PUBLIC ISSUES IN EARTH SCIENCE

THE FUTURE OF ENERGY GASES

U.S. GEOLOGICAL SURVEY CIRCULAR 1115

Drilling for seismically defined reservoir in Cretaceous and Tertiary rocks in the Hoback basin of Wyoming. The Gros Ventre Mountains in the background consist of older Paleozoic rocks. Photograph by B.E. Law.

Steeply dipping Cretaceous strata at the south end of the Green River basin near the Utah-Wyoming border. In the deeper part of the Green River basin, the Cretaceous strata contain major energy gas resources in tight sandstone reservoirs. Photograph by B.E. Law.

Copy in R

THE FUTURE OF ENERGY GASES

PUBLIC ISSUES IN EARTH SCIENCE

U.S. GEOLOGICAL SURVEY CIRCULAR 1115

By

Peter J. McCabe
Donald L. Gautier
Michael D. Lewan
Christine Turner

With contributions from

Robert B. Halley
David G. Howell
Keith A. Kvenvolden
Christopher J. Schenk

Editor

L.M.H. Carter

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Robert M. Hirsch, Acting Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1993

Free on application to
USGS Map Distribution
Box 25286, Building 810
Denver Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

The future of energy gases / by Peter J. McCabe ... [et al.] ; with contributions from Robert B. Halley ... [et al.] ; editor, L.M.H. Carter.

p. cm. — (U.S. Geological Survey circular ; 1115. Public issues in earth science)

Includes bibliographical references.

Supt. of Docs. no.: I 19.3:1115

1. Gas as fuel. I. McCabe, Peter J. II. Carter, Lorna M. III. Series: U.S. Geological Survey circular ; 1115. IV. Series: U.S. Geological Survey circular. Public issues in earth science.

TP345.F88 1994

333.8'233—dc20 93-33689

CIP

FOREWORD

Understanding the nature and occurrence of energy gases is important for two critical issues facing our Nation—the economy and the environment. The U.S. Geological Survey is actively involved in research on the origin, abundance, and availability of energy gases. This research is pertinent to discussions of the future energy mix, global warming, the dependence of the Nation on imported fossil fuels, and the size of gas reserves—all of which are concerns that are being faced daily at local, State, and national levels.

Over the course of the 20th century, dramatic shifts have taken place in the types and sources of energy consumed in the United States. The future energy mix and the technologies used in fuel combustion will be critical in determining the economic and environmental health of the Nation as we move into the 21st century. Energy gases have been a major primary energy source within the United States for much of this century. Recently it has been suggested that increased use of energy gases could help cut the Nation's dependence on imported oil while decreasing the environmental impact of energy use. The use of energy gases rather than other fossil fuels such as coal or oil may benefit the environment by reducing total emissions of carbon dioxide and other pollutants. Although very large volumes of energy gases exist within the Earth's crust, most occur in forms that would be extremely costly to extract. An understanding of the scientific factors that determine the availability and use of energy gases is essential for the development of policies pertinent to the exploration for and utilization of fossil fuels.

The geologic factors governing the generation, migration, and entrapment of energy gases are complex and are ongoing research endeavors of the U.S. Geological Survey. In addition, the U.S. Geological Survey gathers information on the size and nature of these accumulations, which also contributes to a basic understanding of the Nation's energy gas resources. Methane, the most important energy gas, is formed in many ways in nature and is an intrinsic part of the natural environment. However, only under certain conditions is the gas trapped within the Earth's crust in sufficient quantities to allow economic recovery.

The Earth's atmosphere is receiving an increasing methane input from human sources, including (though not restricted to) activities involved in the extraction and transportation of coal, oil, and natural gas. Methane is an important greenhouse gas, which in limited amounts is essential to maintaining the equable climate of our planet, but which could become a major factor in future global warming. By gathering geologic data on methane emissions and by studying the geologic aspects of global climate, the U.S. Geological Survey provides information that can be used in developing national policies on environmental issues.

Wise use of our Nation's resources and the careful stewardship of our public lands depend on the dispersal of accurate and timely Earth Science information. Planners and resource managers need this information to make informed decisions and to plan for the effective use of the Nation's resources. The U.S. Geological Survey is proud to present this report on some of the major issues to be addressed in the future use of energy gases.

Robert M. Hirsch

Acting Director, U.S. Geological Survey

THE ENERGY GASES TEAM (1992-1993)

This USGS study of energy gases was conceived and coordinated by the following team of scientists:

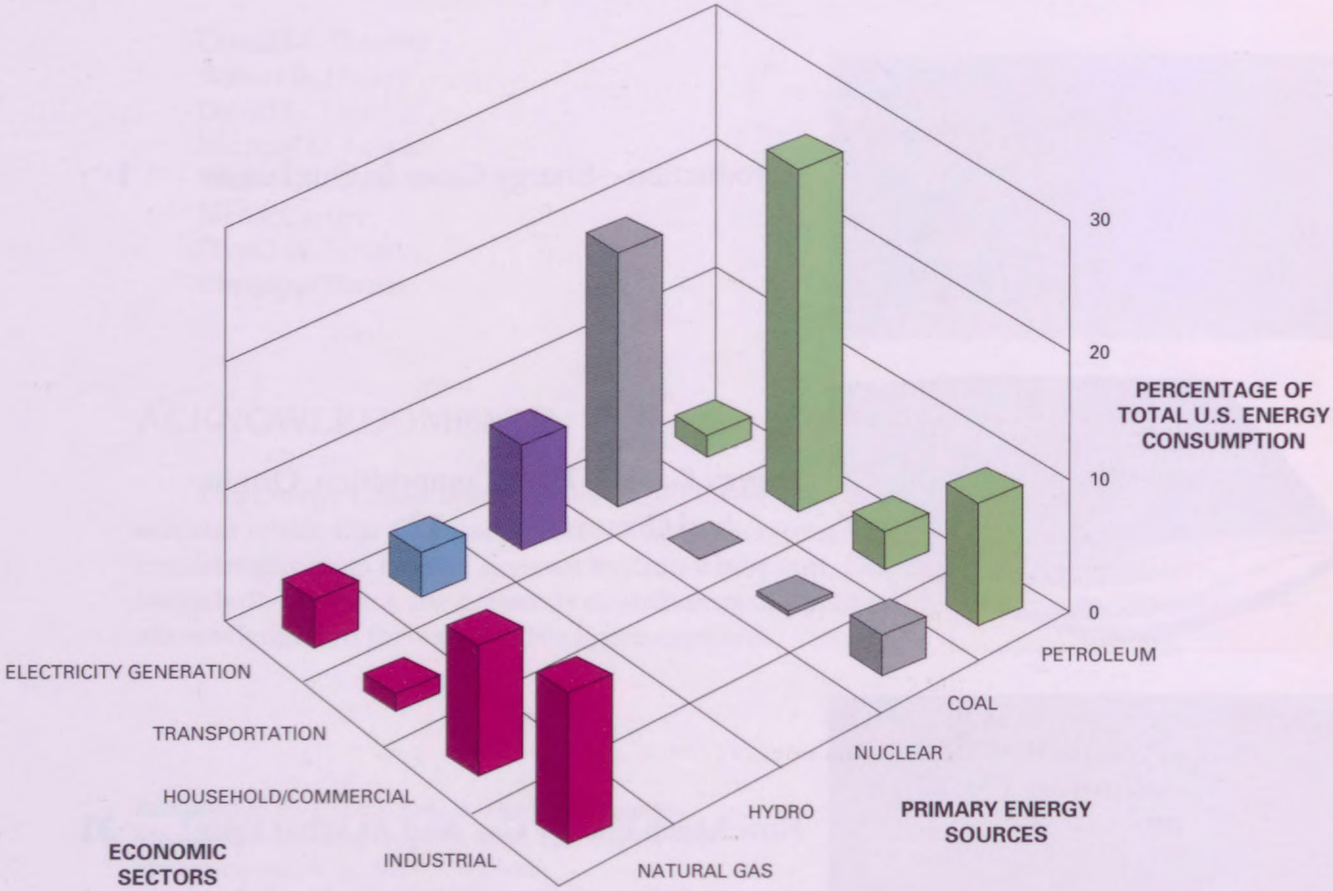
Donald L. Gautier
Robert B. Halley
David G. Howell
Michael D. Lewan
Peter J. McCabe
Jill McCarthy
David W. Scholl
Christine Turner

ACKNOWLEDGMENTS

The Energy Gases Team thanks Gary Hill for his vision and entrepreneurial spirit, without which this Circular would not have been possible. The text has benefited considerably from helpful reviews by Tom Ahlbrandt, Dudley Rice, and Jonathan Swinchatt. We thank the generous contributors of photographs and figures—these are acknowledged in their respective figure captions.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication October 13, 1993
Photocomposition by Joan G. Nadeau
Graphics by Joe Vigil, Leslie Weissleader, Laura Zink, and
Mari L. Kauffmann; coordinated by Mari L. Kauffmann
Design by L.M.H. Carter

CONTENTS



Energy consumption in the United States, 1991, divided by type of use and primary fuel.

INTRODUCTION—
ENERGY GASES IN OUR FUTURE

As we as a Nation become increasingly aware of our ability to change our habitat by our actions, we look more and more toward sources to mitigate effects of human activities on the environment. As we begin to take more responsibility for the energy mix that we use—for transportation, for electricity generation, for heating and cooking and industry—as we begin to take more of a stewardship role for our Nation, we look for forms of energy that are available, efficient, and yet less polluting than others. Energy gases may be one such energy form.

The issue, stripped of all the complexities that attend it, is this: Is it realistic to hope that increased use of energy gas in our energy mix will be the solution we need to fulfill our industrial needs and maintain our standard of living but also decrease the potential damaging effects of energy use on the natural environment?

Part of the mission of the U.S. Geological Survey is to do research on the nature and geologic occurrence of energy gases, and to assess potential future additions to United States reserves. What can we offer to the Nation in the ongoing and increasing concern for the natural environment as this pertains to the Nation's use of energy and the mix of sources that provide this energy? This publication is a gathering of information directed toward that concern, from the standpoint of the nature, occurrence, and geology of energy gas. It presents information on several sides of the energy issue, attempting to balance availability of energy gases against difficulty of production and against price, to balance the present energy mix against possibilities for the future, again from the viewpoint of energy gas use, and to balance environmental quality at the present time with possible scenarios for the future that depend on the energy mix we evolve and choose.

The American people and Congress face difficult decisions concerning the utilization of energy resources and the future environmental consequences of energy use. The purpose of this book is to address scientific issues that will help decisionmakers to come to economically and environmentally sound decisions concerning our resources. In his opening message to the U.S. Department of the Interior in January 1993, newly appointed Secretary Bruce Babbitt stated, "I want to use good science everywhere in this organization. I want to admonish all of you to remember that before a debate begins in Congress or elsewhere, we have a special obligation to the American people and Congress to get the facts straight." This "special obligation" is one of the responsibilities of the USGS in its mission to understand and assess our energy resources.

* * *

Energy gases are the combustible gases found in the Earth's crust. These gases are usually found together with noncombustible gases such as nitrogen and carbon dioxide, and together they constitute what is commonly known as natural gas.

Natural gas = energy gas + other gases
(combustible) (noncombustible)

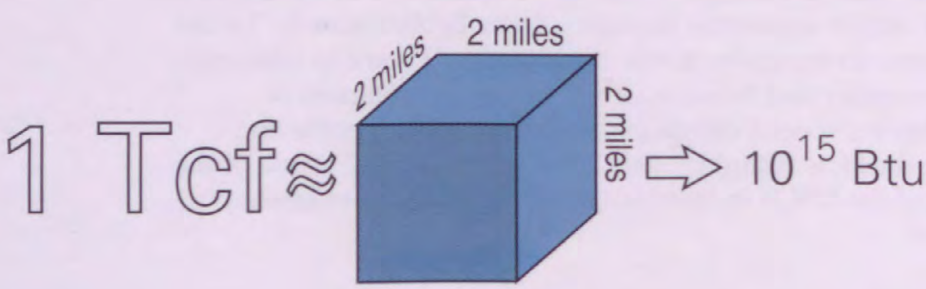
We are familiar with energy gases, as many of us use them to cook our meals and heat our homes and work places. Recently energy gases—and the advantages of using them—have been the subject of much discussion, because, compared to other fossil fuels, energy gases produce less pollution. Carbon dioxide emissions from the burning of energy gases are approximately 50 percent less than those from the burning of coal and 33 percent less than those from the burning of fuel oil.

It may appear from the home and industrial consumption that energy gases already constitute our primary source of energy, but these uses of energy gases actually account for only about 25 percent of the total energy currently consumed in the United States. Electricity generation and transportation together account for almost 65 percent of the energy used in our Nation, and energy gas usage in these categories accounts for less than 10 percent of the total energy consumed. In the future, it may be environmentally and politically desirable to replace imported foreign oil by domestically produced energy gases to power our vehicles. Likewise we may wish to build more gas-powered electrical generating plants rather than coal-powered plants. However, these directions are only feasible if ample supplies of energy gases exist that can be economically developed.

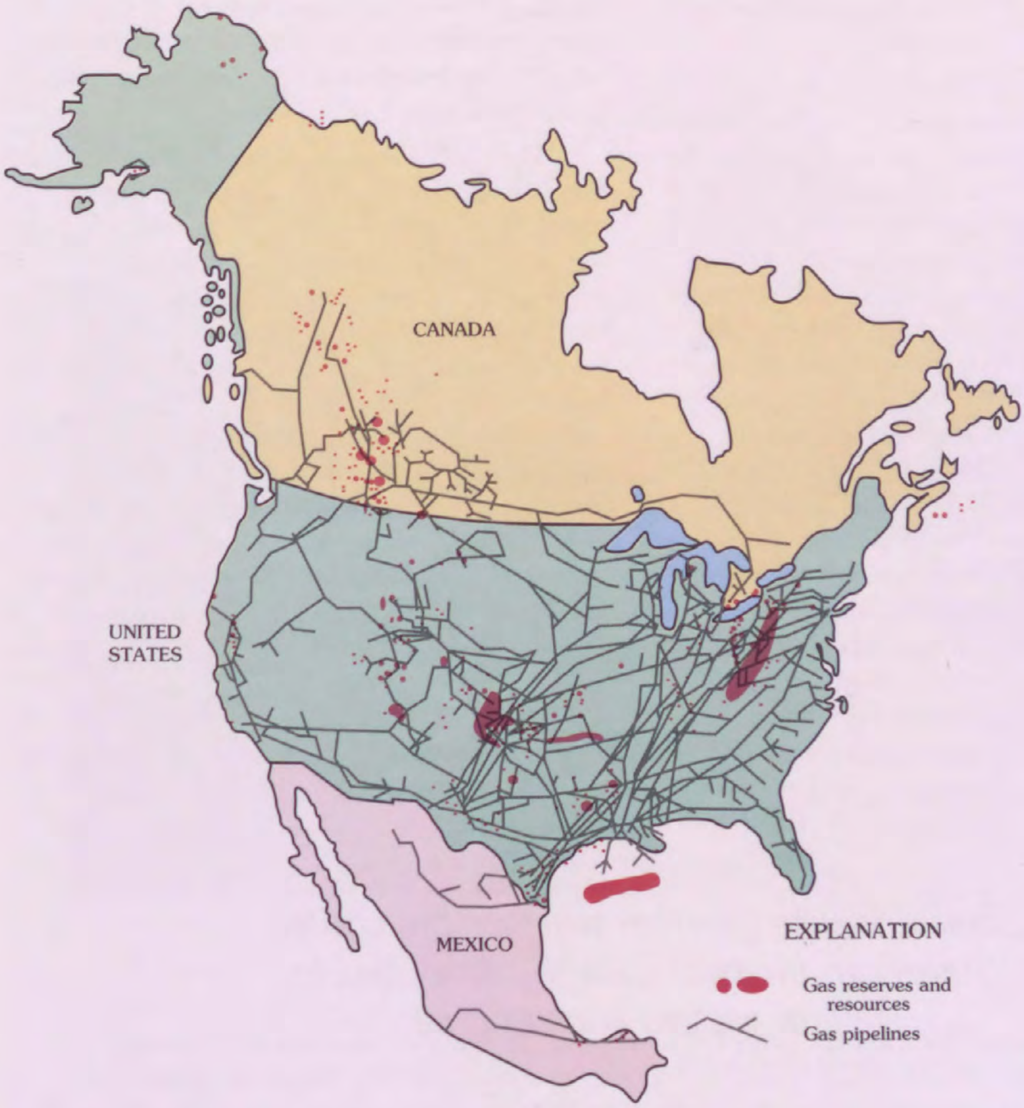
Compared to other fossil fuels, energy gases produce less pollution.

Energy gases currently account for 75 percent of the total United States energy used for cooking and heating in homes and work places. Industries also burn energy gases to produce heat for manufacturing operations ranging from drying newly formed sheets of paper at temperatures just above 212 °F, to processing iron at temperatures near 3,000 °F. Approximately 45 percent of the total energy presently used by industry in the United States is derived from the burning of energy gases.

Methane, the most abundant energy gas, is one of the most abundant compounds on our planet. Methane (CH_4) molecules permeate the air we breathe, bloat our intestines, fill the interstices of much of the Earth's crust, and endanger human lives in coal mines. The amount of methane on Earth is staggering. For example, in only a part of the Green River basin, in a small area of southwestern Wyoming, geologists at the U.S. Geological Survey suggest that at least 5,000 *trillion* cubic feet (Tcf) of natural gas, more



Gas is measured in cubic feet. A trillion cubic feet is enough to fill a cube with sides 2 miles wide! Btu is a measure of the amount of energy obtained from burning a fuel.



A network of pipelines connects areas of natural gas reserves and resources with the population centers that are the market for energy gas.

than 90 percent of which is methane, is entrapped in the porosity of rock reservoirs. Now 5,000 Tcf is more than 6 times the entire cumulative production and use of natural gas in the history of the United States and more than 30 times the current U.S. proved reserves (the amount that can be supplied to market under current economic and operating conditions).

