207	307	5,514
292	Conveyor and conveying equipment	0	5,918	448	6,366
293	Overhead cranes- hoists- and monorai	0	249,261	50	249,311
294	Industrial truck- trailer- and stacker	0	21,777	1,004	22,780
295	Power-driven handtool manufacturin	0	1,223	4,354	5,577
296	Welding and soldering equipment ma	0	10,238	829	11,067
297	Packaging machinery manufacturing	0	679	990	1,668
298	Industrial process furnace and oven	0	32	24	56
299	Fluid power cylinder and actuator ma	0	6,505	86	6,592
300	Fluid power pump and motor manufa	0	1,203	20	1,222
301	Scales- balances- and miscellaneous	0	396	120	516
302	Electronic computer manufacturing	0	25,621	207,359	232,980
303	Computer storage device manufactur	0	937	2,019	2,956
304	Computer terminal manufacturing	0	291	566	857
305	Other computer peripheral equipmen	0	2,702	11,550	14,252
306	Telephone apparatus manufacturing	0	4,518	14,460	18,979
307	Broadcast and wireless communicati	0	4,901	8,466	13,367
308	Other communications equipment ma	0	248,699	4,058	252,757
309	Audio and video equipment manufact	0	962	37,067	38,029
310	Electron tube manufacturing	0	358	1,770	2,128
311	Semiconductors and related device m	0	187,924	151,721	339,645
312	All other electronic component manu	0	47,315	32,605	79,921
313	Electromedical apparatus manufactur	0	1,934	4,503	6,437
314	Search- detection- and navigation in	0	610	1,943	2,553
315	Automatic environmental control man	0	8,932	616	9,548
316	Industrial process variable instrument	0	3,754	3,911	7,665
317	Totalizing fluid meters and counting	0	5,325	2,822	8,147
318	Electricity and signal testing instrum	0	937	488	1,425

	Industry	Direct	Indirect	Induced	Total
319	Analytical laboratory instrument man	0	12,870	4,339	17,209
320	Irradiation apparatus manufacturing	0	21	490	511
321	Watch- clock- and other measuring an	0	3,439	11,996	15,435
322	Software reproducing	0	17,670	15,194	32,864
323	Audio and video media reproduction	0	1,804	3,583	5,387
324	Magnetic and optical recording medi	0	324	432	757
325	Electric lamp bulb and part manufact	0	10	6	16
326	Lighting fixture manufacturing	0	2,674	28	2,702
327	Electric housewares and household f	0	502	843	1,345
328	Household vacuum cleaner manufact	0	43	2,552	2,595
329	Household cooking appliance manufa	0	44	746	790
330	Household refrigerator and home fre	0	0	3	3
331	Household laundry equipment manufa	0	0	8	8
332	Other major household appliance man	0	65	45	110
333	Electric power and specialty transfo	0	2,514	1,478	3,991
334	Motor and generator manufacturing	0	9,851	4,186	14,036
335	Switchgear and switchboard apparatu	0	9,650	1,644	11,294
336	Relay and industrial control manufac	0	3,393	1,801	5,194
337	Storage battery manufacturing	0	4,873	6,258	11,131
338	Primary battery manufacturing	0	58	2,206	2,264
339	Fiber optic cable manufacturing	0	35,016	4,999	40,015
340	Other communication and energy wir	0	32,251	1,417	33,669
341	Wiring device manufacturing	0	923	297	1,219
342	Carbon and graphite product manufac	0	530	329	859
343	Miscellaneous electrical equipment	0	525	2,100	2,625
344	Automobile and light truck manufact	0	3,831	257,849	261,680
345	Heavy duty truck manufacturing	0	0	1,180	1,181
346	Motor vehicle body manufacturing	0	6,363	2,983	9,346
347	Truck trailer manufacturing	0	13	14	27
348	Motor home manufacturing	0	0	3,814	3,814
349	Travel trailer and camper manufactur	0	3	8,588	8,592
350	Motor vehicle parts manufacturing	0	239,216	185,027	424,243
351	Aircraft manufacturing	0	2,593	11,725	14,318
352	Aircraft engine and engine parts man	0	984	1,612	2,596
353	Other aircraft parts and equipment	0	526	1,038	1,565
354	Guided missile and space vehicle ma	0	45	82	127
355	Propulsion units and parts for space	0	0	0	0
356	Railroad rolling stock manufacturing	0	847	541	1,388
357	Ship building and repairing	0	240	436	676
358	Boat building	0	9	2,476	2,485

	Industry	Direct	Indirect	Induced	Total
359	Motorcycle- bicycle- and parts manuf	0	317	1,114	1,431
360	Military armored vehicles and tank p	0	0	101	102
361	All other transportation equipment m	0	17	145	162
362	Wood kitchen cabinet and countertop	0	20,910	35,025	55,935
363	Upholstered household furniture man	0	0	34,967	34,967
364	Nonupholstered wood household furn	0	93	19,558	19,651
365	Metal household furniture manufactu	0	1	6,571	6,571
366	Institutional furniture manufacturing	0	302	498	800
367	Other household and institutional fur	0	330	1,239	1,568
368	Wood office furniture manufacturing	0	5	510	515
369	Custom architectural woodwork and	0	50	352	402
370	Office furniture- except wood- manuf	0	22	62	84
371	Showcases- partitions- shelving- and	0	992	1,917	2,909
372	Mattress manufacturing	0	2	49,395	49,397
373	Blind and shade manufacturing	0	0	23,314	23,314
374	Laboratory apparatus and furniture m	0	6,317	684	7,001
375	Surgical and medical instrument man	0	26,243	22,035	48,277
376	Surgical appliance and supplies manu	0	695,687	55,851	751,538
377	Dental equipment and supplies manuf	0	210	965	1,176
378	Ophthalmic goods manufacturing	0	2,636	39,057	41,693
379	Dental laboratories	0	1,267	17,141	18,409
380	Jewelry and silverware manufacturin	0	1,068	8,087	9,155
381	Sporting and athletic goods manufact	0	2,597	280	2,876
382	Doll- toy- and game manufacturing	0	2	39	40
383	Office supplies- except paper- manuf	0	84	215	299
384	Sign manufacturing	0	7,170	9,509	16,679
385	Gasket- packing- and sealing device	0	2,309	164	2,473
386	Musical instrument manufacturing	0	0	4	4
387	Broom- brush- and mop manufacturi	0	617	363	981
388	Burial casket manufacturing	0	0	3	3
389	Buttons- pins- and all other miscell	0	1,967	2,021	3,987
390	Wholesale trade	0	5,051,060	3,805,692	8,856,752
391	Air transportation	0	178,279	269,064	447,343
392	Rail transportation	0	183,386	79,425	262,811
393	Water transportation	0	72,433	130,428	202,862
394	Truck transportation	0	1,626,691	593,413	2,220,105
395	Transit and ground passenger transpo	0	19,258	87,477	106,734
396	Pipeline transportation	0	98,334	115,361	213,695
397	Scenic and sightseeing transportation	0	163,133	96,555	259,688
398	Postal service	0	145,084	183,711	328,796

	Industry	Direct	Indirect	Induced	Total
399	Couriers and messengers	0	213,185	120,715	333,901
400	Warehousing and storage	0	125,820	84,961	210,780
401	Motor vehicle and parts dealers	0	258,165	1,513,455	1,771,620
402	Furniture and home furnishings store	0	77,921	350,221	428,142
403	Electronics and appliance stores	0	57,530	294,873	352,403
404	Building material and garden supply	0	116,515	680,741	797,256
405	Food and beverage stores	0	229,205	1,309,369	1,538,574
406	Health and personal care stores	0	96,814	538,486	635,300
407	Gasoline stations	0	74,883	370,755	445,639
408	Clothing and clothing accessories sto	0	107,031	609,188	716,218
409	Sporting goods- hobby- book and mus	0	33,758	195,069	228,827
410	General merchandise stores	0	174,377	1,019,938	1,194,315
411	Miscellaneous store retailers	0	81,415	455,835	537,250
412	Nonstore retailers	0	80,298	470,252	550,550
413	Newpaper publishers	0	71,188	111,260	182,449
414	Periodical publishers	0	18,157	48,311	66,468
415	Book publishers	0	1,280	32,309	33,589
416	Database- directory- and other publis	0	18,891	34,695	53,586
417	Software publishers	0	2,957	19,559	22,515
418	Motion picture and video industries	0	36,978	175,258	212,236
419	Sound recording industries	0	4,546	85,756	90,302
420	Radio and television broadcasting	0	109,540	174,358	283,898
421	Cable networks and program distribu	0	43,678	388,377	432,055
422	Telecommunications	0	917,658	1,195,045	2,112,703
423	Information services	0	48,669	31,730	80,399
424	Data processing services	0	81,814	59,463	141,277
425	Nondepository credit intermediation a	0	676,603	693,991	1,370,593
426	Securities- commodity contracts- inv	0	444,721	808,268	1,252,989
427	Insurance carriers	0	1,417,817	1,694,860	3,112,677
428	Insurance agencies- brokerages- and r	0	392,040	474,708	866,747
429	Funds- trusts- and other financial veh	0	8,781	489,392	498,173
430	Monetary authorities and depository c	0	1,121,002	1,713,316	2,834,318
431	Real estate	0	1,567,738	3,049,555	4,617,293
432	Automotive equipment rental and lea	0	209,661	315,351	525,011
433	Video tape and disc rental	0	377	110,182	110,559
434	Machinery and equipment rental and	0	289,328	22,205	311,533
435	General and consumer goods rental ex	0	94,059	156,383	250,441
436	Lessors of nonfinancial intangible ass	0	204,249	152,918	357,167
437	Legal services	0	346,646	1,064,381	1,411,027
438	Accounting and bookkeeping service	0	493,600	304,853	798,453

	Industry	Direct	Indirect	Induced	Total
439	Architectural and engineering service	0	6,657,678	207,698	6,865,376
440	Specialized design services	0	62,325	51,493	113,818
441	Custom computer programming servi	0	95,996	30,611	126,607
442	Computer systems design services	0	78,444	55,518	133,962
443	Other computer related services- inclu	0	119,605	68,713	188,318
444	Management consulting services	0	481,167	303,491	784,658
445	Environmental and other technical co	0	147,244	32,913	180,158
446	Scientific research and development s	0	96,618	57,742	154,360
447	Advertising and related services	0	169,798	223,159	392,957
448	Photographic services	0	4,824	63,750	68,575
449	Veterinary services	0	1,707	114,239	115,946
450	All other miscellaneous professional	0	288,521	192,375	480,896
451	Management of companies and enterp	0	602,002	263,289	865,291
452	Office administrative services	0	381,986	159,407	541,393
453	Facilities support services	0	9,316	4,015	13,331
454	Employment services	0	581,185	225,656	806,841
455	Business support services	0	198,838	197,916	396,754
456	Travel arrangement and reservation s	0	32,211	108,003	140,215
457	Investigation and security services	0	138,310	78,285	216,595
458	Services to buildings and dwellings	0	384,312	328,789	713,101
459	Other support services	0	92,834	96,778	189,612
460	Waste management and remediation s	0	169,433	134,917	304,350
461	Elementary and secondary schools	0	0	111,902	111,902
462	Colleges- universities- and junior col	0	5,516	189,961	195,476
463	Other educational services	0	3,660	261,744	265,404
464	Home health care services	0	0	319,811	319,811
465	Offices of physicians- dentists- and o	0	0	2,615,310	2,615,310
466	Other ambulatory health care services	0	911	807,992	808,904
467	Hospitals	0	0	1,901,621	1,901,621
468	Nursing and residential care facilities	0	0	774,980	774,980
469	Child day care services	0	0	409,169	409,169
470	Social assistance- except child day ca	0	20	310,606	310,626
471	Performing arts companies	0	7,037	49,408	56,445
472	Spectator sports	0	27,606	121,078	148,684
473	Independent artists- writers- and per	0	11,034	17,675	28,709
474	Promoters of performing arts and spo	0	15,879	59,201	75,079
475	Museums- historical sites- zoos- and	0	0	43,770	43,770
476	Fitness and recreational sports center	0	28,360	126,659	155,019
477	Bowling centers	0	0	20,755	20,755
478	Other amusement- gambling- and recr	0	20,770	424,248	445,018

	Industry	Direct	Indirect	Induced	Total
479	Hotels and motels- including casino h	0	115,728	290,920	406,648
480	Other accommodations	0	866	36,949	37,814
481	Food services and drinking places	0	307,369	3,155,132	3,462,501
482	Car washes	0	7,285	85,837	93,122
483	Automotive repair and maintenance-	0	371,157	1,135,171	1,506,328
484	Electronic equipment repair and mai	0	309,532	82,576	392,109
485	Commercial machinery repair and ma	0	453,568	85,175	538,744
486	Household goods repair and mainten	0	115,692	131,199	246,891
487	Personal care services	0	0	330,785	330,785
488	Death care services	0	0	100,545	100,545
489	Drycleaning and laundry services	0	9,267	157,635	166,902
490	Other personal services	0	12,589	341,723	354,313
491	Religious organizations	0	0	207,334	207,334
492	Grantmaking and giving and social a	0	0	144,929	144,929
493	Civic- social- professional and simila	0	110,794	299,570	410,364
494	Private households	0	0	204,622	204,622
495	Federal electric utilities	0	0	0	0
496	Other Federal Government enterprise	0	14,373	36,940	51,313
497	State and local government passenger	0	16,294	74,016	90,311
498	State and local government electric uti	0	33,717	73,310	107,027
499	Other State and local government ente	0	211,906	744,860	956,766
500	Noncomparable imports	0	0	0	0
501	Scrap	0	0	0	0
502	Used and secondhand goods	0	0	0	0
503	State & Local Education	0	0	0	0
504	State & Local Non-Education	0	0	0	0
505	Federal Military	0	0	0	0
506	Federal Non-Military	0	0	0	0
507	Rest of the world adjustment to final	0	0	0	0
508	Inventory valuation adjustment	0	0	0	0
509	Owner-occupied dwellings	0	0	7,665,874	7,665,874
Total		139,536,552	42,311,701	64,166,663	246,014,916

Table 2.
Output Impact—1 Year Oil Production

	Industry	Direct	Indirect	Induced	Total
1	Oilseed farming	$0	$89	$60	$150
2	Grain farming	0	268	7,949	8,217
3	Vegetable and melon farming	0	244	28,182	28,426
4	Tree nut farming	0	5	2,822	2,827
5	Fruit farming	0	10	1,902	1,912
6	Greenhouse and nursery production	0	8,932	45,102	54,035
7	Tobacco farming	0	0	0	0
8	Cotton farming	0	86	1,850	1,936
9	Sugarcane and sugar beet farming	0	1,043	651	1,693
10	All other crop farming	0	3,408	26,418	29,826
11	Cattle ranching and farming	0	3,851	187,641	191,492
12	Poultry and egg production	0	1,042	74,042	75,084
13	Animal production- except cattle and	0	382	14,687	15,069
14	Logging	0	2,245	4,543	6,787
15	Forest nurseries- forest products- and	0	22	49	71
16	Fishing	0	40	956	996
17	Hunting and trapping	0	0	10,094	10,094
18	Agriculture and forestry support activ	0	784	12,512	13,295
19	Oil and gas extraction	149,775,840	13,632,144	346,166	163,754,144
20	Coal mining	0	23,074	9,056	32,130
21	Iron ore mining	0	0	0	0
22	Copper- nickel- lead- and zinc minin	0	0	0	0
23	Gold- silver- and other metal ore min	0	113	27	140
24	Stone mining and quarrying	0	372	331	703
25	Sand- gravel- clay- and refractory mi	0	182	232	414
26	Other nonmetallic mineral mining	0	755	187	942
27	Drilling oil and gas wells	0	96,029	203	96,232
28	Support activities for oil and gas ope	0	3,719,650	7,880	3,727,530
29	Support activities for other mining	0	4	2	6
30	Power generation and supply	0	2,070,181	840,937	2,911,118
31	Natural gas distribution	0	104,981	202,754	307,734
32	Water- sewage and other systems	0	32,911	51,327	84,238
33	New residential 1-unit structures- no	0	0	0	0
34	New multifamily housing structures-	0	0	0	0
35	New residential additions and alterat	0	0	0	0
36	New farm housing units and additions	0	0	0	0
37	Manufacturing and industrial buildin	0	0	0	0
38	Commercial and institutional buildin	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
39	Highway- street- bridge- and tunnel c	0	0	0	0
40	Water- sewer- and pipeline construct	0	0	0	0
41	Other new construction	0	0	0	0
42	Maintenance and repair of farm and	0	4,079	60,421	64,500
43	Maintenance and repair of nonresiden	0	136,203	145,011	281,214
44	Maintenance and repair of highways-	0	0	0	0
45	Other maintenance and repair constru	0	52,345	38,103	90,448
46	Dog and cat food manufacturing	0	5	8,351	8,356
47	Other animal food manufacturing	0	171	5,670	5,841
48	Flour milling	0	114	8,860	8,974
49	Rice milling	0	16	2,398	2,414
50	Malt manufacturing	0	0	0	0
51	Wet corn milling	0	170	561	730
52	Soybean processing	0	12	132	144
53	Other oilseed processing	0	515	1,450	1,965
54	Fats and oils refining and blending	0	202	3,672	3,874
55	Breakfast cereal manufacturing	0	0	0	0
56	Sugar manufacturing	0	231	14,261	14,492
57	Confectionery manufacturing from c	0	2	217	219
58	Confectionery manufacturing from p	0	103	35,592	35,695
59	Nonchocolate confectionery manufac	0	54	5,803	5,857
60	Frozen food manufacturing	0	134	10,886	11,019
61	Fruit and vegetable canning and dryi	0	171	13,087	13,258
62	Fluid milk manufacturing	0	909	84,004	84,913
63	Creamery butter manufacturing	0	26	2,177	2,203
64	Cheese manufacturing	0	155	6,443	6,598
65	Dry- condensed- and evaporated dair	0	721	36,231	36,952
66	Ice cream and frozen dessert manufac	0	926	27,052	27,978
67	Animal- except poultry- slaughtering	0	5,146	207,833	212,979
68	Meat processed from carcasses	0	2,162	168,373	170,535
69	Rendering and meat byproduct proce	0	5,362	3,748	9,110
70	Poultry processing	0	2,462	165,331	167,793
71	Seafood product preparation and pac	0	621	15,575	16,196
72	Frozen cakes and other pastries manu	0	18	4,330	4,348
73	Bread and bakery product- except fr	0	3,412	87,648	91,060
74	Cookie and cracker manufacturing	0	40	5,058	5,098
75	Mixes and dough made from purchase	0	109	18,295	18,404
76	Dry pasta manufacturing	0	10	2,722	2,733
77	Tortilla manufacturing	0	26	9,315	9,340
78	Roasted nuts and peanut butter manu	0	51	8,281	8,332

	Industry	Direct	Indirect	Induced	Total
79	Other snack food manufacturing	0	387	68,718	69,105
80	Coffee and tea manufacturing	0	340	18,458	18,798
81	Flavoring syrup and concentrate man	0	1,373	39,385	40,759
82	Mayonnaise- dressing- and sauce man	0	269	12,584	12,853
83	Spice and extract manufacturing	0	129	18,808	18,937
84	All other food manufacturing	0	305	54,689	54,995
85	Soft drink and ice manufacturing	0	647	64,407	65,054
86	Breweries	0	257	25,222	25,479
87	Wineries	0	24	3,255	3,278
88	Distilleries	0	45	2,121	2,166
89	Tobacco stemming and redrying	0	0	68	68
90	Cigarette manufacturing	0	0	83	83
91	Other tobacco product manufacturing	0	0	2,533	2,533
92	Fiber- yarn- and thread mills	0	23	294	316
93	Broadwoven fabric mills	0	371	5,133	5,504
94	Narrow fabric mills and schiffli embr	0	17	628	645
95	Nonwoven fabric mills	0	192	1,112	1,304
96	Knit fabric mills	0	2	131	133
97	Textile and fabric finishing mills	0	131	1,227	1,359
98	Fabric coating mills	0	85	169	254
99	Carpet and rug mills	0	1	54	55
100	Curtain and linen mills	0	44	3,039	3,083
101	Textile bag and canvas mills	0	33	310	343
102	Tire cord and tire fabric mills	0	0	0	1
103	Other miscellaneous textile product m	0	140	493	633
104	Sheer hosiery mills	0	0	29	29
105	Other hosiery and sock mills	0	0	23	23
106	Other apparel knitting mills	0	6	986	992
107	Cut and sew apparel manufacturing	0	674	125,959	126,632
108	Accessories and other apparel manufa	0	86	7,304	7,389
109	Leather and hide tanning and finishi	0	911	2,037	2,948
110	Footwear manufacturing	0	0	14,325	14,325
111	Other leather product manufacturing	0	615	4,876	5,491
112	Sawmills	0	4,313	8,227	12,540
113	Wood preservation	0	1,525	1,995	3,520
114	Reconstituted wood product manufac	0	626	1,914	2,540
115	Veneer and plywood manufacturing	0	1,714	4,311	6,025
116	Engineered wood member and truss m	0	1,853	3,493	5,346
117	Wood windows and door manufactur	0	3,596	7,716	11,312
118	Cut stock- resawing lumber- and plan	0	201	460	662

	Industry	Direct	Indirect	Induced	Total
119	Other millwork- including flooring	0	2,921	7,718	10,638
120	Wood container and pallet manufactu	0	5,745	9,240	14,985
121	Manufactured home- mobile home- m	0	0	0	0
122	Prefabricated wood building manufac	0	16	29	45
123	Miscellaneous wood product manufac	0	1,992	5,667	7,659
124	Pulp mills	0	0	0	0
125	Paper and paperboard mills	0	26	20	46
126	Paperboard container manufacturing	0	20,293	9,319	29,612
127	Flexible packaging foil manufacturin	0	0	0	0
128	Surface-coated paperboard manufact	0	42	533	575
129	Coated and laminated paper and pack	0	425	665	1,090
130	Coated and uncoated paper bag manu	0	254	567	821
131	Die-cut paper office supplies manufa	0	11	17	28
132	Envelope manufacturing	0	28	47	75
133	Stationery and related product manuf	0	3	8	11
134	Sanitary paper product manufacturin	0	70	2,308	2,378
135	All other converted paper product ma	0	107	67	174
136	Manifold business forms printing	0	2,716	2,943	5,659
137	Books printing	0	563	1,257	1,820
138	Blankbook and looseleaf binder manu	0	86	242	328
139	Commercial printing	0	53,711	48,950	102,661
140	Tradebinding and related work	0	327	226	553
141	Prepress services	0	1,906	1,056	2,962
142	Petroleum refineries	0	1,888,875	570,742	2,459,617
143	Asphalt paving mixture and block ma	0	4,258	3,331	7,590
144	Asphalt shingle and coating material	0	5,308	9,396	14,705
145	Petroleum lubricating oil and grease	0	92,712	5,586	98,298
146	All other petroleum and coal product	0	4,598	590	5,188
147	Petrochemical manufacturing	0	2,564,651	180,256	2,744,906
148	Industrial gas manufacturing	0	448,043	20,560	468,603
149	Synthetic dye and pigment manufactu	0	6,972	3,078	10,051
150	Other basic inorganic chemical manu	0	19,685	4,900	24,585
151	Other basic organic chemical manufa	0	138,281	16,657	154,938
152	Plastics material and resin manufactu	0	21,530	3,320	24,850
153	Synthetic rubber manufacturing	0	2,026	427	2,453
154	Cellulosic organic fiber manufacturin	0	0	0	0
155	Noncellulosic organic fiber manufact	0	14	6	19
156	Nitrogenous fertilizer manufacturing	0	2,020	1,127	3,147
157	Phosphatic fertilizer manufacturing	0	357	673	1,031
158	Fertilizer- mixing only- manufacturin	0	676	1,414	2,091

	Industry	Direct	Indirect	Induced	Total
159	Pesticide and other agricultural chem	0	2,537	5,949	8,487
160	Pharmaceutical and medicine manufa	0	91	216,593	216,683
161	Paint and coating manufacturing	0	416	547	963
162	Adhesive manufacturing	0	5,016	8,460	13,476
163	Soap and other detergent manufactur	0	3,988	19,714	23,702
164	Polish and other sanitation good man	0	9,346	38,156	47,502
165	Surface active agent manufacturing	0	297	142	439
166	Toilet preparation manufacturing	0	641	75,619	76,260
167	Printing ink manufacturing	0	2,156	2,225	4,381
168	Explosives manufacturing	0	2,329	168	2,497
169	Custom compounding of purchased re	0	56,545	5,943	62,488
170	Photographic film and chemical manu	0	1,842	2,904	4,746
171	Other miscellaneous chemical produc	0	413,014	18,408	431,421
172	Plastics packaging materials- film an	0	15,446	40,496	55,942
173	Plastics pipe- fittings- and profile sh	0	15,621	17,373	32,994
174	Laminated plastics plate- sheet- and	0	7,080	4,235	11,315
175	Plastics bottle manufacturing	0	4,459	12,802	17,261
176	Resilient floor covering manufacturi	0	744	1,206	1,950
177	Plastics plumbing fixtures and all othe	0	247,980	60,367	308,347
178	Foam product manufacturing	0	8,455	39,450	47,906
179	Tire manufacturing	0	9	17	26
180	Rubber and plastics hose and belting	0	562	72	633
181	Other rubber product manufacturing	0	632	356	988
182	Vitreous china plumbing fixture man	0	2,851	446	3,298
183	Vitreous china and earthenware artic	0	9	41	50
184	Porcelain electrical supply manufactu	0	16	15	30
185	Brick and structural clay tile manufa	0	24	69	93
186	Ceramic wall and floor tile manufact	0	22	32	54
187	Nonclay refractory manufacturing	0	0	0	0
188	Clay refractory and other structural c	0	0	0	0
189	Glass container manufacturing	0	288	5,461	5,750
190	Glass and glass products- except glas	0	22,964	22,016	44,980
191	Cement manufacturing	0	809	9	818
192	Ready-mix concrete manufacturing	0	1,617	4,076	5,693
193	Concrete block and brick manufactur	0	30	17	48
194	Concrete pipe manufacturing	0	71	163	234
195	Other concrete product manufacturin	0	467	627	1,094
196	Lime manufacturing	0	7	6	13
197	Gypsum product manufacturing	0	10	8	19
198	Abrasive product manufacturing	0	320	309	629