Despite the abundance of natural gas, some resource analysts question whether energy gas can be produced in the United States in quantities large enough to sustain present consumption (about 17 Tcf (trillion cubic feet) per year), let alone whether production can be increased to permit more widespread use as automobile fuel or as a major energy source for electricity generation. The issue is not absolute abundance, but distribution and availability. We need to know such things as (1) the geologic habitats of energy gas accumulations; (2) where the gas occurs geographically; (3) whether it is near pipelines or collection centers; (4) whether it is in physically and politically accessible areas; and (5) whether development and transportation will cost more than the expected market value of the gas. Taking the Green River basin in Wyoming as an example, probably no more than 100 Tcf of its abundant gas will ever be recovered, because so much of the gas lies trapped in rocks that are so impermeable that gas cannot be easily extracted.

People have been aware of natural gas for a long time—at least as long as they have been aware of oil. Natural gas was produced and consumed in China millennia ago. In the United States natural gas wells were drilled as early as the 1820's (long before the first oil well was drilled in Pennsylvania in 1859). But broad gas usage was not really possible until the development of continuous welded pipe during the second decade of the 20th century. Even then, natural gas was considered a hazardous nuisance of oil production, and in many places was flared—burned off at the wellsite—an action no longer permitted in the U.S. By the 1960's huge natural gas reserves had been discovered and natural gas was an important element in the Nation's energy mix. An extensive network of natural gas pipelines had been laid across North America from major producing areas such as the Gulf Coast, the Midcontinent region, and Alberta, to major population centers such as the northeast States and California. However, when price controls took effect in the 1970's, the incentive to find more gas was diminished and the reserve dramatically decreased, as the gas produced was not replaced with new discoveries. The view that natural gas was an increasingly rare commodity began to develop. However, during the 1980's and 1990's interest in natural gas has been on the rise, as oil reserves and discoveries declined in the U.S. and oil imports rose to more than half of domestic consumption. The relatively clean burning qualities of natural gas make it increasingly attractive for use in automobiles, electricity generation, and industrial applications as well as for home heating and cooking. Unlike oil, most natural gas that we use is produced in the U.S.—current imports account for less than 10 percent of domestic consumption of gas.

The continuing demand, and the pressure for increasing usage and supply to meet energy and environmental requirements, have led to serious concerns about the future availability of natural gas. A recent study by the National Petroleum Council (NPC)—a joint industry and government advisory board to the Department of Energy—concluded that natural gas is abundant and available to satisfy virtually any domestic demand over the next few decades. The availability is not without a price, however. More and more, new supplies of natural gas will have to come from technically difficult and less productive sources. In addition to the higher exploration capital required, this will necessitate the drilling of a larger number of wells and a greater environmental impact for the discovery and development of each new Tcf of gas reserve. The NPC concluded that even maintaining present production over the next two decades would require that gas prices and costs to the consumer rise by almost 100 percent, and that by the year 2030, as many as 18 million new oil and gas wells, with their attendant environmental impact, would be necessary. For comparison, fewer than 3.5 million wells have been drilled so far in the entire history of the United States oil and gas industry.

Some analysts question whether the United States can produce enough energy gas to sustain present consumption.

Increased amounts of energy gases may be "what we need" in our energy mix for the foreseeable future. But, as we have stated—and will continue to state throughout—the issue is not simple; read on, and see where the implications lead us.

Buses from Sichuan Province, People's Republic of China, carrying methane gas bladders on their roofs as fuel tanks.

"FILL IT UP WITH GAS"

Although we fuel our vehicles at "gas" stations, most vehicles are designed to use liquid petroleum products such as gasoline or diesel. Combustion engines, however, can also run on energy gas such as methane. Some buses used in the Sichuan Province of the People's Republic of China, for example, are fueled by energy gas, which is carried in large bags at pressures slightly greater than atmospheric pressure (15 pounds per square inch). The low pressure requires that large volumes of energy gas be carried for the bus to travel an appreciable distance before refueling.

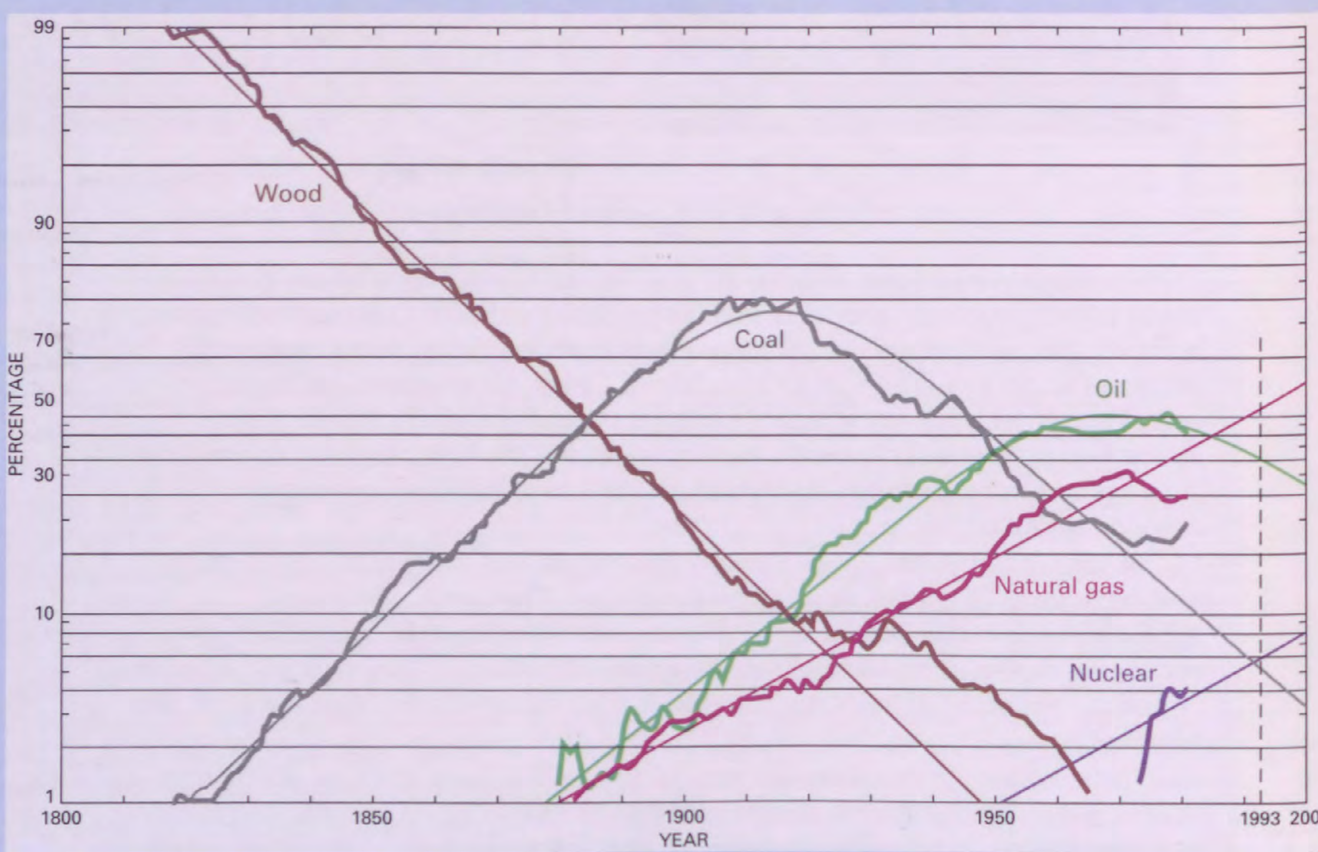
In the United States, several government agencies—from local to Federal—now have fleets of energy gas-powered vehicles. The General Services Administration of the United States Government, for example, uses a fleet of energy gas-powered small trucks at government facilities. They look and operate essentially the same as gasoline-powered trucks; their polluting emissions are just a lot less.

Factors critical in the development of a transition from gasoline- to energy gas-powered vehicles are the supply and cost of energy gases and the distribution and availability of energy gas fueling stations. Over the last several years, a few energy gas fueling stations have been installed in major cities. As more are built, the old request to "fill the car up with gas" will take on new meaning.

PREDICTING FUTURE ENERGY CONSUMPTION

Many past predictions of future energy supply and demand have been unreliable. In the early 1980's, for example, many energy company pundits predicted a threefold increase in the price for petroleum within 10 years; in fact, the price *fell*, in inflation-adjusted dollars. However, the history of energy use demonstrates clear trends, and it is tempting to extrapolate these into the future. The work of M. King Hubbert of the U.S. Geological Survey and others has suggested nearly symmetrical growth and decline in production of any energy source. A symmetry in growth and decline of energy consumption is also suggested in studies by members of the International Institute for Applied Systems Analysis (IIASA), based in Austria.

At the beginning of the 19th century, wood was our primary energy source, while secondary sources included water power, mechanical wind power, peat, agricultural wastes, and animal and human muscle power. With the development of steam power and



the expansion of railroads and the steel industry, the use of coal increased exponentially until the early decades of the 20th century. Oil and natural gas were introduced into the energy mix in the 1870's, and world consumption of these fuels has increased exponentially since then. When plotted as the ratio of its market share compared to the market shares of all other competing energy sources, trends of the consumption of any primary energy over time should show a rise and fall as that fuel first substitutes for other energy sources, and is later replaced by still others.

The total consumption of an energy source may well continue to rise even when its market share falls, if total energy consumption rises overall.

By attempting to fit curves to these trends, predictions have been made well into the 21st century. In the last 20 years, however, there has been a marked divergence from the smoothed curves, as more coal but less gas is consumed. Some gas explorationists claim that the divergence is due to artificial price controls and other government regulations. An alternate view is that the divergence reflects the evolution in uses for energy in modern society. For example, the fall in coal's market share during the first half of the 20th century reflects its declining use for railroads, the steel industry, and domestic heating, whereas its recent rise reflects its increased use for generating electricity. We will have to wait many years to judge the accuracy of current predictions, but they strongly suggest an important role for energy gases in our future.

Consumption of primary energy sources in the United States since the early 19th century. Note the ascendancy of various fuels and their replacement by others. (Modified from Grübler and Nakicenovic in Lee and others (1988); reprinted with permission of International Institute for Applied Systems Analysis.)

ENERGY CHOICES—ARE THINGS ALWAYS AS THEY SEEM?

Many cities restrict the use of wood-burning stoves and fireplaces in an effort to mitigate the harmful effects of smoke pollution. In an effort to preserve the warm and cozy atmosphere of fireplaces but also help reduce pollution, home builders have replaced the traditional fireplace with gas logs. Home owners found this appealing and many newer homes have these installed.

But, is this a good decision? At first appraisal, it appears a satisfactory solution for helping the environment and maintaining the aesthetic and decorative value for which gas logs were intended. Yet, safety regulations generally require that chimney flues be permanently welded open whenever gas logs are installed, which allows a great deal of heat to disappear up the flue. In turn, the consumption of fossil fuels is increased, either by increased usage of natural gas to heat the home or by increased use of coal or other fuels at power plants. Unless the fireplace is covered by glass doors, more rather than less energy is consumed, and more rather than less pollution is added to the atmosphere.

This is an example of an apparent solution to an immediate and localized problem, such as what comes out of a household chimney, in which the ultimate unseen consequence is potentially a bigger problem in terms of energy consumption and pollution. All decisions involving energy choices are similarly complex. Every energy choice involves many costs, not all of them obvious. Some direct costs for power generation that come to mind include the dollar costs of exploration, extraction, transportation, and distribution of the fuel: typical consumers in the home or in the factory pay for this energy on a unit basis on their monthly energy bill. Not so obvious are the indirect costs, a few of which include possible global warming, ozone depletion, acid rain, deforestation, loss of water quality, and loss of wildlife and wildlife habitat. So, an apparently simple decision to install a gas log in the home, while altruistic in intent, may in practice have unforeseen adverse costs.

This does not mean, however, that energy choices have either clear-cut or predictable consequences; constant technological improvements change the tradeoffs involved in our energy choices and a fuel source that once was out of favor can become again a viable option. The development of clean-burning wood pellet stoves, for instance, has revived the use of wood products in home heating. These pellet stoves not only burn efficiently with little pollution but also use a waste product from lumber mills as the fuel source, contributing in two ways to minimizing effects to the environment.

It is clear that we do not completely understand all the consequences of decisions regarding energy choices, in part because they are never static. The solution is for us to carefully watch and document the cascading effects of each energy choice, making informed decisions, but remaining flexible enough to develop new responses as new information becomes available.

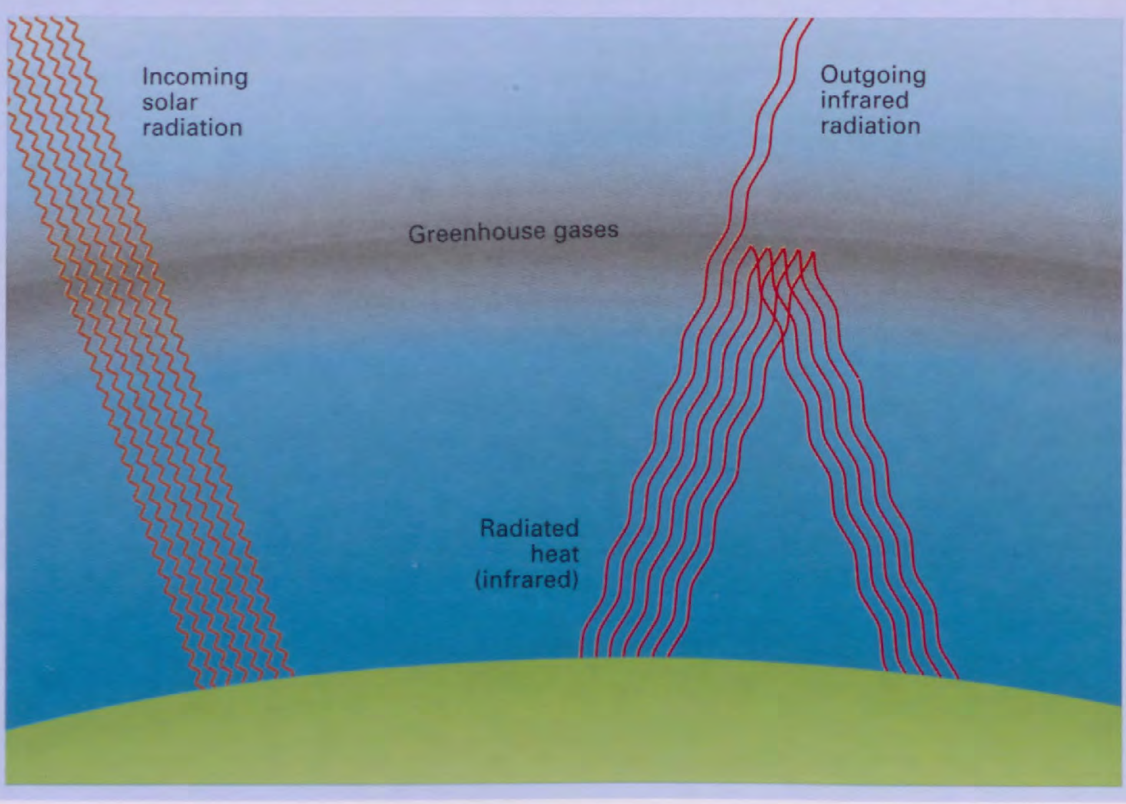
Cozy—but costly? (Reproduced with permission of Village West Publishing, Laconia, N.H.)

ENERGY GASES AND GLOBAL WARMING

The topic of global warming has received much public attention in the last few years and has been a contentious topic in many circles. Climatologists agree that a greenhouse effect, produced by certain atmospheric gases, warms the planet. Man-induced emissions have substantially added to the total amount of these greenhouse gases. However, the cumulative effect of humanity's modification of the atmosphere to the present time is less clear, and predictions about future changes in climate are widely divergent.

The greenhouse effect in the Earth's atmosphere plays an essential role in our planet's climate, and life as we know it would not be possible on Earth if it were not for the presence of greenhouse gases. Major natural greenhouse gases are water vapor and carbon dioxide, but other natural gases such as methane, nitrous oxide, and ozone also play a significant role. Solar radiation passes easily through the Earth's atmosphere and, though some is reflected back into space, most is absorbed by the Earth's surface and warms it. Infrared radiation is emitted from the warmed Earth, but not all of it escapes from the planet. Some is absorbed and re-emitted by the greenhouse gases within the atmosphere. Because some of this radiation is directed back down to the surface, it warms the surface and lower atmosphere. Climatologists have calculated that the Earth's surface is about 91 °F warmer than it would be without the greenhouse effect.

Paleoclimatologists recognize that major variations have occurred in the global climatic pattern throughout Earth's history. How closely are these climatic shifts related to variations in the volume and mix of greenhouse gases in ancient atmospheres? Gases trapped in polar ice indicate a close correlation between the amount of carbon dioxide and methane in the atmosphere and global temperatures over the last 160,000 years. The problem for the paleoclimatologist is to determine what caused what: did the higher amounts of greenhouse gases cause warmer global temperatures or did



Greenhouse gases in the upper atmosphere trap some of the infrared radiation emitted from the Earth due to warming from solar radiation. The so-called "greenhouse effect" plays a vital role in our planet's climate. From an original by Mark Johnsson.

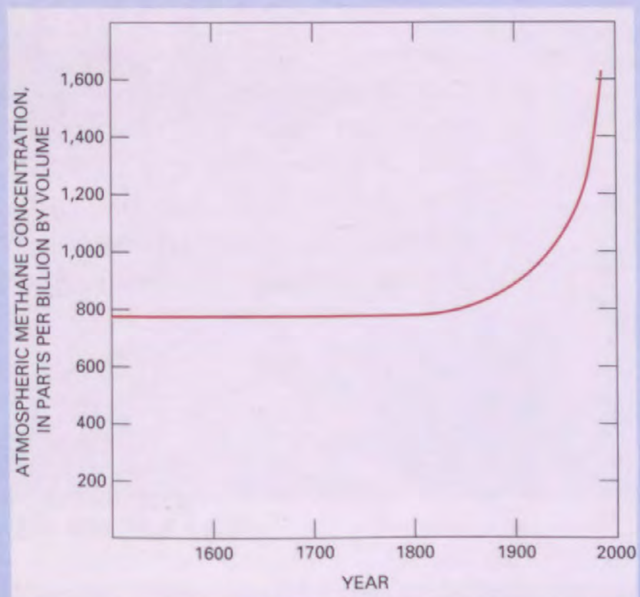
the higher temperatures result in greater natural emission of the gases to the atmosphere? This question so far is unresolved.

Carbon dioxide (CO_2) is produced by burning wood and fossil fuels. The amount of CO_2 in the atmosphere has risen by about 25 percent in the last 200 years due to the increase in burning of fossil fuels since the beginning of the industrial revolution and because of the loss of forests, which act as natural extractors of atmospheric carbon dioxide. Much of that rise in CO_2 has occurred in the last 40 years with the dramatic increase in global energy consumption. The increase in atmospheric methane is even more rapid: the volume of methane in the atmosphere is currently about twice that which existed before the industrial revolution. Compared to carbon dioxide, methane is much more efficient as a greenhouse gas but on the other hand is more rapidly removed from the atmosphere by natural processes. Adding 1 kilogram (2.2 lb) of methane to the amosphere has the same effect as 63 kilograms (138.6 lb) of carbon dioxide over a 20 year period, but is only equivalent to 9 kilograms (19.8 lb) of carbon dioxide over a 500 year period.

Because of the *volume* of emissions, however, carbon dioxide contributes about 55 percent of the calculated increase in greenhouse effect due to anthropogenic gases. In addition to adding to natural greenhouse gases, humans have contributed to the greenhouse effect with emissions of other, non-energy gases, particularly chlorofluorocarbons.

The effect of growth in the volume of greenhouse gases is unclear. United Nations studies predict an average rise of about 0.3 °C per decade over the next century; this would be a dramatic change and would profoundly impact global climate. Many major agricultural areas could turn into deserts, while rising sealevels, due to melting of polar icecaps, could cause flooding of coastal cities. Other models, however, predict much slower *or* much faster rates of global warming. Some climatologists have suggested that an accelerated greenhouse effect could even lead to an ice age because of increased rates of precipitation in polar regions. The uncertain but possibly catastrophic effect of increased additions of greenhouse gases to the atmosphere concerns many people. For example, Vice President Albert Gore has commented in his book **Earth in the Balance** (1993, p. 92) on the addition of greenhouse gases to the atmosphere: "We are in fact conducting a massive, unprecedented—some say unethical—experiment."

The mix of primary energy sources used in the future within the United States and the rest of the world will have a major effect on the total amount of greenhouse gases in the Earth's atmosphere. Substitution of energy gas for gasoline in vehicles and energy gas for coal in power plants could substantially reduce CO_2 emissions. Addition of methane to the atmosphere could be reduced by cutting down on the loss of natural gas from leaking pipelines: engineers have estimated that 15 percent of the methane released annually into the atmosphere comes from leaking pipelines in the former Soviet bloc. Efficient extraction and use of natural gas from underground coal-mining operations could also reduce methane emissions. Most critically, we need to reconcile the necessity of reducing greenhouse gas emissions with the ever-growing demand for energy by a growing world population, many of whose societies have achieved or strive to achieve a standard of living comparable with that of North America.



The amount of methane in the atmosphere has doubled since the middle of the 19th century. Human activities such as farming and the extraction and utilization of fossil fuels now account for about 60 percent of total emissions. (Modified from Pearman and Fraser, in NATURE, v. 332, p. 489 (1988); used with permission of Macmillan Magazines Ltd.; and with permission of the authors.)

MEASURING ENERGY GASES

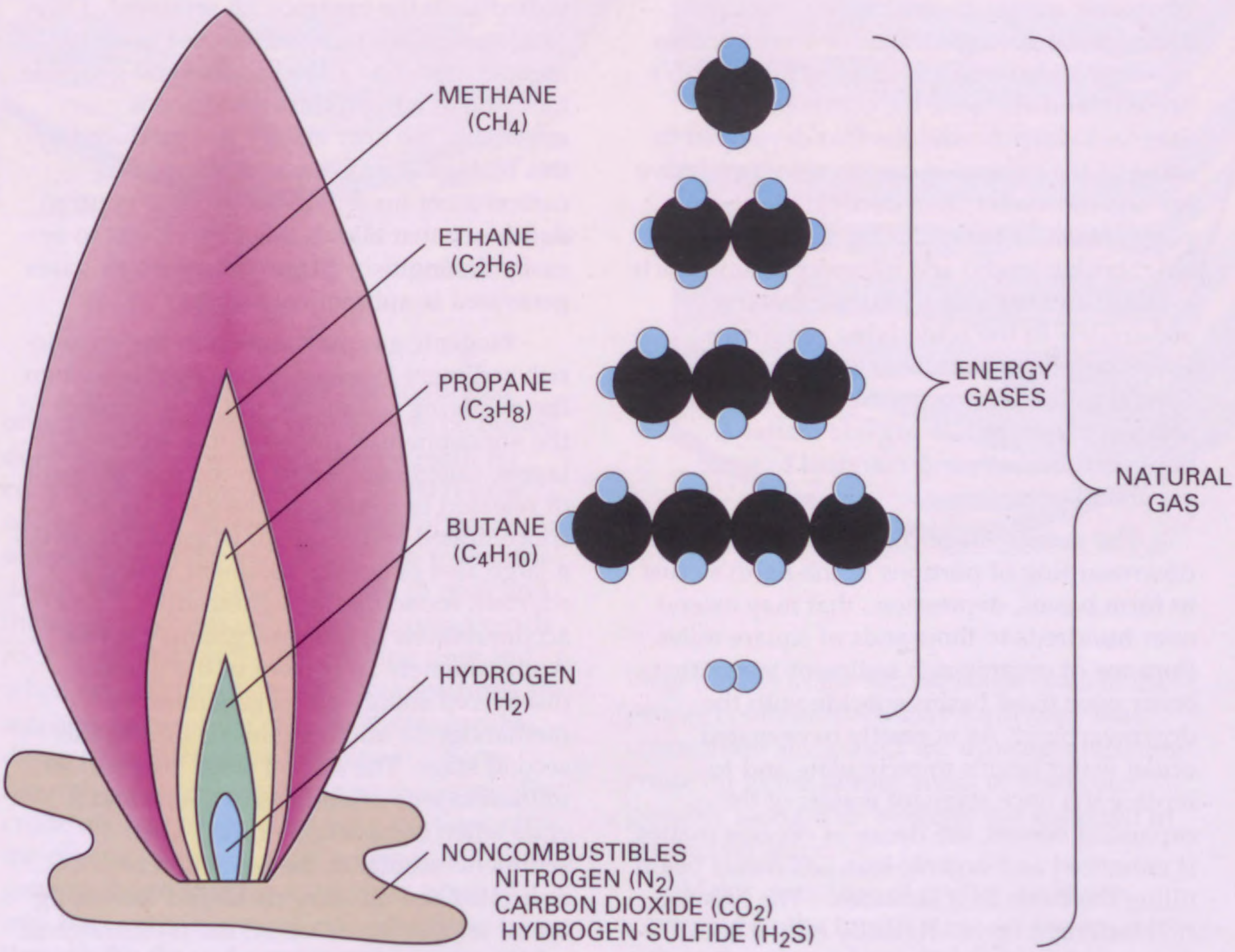
Quantities of natural gas are measured in volume units. A cubic foot of natural gas at a temperature of 60 °F and an atmospheric pressure of 14.7 pounds per square inch is the common unit of measure. Gas production from wells and supplies to power plants are measured in thousands or millions of cubic feet (Mcf and MMcf). Resources and reserves are calculated in trillions of cubic feet (Tcf). How much is a trillion cubic feet?—Enough to fill a cube with sides 2 miles wide!

The amount of energy that is obtained from the burning of a unit volume of natural gas is measured in British thermal units (Btu). One Btu is the amount of heat required to raise the temperature of 1 pound of water from 60 to 61 °F at normal atmospheric pressure (14.7 pounds per square inch). At sea level, it takes about 75 Btu to make a jolly good cup of hot tea. A cubic foot of natural gas on the average gives off 1,000 Btu, but the range of values is 500 to 1,500 Btu. Therefore, 1 cubic foot of some natural gas may make only 7 cups of tea, while another makes as many as 20 cups of tea. Energy content of natural gas varies because natural gas accumulations vary in the amount and types of energy gases they contain: the more noncombustible gases in a natural gas, the lower the Btu value. In addition, how much of any energy gas that is present in a natural gas accumulation—the mix of combustible gases—also influences the Btu value of natural gas. The more carbon atoms in a hydrocarbon gas, the higher its Btu value. To illustrate: methane typically represents more than 80 percent of energy gases. Methane contains one carbon atom per molecule; burning 1 cubic foot of methane gives off 1,012 Btu. Butane, possessing four carbon atoms, has a Btu value more than three times larger than that of methane. Molecular hydrogen, on the other hand, though combustible, contains no carbon atoms; its Btu value is three times smaller than that of methane.

ENERGY GASES—THEIR COMPOSITION, ORIGIN, AND OCCURRENCE

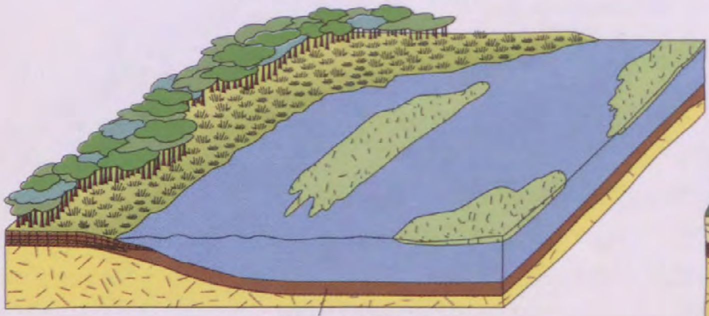
What Are Natural Gas And Energy Gas?

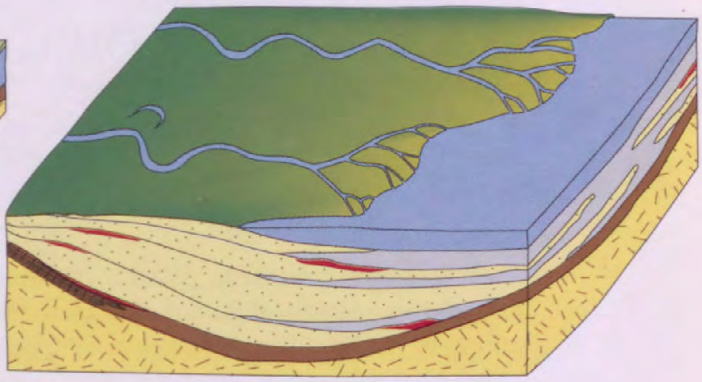
Naturally occurring gases in the Earth's crust are collectively referred to as natural gas. Some of these gases are combustible and give off energy when burned; they are collectively called *energy gases*. Energy gases typically make up more than 75 percent of natural gas. These energy gases are mostly hydrocarbon gases, which are compounds composed of only hydrogen and carbon atoms.



Gases that burn are a source of heat and are referred to as energy gases. These combustible gases are the major components of natural gas, shown in order of abundance; methane constitutes 80–100 percent.

Generation And Occurrence Of Energy Gases Within The Earth's Crust





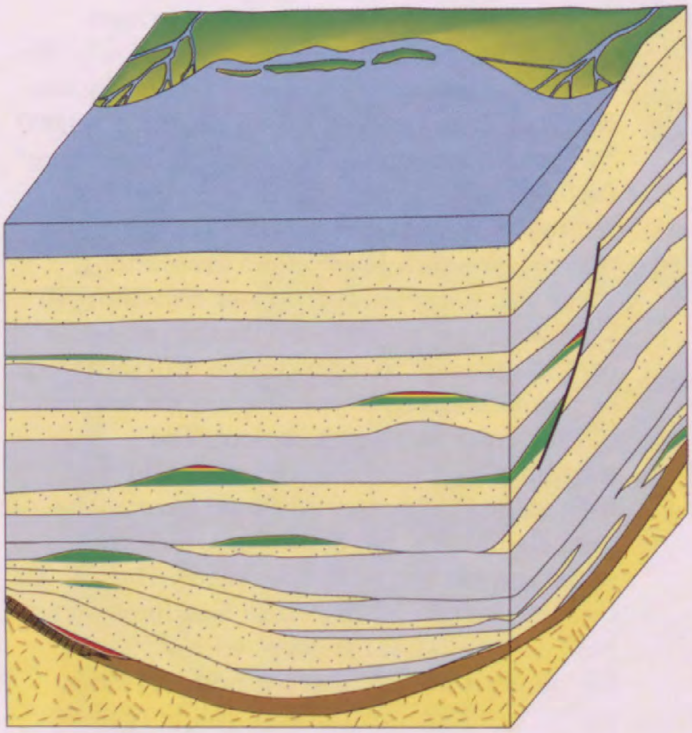
The **first stage** involves the accumulation of organic matter in sedimentary rocks. Throughout geologic time, the world oceans have expanded and receded over the Earth's present land surfaces, the continents. Stagnant water conditions that developed in some of the expanded oceans were conducive for organic matter from decaying higher plants (such as trees, shrubs, grasses from neighboring lands) and microorganisms (such as algae and bacteria in surface waters) to accumulate in the underlying sediments. Eventually, over hundreds of thousands to several millions of years, an unconsolidated sediment layer rich in organic matter is deposited beneath and marginal to some expanded oceans.

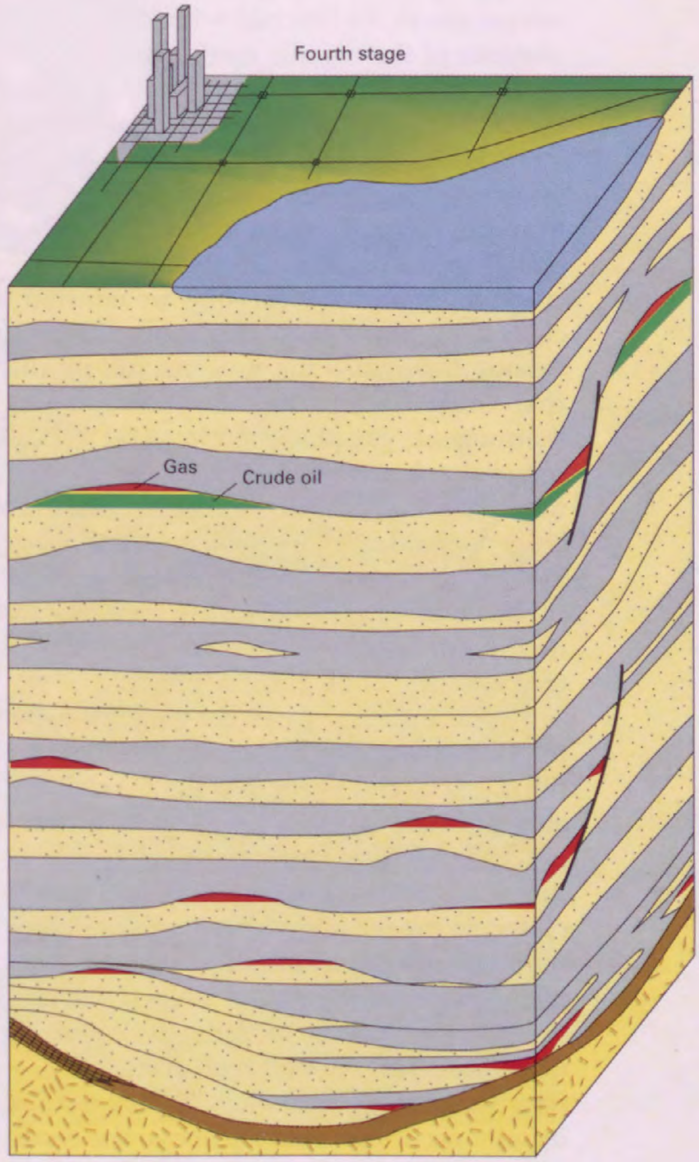
The **second stage** commences with gentle downwarping of portions of the Earth's crust to form basins, depressions that may extend over hundreds to thousands of square miles. Portions of organic-rich sediment layers that occur over these basins subside with the downwarping. As normally oxygenated ocean water begins to recirculate and to replace the once stagnant waters of the expanded oceans, the decay of organic matter is enhanced and organic-lean sediments begin filling the basin as it subsides. The organic-rich sediment layer originally on the ocean floor is gradually buried by the overlying organic-lean sediments as the downwarping of the basin continues.

Certain *methanogenic microorganisms* are buried with the organic-rich sediment. These single-celled microorganisms use some of the organic matter as a food source and generate methane as a byproduct. Methane is essentially the only energy gas produced by this biological process, and many of its carbon atom nuclei have a peculiar neutron deficiency that allows this *biogenic* gas to be easily distinguished from other energy gases generated in subsequent stages.

Biogenic gas may remain in the organic-rich sediment layer, or it may bubble up into the overlying sediments and finally escape to the atmosphere. If impermeable sediment layers, called *seals*, occur in the upward path of released biogenic gas, the gas may be concentrated and trapped; when a seal covers a large area of porous sediment, called a *reservoir*, economically significant accumulations of biogenic gas may result. Approximately 20 percent of the world's discovered energy gas is generated by methanogenic microorganisms during this second stage. The second stage lasts for one million to tens of millions of years, and it ends when compaction of the buried sediments results in the formation of indurated sedimentary rocks and increasing burial temperatures kill off the methanogenic microorganisms. Typically these conditions occur when the organic-rich layer reaches a burial depth of more than 3,000 ft.

May Be Explained In Five Stages, Which Cover Millions Of Years





During the **third stage**, the indurated organic-rich rock layer continues to be buried deeper, as downwarping and sediment fill continue for another 9,000 to 18,000 ft over several million to tens of millions of years. As temperature and pressure increase with burial depth, the organic matter begins to cook and thermally decompose within the organic-rich rock layer. With sufficient cooking time and when appropriate increasing temperatures are reached, some of the organic matter breaks down to form *crude oil (petroleum).* Some natural gas is generated during this stage. The crude oil may be expelled from portions of the organic-rich rock layer where it is generated, whereupon it migrates upward into the overlying rocks and sediments through cracks and porous rocks because its density is lower than that of water (oil floats on water). Similar to the earlier formed biogenic gas in the second stage, seals in the proper configurations may form *traps* that concentrate and collect the upward-migrating crude oil in the porous rocks of reservoirs, possibly along with biogenic gas collected in the second stage.