	Industry	Direct	Indirect	Induced	Total
199	Cut stone and stone product manufac	0	3	26	29
200	Ground or treated minerals and earth	0	4	2	5
201	Mineral wool manufacturing	0	30	161	190
202	Miscellaneous nonmetallic mineral p	0	927	232	1,159
203	Iron and steel mills	0	96,357	1,720	98,077
204	Ferroalloy and related product manuf	0	255	4	259
205	Iron- steel pipe and tube from purchas	0	16,110	260	16,370
206	Rolled steel shape manufacturing	0	6,548	113	6,661
207	Steel wire drawing	0	2,450	1,116	3,566
208	Alumina refining	0	865	213	1,078
209	Primary aluminum production	0	87	34	121
210	Secondary smelting and alloying of	0	13	4	17
211	Aluminum sheet- plate- and foil man	0	85	142	227
212	Aluminum extruded product manufac	0	821	111	932
213	Other aluminum rolling and drawing	0	103	72	175
214	Primary smelting and refining of cop	0	261	67	327
215	Primary nonferrous metal- except co	0	152	73	226
216	Copper rolling- drawing- and extrudi	0	102	29	130
217	Copper wire- except mechanical- dra	0	546	308	855
218	Secondary processing of copper	0	0	0	0
219	Nonferrous metal- except copper and	0	24	14	38
220	Secondary processing of other nonfer	0	30	20	51
221	Ferrous metal foundaries	0	239	27	267
222	Aluminum foundries	0	573	133	705
223	Nonferrous foundries- except alumi	0	211	49	260
224	Iron and steel forging	0	522	94	615
225	Nonferrous forging	0	63	8	71
226	Custom roll forming	0	16	10	26
227	All other forging and stamping	0	481	221	702
228	Cutlery and flatware- except preciou	0	37	396	433
229	Hand and edge tool manufacturing	0	1,611	2,751	4,363
230	Saw blade and handsaw manufacturi	0	112	48	161
231	Kitchen utensil- pot- and pan manufa	0	2	87	88
232	Prefabricated metal buildings and c	0	109	179	288
233	Fabricated structural metal manufact	0	10,282	1,027	11,309
234	Plate work manufacturing	0	8,085	499	8,584
235	Metal window and door manufacturi	0	3,122	1,249	4,371
236	Sheet metal work manufacturing	0	3,483	2,362	5,845
237	Ornamental and architectural metal	0	379	342	721
238	Power boiler and heat exchanger man	0	811	56	868

	Industry	Direct	Indirect	Induced	Total
239	Metal tank- heavy gauge- manufactur	0	376	41	416
240	Metal can- box- and other container	0	3,868	4,978	8,846
241	Hardware manufacturing	0	761	1,711	2,472
242	Spring and wire product manufacturi	0	7,434	5,035	12,469
243	Machine shops	0	134,934	12,840	147,773
244	Turned product and screw- nut- and	0	26,872	3,086	29,958
245	Metal heat treating	0	15,123	794	15,918
246	Metal coating and nonprecious engra	0	23,955	1,339	25,294
247	Electroplating- anodizing- and colori	0	41,597	2,140	43,737
248	Metal valve manufacturing	0	196,796	3,665	200,461
249	Ball and roller bearing manufacturing	0	7,902	263	8,165
250	Small arms manufacturing	0	0	0	0
251	Other ordnance and accessories manu	0	0	0	0
252	Fabricated pipe and pipe fitting manu	0	868	862	1,731
253	Industrial pattern manufacturing	0	17	2	19
254	Enameled iron and metal sanitary wa	0	1,069	36	1,105
255	Miscellaneous fabricated metal produ	0	114	84	198
256	Ammunition manufacturing	0	1	1	1
257	Farm machinery and equipment manu	0	13,517	1,662	15,179
258	Lawn and garden equipment manufac	0	1,424	6,409	7,833
259	Construction machinery manufacturi	0	569,329	1,788	571,118
260	Mining machinery and equipment ma	0	7,219	35	7,254
261	Oil and gas field machinery and equ	0	825,157	2,674	827,830
262	Sawmill and woodworking machiner	0	123	863	986
263	Plastics and rubber industry machine	0	1,436	671	2,107
264	Paper industry machinery manufactur	0	57	31	88
265	Textile machinery manufacturing	0	19	13	32
266	Printing machinery and equipment m	0	146	101	247
267	Food product machinery manufacturi	0	385	815	1,200
268	Semiconductor machinery manufactu	0	261	179	440
269	All other industrial machinery manuf	0	1,521	1,435	2,956
270	Office machinery manufacturing	0	281	501	782
271	Optical instrument and lens manufact	0	250	685	935
272	Photographic and photocopying equi	0	145	484	629
273	Other commercial and service indust	0	806	514	1,320
274	Automatic vending- commercial laun	0	274	616	890
275	Air purification equipment manufact	0	4	4	8
276	Industrial and commercial fan and b	0	22	12	33
277	Heating equipment- except warm air	0	0	0	0
278	AC- refrigeration- and forced air heat	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
279	Industrial mold manufacturing	0	224	37	260
280	Metal cutting machine tool manufact	0	898	145	1,043
281	Metal forming machine tool manufac	0	79	45	124
282	Special tool- die- jig- and fixture ma	0	1,382	368	1,749
283	Cutting tool and machine tool access	0	3,348	457	3,804
284	Rolling mill and other metalworking	0	238	44	282
285	Turbine and turbine generator set uni	0	2,138	987	3,125
286	Other engine equipment manufacturi	0	19,733	5,230	24,963
287	Speed changers and mechanical power	0	22,650	1,172	23,822
288	Pump and pumping equipment manuf	0	1,131	66	1,197
289	Air and gas compressor manufacturin	0	83	44	128
290	Measuring and dispensing pump man	0	40	1	41
291	Elevator and moving stairway manufa	0	1,411	175	1,587
292	Conveyor and conveying equipment	0	62,743	256	63,000
293	Overhead cranes- hoists- and monorai	0	5,226	29	5,255
294	Industrial truck- trailer- and stacker	0	2,272	574	2,847
295	Power-driven handtool manufacturin	0	3,695	2,492	6,187
296	Welding and soldering equipment ma	0	1,205	474	1,679
297	Packaging machinery manufacturing	0	575	566	1,141
298	Industrial process furnace and oven	0	31	13	44
299	Fluid power cylinder and actuator ma	0	6,295	49	6,345
300	Fluid power pump and motor manufa	0	397	11	408
301	Scales- balances- and miscellaneous	0	446	69	515
302	Electronic computer manufacturing	0	33,221	118,678	151,899
303	Computer storage device manufactur	0	916	1,156	2,072
304	Computer terminal manufacturing	0	320	324	643
305	Other computer peripheral equipmen	0	3,049	6,610	9,660
306	Telephone apparatus manufacturing	0	1,858	8,276	10,134
307	Broadcast and wireless communicati	0	1,918	4,846	6,763
308	Other communications equipment ma	0	2,464	2,322	4,786
309	Audio and video equipment manufact	0	420	21,215	21,635
310	Electron tube manufacturing	0	159	1,013	1,172
311	Semiconductors and related device m	0	127,702	86,834	214,536
312	All other electronic component manu	0	31,663	18,661	50,324
313	Electromedical apparatus manufactur	0	19	2,577	2,596
314	Search- detection- and navigation in	0	843	1,112	1,955
315	Automatic environmental control man	0	307	352	660
316	Industrial process variable instrument	0	5,535	2,239	7,774
317	Totalizing fluid meters and counting	0	2,811	1,615	4,427
318	Electricity and signal testing instrum	0	336	279	615

	Industry	Direct	Indirect	Induced	Total
319	Analytical laboratory instrument man	0	1,426	2,484	3,909
320	Irradiation apparatus manufacturing	0	7	281	288
321	Watch- clock- and other measuring an	0	1,238	6,865	8,103
322	Software reproducing	0	17,424	8,696	26,120
323	Audio and video media reproduction	0	1,483	2,050	3,534
324	Magnetic and optical recording medi	0	190	247	437
325	Electric lamp bulb and part manufact	0	1	3	4
326	Lighting fixture manufacturing	0	4	16	19
327	Electric housewares and household f	0	5	482	488
328	Household vacuum cleaner manufact	0	11	1,460	1,471
329	Household cooking appliance manufa	0	13	427	441
330	Household refrigerator and home fre	0	0	1	1
331	Household laundry equipment manufa	0	0	5	5
332	Other major household appliance man	0	26	26	52
333	Electric power and specialty transfo	0	2,660	846	3,506
334	Motor and generator manufacturing	0	5,087	2,396	7,483
335	Switchgear and switchboard apparatu	0	1,604	941	2,545
336	Relay and industrial control manufac	0	5,413	1,031	6,443
337	Storage battery manufacturing	0	1,534	3,582	5,116
338	Primary battery manufacturing	0	30	1,263	1,293
339	Fiber optic cable manufacturing	0	2,869	2,861	5,730
340	Other communication and energy wir	0	1,191	811	2,003
341	Wiring device manufacturing	0	831	170	1,001
342	Carbon and graphite product manufac	0	1,226	188	1,414
343	Miscellaneous electrical equipment	0	332	1,202	1,533
344	Automobile and light truck manufact	0	3,700	147,571	151,272
345	Heavy duty truck manufacturing	0	0	676	676
346	Motor vehicle body manufacturing	0	1,251	1,707	2,958
347	Truck trailer manufacturing	0	4	8	13
348	Motor home manufacturing	0	0	2,183	2,183
349	Travel trailer and camper manufactur	0	0	4,916	4,916
350	Motor vehicle parts manufacturing	0	231,073	105,895	336,968
351	Aircraft manufacturing	0	2,245	6,710	8,956
352	Aircraft engine and engine parts man	0	950	923	1,873
353	Other aircraft parts and equipment	0	312	594	906
354	Guided missile and space vehicle ma	0	42	47	89
355	Propulsion units and parts for space	0	0	0	0
356	Railroad rolling stock manufacturing	0	892	309	1,201
357	Ship building and repairing	0	235	250	485
358	Boat building	0	8	1,417	1,426

	Industry	Direct	Indirect	Induced	Total
359	Motorcycle- bicycle- and parts manuf	0	596	638	1,234
360	Military armored vehicles and tank p	0	0	58	58
361	All other transportation equipment m	0	4	83	87
362	Wood kitchen cabinet and countertop	0	5,988	20,045	26,033
363	Upholstered household furniture man	0	0	20,011	20,011
364	Nonupholstered wood household furn	0	45	11,192	11,237
365	Metal household furniture manufactu	0	0	3,760	3,760
366	Institutional furniture manufacturing	0	88	285	373
367	Other household and institutional fur	0	117	709	826
368	Wood office furniture manufacturing	0	3	292	295
369	Custom architectural woodwork and	0	23	202	225
370	Office furniture- except wood- manuf	0	13	35	48
371	Showcases- partitions- shelving- and	0	706	1,097	1,803
372	Mattress manufacturing	0	0	28,267	28,267
373	Blind and shade manufacturing	0	0	13,343	13,343
374	Laboratory apparatus and furniture m	0	42	392	433
375	Surgical and medical instrument man	0	62	12,611	12,673
376	Surgical appliance and supplies manu	0	1,298	31,965	33,263
377	Dental equipment and supplies manuf	0	0	553	553
378	Ophthalmic goods manufacturing	0	1,640	22,354	23,994
379	Dental laboratories	0	6	9,811	9,817
380	Jewelry and silverware manufacturin	0	30	4,628	4,657
381	Sporting and athletic goods manufact	0	5	160	165
382	Doll- toy- and game manufacturing	0	1	22	23
383	Office supplies- except paper- manuf	0	43	123	167
384	Sign manufacturing	0	6,324	5,442	11,766
385	Gasket- packing- and sealing device	0	960	94	1,054
386	Musical instrument manufacturing	0	0	2	2
387	Broom- brush- and mop manufacturi	0	220	208	428
388	Burial casket manufacturing	0	0	2	2
389	Buttons- pins- and all other miscell	0	491	1,156	1,647
390	Wholesale trade	0	2,058,366	2,178,148	4,236,513
391	Air transportation	0	60,760	153,984	214,744
392	Rail transportation	0	120,649	45,457	166,106
393	Water transportation	0	71,299	74,649	145,948
394	Truck transportation	0	506,833	339,623	846,456
395	Transit and ground passenger transpo	0	8,652	50,063	58,715
396	Pipeline transportation	0	770,922	66,026	836,948
397	Scenic and sightseeing transportation	0	64,023	55,261	119,284
398	Postal service	0	79,903	105,140	185,043