Major quantities of energy gases are generated in the **fourth stage**, as the organic-rich rock layer and trapped crude oil in reservoirs are buried to depths exceeding 18,000 ft. Organic matter in the organic-rich rock layer continues to cook during this stage. As appropriate cooking times and increasing temperatures are reached with burial, portions of the organic matter thermally decompose to form energy gases. In addition, trapped crude oil in reservoirs that remain intact with burial also thermally decomposes to form energy gases. Energy gases derived from the thermal decomposition of organic matter in the organic-rich rock layer and crude oil in buried reservoirs are referred to collectively as *thermogenic gas*. At present we cannot distinguish thermogenic gas produced from organic matter in rocks from thermogenic gas produced from oil in buried reservoirs. However, both of these thermogenic gases can be distinguished from biogenic gas because they have a full range of hydrocarbon gases (methane, ethane, propane, butane) and because they lack the neutron deficiency in the carbon-atom nuclei characteristic of biogenic methane.

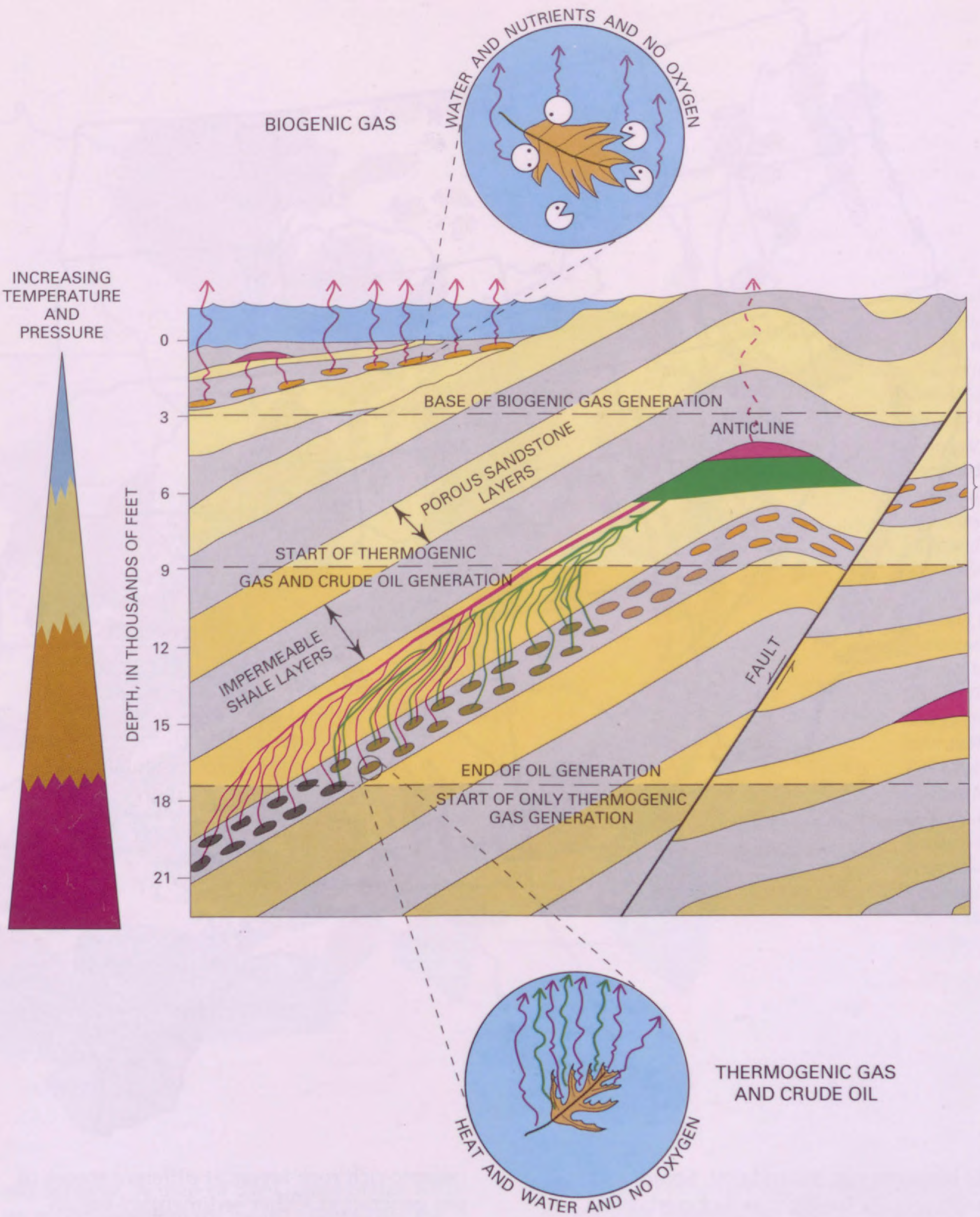
As the energy gases are generated, they migrate upward by buoyancy through water-filled cracks and pores into the overlying rock and sediment layers. This gas may collect in newly formed reservoir traps solely as a thermogenic gas accumulation, or it may collect in preexisting reservoir traps with crude oil formed in the third stage or with biogenic gas formed in the second stage.

Thermogenic or biogenic gas occurring in the same reservoir trap with crude oil is referred to as *associated gas*. Associated gas usually occurs as a *gas cap* above the crude oil in a reservoir trap because gas is lighter than oil. Associated gas in some deep reservoir traps at high pressures may be dissolved in crude oil and thus will not occur as a gas cap until the pressure is reduced by leaks or ruptures in the trap. Thermogenic or biogenic gas occurring in traps independent of crude oil is called *nonassociated gas*. Under certain temperature and pressure conditions, energy gases in some nonassociated gases may mix with pore water in a reservoir trap and freeze to form a solid referred to as a *gas hydrate*.

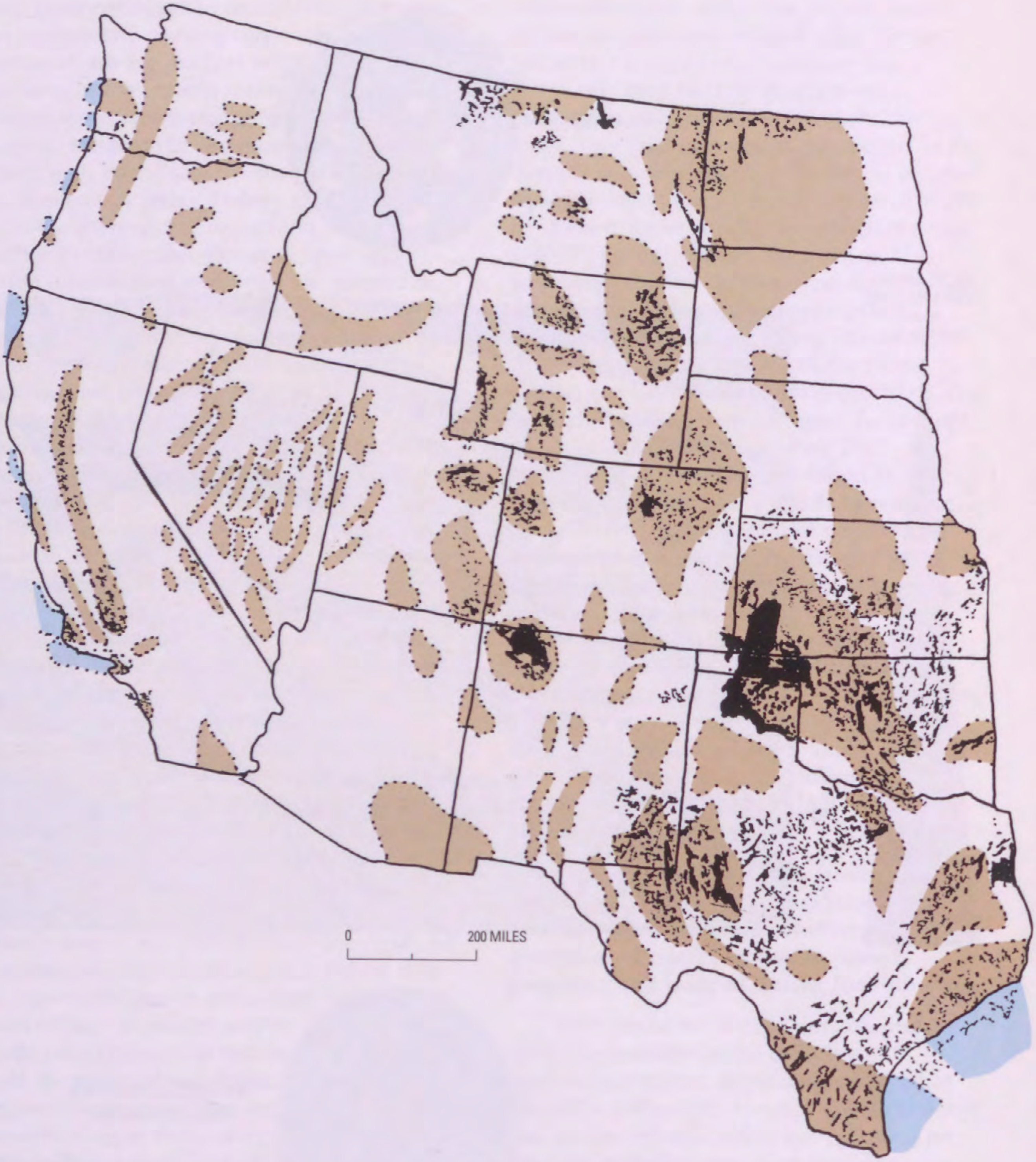
Only about 40 to 60 percent of the original organic matter in the source rock migrates out as crude oil or natural gas by the end of the fourth stage. The organic matter left behind continues to cook with further burial into a solid carbon residue that eventually may become graphite—the material used in pencils and to lubricate locks. This final conversion only occurs in the deepest of sedimentary basins where organic-rich rock layers exceed burial depths of 45,000 ft. These extreme conditions of high pressure (>60,000 pounds per square inch) and high temperature (>600 °F) transform the original organic-rich rock layer into a graphitic metamorphic rock layer. Water remaining in this rock layer may react with the pure-carbon graphite to form carbon dioxide (CO_2) or methane (CH_4) depending on the amount of molecular hydrogen present. The significance of methane generation in this **fifth stage** is at present difficult to evaluate because of the great depths at which these metamorphic reactions take place. The deepest well so far drilled in a sedimentary basin is only 31,441 ft deep, with a temperature of 485 °F at the bottom of the well. Therefore, our understanding of metamorphic rocks is based on studies where they have been uplifted and exposed at the Earth's surface in mountain ranges, and where they have been experimentally simulated in laboratories at high temperatures and pressures.

Only a few sedimentary basins currently reach these extreme conditions, and we do not yet know whether significant quantities of energy gases are actually generated and trapped during the fifth stage.

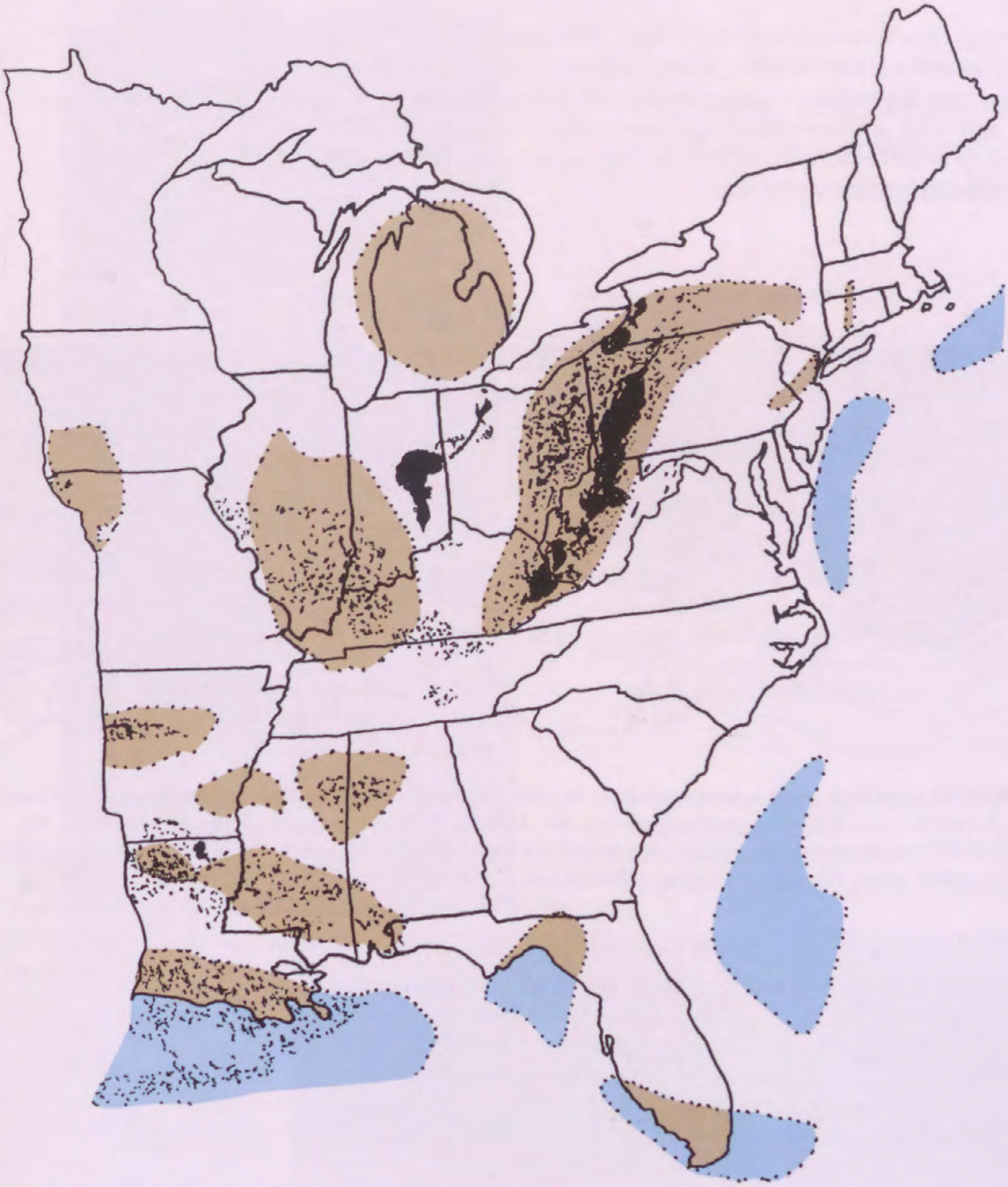
Whether or not energy gas accumulates in usable amounts in the crust is a complicated matter, depending on whether migration pathways of energy gases converge into an area of rock where gas can pool, on the type and efficiency of an available trap, on the mixture of thermogenic and biogenic gases, and on timing and temperatures of gas generation. Moreover, not all sedimentary basins go through all five stages of gas generation: downwarping of some sedimentary basins may stop after the second or third stage, resulting in only the occurrence



Most of the energy gas and crude oil trapped in reservoirs in the Earth's crust is generated by biological and thermal processes that break down organic matter as it is buried in sedimentary basins over geologic time. Efficient production and use of the most favorable energy gases require an understanding of the geologic factors that determine the composition and location of natural gas at depth in the Earth's crust.



of biogenic gas or crude oil. Some sedimentary basins may not contain an organic-rich rock layer to serve as a source for energy gases, and some may contain several organic-rich rock layers at different stages of gas generation. Other sedimentary basins may not have developed traps and thus would lose any generated energy gases to the

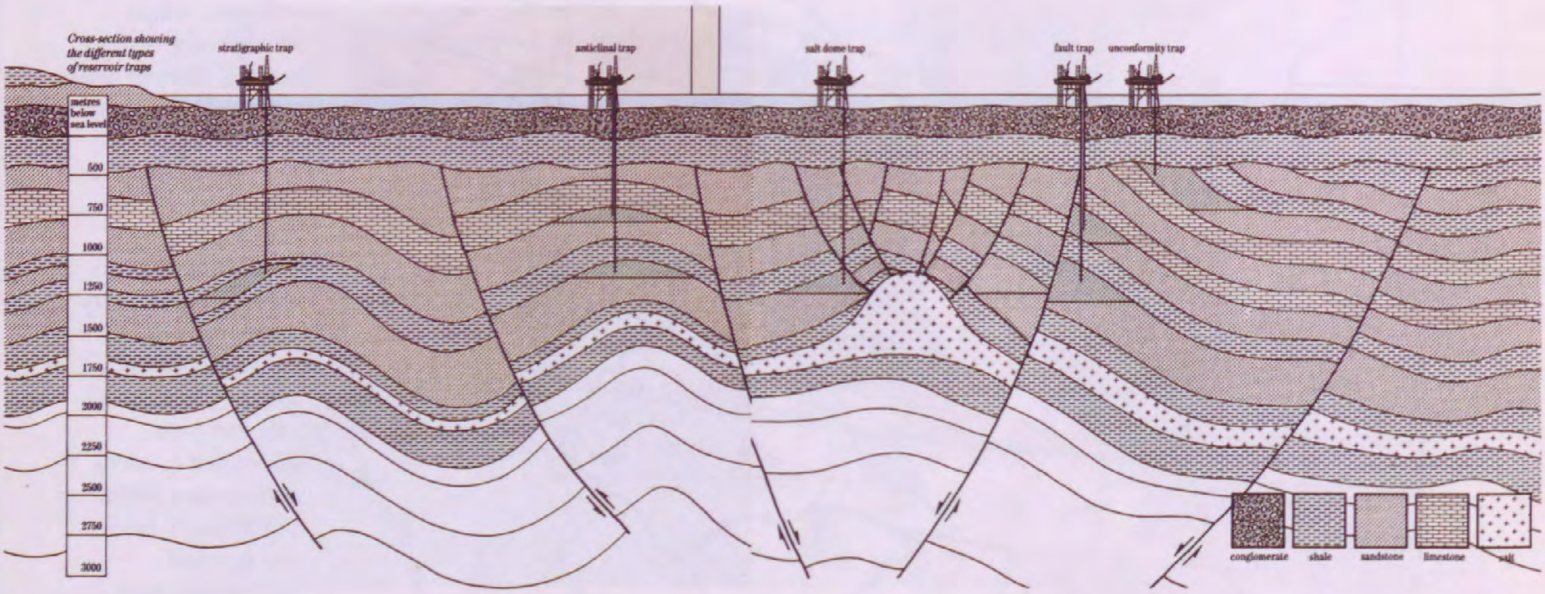


Is there a gas field near you? Major sedimentary basins onshore (brown) and offshore (blue) in the United States showing occurrence of energy gas reservoirs. Sedimentary basins do not occur in every State and accumulations of energy gases (black) have not been discovered in every sedimentary basin. Sedimentary basin and gas field information from Potential Gas Committee map, © Terra Graphics, Denver, Colo. By permission of Potential Gas Committee and Terra Graphics.

atmosphere. A map of the United States with its major sedimentary basins shows that the occurrences of energy gases are limited and not universal. Therefore, it becomes important for geologists, geochemists, and geophysicists to develop ways to determine which basins have the best potential for energy gases and to find accumulations of energy gases still hidden within the vastness of sedimentary basins.