	Industry	Direct	Indirect	Induced	Total
399	Couriers and messengers	0	379,530	69,089	448,619
400	Warehousing and storage	0	253,739	48,626	302,365
401	Motor vehicle and parts dealers	0	30,534	866,205	896,739
402	Furniture and home furnishings store	0	9,216	200,444	209,660
403	Electronics and appliance stores	0	6,804	168,767	175,571
404	Building material and garden supply	0	13,780	389,613	403,393
405	Food and beverage stores	0	27,109	749,399	776,508
406	Health and personal care stores	0	11,450	308,195	319,646
407	Gasoline stations	0	8,857	212,197	221,053
408	Clothing and clothing accessories sto	0	12,659	348,660	361,319
409	Sporting goods- hobby- book and mus	0	3,993	111,645	115,638
410	General merchandise stores	0	20,624	583,747	604,371
411	Miscellaneous store retailers	0	9,629	260,891	270,520
412	Nonstore retailers	0	9,497	269,142	278,639
413	Newpaper publishers	0	62,760	63,677	126,438
414	Periodical publishers	0	16,971	27,650	44,621
415	Book publishers	0	2,036	18,491	20,527
416	Database- directory- and other publis	0	18,025	19,857	37,881
417	Software publishers	0	67,674	11,194	78,868
418	Motion picture and video industries	0	22,786	100,302	123,088
419	Sound recording industries	0	2,049	49,082	51,130
420	Radio and television broadcasting	0	95,320	99,789	195,109
421	Cable networks and program distribu	0	35,573	222,269	257,841
422	Telecommunications	0	344,918	683,973	1,028,891
423	Information services	0	24,551	18,159	42,710
424	Data processing services	0	97,618	34,032	131,650
425	Nondepository credit intermediation a	0	686,211	397,184	1,083,395
426	Securities- commodity contracts- inv	0	403,513	462,616	866,129
427	Insurance carriers	0	157,362	969,987	1,127,349
428	Insurance agencies- brokerages- and r	0	43,515	271,680	315,196
429	Funds- trusts- and other financial veh	0	1,239	280,074	281,312
430	Monetary authorities and depository c	0	1,744,949	980,629	2,725,579
431	Real estate	0	868,205	1,745,419	2,613,624
432	Automotive equipment rental and lea	0	94,214	180,478	274,691
433	Video tape and disc rental	0	208	63,057	63,265
434	Machinery and equipment rental and	0	136,873	12,709	149,582
435	General and consumer goods rental ex	0	48,632	89,496	138,128
436	Lessors of nonfinancial intangible ass	0	11,143,983	87,518	11,231,501
437	Legal services	0	1,151,410	609,179	1,760,588
438	Accounting and bookkeeping service	0	296,673	174,478	471,150

	Industry	Direct	Indirect	Induced	Total
439	Architectural and engineering service	0	655,097	118,871	773,968
440	Specialized design services	0	82,353	29,470	111,824
441	Custom computer programming servi	0	2,349,947	17,520	2,367,466
442	Computer systems design services	0	207,832	31,775	239,607
443	Other computer related services- inclu	0	290,687	39,326	330,013
444	Management consulting services	0	922,622	173,696	1,096,319
445	Environmental and other technical co	0	67,962	18,837	86,799
446	Scientific research and development s	0	720,140	33,047	753,187
447	Advertising and related services	0	150,990	127,720	278,710
448	Photographic services	0	3,952	36,484	40,436
449	Veterinary services	0	414	65,379	65,793
450	All other miscellaneous professional	0	1,386,734	110,101	1,496,835
451	Management of companies and enterp	0	1,499,327	150,688	1,650,015
452	Office administrative services	0	148,103	91,232	239,335
453	Facilities support services	0	4,927	2,298	7,225
454	Employment services	0	254,250	129,148	383,398
455	Business support services	0	346,345	113,271	459,616
456	Travel arrangement and reservation s	0	21,403	61,810	83,212
457	Investigation and security services	0	102,058	44,804	146,862
458	Services to buildings and dwellings	0	253,817	188,171	441,988
459	Other support services	0	46,811	55,388	102,199
460	Waste management and remediation s	0	71,024	77,217	148,242
461	Elementary and secondary schools	0	0	64,034	64,034
462	Colleges- universities- and junior col	0	8,400	108,708	117,107
463	Other educational services	0	5,863	149,796	155,659
464	Home health care services	0	0	183,030	183,030
465	Offices of physicians- dentists- and o	0	0	1,496,831	1,496,831
466	Other ambulatory health care services	0	463	462,425	462,888
467	Hospitals	0	0	1,088,301	1,088,301
468	Nursing and residential care facilities	0	0	443,508	443,508
469	Child day care services	0	0	234,149	234,149
470	Social assistance- except child day ca	0	26	177,748	177,774
471	Performing arts companies	0	2,271	28,277	30,548
472	Spectator sports	0	17,355	69,296	86,650
473	Independent artists- writers- and per	0	5,964	10,116	16,079
474	Promoters of performing arts and spo	0	6,819	33,881	40,700
475	Museums- historical sites- zoos- and	0	0	25,048	25,048
476	Fitness and recreational sports center	0	7,975	72,488	80,462
477	Bowling centers	0	0	11,878	11,878
478	Other amusement- gambling- and recr	0	5,115	242,789	247,904

	Industry	Direct	Indirect	Induced	Total
479	Hotels and motels- including casino h	0	45,216	166,487	211,703
480	Other accommodations	0	2,209	21,145	23,354
481	Food services and drinking places	0	133,039	1,805,800	1,938,839
482	Car washes	0	3,843	49,125	52,968
483	Automotive repair and maintenance-	0	79,822	649,663	729,485
484	Electronic equipment repair and mai	0	97,337	47,261	144,598
485	Commercial machinery repair and ma	0	71,356	48,748	120,104
486	Household goods repair and mainten	0	35,396	75,086	110,482
487	Personal care services	0	0	189,315	189,315
488	Death care services	0	0	57,545	57,545
489	Drycleaning and laundry services	0	5,439	90,212	95,651
490	Other personal services	0	6,778	195,560	202,339
491	Religious organizations	0	0	118,650	118,650
492	Grantmaking and giving and social a	0	0	82,938	82,938
493	Civic- social- professional and simila	0	137,877	171,443	309,320
494	Private households	0	0	117,103	117,103
495	Federal electric utilities	0	0	0	0
496	Other Federal Government enterprise	0	7,787	21,142	28,929
497	State and local government passenger	0	7,321	42,359	49,680
498	State and local government electric uti	0	113,145	41,959	155,103
499	Other State and local government ente	0	153,735	426,300	580,036
500	Noncomparable imports	0	0	0	0
501	Scrap	0	0	0	0
502	Used and secondhand goods	0	0	0	0
503	State & Local Education	0	0	0	0
504	State & Local Non-Education	0	0	0	0
505	Federal Military	0	0	0	0
506	Federal Non-Military	0	0	0	0
507	Rest of the world adjustment to final	0	0	0	0
508	Inventory valuation adjustment	0	0	0	0
509	Owner-occupied dwellings	0	0	4,387,204	4,387,204
Total		149,775,840	61,407,643	36,724,135	247,907,611

Table 3.
Employment Impact—Plant Production

	Industry	Direct	Indirect	Induced	Total
1	Oilseed farming	0	0	0	0
2	Grain farming	0	0	0.5	0.5
3	Vegetable and melon farming	0	0	0.6	0.6
4	Tree nut farming	0	0	0.1	0.1
5	Fruit farming	0	0	0.1	0.1
6	Greenhouse and nursery production	0	0.3	1.5	1.7
7	Tobacco farming	0	0	0	0
8	Cotton farming	0	0	0	0
9	Sugarcane and sugar beet farming	0	0	0.1	0.1
10	All other crop farming	0	0.8	0.5	1.3
11	Cattle ranching and farming	0	0.1	5.6	5.7
12	Poultry and egg production	0	0	0.6	0.6
13	Animal production- except cattle and	0	0	1.2	1.3
14	Logging	0	0.4	0	0.4
15	Forest nurseries- forest products- and	0	0	0	0
16	Fishing	0	0	0.1	0.1
17	Hunting and trapping	0	0	0.2	0.2
18	Agriculture and forestry support activ	0	0.3	1.2	1.5
19	Oil and gas extraction	0	1.5	0.9	2.4
20	Coal mining	0	0	0	0.1
21	Iron ore mining	0	0	0	0
22	Copper- nickel- lead- and zinc minin	0	0	0	0
23	Gold- silver- and other metal ore min	0	0	0	0
24	Stone mining and quarrying	0	0.1	0	0.1
25	Sand- gravel- clay- and refractory mi	0	0.1	0	0.1
26	Other nonmetallic mineral mining	0	0	0	0
27	Drilling oil and gas wells	0	0	0	0
28	Support activities for oil and gas ope	184.2	0.9	0.1	185.2
29	Support activities for other mining	0	0	0	0
30	Power generation and supply	0	0.7	1.5	2.2
31	Natural gas distribution	0	0.1	0.4	0.5
32	Water- sewage and other systems	0	0.1	0.4	0.5
33	New residential 1-unit structures- no	0	0	0	0
34	New multifamily housing structures-	0	0	0	0
35	New residential additions and alterat	0	0	0	0
36	New farm housing units and additions	0	0	0	0
37	Manufacturing and industrial buildin	1,163.00	0	0	1,163.00

	Industry	Direct	Indirect	Induced	Total
38	Commercial and institutional buildin	0	0	0	0
39	Highway- street- bridge- and tunnel c	0	0	0	0
40	Water- sewer- and pipeline construct	0	0	0	0
41	Other new construction	0	0	0	0
42	Maintenance and repair of farm and	0	0	0.6	0.7
43	Maintenance and repair of nonresiden	0	3.7	2.7	6.3
44	Maintenance and repair of highways-	0	0	0	0
45	Other maintenance and repair constru	0	0.4	0.9	1.3
46	Dog and cat food manufacturing	0	0	0	0
47	Other animal food manufacturing	0	0	0	0
48	Flour milling	0	0	0	0
49	Rice milling	0	0	0	0
50	Malt manufacturing	0	0	0	0
51	Wet corn milling	0	0	0	0
52	Soybean processing	0	0	0	0
53	Other oilseed processing	0	0	0	0
54	Fats and oils refining and blending	0	0	0	0
55	Breakfast cereal manufacturing	0	0	0	0
56	Sugar manufacturing	0	0	0	0
57	Confectionery manufacturing from c	0	0	0	0
58	Confectionery manufacturing from p	0	0	0.2	0.2
59	Nonchocolate confectionery manufac	0	0	0.1	0.1
60	Frozen food manufacturing	0	0	0.1	0.1
61	Fruit and vegetable canning and dryi	0	0	0.1	0.1
62	Fluid milk manufacturing	0	0	0.3	0.3
63	Creamery butter manufacturing	0	0	0	0
64	Cheese manufacturing	0	0	0	0
65	Dry- condensed- and evaporated dair	0	0	0.1	0.1
66	Ice cream and frozen dessert manufac	0	0	0.1	0.1
67	Animal- except poultry- slaughtering	0	0	1	1.1
68	Meat processed from carcasses	0	0	0.8	0.9
69	Rendering and meat byproduct proce	0	0	0	0
70	Poultry processing	0	0	1.6	1.6
71	Seafood product preparation and pac	0	0	0.1	0.1
72	Frozen cakes and other pastries manu	0	0	0	0
73	Bread and bakery product- except fr	0	0	1.2	1.3
74	Cookie and cracker manufacturing	0	0	0	0
75	Mixes and dough made from purchase	0	0	0.1	0.1
76	Dry pasta manufacturing	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
77	Tortilla manufacturing	0	0	0.1	0.1
78	Roasted nuts and peanut butter manu	0	0	0	0
79	Other snack food manufacturing	0	0	0.2	0.2
80	Coffee and tea manufacturing	0	0	0.1	0.1
81	Flavoring syrup and concentrate man	0	0	0	0
82	Mayonnaise- dressing- and sauce man	0	0	0.1	0.1
83	Spice and extract manufacturing	0	0	0.1	0.1
84	All other food manufacturing	0	0	0.3	0.3
85	Soft drink and ice manufacturing	0	0	0.2	0.2
86	Breweries	0	0	0	0
87	Wineries	0	0	0	0
88	Distilleries	0	0	0	0
89	Tobacco stemming and redrying	0	0	0	0
90	Cigarette manufacturing	0	0	0	0
91	Other tobacco product manufacturing	0	0	0	0
92	Fiber- yarn- and thread mills	0	0	0	0
93	Broadwoven fabric mills	0	0	0.1	0.1
94	Narrow fabric mills and schiffli embr	0	0	0	0
95	Nonwoven fabric mills	0	0	0	0
96	Knit fabric mills	0	0	0	0
97	Textile and fabric finishing mills	0	0	0	0
98	Fabric coating mills	0	0	0	0
99	Carpet and rug mills	0	0	0	0
100	Curtain and linen mills	0	0	0	0
101	Textile bag and canvas mills	0	0	0	0
102	Tire cord and tire fabric mills	0	0	0	0
103	Other miscellaneous textile product m	0	0	0	0
104	Sheer hosiery mills	0	0	0	0
105	Other hosiery and sock mills	0	0	0	0
106	Other apparel knitting mills	0	0	0	0
107	Cut and sew apparel manufacturing	0	0	1.6	1.6
108	Accessories and other apparel manufa	0	0	0.1	0.1
109	Leather and hide tanning and finishi	0	0	0	0
110	Footwear manufacturing	0	0	0.2	0.2
111	Other leather product manufacturing	0	0	0.1	0.1
112	Sawmills	0	0.6	0.1	0.6
113	Wood preservation	0	0.3	0	0.3
114	Reconstituted wood product manufac	0	0.1	0	0.1
115	Veneer and plywood manufacturing	0	0.6	0	0.6

	Industry	Direct	Indirect	Induced	Total
116	Engineered wood member and truss m	0	1	0	1
117	Wood windows and door manufactur	0	0.1	0.1	0.2
118	Cut stock- resawing lumber- and plan	0	0	0	0.1
119	Other millwork- including flooring	0	0.5	0.1	0.6
120	Wood container and pallet manufactu	0	0.2	0.2	0.3
121	Manufactured home- mobile home- m	0	0	0	0
122	Prefabricated wood building manufac	0	0	0	0
123	Miscellaneous wood product manufac	0	0.1	0.1	0.2
124	Pulp mills	0	0	0	0
125	Paper and paperboard mills	0	0	0	0
126	Paperboard container manufacturing	0	0.1	0.1	0.1
127	Flexible packaging foil manufacturin	0	0	0	0
128	Surface-coated paperboard manufact	0	0	0	0
129	Coated and laminated paper and pack	0	0	0	0
130	Coated and uncoated paper bag manu	0	0	0	0
131	Die-cut paper office supplies manufa	0	0	0	0
132	Envelope manufacturing	0	0	0	0
133	Stationery and related product manuf	0	0	0	0
134	Sanitary paper product manufacturin	0	0	0	0
135	All other converted paper product ma	0	0	0	0
136	Manifold business forms printing	0	0	0	0.1
137	Books printing	0	0	0	0
138	Blankbook and looseleaf binder manu	0	0	0	0
139	Commercial printing	0	0.8	1.2	2
140	Tradebinding and related work	0	0	0	0
141	Prepress services	0	0	0	0
142	Petroleum refineries	0	0.5	0.3	0.8
143	Asphalt paving mixture and block ma	0	0.3	0	0.4
144	Asphalt shingle and coating material	0	0.1	0	0.1
145	Petroleum lubricating oil and grease	0	0	0	0.1
146	All other petroleum and coal product	0	0	0	0
147	Petrochemical manufacturing	0	0.2	0.1	0.3
148	Industrial gas manufacturing	0	0.1	0	0.1
149	Synthetic dye and pigment manufactu	0	0	0	0
150	Other basic inorganic chemical manu	0	0	0	0
151	Other basic organic chemical manufa	0	0	0	0.1
152	Plastics material and resin manufactu	0	0	0	0
153	Synthetic rubber manufacturing	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
154	Cellulosic organic fiber manufacturin	0	0	0	0
155	Noncellulosic organic fiber manufact	0	0	0	0
156	Nitrogenous fertilizer manufacturing	0	0	0	0
157	Phosphatic fertilizer manufacturing	0	0	0	0
158	Fertilizer- mixing only- manufacturin	0	0.1	0	0.1
159	Pesticide and other agricultural chem	0	0	0	0
160	Pharmaceutical and medicine manufa	0	0	0.6	0.6
161	Paint and coating manufacturing	0	0	0	0
162	Adhesive manufacturing	0	0.1	0	0.1
163	Soap and other detergent manufactur	0	0	0.1	0.1
164	Polish and other sanitation good man	0	0	0.1	0.2
165	Surface active agent manufacturing	0	0	0	0
166	Toilet preparation manufacturing	0	0	0.2	0.3
167	Printing ink manufacturing	0	0	0	0
168	Explosives manufacturing	0	0	0	0
169	Custom compounding of purchased re	0	0.1	0	0.2
170	Photographic film and chemical manu	0	0	0	0
171	Other miscellaneous chemical produc	0	0.1	0.1	0.2
172	Plastics packaging materials- film an	0	0.2	0.3	0.4
173	Plastics pipe- fittings- and profile sh	0	0.5	0.1	0.6
174	Laminated plastics plate- sheet- and	0	0.1	0	0.1
175	Plastics bottle manufacturing	0	0	0.1	0.1
176	Resilient floor covering manufacturi	0	0	0	0
177	Plastics plumbing fixtures and all othe	0	3.5	0.6	4.1
178	Foam product manufacturing	0	0.3	0.3	0.6
179	Tire manufacturing	0	0	0	0
180	Rubber and plastics hose and belting	0	0	0	0
181	Other rubber product manufacturing	0	0	0	0
182	Vitreous china plumbing fixture man	0	0	0	0
183	Vitreous china and earthenware artic	0	0	0	0
184	Porcelain electrical supply manufactu	0	0	0	0
185	Brick and structural clay tile manufa	0	0	0	0
186	Ceramic wall and floor tile manufact	0	0	0	0
187	Nonclay refractory manufacturing	0	0	0	0
188	Clay refractory and other structural c	0	0	0	0
189	Glass container manufacturing	0	0	0	0
190	Glass and glass products- except glas	0	0.2	0.2	0.4
191	Cement manufacturing	0	0	0	0
192	Ready-mix concrete manufacturing	0	1.1	0	1.1

	Industry	Direct	Indirect	Induced	Total
193	Concrete block and brick manufactur	0	0	0	0
194	Concrete pipe manufacturing	0	0	0	0
195	Other concrete product manufacturin	0	0.1	0	0.1
196	Lime manufacturing	0	0	0	0
197	Gypsum product manufacturing	0	0	0	0
198	Abrasive product manufacturing	0	0	0	0
199	Cut stone and stone product manufac	0	0	0	0
200	Ground or treated minerals and earth	0	0	0	0
201	Mineral wool manufacturing	0	0	0	0
202	Miscellaneous nonmetallic mineral p	0	0	0	0
203	Iron and steel mills	0	0	0	0.1
204	Ferroalloy and related product manuf	0	0	0	0
205	Iron- steel pipe and tube from purchas	0	0	0	0
206	Rolled steel shape manufacturing	0	0	0	0
207	Steel wire drawing	0	0	0	0
208	Alumina refining	0	0	0	0
209	Primary aluminum production	0	0	0	0
210	Secondary smelting and alloying of	0	0	0	0
211	Aluminum sheet- plate- and foil man	0	0	0	0
212	Aluminum extruded product manufac	0	0	0	0
213	Other aluminum rolling and drawing	0	0	0	0
214	Primary smelting and refining of cop	0	0	0	0
215	Primary nonferrous metal- except co	0	0	0	0
216	Copper rolling- drawing- and extrudi	0	0	0	0
217	Copper wire- except mechanical- dra	0	0	0	0
218	Secondary processing of copper	0	0	0	0
219	Nonferrous metal- except copper and	0	0	0	0
220	Secondary processing of other nonfer	0	0	0	0
221	Ferrous metal foundaries	0	0	0	0
222	Aluminum foundries	0	0	0	0
223	Nonferrous foundries- except alumi	0	0	0	0
224	Iron and steel forging	0	0	0	0
225	Nonferrous forging	0	0	0	0
226	Custom roll forming	0	0	0	0
227	All other forging and stamping	0	0	0	0
228	Cutlery and flatware- except preciou	0	0	0	0
229	Hand and edge tool manufacturing	0	0	0	0
230	Saw blade and handsaw manufacturi	0	0	0	0
231	Kitchen utensil- pot- and pan manufa	0	0	0	0
232	Prefabricated metal buildings and c	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
233	Fabricated structural metal manufact	0	0.6	0	0.6
234	Plate work manufacturing	0	0	0	0.1
235	Metal window and door manufacturi	0	0.3	0	0.3
236	Sheet metal work manufacturing	0	1.6	0	1.6
237	Ornamental and architectural metal	0	0.2	0	0.2
238	Power boiler and heat exchanger man	0	0	0	0
239	Metal tank- heavy gauge- manufactur	0	0	0	0
240	Metal can- box- and other container	0	0.1	0	0.1
241	Hardware manufacturing	0	0	0	0.1
242	Spring and wire product manufacturi	0	0.1	0.1	0.2
243	Machine shops	0	1	0.2	1.2
244	Turned product and screw- nut- and	0	0.2	0	0.2
245	Metal heat treating	0	0.1	0	0.1
246	Metal coating and nonprecious engra	0	0.1	0	0.2
247	Electroplating- anodizing- and colori	0	0.3	0	0.3
248	Metal valve manufacturing	0	2.5	0	2.5
249	Ball and roller bearing manufacturing	0	0	0	0
250	Small arms manufacturing	0	0	0	0
251	Other ordnance and accessories manu	0	0	0	0
252	Fabricated pipe and pipe fitting manu	0	0.1	0	0.1
253	Industrial pattern manufacturing	0	0	0	0
254	Enameled iron and metal sanitary wa	0	0	0	0
255	Miscellaneous fabricated metal produ	0	0	0	0
256	Ammunition manufacturing	0	0	0	0
257	Farm machinery and equipment manu	0	0	0	0
258	Lawn and garden equipment manufac	0	0	0	0
259	Construction machinery manufacturi	0	0.2	0	0.2
260	Mining machinery and equipment ma	0	0	0	0
261	Oil and gas field machinery and equ	0	1	0	1
262	Sawmill and woodworking machiner	0	0	0	0
263	Plastics and rubber industry machine	0	0	0	0
264	Paper industry machinery manufactur	0	0	0	0
265	Textile machinery manufacturing	0	0	0	0
266	Printing machinery and equipment m	0	0	0	0
267	Food product machinery manufacturi	0	0	0	0
268	Semiconductor machinery manufactu	0	0	0	0
269	All other industrial machinery manuf	0	0	0	0
270	Office machinery manufacturing	0	0	0	0
271	Optical instrument and lens manufact	0	0	0	0
272	Photographic and photocopying equi	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
273	Other commercial and service indust	0	0	0	0
274	Automatic vending- commercial laun	0	0	0	0
275	Air purification equipment manufact	0	0	0	0
276	Industrial and commercial fan and b	0	0	0	0
277	Heating equipment- except warm air	0	0	0	0
278	AC- refrigeration- and forced air heat	0	0	0	0
279	Industrial mold manufacturing	0	0	0	0
280	Metal cutting machine tool manufact	0	0	0	0
281	Metal forming machine tool manufac	0	0	0	0
282	Special tool- die- jig- and fixture ma	0	0	0	0
283	Cutting tool and machine tool access	0	0	0	0
284	Rolling mill and other metalworking	0	0	0	0
285	Turbine and turbine generator set uni	0	0	0	0
286	Other engine equipment manufacturi	0	0	0	0
287	Speed changers and mechanical power	0	0	0	0.1
288	Pump and pumping equipment manuf	0	0	0	0
289	Air and gas compressor manufacturin	0	0	0	0
290	Measuring and dispensing pump man	0	0	0	0
291	Elevator and moving stairway manufa	0	0	0	0
292	Conveyor and conveying equipment	0	0	0	0
293	Overhead cranes- hoists- and monorai	0	1.2	0	1.2
294	Industrial truck- trailer- and stacker	0	0.1	0	0.1
295	Power-driven handtool manufacturin	0	0	0	0
296	Welding and soldering equipment ma	0	0	0	0.1
297	Packaging machinery manufacturing	0	0	0	0
298	Industrial process furnace and oven	0	0	0	0
299	Fluid power cylinder and actuator ma	0	0	0	0
300	Fluid power pump and motor manufa	0	0	0	0
301	Scales- balances- and miscellaneous	0	0	0	0
302	Electronic computer manufacturing	0	0	0.3	0.3
303	Computer storage device manufactur	0	0	0	0
304	Computer terminal manufacturing	0	0	0	0
305	Other computer peripheral equipmen	0	0	0	0
306	Telephone apparatus manufacturing	0	0	0	0
307	Broadcast and wireless communicati	0	0	0	0
308	Other communications equipment ma	0	0.8	0	0.9
309	Audio and video equipment manufact	0	0	0.1	0.1
310	Electron tube manufacturing	0	0	0	0
311	Semiconductors and related device m	0	0.3	0.3	0.6

	Industry	Direct	Indirect	Induced	Total
312	All other electronic component manu	0	0.2	0.1	0.4
313	Electromedical apparatus manufactur	0	0	0	0
314	Search- detection- and navigation in	0	0	0	0
315	Automatic environmental control man	0	0	0	0
316	Industrial process variable instrument	0	0	0	0
317	Totalizing fluid meters and counting	0	0	0	0
318	Electricity and signal testing instrum	0	0	0	0
319	Analytical laboratory instrument man	0	0	0	0.1
320	Irradiation apparatus manufacturing	0	0	0	0
321	Watch- clock- and other measuring an	0	0	0.1	0.1
322	Software reproducing	0	0	0	0.1
323	Audio and video media reproduction	0	0	0	0
324	Magnetic and optical recording medi	0	0	0	0
325	Electric lamp bulb and part manufact	0	0	0	0
326	Lighting fixture manufacturing	0	0	0	0
327	Electric housewares and household f	0	0	0	0
328	Household vacuum cleaner manufact	0	0	0	0
329	Household cooking appliance manufa	0	0	0	0
330	Household refrigerator and home fre	0	0	0	0
331	Household laundry equipment manufa	0	0	0	0
332	Other major household appliance man	0	0	0	0
333	Electric power and specialty transfo	0	0	0	0
334	Motor and generator manufacturing	0	0	0	0.1
335	Switchgear and switchboard apparatu	0	0	0	0
336	Relay and industrial control manufac	0	0	0	0
337	Storage battery manufacturing	0	0	0	0
338	Primary battery manufacturing	0	0	0	0
339	Fiber optic cable manufacturing	0	0.1	0	0.1
340	Other communication and energy wir	0	0.1	0	0.1
341	Wiring device manufacturing	0	0	0	0
342	Carbon and graphite product manufac	0	0	0	0
343	Miscellaneous electrical equipment	0	0	0	0
344	Automobile and light truck manufact	0	0	0.3	0.3
345	Heavy duty truck manufacturing	0	0	0	0
346	Motor vehicle body manufacturing	0	0	0	0
347	Truck trailer manufacturing	0	0	0	0
348	Motor home manufacturing	0	0	0	0
349	Travel trailer and camper manufactur	0	0	0.1	0.1