How And Where Does Energy Gas Accumulate?

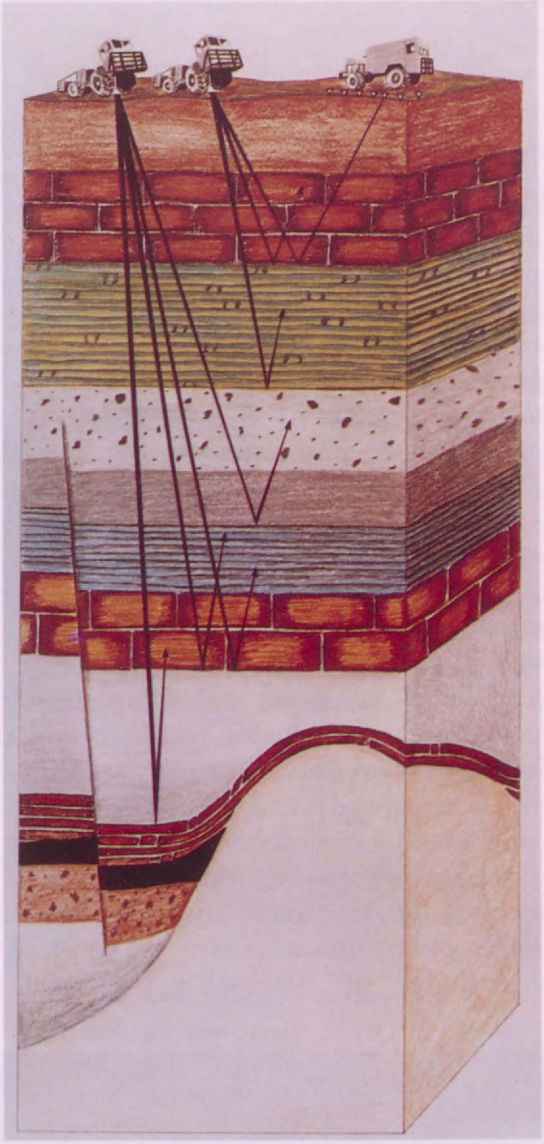
Most energy gas accumulations have been discovered during the search for oil in sedimentary basins. Energy gas may occur in a variety of traps, which are favorable irregularities in rock layers that can concentrate and hold upward-migrating gases or liquids. The main feature of a trap is that it consists of porous rock layers that are overlain by impermeable layers, known as *seals*.



Traps take on many forms. Stratigraphic traps form where a porous rock layer becomes impermeable laterally. One kind of structural trap is an anticline, formed when rocks push upward into a fold, that may trap gas in a dome. Movement along a fault may also result in a porous rock being overlain by an impermeable rock layer. In another type of trap, salts buried in a basin slowly flow upward. Porous rock layers folded and cut by these salt masses can form excellent traps. Illustration courtesy of British Gas.

Finding traps in sedimentary basins is a time-consuming, difficult, and expensive undertaking. Techniques of reflection seismology provide some help. In reflection seismology, sound waves are transmitted from the surface into a sedimentary basin and sound waves that echo back to the surface from some rock layers are collected. This process is repeated along several traverses over areas of exploration interest. Collected data are computer processed to yield seismic profiles, images of the subsurface below the traverses, from which interpretations of potential traps may be made. Seismic surveys may be conducted on land or water, and either way they are expensive and time consuming.

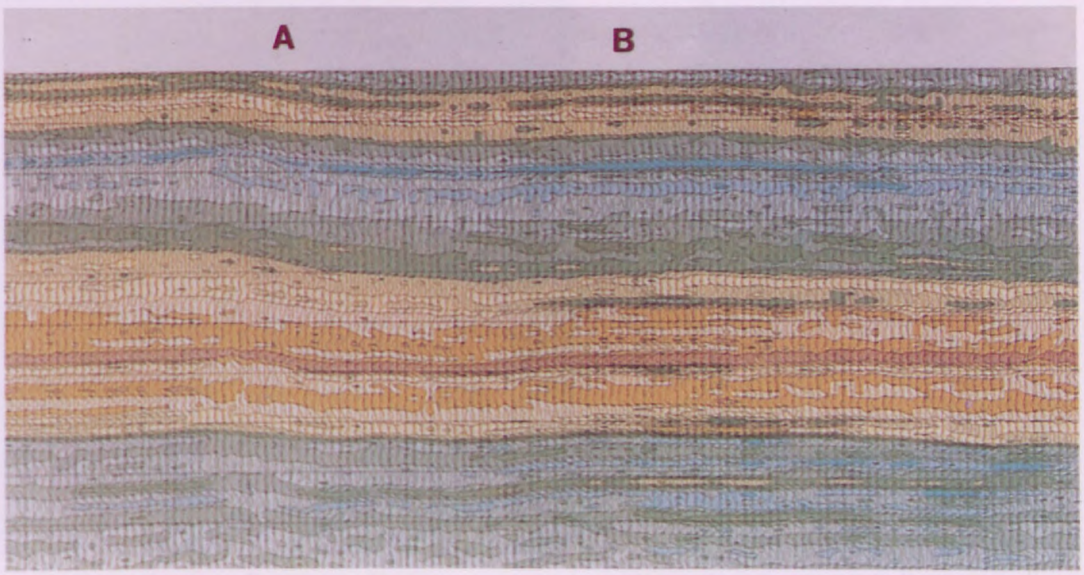
Further advances in the application of this technology are of great importance in future exploration for energy gases.



Finding traps in sedimentary basins is a time-consuming, difficult, and expensive undertaking.

An image of rock layers and potential traps under the Earth's surface can be obtained by transmitting sound waves into the crust and recording the sound waves that echo back from the boundaries between rock layers. Computer processing of these returning sound waves results in a seismic profile or section.

In this seismic profile, anticlines that may have trapped accumulations of energy gases occur under positions A and B.



Planning And Executing Strategies For Recovering Energy Gas

Once a potential trap has been interpreted on a seismic profile and evaluated, an exploration well is drilled to test the prospect. Exploration wells drilled on land typically cost $35 per foot, but may cost as much as $400 per foot (1993 prices) under difficult or deep drilling conditions. Exploration wells drilled offshore are more expensive because of the costs of constructing and using drilling platforms. Typical offshore drilling costs are approximately $1,000 per foot, but may rise to more than $2,000 per foot (1993 prices) under deep-water or deep drilling conditions. Energy gas accumulations occur at depths down to more than 19,000 ft below the Earth's surface. Thus, a 10,000 ft well may cost from $350 thousand to $20 million, depending on drilling difficulties and whether the drilling is on land (onshore) or at sea (offshore). More than 208 thousand exploration wells were drilled in the United States between 1970 and 1990, and only one out of every four encountered producible crude oil or energy gases. Exploration wells are obviously a risky business that requires a great deal of capital.

If significant quantities of energy gases are encountered in an exploration well, then several appraisal wells are drilled to define the size of the accumulation and determine how best to produce it from the reservoir. Engineering strategies for efficient production require that the hydrocarbon and Btu content of the trapped energy gases be carefully evaluated, and that the porosity and flow capacity of the reservoir be thoroughly characterized. A reservoir that consists of porous rocks that allow flow of energy gases between pores and directly into a well is called a *conventional* reservoir. *Unconventional* reservoirs, on the other hand, consist of rocks that have restricted flow of energy gases between pores and depend on fractures for flow into a well. Examples of unconventional reservoirs include coal beds and low-permeability ("tight") sandstones. Although the energy gas accumulations in unconventional reservoirs usually extend

Drilling platform, Morecambe Bay Central Complex gas field off Lancashire coast. Courtesy of British Gas, London.

over an area greater than that of conventional reservoirs, unconventional reservoir accumulations require more development wells and special production techniques, such as artificial fracturing or the removal of water, to stimulate flow of gas to the well. These procedures cost more and make unconventional reservoirs less attractive for developing production. As a result, most energy gas production in the United States is from conventional reservoirs—less than 15 percent of recent production has come from unconventional reservoirs.

Over the last several years, energy gas production from unconventional reservoirs has increased because of Federal tax credits legislated to encourage development of this source of energy gases. As of 1991, the United States has produced a total of almost 750 Tcf (trillion cubic feet) of energy gas, predominantly from conventional reservoirs. More than half this energy gas was produced from onshore and offshore sedimentary basins in Texas and Louisiana.

Important questions now are "How much energy gas remains in the other sedimentary basins of the United States?" and "Does this undiscovered energy gas occur in conventional or unconventional reservoirs?"

The economic viability of an energy gas accumulation depends largely on its proximity to a pipeline for transport to markets. Unlike crude oil, energy gases currently cannot be economically transported in storage tanks by truck or train.

Energy gases from a production well are piped to an extraction facility where impurities such as water and heavy hydrocarbons are removed; useful products are then transported to market in pipelines at pressures as high as 1,000 pounds per square inch. As an alternative, energy gases can also be converted to liquid natural gas (LNG), by lowering their temperature to about –250 °F. Although energy gas takes up 600 times less volume as a liquid, the energy cost of liquefying the gas and the need for highly insulated transport tanks make this alternative uneconomical for the United States at current gas prices. (LNG should not be confused with LPG, liquefied petroleum gas, which consists of only propane or butane. These gases can be liquefied at room temperature by compressing them at higher pressures. This type of liquefied gas is used for heating and cooking in homes remote from pipelines and is also referred to as *bottle gas, LP gas, propane,* or *butane.*)

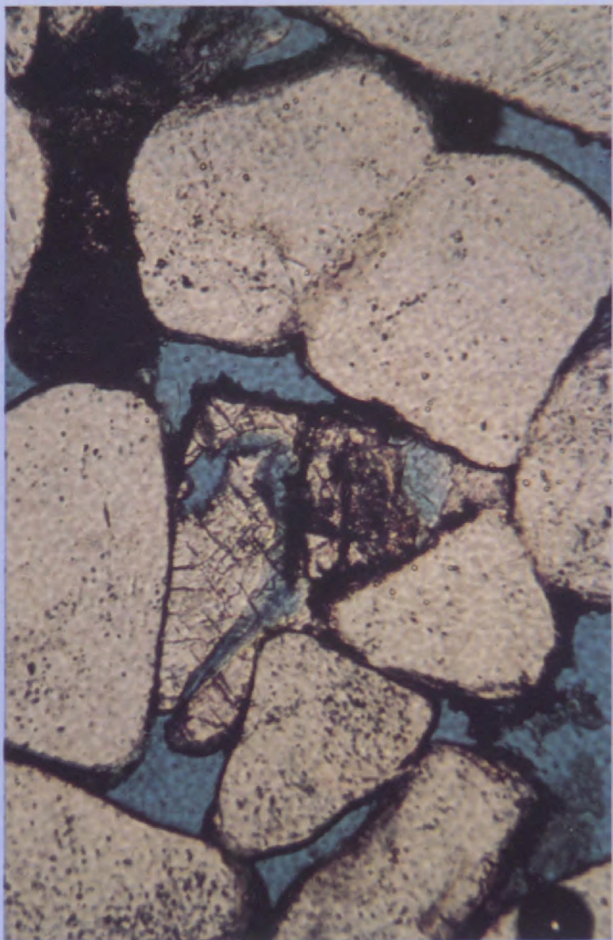
Another transportation alternative that has been considered is the chemical conversion of energy gas to a liquid such as wood alcohol (methanol). Methane at the production site could be converted to liquid methanol, transported like crude oil, and converted back to methane at the market place. The challenge that remains in this alternative is developing technology capable of making the chemical conversion cost effective and environmentally sound.

Between 1970 and 1990 only one out of four wells drilled in the United States encountered producible crude oil or energy gases.

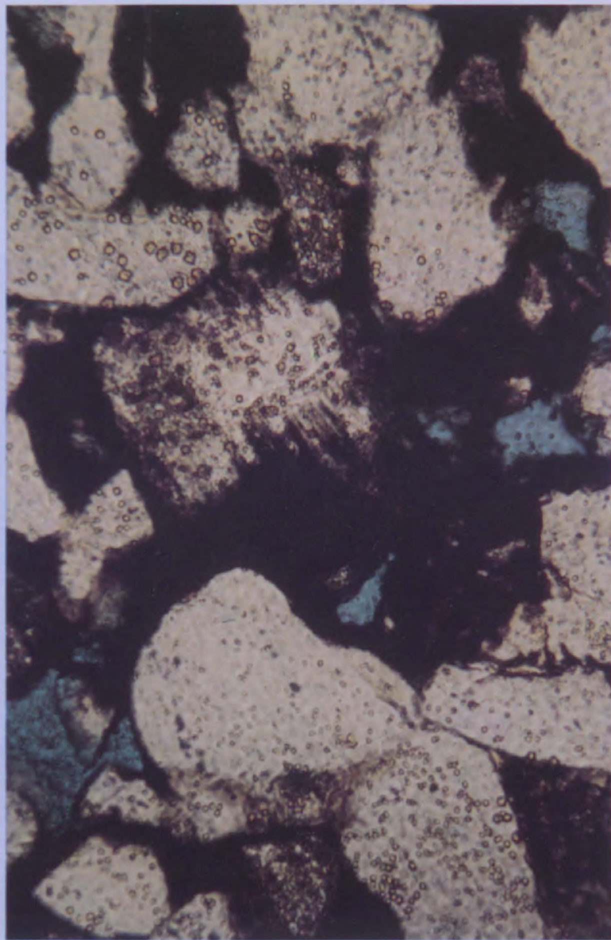
WHAT MAKES A GOOD RESERVOIR?

Most accessible gas reservoirs have been found where sedimentary rock layers have undergone structural deformation, such as faulting or folding, or where a break in deposition, called an unconformity, has occurred. Other conditions in the rock also exist, on a much smaller scale, that are just as critical in determining whether extraction of a gas resource is possible.

Gas is trapped in microscopic pores within rock. The volume of gas a rock can contain is determined by its *porosity*—the size and abundance of the pore space in the rock. Sedimentary petrographers make thin sections of rock and fill the pores with a blue epoxy, which allows them to assess the rock's porosity. An equally important characteristic is the rock's *permeability*—how easily the gas can migrate from one pore to another through the rock. Extracting gas from a highly permeable rock is easier than extracting it from a low-permeability or "tight" rock. As sediment is buried and compressed and consolidated into sedimentary rock, the original porosity and permeability decrease; typically, the rocks buried the deepest are the tightest. Some tight reservoirs may yield gas, however, if the rock is fractured. Natural



Thin section of a sandstone with high porosity. The pore space (blue) occurs between rounded sand grains, which are about 1/3 millimeter in diameter.



Thin section of a sandstone with low porosity. Note how the original pore space has been infilled.

fractures may act as conduits for gas migration; where natural fractures are absent, artificially fracturing the rock may help to release trapped gas.

Burial depth is not the only factor in determining porosity and permeability of a rock, however, and often creative geology—looking beyond the norm—is what it takes to be a successful explorationist. For example, water enclosed in the pores in rock can be an important agent of change. As chemical composition of pore water varies through geologic time, mineral cements may precipitate within pore spaces, thus reducing porosity and permeability, or mineral grains may dissolve, creating new pore space. So tight reservoirs may occur at shallow depths and permeable reservoirs at great depth. One of the most significant plays in the United States in the 1980's is a deep gas play 19,000 ft deep in offshore Alabama, in sandstones of the Norphlet Formation (dated as Late Jurassic); the rocks have anomalously high porosity (as much as 20 percent) and are estimated to hold gas reserves of 8–12 Tcf.

In order to trap gas that is migrating upward, a reservoir must be capped by a good rock seal. Unfortunately for ease of extraction, many reservoirs are split by impermeable layers, similar to seal rocks but thinner and less persistent. These layers divide the reservoir into compartments between which gas migrates only slowly. The amount of consistency or continuity between layers of rock in a reservoir is a measure of reservoir heterogeneity, which is determined by the original depositional environment of the sediment. Sedimentologists have recently begun to develop 3-dimensional models that describe in detail the geometry of beds deposited in various environments, and to extrapolate what they learn from these outcrop studies to interpret the nature of subsurface reservoir rocks. These models predict the nature of heterogeneities within a reservoir, so that wells can be oriented to access gas from as many compartments in a heterogeneous reservoir as possible.

Cretaceous strata in the canyon country of southern Utah, composed of sandstones (cliff forming) and shales (slopes) deposited by rivers 85 million years ago. The complex geometry of these bedded sedimentary rocks can provide analogs for certain reservoirs (sandstones) and seals (mudstones) in the subsurface. The entire outcrop shown is about 650 ft high.

INORGANIC GASES—AN OUT-OF-THIS-WORLD IDEA?

The theory that hydrocarbons are derived from the decomposition of organic matter is supported by scientific evidence and is widely accepted. Generation of gas is interpreted to be due to the microbial and chemical decomposition of plant debris and microorganisms under conditions of elevated temperature and pressure associated with deep burial. But what if this theory is incorrect? What if oil and gas were inorganically derived, not organically derived? Proponents of the inorganic origin of natural gas challenge the commonly held view that the presence of organic components in oil and gas implies an organic origin. They suggest that all hydrocarbons originate not from the decomposition of organic matter but rather from the accumulation of carbon and hydrogen in the Earth's mantle as our planet accreted during the formation of the solar system. These hydrocarbons then outgassed as a long, slow "flux of methane" from the mantle upward to the surface throughout geologic time. It has been suggested that outgassing of methane from the Earth's mantle could result in economically recoverable accumulations of methane in the Earth's crust if proper traps exist in the crust to capture the gas.