	Industry	Direct	Indirect	Induced	Total
350	Motor vehicle parts manufacturing	0	0.8	0.6	1.4
351	Aircraft manufacturing	0	0	0	0
352	Aircraft engine and engine parts man	0	0	0	0
353	Other aircraft parts and equipment	0	0	0	0
354	Guided missile and space vehicle ma	0	0	0	0
355	Propulsion units and parts for space	0	0	0	0
356	Railroad rolling stock manufacturing	0	0	0	0
357	Ship building and repairing	0	0	0	0
358	Boat building	0	0	0	0
359	Motorcycle- bicycle- and parts manuf	0	0	0	0
360	Military armored vehicles and tank p	0	0	0	0
361	All other transportation equipment m	0	0	0	0
362	Wood kitchen cabinet and countertop	0	0.2	0.3	0.5
363	Upholstered household furniture man	0	0	0.3	0.3
364	Nonupholstered wood household furn	0	0	0.2	0.2
365	Metal household furniture manufactu	0	0	0.1	0.1
366	Institutional furniture manufacturing	0	0	0	0
367	Other household and institutional fur	0	0	0	0
368	Wood office furniture manufacturing	0	0	0	0
369	Custom architectural woodwork and	0	0	0	0
370	Office furniture- except wood- manuf	0	0	0	0
371	Showcases- partitions- shelving- and	0	0	0	0
372	Mattress manufacturing	0	0	0.2	0.2
373	Blind and shade manufacturing	0	0	0.2	0.2
374	Laboratory apparatus and furniture m	0	0	0	0
375	Surgical and medical instrument man	0	0.1	0.1	0.2
376	Surgical appliance and supplies manu	0	2.8	0.2	3
377	Dental equipment and supplies manuf	0	0	0	0
378	Ophthalmic goods manufacturing	0	0	0.2	0.2
379	Dental laboratories	0	0	0.3	0.3
380	Jewelry and silverware manufacturin	0	0	0	0.1
381	Sporting and athletic goods manufact	0	0	0	0
382	Doll- toy- and game manufacturing	0	0	0	0
383	Office supplies- except paper- manuf	0	0	0	0
384	Sign manufacturing	0	0.1	0.1	0.2
385	Gasket- packing- and sealing device	0	0	0	0
386	Musical instrument manufacturing	0	0	0	0
387	Broom- brush- and mop manufacturi	0	0	0	0
388	Burial casket manufacturing	0	0	0	0
389	Buttons- pins- and all other miscell	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
390	Wholesale trade	0	33.1	25	58.1
391	Air transportation	0	0.8	1.2	2
392	Rail transportation	0	0.7	0.3	1
393	Water transportation	0	0.1	0.3	0.4
394	Truck transportation	0	16.8	6.1	22.9
395	Transit and ground passenger transpo	0	0.4	1.7	2.1
396	Pipeline transportation	0	0.1	0.1	0.3
397	Scenic and sightseeing transportation	0	1.8	1.1	2.9
398	Postal service	0	1.6	2.1	3.7
399	Couriers and messengers	0	3.9	2.2	6.1
400	Warehousing and storage	0	1.6	1.1	2.6
401	Motor vehicle and parts dealers	0	2.8	16.5	19.3
402	Furniture and home furnishings store	0	1.1	5.2	6.3
403	Electronics and appliance stores	0	0.8	4.1	5
404	Building material and garden supply	0	1.7	10.1	11.8
405	Food and beverage stores	0	4.1	23.6	27.7
406	Health and personal care stores	0	1.6	8.7	10.2
407	Gasoline stations	0	1.5	7.3	8.8
408	Clothing and clothing accessories sto	0	2.2	12.6	14.8
409	Sporting goods- hobby- book and mus	0	1	5.5	6.5
410	General merchandise stores	0	3.4	20.1	23.6
411	Miscellaneous store retailers	0	2.4	13.6	16
412	Nonstore retailers	0	1.9	11.2	13.1
413	Newpaper publishers	0	0.6	0.9	1.5
414	Periodical publishers	0	0.1	0.2	0.3
415	Book publishers	0	0	0.1	0.1
416	Database- directory- and other publis	0	0.1	0.1	0.1
417	Software publishers	0	0	0.1	0.1
418	Motion picture and video industries	0	0.3	1.3	1.5
419	Sound recording industries	0	0	0.2	0.2
420	Radio and television broadcasting	0	0.6	0.9	1.5
421	Cable networks and program distribu	0	0	0.4	0.4
422	Telecommunications	0	2.7	3.5	6.1
423	Information services	0	0.2	0.1	0.3
424	Data processing services	0	0.4	0.3	0.7
425	Nondepository credit intermediation a	0	4.4	4.5	8.9
426	Securities- commodity contracts- inv	0	4.4	7.9	12.3
427	Insurance carriers	0	7.6	9.1	16.8
428	Insurance agencies- brokerages- and r	0	3.4	4.1	7.5

	Industry	Direct	Indirect	Induced	Total
429	Funds- trusts- and other financial veh	0	0	1.4	1.5
430	Monetary authorities and depository c	0	5.2	8	13.3
431	Real estate	0	8.1	15.8	23.9
432	Automotive equipment rental and lea	0	1.2	1.9	3.1
433	Video tape and disc rental	0	0	1.1	1.1
434	Machinery and equipment rental and	0	2.8	0.2	3
435	General and consumer goods rental ex	0	0.8	1.4	2.3
436	Lessors of nonfinancial intangible ass	0	0	0	0
437	Legal services	0	2.7	8.2	10.9
438	Accounting and bookkeeping service	0	5.9	3.6	9.5
439	Architectural and engineering service	0	64.2	2	66.2
440	Specialized design services	0	0.6	0.5	1.1
441	Custom computer programming servi	0	1	0.3	1.3
442	Computer systems design services	0	0.9	0.6	1.5
443	Other computer related services- inclu	0	0.6	0.4	1
444	Management consulting services	0	3.8	2.4	6.2
445	Environmental and other technical co	0	1	0.2	1.2
446	Scientific research and development s	0	0.9	0.5	1.5
447	Advertising and related services	0	1.5	2	3.6
448	Photographic services	0	0.1	1	1.1
449	Veterinary services	0	0	1.9	1.9
450	All other miscellaneous professional	0	0.6	0.4	1
451	Management of companies and enterp	0	4.6	2	6.7
452	Office administrative services	0	2	0.8	2.8
453	Facilities support services	0	0.1	0	0.2
454	Employment services	0	25.4	9.9	35.2
455	Business support services	0	2.8	2.8	5.6
456	Travel arrangement and reservation s	0	0.3	0.9	1.2
457	Investigation and security services	0	3.7	2.1	5.7
458	Services to buildings and dwellings	0	8.1	7	15.1
459	Other support services	0	0.9	0.9	1.8
460	Waste management and remediation s	0	1.1	0.9	2
461	Elementary and secondary schools	0	0	3.9	3.9
462	Colleges- universities- and junior col	0	0.1	3.4	3.5
463	Other educational services	0	0.1	4.9	4.9
464	Home health care services	0	0	11.7	11.7
465	Offices of physicians- dentists- and o	0	0	23.4	23.4

	Industry	Direct	Indirect	Induced	Total
466	Other ambulatory health care services	0	0	6.1	6.1
467	Hospitals	0	0	18.4	18.4
468	Nursing and residential care facilities	0	0	18.5	18.5
469	Child day care services	0	0	12.2	12.2
470	Social assistance- except child day ca	0	0	10.1	10.1
471	Performing arts companies	0	0.3	2.4	2.8
472	Spectator sports	0	0.6	2.5	3.1
473	Independent artists- writers- and per	0	0.2	0.3	0.5
474	Promoters of performing arts and spo	0	0.5	1.7	2.2
475	Museums- historical sites- zoos- and	0	0	0.7	0.7
476	Fitness and recreational sports center	0	0.8	3.4	4.2
477	Bowling centers	0	0	0.5	0.5
478	Other amusement- gambling- and recr	0	0.4	7.5	7.9
479	Hotels and motels- including casino h	0	1.8	4.4	6.2
480	Other accommodations	0	0	0.4	0.5
481	Food services and drinking places	0	6.6	67.6	74.2
482	Car washes	0	0.2	2.2	2.4
483	Automotive repair and maintenance-	0	5.3	16.1	21.3
484	Electronic equipment repair and mai	0	2.6	0.7	3.3
485	Commercial machinery repair and ma	0	4.3	0.8	5.1
486	Household goods repair and mainten	0	0.8	0.9	1.6
487	Personal care services	0	0	6.6	6.6
488	Death care services	0	0	1.6	1.6
489	Drycleaning and laundry services	0	0.2	3.9	4.2
490	Other personal services	0	0.1	2.9	3
491	Religious organizations	0	0	6.3	6.3
492	Grantmaking and giving and social a	0	0	1.8	1.8
493	Civic- social- professional and simila	0	1.7	4.7	6.5
494	Private households	0	0	20.2	20.2
495	Federal electric utilities	0	0	0	0
496	Other Federal Government enterprise	0	0.2	0.4	0.6
497	State and local government passenger	0	0.4	1.9	2.3
498	State and local government electric uti	0	0.1	0.2	0.2
499	Other State and local government ente	0	1.1	4	5.1
500	Noncomparable imports	0	0	0	0
501	Scrap	0	0	0	0
502	Used and secondhand goods	0	0	0	0
503	State & Local Education	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
504	State & Local Non-Education	0	0	0	0
505	Federal Military	0	0	0	0
506	Federal Non-Military	0	0	0	0
507	Rest of the world adjustment to final	0	0	0	0
508	Inventory valuation adjustment	0	0	0	0
509	Owner-occupied dwellings	0	0	0	0
Total		1,347.10	327.7	613.6	2,288.50

Table 4.
Employment Impact—1 Year Oil Production

	Industry	Direct	Indirect	Induced	Total
1	Oilseed farming	0	0	0	0
2	Grain farming	0	0	0.3	0.3
3	Vegetable and melon farming	0	0	0.3	0.4
4	Tree nut farming	0	0	0	0
5	Fruit farming	0	0	0	0
6	Greenhouse and nursery production	0	0.2	0.8	1
7	Tobacco farming	0	0	0	0
8	Cotton farming	0	0	0	0
9	Sugarcane and sugar beet farming	0	0.1	0	0.1
10	All other crop farming	0	0	0.3	0.3
11	Cattle ranching and farming	0	0.1	3.2	3.3
12	Poultry and egg production	0	0	0.3	0.3
13	Animal production- except cattle and	0	0	0.7	0.7
14	Logging	0	0	0	0
15	Forest nurseries- forest products- and	0	0	0	0
16	Fishing	0	0	0.1	0.1
17	Hunting and trapping	0	0	0.1	0.1
18	Agriculture and forestry support activ	0	0	0.7	0.7
19	Oil and gas extraction	231.7	21.1	0.5	253.3
20	Coal mining	0	0.1	0	0.1
21	Iron ore mining	0	0	0	0
22	Copper- nickel- lead- and zinc minin	0	0	0	0
23	Gold- silver- and other metal ore min	0	0	0	0
24	Stone mining and quarrying	0	0	0	0
25	Sand- gravel- clay- and refractory mi	0	0	0	0
26	Other nonmetallic mineral mining	0	0	0	0
27	Drilling oil and gas wells	0	0.4	0	0.4
28	Support activities for oil and gas ope	0	25.4	0.1	25.4
29	Support activities for other mining	0	0	0	0
30	Power generation and supply	0	2.2	0.9	3
31	Natural gas distribution	0	0.1	0.2	0.3
32	Water- sewage and other systems	0	0.1	0.2	0.4
33	New residential 1-unit structures- no	0	0	0	0
34	New multifamily housing structures-	0	0	0	0
35	New residential additions and alterat	0	0	0	0
36	New farm housing units and additions	0	0	0	0
37	Manufacturing and industrial buildin	0	0	0	0
38	Commercial and institutional buildin	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
39	Highway- street- bridge- and tunnel c	0	0	0	0
40	Water- sewer- and pipeline construct	0	0	0	0
41	Other new construction	0	0	0	0
42	Maintenance and repair of farm and	0	0	0.4	0.4
43	Maintenance and repair of nonresiden	0	1.4	1.5	3
44	Maintenance and repair of highways-	0	0	0	0
45	Other maintenance and repair constru	0	0.7	0.5	1.3
46	Dog and cat food manufacturing	0	0	0	0
47	Other animal food manufacturing	0	0	0	0
48	Flour milling	0	0	0	0
49	Rice milling	0	0	0	0
50	Malt manufacturing	0	0	0	0
51	Wet corn milling	0	0	0	0
52	Soybean processing	0	0	0	0
53	Other oilseed processing	0	0	0	0
54	Fats and oils refining and blending	0	0	0	0
55	Breakfast cereal manufacturing	0	0	0	0
56	Sugar manufacturing	0	0	0	0
57	Confectionery manufacturing from c	0		0	0
58	Confectionery manufacturing from p	0	0	0.1	0.1
59	Nonchocolate confectionery manufac	0	0	0	0
60	Frozen food manufacturing	0	0	0	0
61	Fruit and vegetable canning and dryi	0	0	0	0
62	Fluid milk manufacturing	0	0	0.2	0.2
63	Creamery butter manufacturing	0	0	0	0
64	Cheese manufacturing	0	0	0	0
65	Dry- condensed- and evaporated dair	0	0	0	0
66	Ice cream and frozen dessert manufac	0	0	0.1	0.1
67	Animal- except poultry- slaughtering	0	0	0.6	0.6
68	Meat processed from carcasses	0	0	0.5	0.5
69	Rendering and meat byproduct proce	0	0	0	0
70	Poultry processing	0	0	0.9	0.9
71	Seafood product preparation and pac	0	0	0.1	0.1
72	Frozen cakes and other pastries manu	0	0	0	0
73	Bread and bakery product- except fr	0	0	0.7	0.7
74	Cookie and cracker manufacturing	0	0	0	0
75	Mixes and dough made from purchase	0	0	0	0
76	Dry pasta manufacturing	0	0	0	0
77	Tortilla manufacturing	0	0	0.1	0.1
78	Roasted nuts and peanut butter manu	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
79	Other snack food manufacturing	0	0	0.1	0.1
80	Coffee and tea manufacturing	0	0	0	0
81	Flavoring syrup and concentrate man	0	0	0	0
82	Mayonnaise- dressing- and sauce man	0	0	0	0
83	Spice and extract manufacturing	0	0	0	0
84	All other food manufacturing	0	0	0.2	0.2
85	Soft drink and ice manufacturing	0	0	0.1	0.1
86	Breweries	0	0	0	0
87	Wineries	0	0	0	0
88	Distilleries	0	0	0	0
89	Tobacco stemming and redrying	0	0	0	0
90	Cigarette manufacturing	0	0	0	0
91	Other tobacco product manufacturing	0	0	0	0
92	Fiber- yarn- and thread mills	0	0	0	0
93	Broadwoven fabric mills	0	0	0	0
94	Narrow fabric mills and schiffli embr	0	0	0	0
95	Nonwoven fabric mills	0	0	0	0
96	Knit fabric mills	0	0	0	0
97	Textile and fabric finishing mills	0	0	0	0
98	Fabric coating mills	0	0	0	0
99	Carpet and rug mills	0	0	0	0
100	Curtain and linen mills	0	0	0	0
101	Textile bag and canvas mills	0	0	0	0
102	Tire cord and tire fabric mills	0	0	0	0
103	Other miscellaneous textile product m	0	0	0	0
104	Sheer hosiery mills	0	0	0	0
105	Other hosiery and sock mills	0	0	0	0
106	Other apparel knitting mills	0	0	0	0
107	Cut and sew apparel manufacturing	0	0	0.9	0.9
108	Accessories and other apparel manufa	0	0	0.1	0.1
109	Leather and hide tanning and finishi	0	0	0	0
110	Footwear manufacturing	0	0	0.1	0.1
111	Other leather product manufacturing	0	0	0.1	0.1
112	Sawmills	0	0	0	0.1
113	Wood preservation	0	0	0	0
114	Reconstituted wood product manufac	0	0	0	0
115	Veneer and plywood manufacturing	0	0	0	0
116	Engineered wood member and truss m	0	0	0	0
117	Wood windows and door manufactur	0	0	0	0.1
118	Cut stock- resawing lumber- and plan	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
119	Other millwork- including flooring	0	0	0	0.1
120	Wood container and pallet manufactu	0	0.1	0.1	0.2
121	Manufactured home- mobile home- m	0	0	0	0
122	Prefabricated wood building manufac	0	0	0	0
123	Miscellaneous wood product manufac	0	0	0.1	0.1
124	Pulp mills	0	0	0	0
125	Paper and paperboard mills	0	0	0	0
126	Paperboard container manufacturing	0	0.1	0	0.1
127	Flexible packaging foil manufacturin	0	0	0	0
128	Surface-coated paperboard manufact	0	0	0	0
129	Coated and laminated paper and pack	0	0	0	0
130	Coated and uncoated paper bag manu	0	0	0	0
131	Die-cut paper office supplies manufa	0	0	0	0
132	Envelope manufacturing	0	0	0	0
133	Stationery and related product manuf	0	0	0	0
134	Sanitary paper product manufacturin	0	0	0	0
135	All other converted paper product ma	0	0	0	0
136	Manifold business forms printing	0	0	0	0
137	Books printing	0	0	0	0
138	Blankbook and looseleaf binder manu	0	0	0	0
139	Commercial printing	0	0.7	0.7	1.4
140	Tradebinding and related work	0	0	0	0
141	Prepress services	0	0	0	0
142	Petroleum refineries	0	0.5	0.1	0.6
143	Asphalt paving mixture and block ma	0	0	0	0
144	Asphalt shingle and coating material	0	0	0	0
145	Petroleum lubricating oil and grease	0	0.1	0	0.1
146	All other petroleum and coal product	0	0	0	0
147	Petrochemical manufacturing	0	0.9	0.1	0.9
148	Industrial gas manufacturing	0	0.5	0	0.6
149	Synthetic dye and pigment manufactu	0	0	0	0
150	Other basic inorganic chemical manu	0	0	0	0.1
151	Other basic organic chemical manufa	0	0.2	0	0.2
152	Plastics material and resin manufactu	0	0	0	0
153	Synthetic rubber manufacturing	0	0	0	0
154	Cellulosic organic fiber manufacturin	0	0	0	0
155	Noncellulosic organic fiber manufact	0	0	0	0
156	Nitrogenous fertilizer manufacturing	0	0	0	0
157	Phosphatic fertilizer manufacturing	0	0	0	0
158	Fertilizer- mixing only- manufacturin	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
159	Pesticide and other agricultural chem	0	0	0	0
160	Pharmaceutical and medicine manufa	0	0	0.3	0.3
161	Paint and coating manufacturing	0	0	0	0
162	Adhesive manufacturing	0	0	0	0
163	Soap and other detergent manufactur	0	0	0	0
164	Polish and other sanitation good man	0	0	0.1	0.1
165	Surface active agent manufacturing	0	0	0	0
166	Toilet preparation manufacturing	0	0	0.1	0.1
167	Printing ink manufacturing	0	0	0	0
168	Explosives manufacturing	0	0	0	0
169	Custom compounding of purchased re	0	0.2	0	0.2
170	Photographic film and chemical manu	0	0	0	0
171	Other miscellaneous chemical produc	0	1	0	1
172	Plastics packaging materials- film an	0	0.1	0.2	0.2
173	Plastics pipe- fittings- and profile sh	0	0.1	0.1	0.1
174	Laminated plastics plate- sheet- and	0	0	0	0
175	Plastics bottle manufacturing	0	0	0	0.1
176	Resilient floor covering manufacturi	0	0	0	0
177	Plastics plumbing fixtures and all othe	0	1.5	0.4	1.8
178	Foam product manufacturing	0	0	0.2	0.2
179	Tire manufacturing	0	0	0	0
180	Rubber and plastics hose and belting	0	0	0	0
181	Other rubber product manufacturing	0	0	0	0
182	Vitreous china plumbing fixture man	0	0	0	0
183	Vitreous china and earthenware artic	0	0	0	0
184	Porcelain electrical supply manufactu	0	0	0	0
185	Brick and structural clay tile manufa	0	0	0	0
186	Ceramic wall and floor tile manufact	0	0	0	0
187	Nonclay refractory manufacturing	0	0	0	0
188	Clay refractory and other structural c	0	0	0	0
189	Glass container manufacturing	0	0	0	0
190	Glass and glass products- except glas	0	0.1	0.1	0.2
191	Cement manufacturing	0	0	0	0
192	Ready-mix concrete manufacturing	0	0	0	0
193	Concrete block and brick manufactur	0	0	0	0
194	Concrete pipe manufacturing	0	0	0	0
195	Other concrete product manufacturin	0	0	0	0
196	Lime manufacturing	0	0	0	0
197	Gypsum product manufacturing	0	0	0	0
198	Abrasive product manufacturing	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
199	Cut stone and stone product manufac	0	0	0	0
200	Ground or treated minerals and earth	0	0	0	0
201	Mineral wool manufacturing	0	0	0	0
202	Miscellaneous nonmetallic mineral p	0	0	0	0
203	Iron and steel mills	0	0.2	0	0.2
204	Ferroalloy and related product manuf	0	0	0	0
205	Iron- steel pipe and tube from purchas	0	0.1	0	0.1
206	Rolled steel shape manufacturing	0	0	0	0
207	Steel wire drawing	0	0	0	0
208	Alumina refining	0	0	0	0
209	Primary aluminum production	0	0	0	0
210	Secondary smelting and alloying of	0	0	0	0
211	Aluminum sheet- plate- and foil man	0	0	0	0
212	Aluminum extruded product manufac	0	0	0	0
213	Other aluminum rolling and drawing	0	0	0	0
214	Primary smelting and refining of cop	0	0	0	0
215	Primary nonferrous metal- except co	0	0	0	0
216	Copper rolling- drawing- and extrudi	0	0	0	0
217	Copper wire- except mechanical- dra	0	0	0	0
218	Secondary processing of copper	0	0	0	0
219	Nonferrous metal- except copper and	0	0	0	0
220	Secondary processing of other nonfer	0	0	0	0
221	Ferrous metal foundaries	0	0	0	0
222	Aluminum foundries	0	0	0	0
223	Nonferrous foundries- except alumi	0	0	0	0
224	Iron and steel forging	0	0	0	0
225	Nonferrous forging	0	0	0	0
226	Custom roll forming	0	0	0	0
227	All other forging and stamping	0	0	0	0
228	Cutlery and flatware- except preciou	0	0	0	0
229	Hand and edge tool manufacturing	0	0	0	0
230	Saw blade and handsaw manufacturi	0	0	0	0
231	Kitchen utensil- pot- and pan manufa	0	0	0	0
232	Prefabricated metal buildings and c	0	0	0	0
233	Fabricated structural metal manufact	0	0.1	0	0.1
234	Plate work manufacturing	0	0	0	0
235	Metal window and door manufacturi	0	0	0	0
236	Sheet metal work manufacturing	0	0	0	0
237	Ornamental and architectural metal	0	0	0	0
238	Power boiler and heat exchanger man	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
239	Metal tank- heavy gauge- manufactur	0	0	0	0
240	Metal can- box- and other container	0	0	0	0
241	Hardware manufacturing	0	0	0	0
242	Spring and wire product manufacturi	0	0	0	0.1
243	Machine shops	0	1.2	0.1	1.3
244	Turned product and screw- nut- and	0	0.2	0	0.2
245	Metal heat treating	0	0.1	0	0.1
246	Metal coating and nonprecious engra	0	0.2	0	0.2
247	Electroplating- anodizing- and colori	0	0.3	0	0.3
248	Metal valve manufacturing	0	0.8	0	0.8
249	Ball and roller bearing manufacturing	0	0	0	0
250	Small arms manufacturing	0	0	0	0
251	Other ordnance and accessories manu	0	0	0	0
252	Fabricated pipe and pipe fitting manu	0	0	0	0
253	Industrial pattern manufacturing	0	0	0	0
254	Enameled iron and metal sanitary wa	0	0	0	0
255	Miscellaneous fabricated metal produ	0	0	0	0
256	Ammunition manufacturing	0	0	0	0
257	Farm machinery and equipment manu	0	0	0	0.1
258	Lawn and garden equipment manufac	0	0	0	0
259	Construction machinery manufacturi	0	1.3	0	1.4
260	Mining machinery and equipment ma	0	0	0	0
261	Oil and gas field machinery and equ	0	3.3	0	3.3
262	Sawmill and woodworking machiner	0	0	0	0
263	Plastics and rubber industry machine	0	0	0	0
264	Paper industry machinery manufactur	0	0	0	0
265	Textile machinery manufacturing	0	0	0	0
266	Printing machinery and equipment m	0	0	0	0
267	Food product machinery manufacturi	0	0	0	0
268	Semiconductor machinery manufactu	0	0	0	0
269	All other industrial machinery manuf	0	0	0	0
270	Office machinery manufacturing	0	0	0	0
271	Optical instrument and lens manufact	0	0	0	0
272	Photographic and photocopying equi	0	0	0	0
273	Other commercial and service indust	0	0	0	0
274	Automatic vending- commercial laun	0	0	0	0
275	Air purification equipment manufact	0	0	0	0
276	Industrial and commercial fan and b	0	0	0	0
277	Heating equipment- except warm air	0	0	0	0
278	AC- refrigeration- and forced air heat	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
279	Industrial mold manufacturing	0	0	0	0
280	Metal cutting machine tool manufact	0	0	0	0
281	Metal forming machine tool manufac	0	0	0	0
282	Special tool- die- jig- and fixture ma	0	0	0	0
283	Cutting tool and machine tool access	0	0	0	0
284	Rolling mill and other metalworking	0	0	0	0
285	Turbine and turbine generator set uni	0	0	0	0
286	Other engine equipment manufacturi	0	0	0	0
287	Speed changers and mechanical power	0	0.1	0	0.1
288	Pump and pumping equipment manuf	0	0	0	0
289	Air and gas compressor manufacturin	0	0	0	0
290	Measuring and dispensing pump man	0	0	0	0
291	Elevator and moving stairway manufa	0	0	0	0
292	Conveyor and conveying equipment	0	0.3	0	0.3
293	Overhead cranes- hoists- and monorai	0	0	0	0
294	Industrial truck- trailer- and stacker	0	0	0	0
295	Power-driven handtool manufacturin	0	0	0	0
296	Welding and soldering equipment ma	0	0	0	0
297	Packaging machinery manufacturing	0	0	0	0
298	Industrial process furnace and oven	0	0	0	0
299	Fluid power cylinder and actuator ma	0	0	0	0
300	Fluid power pump and motor manufa	0	0	0	0
301	Scales- balances- and miscellaneous	0	0	0	0
302	Electronic computer manufacturing	0	0	0.2	0.2
303	Computer storage device manufactur	0	0	0	0
304	Computer terminal manufacturing	0	0	0	0
305	Other computer peripheral equipmen	0	0	0	0
306	Telephone apparatus manufacturing	0	0	0	0
307	Broadcast and wireless communicati	0	0	0	0
308	Other communications equipment ma	0	0	0	0
309	Audio and video equipment manufact	0	0	0	0
310	Electron tube manufacturing	0	0	0	0
311	Semiconductors and related device m	0	0.2	0.1	0.4
312	All other electronic component manu	0	0.1	0.1	0.2
313	Electromedical apparatus manufactur	0	0	0	0
314	Search- detection- and navigation in	0	0	0	0
315	Automatic environmental control man	0	0	0	0
316	Industrial process variable instrument	0	0	0	0
317	Totalizing fluid meters and counting	0	0	0	0
318	Electricity and signal testing instrum	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
319	Analytical laboratory instrument man	0	0	0	0
320	Irradiation apparatus manufacturing	0	0	0	0
321	Watch- clock- and other measuring an	0	0	0	0
322	Software reproducing	0	0	0	0.1
323	Audio and video media reproduction	0	0	0	0
324	Magnetic and optical recording medi	0	0	0	0
325	Electric lamp bulb and part manufact	0	0	0	0
326	Lighting fixture manufacturing	0	0	0	0
327	Electric housewares and household f	0	0	0	0
328	Household vacuum cleaner manufact	0	0	0	0
329	Household cooking appliance manufa	0	0	0	0
330	Household refrigerator and home fre	0	0	0	0
331	Household laundry equipment manufa	0	0	0	0
332	Other major household appliance man	0	0	0	0
333	Electric power and specialty transfo	0	0	0	0
334	Motor and generator manufacturing	0	0	0	0
335	Switchgear and switchboard apparatu	0	0	0	0
336	Relay and industrial control manufac	0	0	0	0
337	Storage battery manufacturing	0	0	0	0
338	Primary battery manufacturing	0	0	0	0
339	Fiber optic cable manufacturing	0	0	0	0
340	Other communication and energy wir	0	0	0	0
341	Wiring device manufacturing	0	0	0	0
342	Carbon and graphite product manufac	0	0	0	0
343	Miscellaneous electrical equipment	0	0	0	0
344	Automobile and light truck manufact	0	0	0.1	0.2
345	Heavy duty truck manufacturing	0	0	0	0
346	Motor vehicle body manufacturing	0	0	0	0
347	Truck trailer manufacturing	0	0	0	0
348	Motor home manufacturing	0	0	0	0
349	Travel trailer and camper manufactur	0	0	0	0
350	Motor vehicle parts manufacturing	0	0.8	0.4	1.1
351	Aircraft manufacturing	0	0	0	0
352	Aircraft engine and engine parts man	0	0	0	0
353	Other aircraft parts and equipment	0	0	0	0
354	Guided missile and space vehicle ma	0	0	0	0
355	Propulsion units and parts for space	0	0	0	0
356	Railroad rolling stock manufacturing	0	0	0	0
357	Ship building and repairing	0	0	0	0
358	Boat building	0	0	0	0