Proponents of the concept that methane in natural gas is of inorganic origin point out that methane is present in the atmospheres of the gaseous planets of the Solar System even though it is highly unlikely that those planets ever supported life. The atmosphere of Jupiter, for example, though consisting dominantly of hydrogen and helium, contains a very small amount of methane—just under 1 part per thousand. Temperature, pressure, and atmospheric conditions on Jupiter and the other gaseous planets would make life, at least as we know it, totally impossible. Clearly methane can be purely inorganic in nature and, in fact, most scientists agree that at least some of the methane on Earth is not of organic origin. Methane that emanates from mid-oceanic ridges, for example, contains what is generally agreed to be mantle-derived methane. But even though some inorganic methane is known to exist, most scientists doubt that commercial quantities of the gas ever escape the Earth's mantle because carbon dioxide and water are the main fluids in the mantle. Moreover, most geologists believe that the greater part of mantle degassing of methane was completed very rapidly after the formation of the planet and that only the last gasps of the process can be detected today. If this is true, then most inorganic gas would have escaped to the Earth's surface prior to the formation of sedimentary basins and potential reservoirs. Even if significant quantities of methane existed in the mantle, chances are good that the

Gaseous planet Jupiter with moons. Jupiter's atmosphere contains about 99.9 percent hydrogen and helium with minor amounts of methane and ammonia. The presence of methane on planets where life apparently never developed has been used by a few to argue that the methane of natural gas reservoirs on our planet could be of inorganic origin. However, this theory is not generally accepted by geologists. Photograph from Voyager Spacecraft courtesy of Jet Propulsion Laboratory, Pasadena, Calif.

gas would convert to carbon dioxide and water in the upper mantle, if it migrated at all.

So far, no economic accumulations of gas have been found that cannot be explained by the organic theory. Geochemical analysis of gas samples from producing fields in the United States, for example, clearly shows that over 99 percent of the gas is of organic origin.

METHANE—A QUIRKY GAS

Microscopic organisms that produce methane are among the most primitive of all living things. Some biologists consider them to have branched off early in the history of life on Earth from primitive life forms that were also the ancestors of bacteria. Unlike animals that use sugars, proteins, and carbohydrates as food, methanogenic (methane-producing) microorganisms use substances like carbon dioxide, methanol, acetate, and formate as food. This may sound like the stuff of science fiction, and indeed the chemistry used by these organisms to derive their energy is unique. Their metabolism produces methane as a byproduct.

Like bacteria, these microorganisms exist as single cells lacking a nucleus. Unlike bacteria, they consume hydrogen as well as carbon to make methane, deriving chemical energy from the reaction: $4H_2+CO_2 \rightarrow CH_4+2H_2O$ which is chemical shorthand for saying the microorganisms take hydrogen and carbon dioxide and make methane and water. Because elemental hydrogen is required for these organisms to live, they cannot live in the presence of oxygen, which reacts quickly with hydrogen to form water. Methane-producing microorganisms live only in environments that are isolated from air.

Despite this severe environmental restriction, methanogenic microorganisms are surprisingly widespread. They live in almost all animals, including you and me, and

Although methane is released during the extraction and utilization of fossil fuels, much more is released from rice paddies and livestock.

they are particularly abundant in—of all things—termites and cows. These two creatures process large amounts of cellulose in the form of wood and grass and, thanks to the microorganisms they contain, they are copious methane producers.

Methanogenic microorganisms are also abundant in soils and thrive in mud on ocean floors, lake bottoms, riverbeds, shores, and swamps. It is in this last environment that these microorganisms are responsible for producing "swamp gas," which, when ignited, can give rise to night lights possessing a considerable element of mystery. In the northern United States and Canada, many youngsters are surprised by the vigor of a winter flare produced by igniting methane trapped beneath ice and released through a drill hole. It is a vivid reminder that methane is produced all around us and normally escapes to the atmosphere unseen.

Methanogenic microorganisms are essential for recycling carbon through the biosphere. They form an essential link in the reprocessing of the debris of more complex life forms back to simple molecules that escape to the atmosphere. Methane constitutes about 1 part per million of the gas in the atmosphere, where it reacts over time with oxygen to form carbon dioxide. Humans have unwittingly helped create several "environments" that are particularly favorable for methanogenic microorganisms to thrive and release methane to the atmosphere. These "environments" include rice paddies, the stomachs of cows in our beef and dairy herds, and the landfill sites where we dispose of our trash. It has been suggested that the addition of methane to the atmosphere from these sources could contribute to global warming.

Human activities have inadvertently raised the levels of methane emission into the atmosphere. Original slide by D.W. Houseknecht.

HYDROGEN—A FUEL OF THE FUTURE?

The unforgettable sight of the burning *Hindenburg* in 1937 spelled the end of the airship era and hydrogen became synonymous with danger for a whole generation. The detonation of the first hydrogen explosive device in 1952 made hydrogen once again an element of concern for the public. Recently, however, the possible role of hydrogen as a fuel of the future has received considerable attention: unlike methane, coal, and petroleum, hydrogen produces no major pollutants or greenhouse gases when burned—just water vapor. Unlike other energy gases, however, there are no large natural reserves of hydrogen in the Earth's crust—hydrogen is not a fossil fuel.

Hydrogen produces no major pollutants or greenhouse gases when burned—just water vapor.

For any quantity that could be usable as an energy fuel, hydrogen must be manufactured; the process of its manufacture is the electrolysis of water (H_2O), which requires expenditure of considerable energy to generate the necessary electricity. That energy would be generated by burning fossil fuels such as coal or natural gas. Because of the inherent loss of energy involved in the conversion of one fuel to another, use of hydrogen as an energy fuel could well entail higher levels of carbon dioxide and other emissions per Btu used by the consumer than is the case for other fuels.

Proponents of hydrogen as a fuel, however, point out its considerable advantages as a medium to store and transport energy (much as we use batteries and electrical currents to store and transport energy). Although generation of hydrogen from fossil fuels is inefficient, the reverse is not necessarily true: hydrogen can be converted to thermal, mechanical, or electrical energy more efficiently than can any fossil fuel. Proponents see that hydrogen could be used for many purposes including home heating, cooking, and as a pollution-reducing fuel for automobiles and airplanes. Although the use of hydrogen could theoretically lower carbon dioxide emissions, its use would not necessarily reduce the greenhouse effect: water vapor has the largest effect of any greenhouse gas, and the effect of substantially increased production of water vapor—particularly at high altitudes from airplanes—is not well understood. It has been calculated, however, that a hydrogen-fueled jet aircraft would use 19 percent less energy than one fueled by current aviation fuel. If that efficiency converts to lower fuel weight, then hydrogen-fueled airplanes of the future could carry larger payloads than today's planes.

The use of hydrogen will likely be limited if it has to be created by burning fossil fuels. Perhaps future advances in the development of more efficient solar or other renewable energy sources (for example, wind and hydro-electric) will allow the generation of cheap hydrogen that could easily be stored and transported to areas where power is needed. Although such generation would result in no atmospheric pollution, creating any large-scale hydrogen-generation facility would inevitably exact an environmental cost—valleys flooded to create reservoirs, or vast tracts of land covered with solar panels or wind turbines.

The use of hydrogen will likely be limited if it has to be created by burning fossil fuels.

HOW MUCH ENERGY GAS AND AT WHAT PRICE?

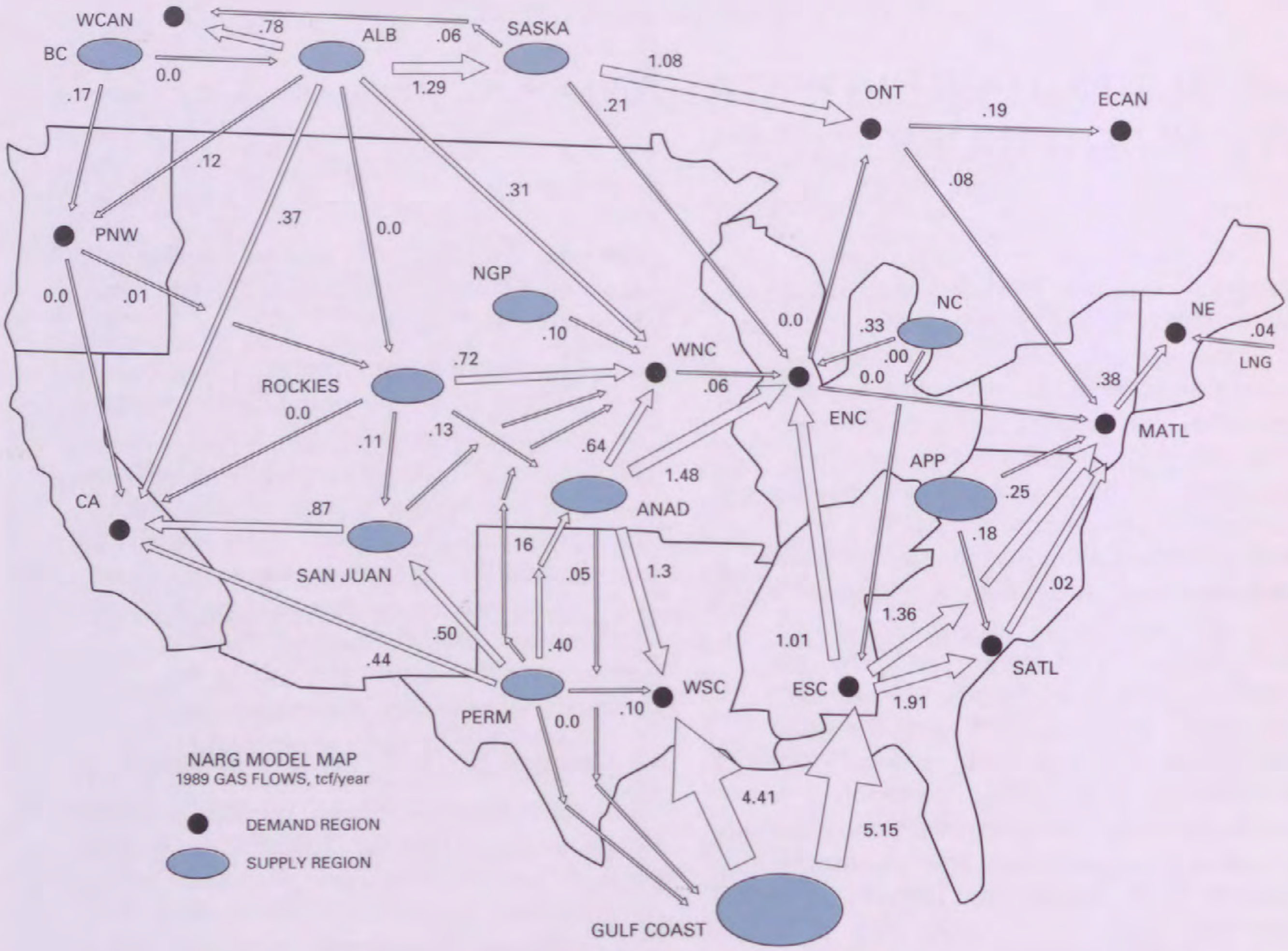
Geologists, petrochemists, industry analysts, computer modelers, statisticians all agree that natural gas and particularly methane are extremely abundant on our planet. In spite of the many and varied kinds of natural gas resources and their varied potential for exploitation, however, the question of whether natural gas resources can be reliably delivered to the public under current technical and economic conditions arouses strong differences of opinion. Why is this so? First of all is the question of terminology: What are *reserves*? What are *resources*? Not all geologists, economists, engineers, and politicians mean the same thing when they use the same words! (Part of the glossary at the end of this report defines some commonly used terms.) A second problem is the discovery and economic recoverability of gas: What part of our natural gas endowment can we count on to be added to our domestic energy supply?

Our question, "How much natural gas is available for use as an energy source?" immediately entails the question, "available to whom? and at what price?" What we need to know is the amount of energy gas that is available to our modern, complex society for domestic use, for transportation, and for electricity generation; and what it will cost to acquire and supply this energy gas.

By the end of 1990, the lower 48 States had produced and consumed a total of about 750 Tcf of energy gas. That same year, the Energy Information Administration reported about 160 Tcf of *proved reserves*. Proved reserves represent the quantity of natural gas available for production using existing infrastructure and current economic conditions—this number has changed significantly during the past three decades. Between 1965 and 1970, proved reserves were at an all-time high, almost 300 Tcf; since then, they have decreased.

The rate of current production of energy gas is about 17 Tcf per year. Dividing current proved reserves (160 Tcf) by current production (17 Tcf) gives a figure of 9.4, from which it is tempting to conclude that the U.S. reserves constitute a 9- or 10-year supply. But concluding that energy gas supplies will run out within one decade is an incorrect assumption: proved reserves are not a measure of the supply but only of the immediate inventory. An analogy from everyday life may help: supermarket warehouses in the United States contain only a 2-month supply of staple groceries, but that does not mean that the United States will go hungry within a few weeks. Food warehouses replace their supplies with staples furnished by producers; likewise gas companies replace their gas reserves with new producing wells and fields. Just as the rate and amount at which food can be produced and supplied to the supermarket warehouses are important to the food industry and the consumer, so it is critical in the area of energy fuel to assess the recoverable resources of energy gas and the rate and amount in which they can augment the proved reserves.

Geologists consider that additions to existing reserves can come from (1) discovery, through exploratory drilling, of previously unknown *conventional* fields; (2) growth of reserves through extensions and new-pool discoveries within existing fields, infill drilling, increased recovery efficiency on existing fields, and upward revision of reserve estimates; (3) development of resources from *unconventional* categories.



The present distribution of natural gas within the United States and Canada, showing movement of gas from major producing areas to areas of use. Size of arrows indicates relative size of gas flow within pipelines in 1989. This view divides the United States into nine "demand regions"; "supply regions" are major geologic basins from which natural gas is extracted. Imported liquefied natural gas (LNG) currently supplies less than 0.3 percent of the United States' consumption of natural gas. The future pattern of gas flow will depend on growth in demand and size of new reserves found in the United States. Illustration from 1991 Fuels Report Working Paper: Natural Gas Market Outlook (P300–91–018WP6), Dec. 1991, published by the California Energy Commission.

Conventional Resources Of Energy Gas

Conventional resources are those that are readily producible with existing technology and without dramatic increases in price. The vast majority of energy gas produced to 1993 has come from conventional resources, and conventional resources still account for almost 90 percent of the current U.S. production of 17 Tcf per year. Thus knowing how much of the conventional resource will be available, and for how long, is critical.

A great deal of the conventional energy gas resource was originally discovered as a byproduct of oil exploration, and until the development of continuous welded pipe in the 1920's, natural gas was considered mainly as a nuisance for oil development. To this day, some gas discoveries are still considered of little or no value. For example, the large amounts of natural gas in northern Alaska are of no current value except for local use and, in some parts of the world, the gas that is produced along with oil is burned off (flared) at the well site.

In recent decades conventional resources of energy gases have increasingly been discovered as a result of exploration for energy gases themselves, rather than as a byproduct of oil exploration. This trend will likely persist, especially with the continued decline in oil exploration in the lower 48 States.

Undiscovered resources are by definition unknown quantities—whose whereabouts and abundance are not known. Nevertheless, petroleum geologists, engineers, and analysts can produce reasonable estimates of as-yet undiscovered conventional resources, using statistical trends of exploration and discovery success as well as geologic analog. We can evaluate how successful exploration drilling has been in the past, and assess the possibility of energy gas occurrence in new areas by analogy with previously explored areas.

Several organizations have estimated the undiscovered conventional recoverable resources of the United States. In 1987, the USGS and the Minerals Management Service (MMS) completed an assessment, using geologic interpretations and data from previous exploration and drilling, to estimate the size and number of undiscovered energy gas accumulations. The two groups estimated the total undiscovered conventionally recoverable gas resource onshore and in State waters (USGS) and in the Federal offshore (MMS) at 300–500 Tcf, with a mean of about 400 Tcf. Between 208 and 326 Tcf—a significant part of the estimate—was believed by the analysts to be recoverable with existing technology and under current (or similar) economic conditions.

The National Petroleum Council (an advisory committee to the Secretary of Energy), assembling experts in oil and gas resources representing industry, education, and government, prepared a more recent assessment of natural gas. The consensus of this knowledgeable group concerning the economically recoverable conventional resource was that it amounted to about 413 Tcf.

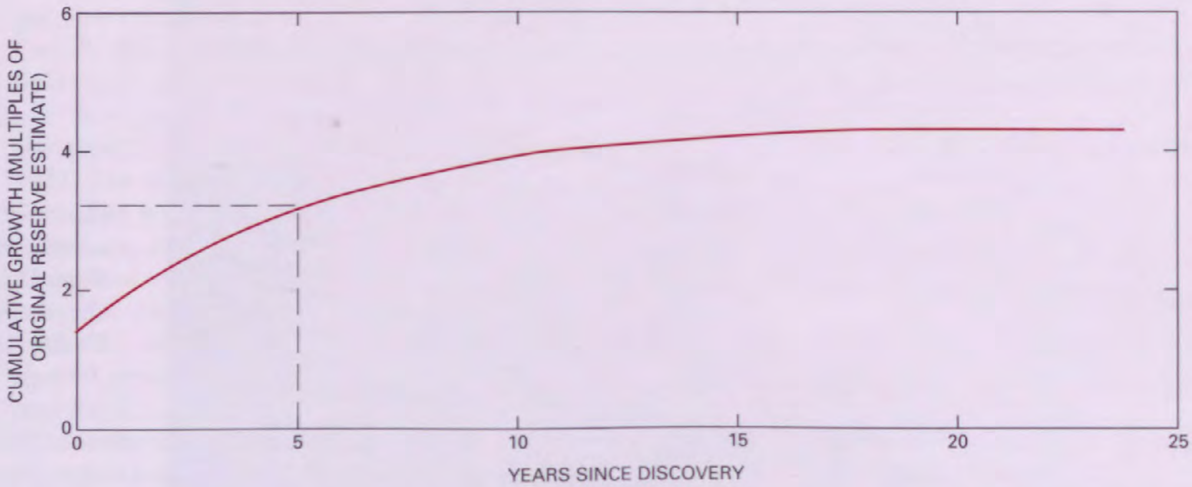
Flaring of gas at a well in the Niger Delta. Original slide by Dudley Rice.

Various other groups have also estimated the undiscovered conventional resource of the United States; most have placed the resource in the range of 300–500 Tcf. These estimates probably give a reasonable idea of the extent of undiscovered energy gas available at today's prices and with today's equipment, provided that industry has access to the areas of the country that contain these undiscovered fields.

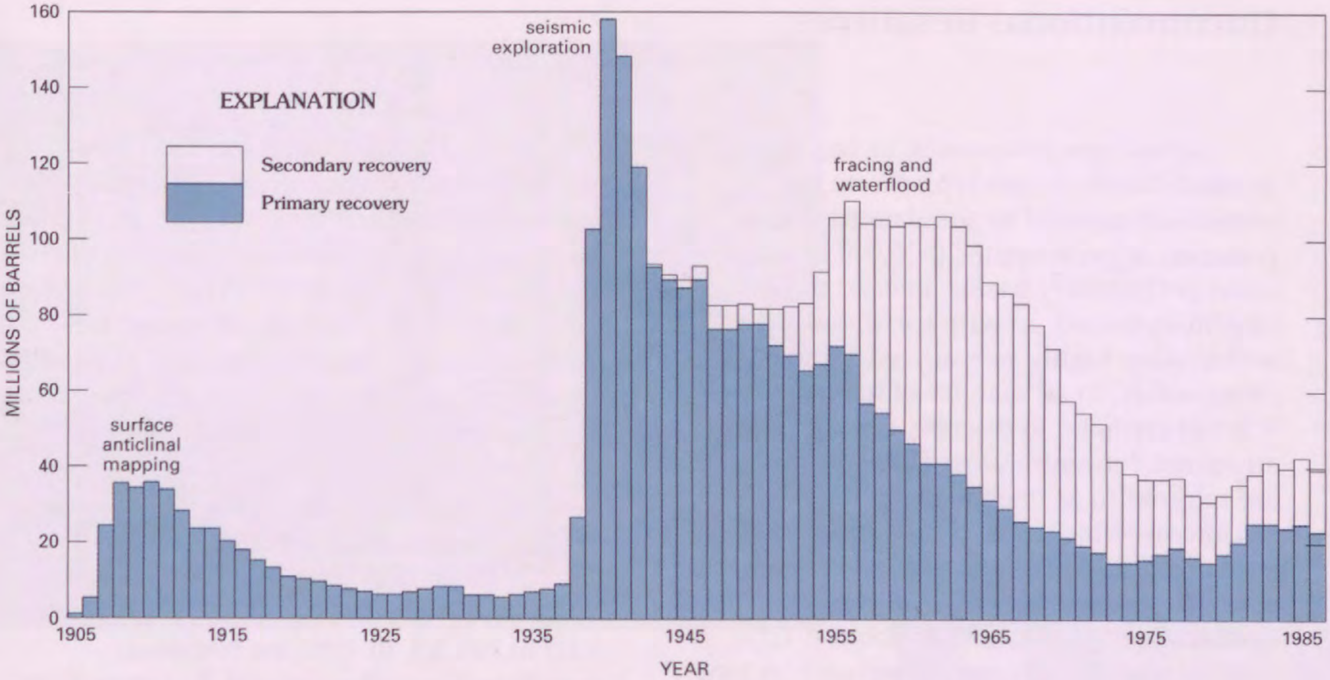
Although the amount of gas in a reservoir does not vary, the amount that is calculated to be recoverable from a gas field usually increases through time.

Growth Of Reserves

Although the amount of gas in a reservoir does not vary—except on a geologic time span—the amount that is calculated to be recoverable from a gas field usually increases through time. The increase in these calculated numbers is known as *reserve growth*. At the time a gas field is discovered, engineers make an initial estimate of the total amount of gas that will be recovered from that field between the time of discovery and the time when the field is finally abandoned—years, decades, even centuries later. As development and production proceed, this estimated ultimate recovery (EUR) changes; from an initial engineering estimate, the EUR becomes the total of proved reserves and cumulative production of gas from the field. In practice, then, the EUR generally grows through time, and this upward growth is the reserve growth or reserve appreciation. From an economic standpoint reserve growth can be viewed as the cheapest possible increase in natural gas resources because it generally requires no direct exploration costs and little development cost.



Curve of typical growth of estimated ultimate recovery (produced gas + proved reserves) through time following field discovery. Cumulative growth is in multiples of the original reserve estimate. Thus after 5 years of production, EUR is typically more than three times the original figure. Modified from National Petroleum Council, 1992, Potential for Natural Gas in the United States.



Field growth and production growth, using an example from oil production; Illinois basin, 1905–1988. Peak producing periods (early 1900's, late 1930's to early 1940's, and late 1950's) reflect evolving exploration and engineering methods. Courtesy of Richard F. Mast and Richard H. Howard.

Reserve growth results from the interaction of a number of factors. As a rule, the industry is inherently conservative in how it describes proved reserves—operating companies have no financial incentive to be anything but low in their initial reserve estimates. Improvement, as the field is produced, on the original conservative estimates provides one kind of reserve growth. As knowledge of reservoir characteristics increases during drilling and production, a larger fraction of the in-place resource may come within reach. Fields also grow by extensions along their margins, by the discovery of new reservoirs or pools within the existing field, by infill-drilling within the existing field, and by application of new technologies.

The *growth* of existing fields and reserves will add to our Nation's proved reserves. How much reserve growth can the U.S. count on to augment gas resources? In 1987, using records kept by the American Petroleum Institute and the American Gas Association, the USGS estimated reserve growth for pre-1987 fields to be slightly less than 100 Tcf. The Energy Information Administration, which has been compiling estimates of reserves for about 46,000 oil and (or) gas fields since 1977, estimated reserve growth in pre-1988 fields at nearly 265 Tcf. The lack of agreement in the two numbers probably results in part because the data set used by EIA includes an extremely active period of drilling in the late 1970's and early to mid 1980's. The National Petroleum Council, considering both these prior reports, estimated reserve growth by the year 2030 in conventional fields to be about 203 Tcf after the drilling of a total of 4 million gas wells and 14 million oil wells. The NPC predicted an additional 33 Tcf of reserve growth from unconventional accumulations of natural gas.

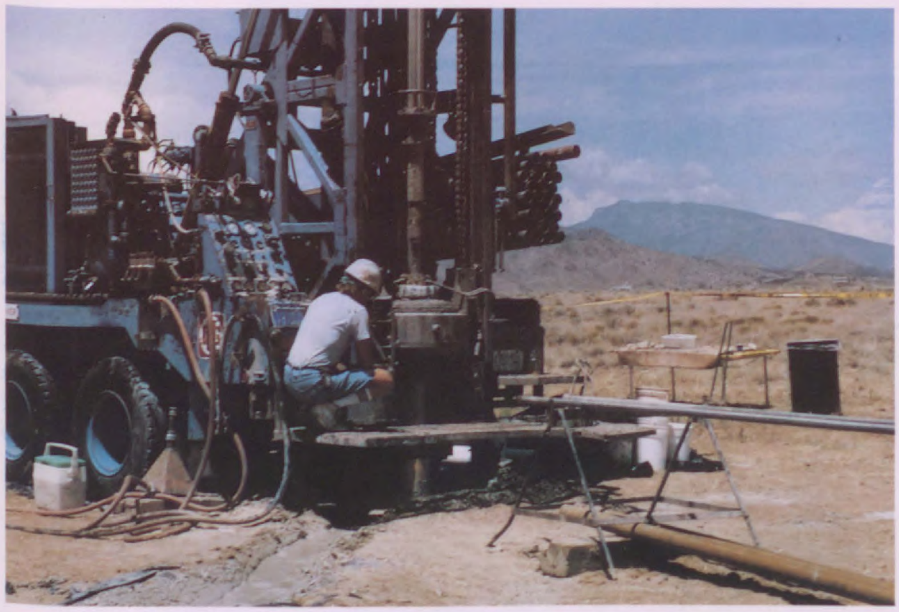
Unconventional Resources

Natural gas also occurs, in vast quantity, in much harder-to-reach places on our planet—in regional accumulations at low pressure, at great depths (>15,000 ft) within some sedimentary basins, in crystalline structures bound up with ice, dissolved within deep highly pressurized brines—in other words, in all manner of habitats where it is not confined to discrete, conventional structural concentrations. These occurrences are referred to as unconventional gas resources—which, vast though they may be, would require extraordinary technologies or currently nonexistent technologies for production. At present only about 2 Tcf of total production has come from sources that can be classified as unconventional; these sources are tight reservoirs, coal-bed gas, and shale gas.

Tight gas has a legal definition based on the fluid permeability of the reservoir rock that contains it: to qualify for the tax incentives formerly available, the reservoirs must have permeabilities of 0.1 millidarcies or less. Such permeabilities are far below those of conventional reservoirs, which commonly have permeabilities of tens, hundreds, or even thousands of millidarcies. For comparison, good-quality concrete has a permeability of 1–10 millidarcies. Most of the known tight gas resources are in the Green River and Uinta-Piceance basins in Wyoming, Utah and Colorado, and in East Texas. Tight gas resources in place are huge, but at present only a small fraction of that resource is available for production. The National Petroleum Council estimated approximately 230 Tcf of energy gas to be available from tight gas reservoirs given existing technology but without reference to price; with moderate advances in technology this figure might increase to about 350 Tcf.

Coal-bed gas consists largely of methane whose source and reservoir rock both consist of a seam of relatively pure coal. A growing recognition of its potential for use as an energy fuel has inspired considerable activity in identifying, characterizing, and developing coal gas resources. Annual production of coal-bed gas in 1991 was about 350 Bcf (billion cubic feet), about 2 percent of annual U.S. production, but a dramatic increase from only 3 years before, when annual production stood at about 40 Bcf. Virtually all this methane development and production has taken place in two sedimentary basins, the San Juan Basin of New Mexico and Colorado and the Black Warrior Basin of Alabama and Mississippi. Estimates of coal-bed gas resource vary from 5 Tcf to 100 Tcf. In 1992 the National Petroleum Council estimated that more than 60 Tcf is recoverable with current technology, a figure that could increase to about 100 Tcf with some modest technologic breakthroughs. Coal-bed gas as a resource, however, is sensitive to price and tax incentives, and the elimination of the 1989 Section 29 Federal tax credit seems to have depressed interest in coal-bed gas development.

Natural gas contained in organic-rich shale (fine-grained, clay-rich sedimentary rock having very low permeability and high sensitivity to water) has been considered in many studies as a separate category of unconventional energy gas supply. The principal areas of interest and possible resource include the Appalachian basin, especially West Virginia, Virginia, Kentucky, and Ohio (Devonian shales) and Michigan (the Upper Devonian Antrim Shale). Other potential areas include the Illinois basin, the Denver basin, the Uinta-Piceance basin, and elsewhere in the western interior of North America. These shale units have been estimated to contain thousands of Tcf, and the National Petroleum Council concluded in 1992 that between 38 and 57 Tcf would be available for production over the next few decades.



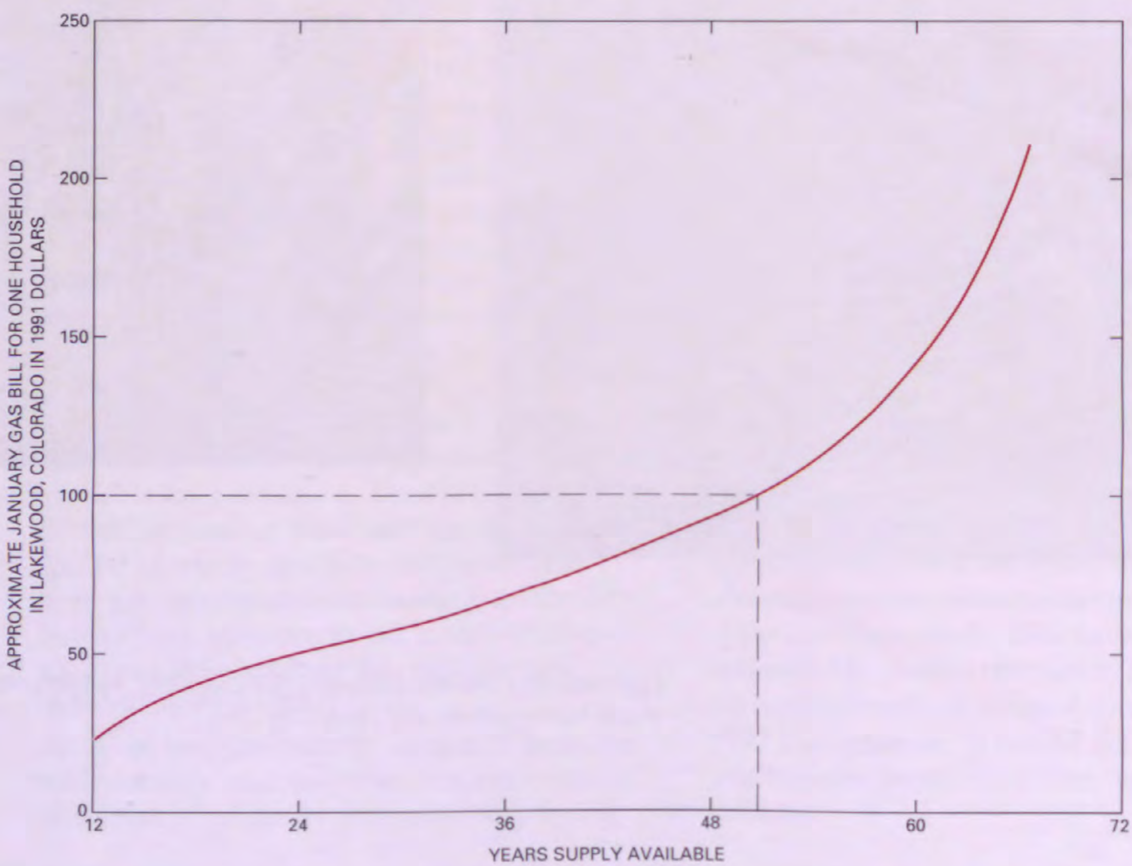
Exploration for coal-bed methane involves drilling, pulling core of coal-bearing strata, and examining core.

Availability And Price

Uncertainties concerning energy gas supply have persisted ever since the gas shortages of the 1970's. Available evidence suggests that natural gas is abundant in the United States, but the abundance is *price dependent*. Proved reserves of 160 Tcf are, by definition, available for production, at today's prices. Reserve growth of existing fields at current price and demand could add an additional 160 Tcf. Beyond this, reserve additions will require progressively greater effort and expense. Conventional gas fields yet to be discovered will almost certainly be smaller, deeper, and of lesser quality than older fields. Many analysts predict, therefore, that energy gas production would decline if the current price structure continued.

The large energy gas resource coupled with the variety of gas occurrence suggests that with each increment of price increase, new gas resources become available. In terms of current dollars and today's technology, the National Petroleum Council has projected that an increase of about $1 per Mcf (thousand cubic feet) in wellhead price (the price paid to the primary producer) would yield an additional 80 Tcf, because more dollars would be made available for industry research, exploration, and advances in drilling technology. At higher prices, however, some demand could be filled from sources other than the lower 48 States.

The United States already imports about 10 percent of its energy gas consumption, of which about 97 percent currently is piped from Canada. Canadian natural gas resources are abundant, with proved reserves exceeding 70 Tcf. Undiscovered conventional resources are estimated at more than 500 Tcf and there are also large volumes of unconventional resources. In the future, pipelines could also bring gas from Mexico to the U.S. market. Mexico's reserves of natural gas, almost all of which are associated with oil reserves, are

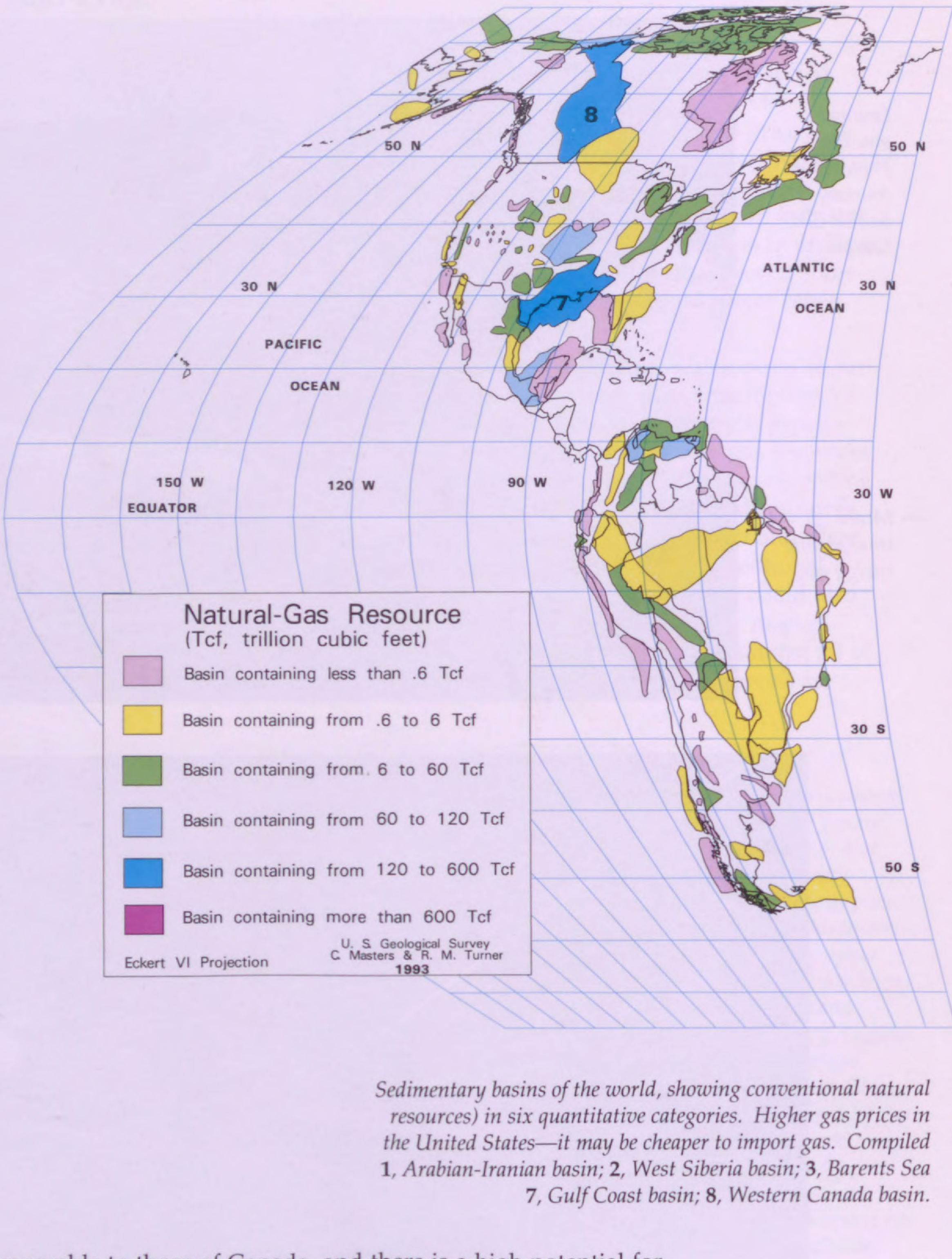


Large amounts of natural gas are available—but availability depends on price. From this figure, which projects current conditions of price and supply, if a typical household in Lakewood, Colo., could pay $100 per month (1991 dollars) for gas, then just over 50 years' worth of gas could be made available for use.