	Industry	Direct	Indirect	Induced	Total
359	Motorcycle- bicycle- and parts manuf	0	0	0	0
360	Military armored vehicles and tank p	0	0	0	0
361	All other transportation equipment m	0	0	0	0
362	Wood kitchen cabinet and countertop	0	0.1	0.2	0.2
363	Upholstered household furniture man	0	0	0.1	0.1
364	Nonupholstered wood household furn	0	0	0.1	0.1
365	Metal household furniture manufactu	0	0	0	0
366	Institutional furniture manufacturing	0	0	0	0
367	Other household and institutional fur	0	0	0	0
368	Wood office furniture manufacturing	0	0	0	0
369	Custom architectural woodwork and	0	0	0	0
370	Office furniture- except wood- manuf	0	0	0	0
371	Showcases- partitions- shelving- and	0	0	0	0
372	Mattress manufacturing	0	0	0.1	0.1
373	Blind and shade manufacturing	0	0	0.1	0.1
374	Laboratory apparatus and furniture m	0	0	0	0
375	Surgical and medical instrument man	0	0	0.1	0.1
376	Surgical appliance and supplies manu	0	0	0.1	0.1
377	Dental equipment and supplies manuf	0	0	0	0
378	Ophthalmic goods manufacturing	0	0	0.1	0.1
379	Dental laboratories	0	0	0.2	0.2
380	Jewelry and silverware manufacturin	0	0	0	0
381	Sporting and athletic goods manufact	0	0	0	0
382	Doll- toy- and game manufacturing	0	0	0	0
383	Office supplies- except paper- manuf	0	0	0	0
384	Sign manufacturing	0	0.1	0.1	0.1
385	Gasket- packing- and sealing device	0	0	0	0
386	Musical instrument manufacturing	0	0	0	0
387	Broom- brush- and mop manufacturi	0	0	0	0
388	Burial casket manufacturing	0	0	0	0
389	Buttons- pins- and all other miscell	0	0	0	0
390	Wholesale trade	0	13.5	14.3	27.8
391	Air transportation	0	0.3	0.7	0.9
392	Rail transportation	0	0.4	0.2	0.6
393	Water transportation	0	0.1	0.1	0.3
394	Truck transportation	0	5.2	3.5	8.7
395	Transit and ground passenger transpo	0	0.2	1	1.2
396	Pipeline transportation	0	0.9	0.1	1
397	Scenic and sightseeing transportation	0	0.7	0.6	1.3
398	Postal service	0	0.9	1.2	2.1

	Industry	Direct	Indirect	Induced	Total
399	Couriers and messengers	0	6.9	1.3	8.2
400	Warehousing and storage	0	3.2	0.6	3.8
401	Motor vehicle and parts dealers	0	0.3	9.5	9.8
402	Furniture and home furnishings store	0	0.1	3	3.1
403	Electronics and appliance stores	0	0.1	2.4	2.5
404	Building material and garden supply	0	0.2	5.8	6
405	Food and beverage stores	0	0.5	13.5	14
406	Health and personal care stores	0	0.2	5	5.1
407	Gasoline stations	0	0.2	4.2	4.4
408	Clothing and clothing accessories sto	0	0.3	7.2	7.5
409	Sporting goods- hobby- book and mus	0	0.1	3.2	3.3
410	General merchandise stores	0	0.4	11.5	11.9
411	Miscellaneous store retailers	0	0.3	7.8	8.1
412	Nonstore retailers	0	0.2	6.4	6.6
413	Newpaper publishers	0	0.5	0.5	1.1
414	Periodical publishers	0	0.1	0.1	0.2
415	Book publishers	0	0	0.1	0.1
416	Database- directory- and other publis	0	0	0.1	0.1
417	Software publishers	0	0.2	0	0.3
418	Motion picture and video industries	0	0.2	0.7	0.9
419	Sound recording industries	0	0	0.1	0.1
420	Radio and television broadcasting	0	0.5	0.5	1
421	Cable networks and program distribu	0	0	0.2	0.3
422	Telecommunications	0	1	2	3
423	Information services	0	0.1	0.1	0.2
424	Data processing services	0	0.5	0.2	0.6
425	Nondepository credit intermediation a	0	4.4	2.6	7
426	Securities- commodity contracts- inv	0	3.9	4.5	8.5
427	Insurance carriers	0	0.8	5.2	6.1
428	Insurance agencies- brokerages- and r	0	0.4	2.4	2.7
429	Funds- trusts- and other financial veh	0	0	0.8	0.8
430	Monetary authorities and depository c	0	8.2	4.6	12.8
431	Real estate	0	4.5	9	13.5
432	Automotive equipment rental and lea	0	0.6	1.1	1.6
433	Video tape and disc rental	0	0	0.7	0.7
434	Machinery and equipment rental and	0	1.3	0.1	1.5
435	General and consumer goods rental ex	0	0.4	0.8	1.2
436	Lessors of nonfinancial intangible ass	0	1.3	0	1.3
437	Legal services	0	8.9	4.7	13.5
438	Accounting and bookkeeping service	0	3.5	2.1	5.6

	Industry	Direct	Indirect	Induced	Total
439	Architectural and engineering service	0	6.3	1.1	7.5
440	Specialized design services	0	0.8	0.3	1.1
441	Custom computer programming servi	0	24.7	0.2	24.9
442	Computer systems design services	0	2.4	0.4	2.7
443	Other computer related services- inclu	0	1.6	0.2	1.8
444	Management consulting services	0	7.3	1.4	8.7
445	Environmental and other technical co	0	0.4	0.1	0.6
446	Scientific research and development s	0	6.8	0.3	7.1
447	Advertising and related services	0	1.4	1.2	2.5
448	Photographic services	0	0.1	0.6	0.6
449	Veterinary services	0	0	1.1	1.1
450	All other miscellaneous professional	0	2.8	0.2	3.1
451	Management of companies and enterp	0	11.5	1.2	12.7
452	Office administrative services	0	0.8	0.5	1.3
453	Facilities support services	0	0.1	0	0.1
454	Employment services	0	11.1	5.6	16.7
455	Business support services	0	4.9	1.6	6.5
456	Travel arrangement and reservation s	0	0.2	0.5	0.7
457	Investigation and security services	0	2.7	1.2	3.9
458	Services to buildings and dwellings	0	5.4	4	9.4
459	Other support services	0	0.4	0.5	1
460	Waste management and remediation s	0	0.5	0.5	1
461	Elementary and secondary schools	0	0	2.3	2.3
462	Colleges- universities- and junior col	0	0.1	1.9	2.1
463	Other educational services	0	0.1	2.8	2.9
464	Home health care services	0	0	6.7	6.7
465	Offices of physicians- dentists- and o	0	0	13.4	13.4
466	Other ambulatory health care services	0	0	3.5	3.5
467	Hospitals	0	0	10.5	10.5
468	Nursing and residential care facilities	0	0	10.6	10.6
469	Child day care services	0	0	7	7
470	Social assistance- except child day ca	0	0	5.8	5.8
471	Performing arts companies	0	0.1	1.4	1.5
472	Spectator sports	0	0.4	1.4	1.8
473	Independent artists- writers- and per	0	0.1	0.2	0.3
474	Promoters of performing arts and spo	0	0.2	1	1.2
475	Museums- historical sites- zoos- and	0	0	0.4	0.4
476	Fitness and recreational sports center	0	0.2	2	2.2
477	Bowling centers	0	0	0.3	0.3
478	Other amusement- gambling- and recr	0	0.1	4.3	4.4

	Industry	Direct	Indirect	Induced	Total
479	Hotels and motels- including casino h	0	0.7	2.5	3.2
480	Other accommodations	0	0	0.3	0.3
481	Food services and drinking places	0	2.9	38.7	41.5
482	Car washes	0	0.1	1.2	1.3
483	Automotive repair and maintenance-	0	1.1	9.2	10.3
484	Electronic equipment repair and mai	0	0.8	0.4	1.2
485	Commercial machinery repair and ma	0	0.7	0.5	1.1
486	Household goods repair and mainten	0	0.2	0.5	0.7
487	Personal care services	0	0	3.8	3.8
488	Death care services	0	0	0.9	0.9
489	Drycleaning and laundry services	0	0.1	2.3	2.4
490	Other personal services	0	0.1	1.6	1.7
491	Religious organizations	0	0	3.6	3.6
492	Grantmaking and giving and social a	0	0	1	1
493	Civic- social- professional and simila	0	2.2	2.7	4.9
494	Private households	0	0	11.6	11.6
495	Federal electric utilities	0	0	0	0
496	Other Federal Government enterprise	0	0.1	0.2	0.3
497	State and local government passenger	0	0.2	1.1	1.3
498	State and local government electric uti	0	0.3	0.1	0.4
499	Other State and local government ente	0	0.8	2.3	3.1
500	Noncomparable imports	0	0	0	0
501	Scrap	0	0	0	0
502	Used and secondhand goods	0	0	0	0
503	State & Local Education	0	0	0	0
504	State & Local Non-Education	0	0	0	0
505	Federal Military	0	0	0	0
506	Federal Non-Military	0	0	0	0
507	Rest of the world adjustment to final	0	0	0	0
508	Inventory valuation adjustment	0	0	0	0
509	Owner-occupied dwellings	0	0	0	0
Total		231.7	249.1	351.2	832