Laying pipeline. Photograph courtesy of British Gas, London.

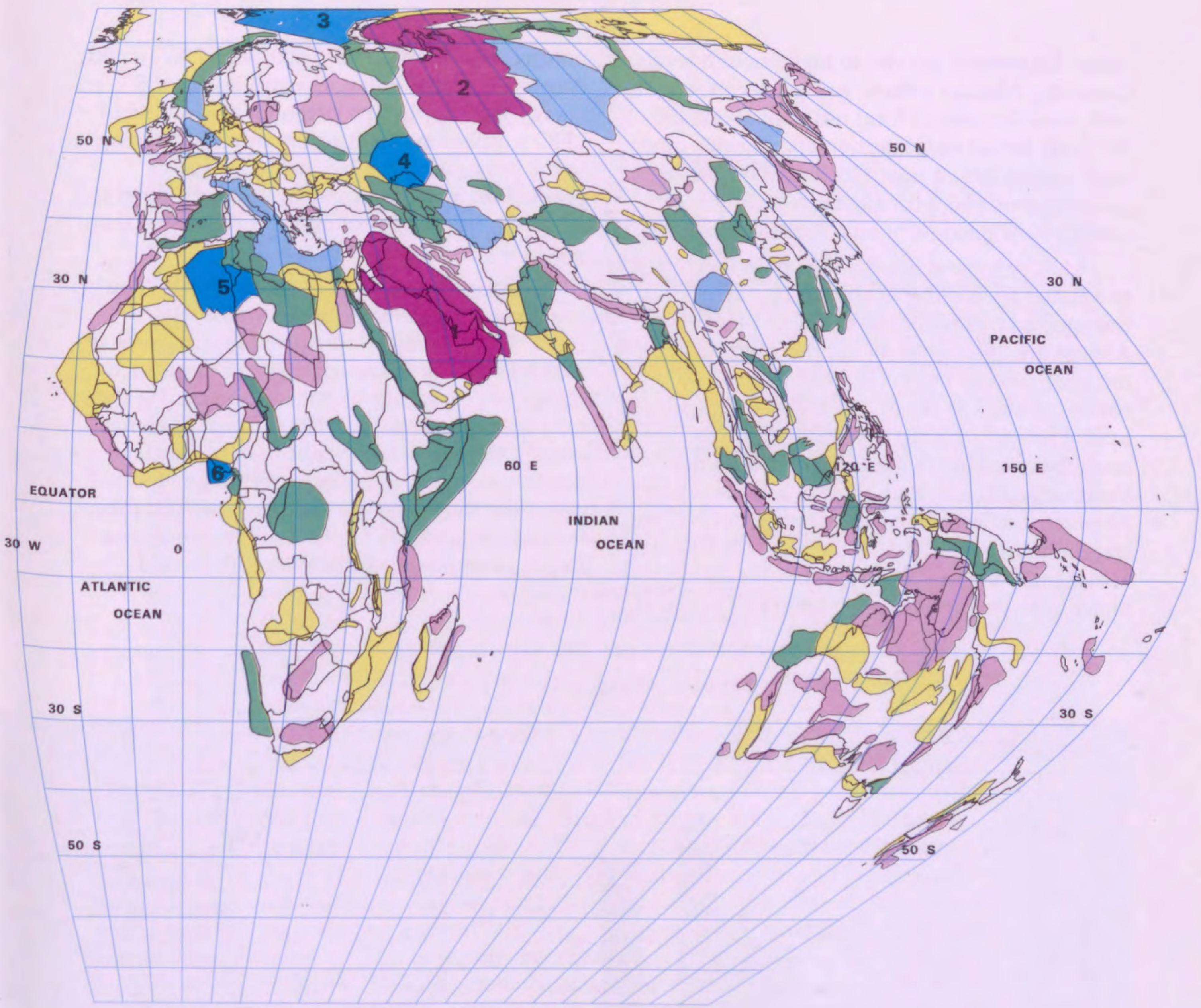
Means of transporting energy gas.

LNG (liquefied natural gas) tanker. Photograph courtesy of Phillips Petroleum Company.



Sedimentary basins of the world, showing conventional natural resources) in six quantitative categories. Higher gas prices in the United States—it may be cheaper to import gas. Compiled **1**, *Arabian-Iranian basin;* **2**, *West Siberia basin;* **3**, *Barents Sea* **7**, *Gulf Coast basin;* **8**, *Western Canada basin.*

comparable to those of Canada, and there is a high potential for undiscovered conventional and unconventional resources. Although Canada and Mexico must satisfy their domestic demand before any exports are permitted, natural gas from these countries can probably



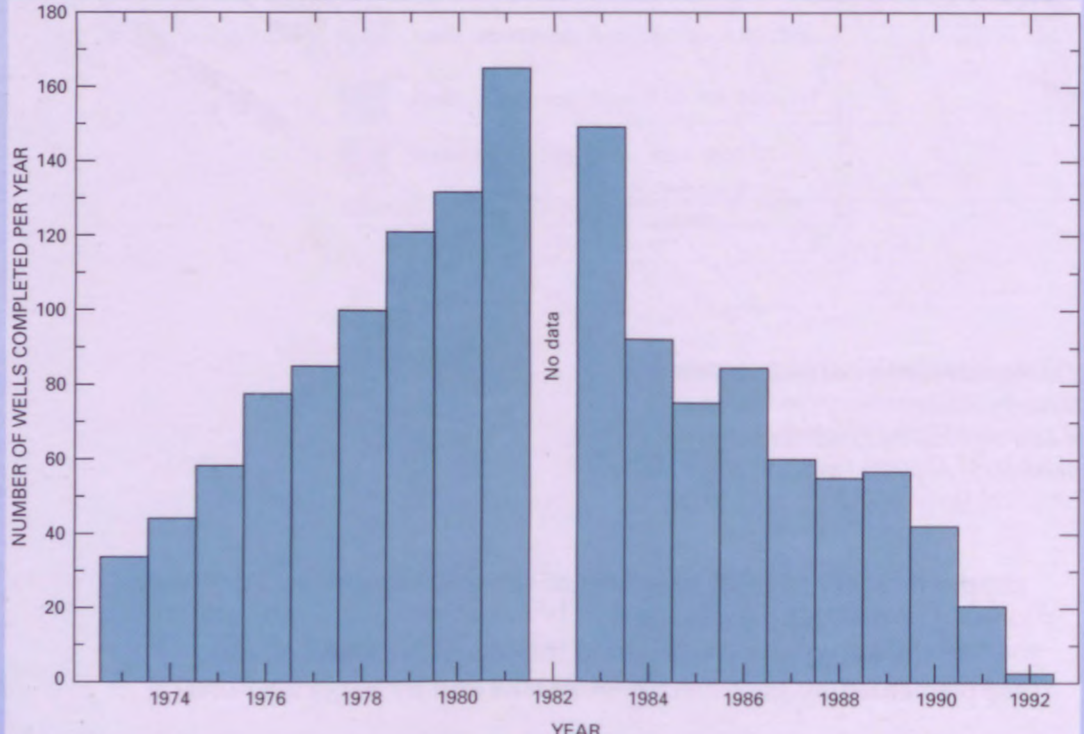
gas futures (the sum of identified reserves and undiscovered
the future may not necessarily equate to higher production in
by Charles D. Masters; data digitized by Robert Turner.
basin; **4**, *North Caspian basin;* **5**, *Algerian basins;* **6**, *Niger Delta;*

supply most foreseeable shortfalls of U.S. production until the second decade of the 21st century.

In the long run, production in the lower 48 States could be supplemented by gas piped from Alaska and by imports of LNG if prices for natural gas rise to high enough levels. Currently Alaskan natural gas is uneconomic, with the exception of local usage of about 400 Bcf/year for oil well injection and various other uses. Alaska has at least 100 Tcf of conventional gas resources and a considerable but unevaluated unconventional resource base.

LNG is natural gas that has been converted to a liquid by cooling to about –250 °F; it is transported by specially constructed tankers. Almost one-quarter of all natural gas traded on the international market is LNG. Some countries, such as Japan, are entirely dependent upon LNG as a source of natural gas. LNG could be available to the United States from Venezuela, Algeria, and Nigeria and elsewhere. At present, relatively small volumes of LNG are imported into the U.S.—in the range of 100–200 MMcf (million cubic feet) per day. However, many analysts predict that if wellhead prices of natural gas exceed \$4.50–\$5.00/Mcf, LNG could become available in large quantities for U.S. energy gas supply. The potential availability of LNG supplies may ultimately provide a ceiling to the price/supply relationship for gas production in North America—at some point it may become cheaper to import LNG rather than produce gas domestically.

It appears that enough energy gas will be available to fill demand well into the 21st century. How much of the available resource is developed, and when, will depend upon such things as governmental policies concerning the environment, on the perceived threat of climate change, and on world political and financial conditions. As this entire report has suggested, decisions on energy use are extremely complex; they are ongoing decisions that have immense implications for our country and the world.



The number of deep basin wells completed for gas exploration in the Gulf Coast region peaked in the early 1980's.

GAS IN DEEP BASINS

Wellhead prices of gas produced from depths greater than 15,000 ft were decontrolled by the 1978 Natural Gas Policy Act. Since then the depth of 15,000 ft has commonly been used to separate deep gas plays from other gas accumulations. There undoubtedly are large volumes of energy gases in the deep parts of some basins, and some promoters have touted the idea that gas in deep basins will be the major source of gas production in the future. Exploration efforts to date, however, have not been successful in bringing many deep basin gas accumulations into commercial production.

In the last 20 years more than 2,100 gas exploration wells have been drilled to depths greater than 15,000 ft in the Gulf Coast region. The number of gas wells completed each year grew during the 1970's, especially after implementation of the 1978 Natural Gas Policy Act, and reached a peak in the early 1980's. Since then the number of gas wells completed each year has fallen dramatically, and there is currently little interest in gas exploration in deep basins.

Although large amounts of deep gas exist, the extremely high costs of drilling to depths exceeding 15,000 ft make production marginally economic with the present market prices for natural gas. Production of gas from sandstones of the Norphlet Formation offshore Alabama presents a typical problem. The estimated reserves in the Norphlet Formation range from 8 to 12 Tcf—equivalent to more than half the United States consumption in 1 year. Despite this reserve, only one field is producing gas from the Norphlet Formation. In addition to drilling costs, the cost of piping the gas onshore and removing the hydrogen sulfide it contains generally makes the gas too expensive to produce. The Springer Formation of the Anadarko basin in southern Oklahoma occurs at depths of 18,000–20,000 ft, and wells completed in this play had excellent initial production—10 MMcf (million cubic feet) per day. This production was not sustained, however, apparently because clay particles in the reservoir rapidly reduced permeability. The play has now been abandoned.

To 1989, gas from deep basins accounted for 7 percent of the total energy gas produced in the United States. This percentage may increase in the future, but a substantial increase in production likely will not occur without a significant rise in gas prices.

COAL-BED GAS—ONCE A HAZARD, NOW A RESOURCE

Geologists see many possible sources for our future energy needs. Some sources, such as oil shales and oil sands, have been widely touted as "fuels of the future" since the early parts of the 20th century. A decade ago processes such as in-situ gasification of coal seams and coal liquefaction were predicted to be widely used in the 1990's. Future development of fusion-powered electrical generating plants has long promised unlimited cheap energy. The promised day may never arrive for some of these possible energy sources, and it is easy to be cynical about currently uneconomic possibilities. In some cases, however, development has occurred more rapidly than many people forecast. The rapid rise in interest in coal-bed methane over the last decade, for example, was not widely predicted.

Coal beds originate as peats that formed in ancient swamps. As plant material is transformed to coal, large amounts of methane-rich gas are produced and stored in the coal matrix; because of the nature of coal, it can hold much more gas per unit volume than other rocks. When a coal is mined there is a substantial release in pressure, and water escapes from the coal. Methane gas is released in association with this depressurization and dewatering. If not properly ventilated, methane may rapidly accumulate in underground mines and result in devastating explosions.

In the old days, miners carried canaries whose death gave an early warning of the presence of the odorless gas. Some unfortunate workers were assigned the task of searching out and igniting small pockets of gas before dangerous amounts could accumulate. These workers, called penitents because they dressed in heavy monkish clothing to avoid being scorched, carried long sticks with lighted candles fixed at the end. Not surprisingly, many perished on the job. Today mines are better ventilated, and explosions from coal-bed gas are far less frequent.

Explosions due to accidental ignition of methane were common in 19th century coal mines. Original wood engraving from Simonin, 1869.

In a few mining operations attempts are made to extract gas (called "gob gas") from wells drilled in the area in advance of mining, to bleed off as much as possible and help reduce accumulation of methane in the mine itself. Although gob gas in some situations is emitted to the atmosphere, it can be a useful byproduct of coal-mining operations and is occasionally sold for a profit.

The first attempts at extracting gas from coals that are not economic to mine date from the late 19th century, but the first significant commercial production of gas from such coals did not take place until the late 1970's. By the end of 1991, about 5,000 wells were producing about 1 Bcf (billion cubic feet) of gas per day from coal beds in the United States. This rapid development was encouraged by favorable Federal tax credits, introduced in the mid-1980's, which not only increased the rate of exploration but also aided the development of new technologies for more efficient extraction of coal-bed gas. Coal-bed methane development to 1993 has mainly been within the Black Warrior Basin of the Southern Appalachian region and the San Juan Basin of the southern Rocky Mountain region, but knowledge and technology gained from development in these areas are now being applied to many other coal-bearing basins in the United States. In particular, the Piceance basin of Colorado, the Appalachian basin, the Raton Basin of New Mexico, and the Wind River and Powder River basins of Wyoming show promise for coal-bed methane. Interest in coal-bed methane is now also growing in many other countries.

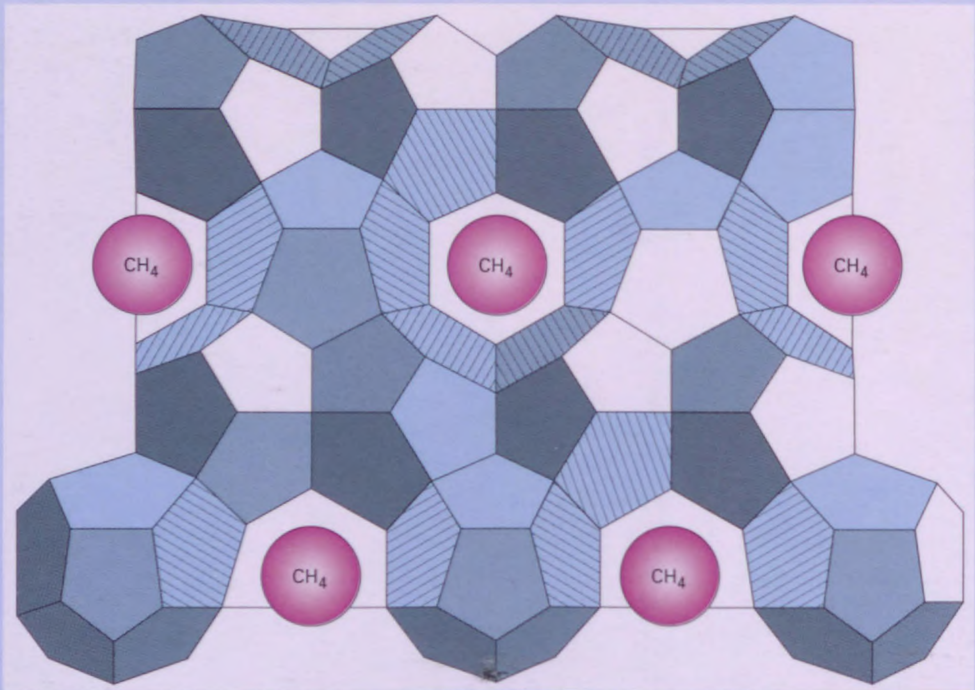
Energy gases for our use in the future may come from many sources. Other unconventional sources of energy gases, such as tight reservoirs, hydrates, and deep basins, may not live up to their promise within our lifetimes, but sound geologic and engineering research may well result in many energy gases making the transition between the artificial categories of unconventional and conventional resources.

A 19th century "penitent" carrying a candle-tipped stick and trying to stay alive while burning off pockets of accumulated methane, to further others' safety in a coal-mining operation. Original wood engraving from Simonin, 1869.

HYDRATES—A SUPERABUNDANCE OF ENERGY GASES

Gas hydrates are naturally occurring solids composed of water molecules forming a rigid lattice of cages, most of which contain a molecule of natural gas, mainly methane. Natural gas hydrates occur worldwide in polar regions associated with onshore and offshore permafrost, and in marine sediment of the outer continental margins in many parts of the world. The total amount of methane in gas hydrates is immense. The amount of carbon bound in the methane (CH_4) molecules is estimated to be twice the total amount of carbon found in all known fossil fuels (that is, coal, oil, and gas in conventional reservoirs) on Earth.

Although naturally occurring gas hydrates were recognized in the 1960's, development of effective techniques to recover them has been slow. Development of the Messoyakha gas field in western Siberia during the last 25 years has proven that appreciable quantities of methane can be recovered from gas hydrates, but production proved to be prohibitively expensive. Large-scale commercial development of gas hydrates is most likely many years away; it will require development of cost-effective technologies to recover methane from the hydrates. If it is ever commercially viable for the United States to develop gas hydrates, the first production would likely be on the North Slope of Alaska. The released gas would probably be first used to help recover oil from older oil fields where pressure is waning, rather than being used as fuel. One day, however, it is possible that gas hydrates may



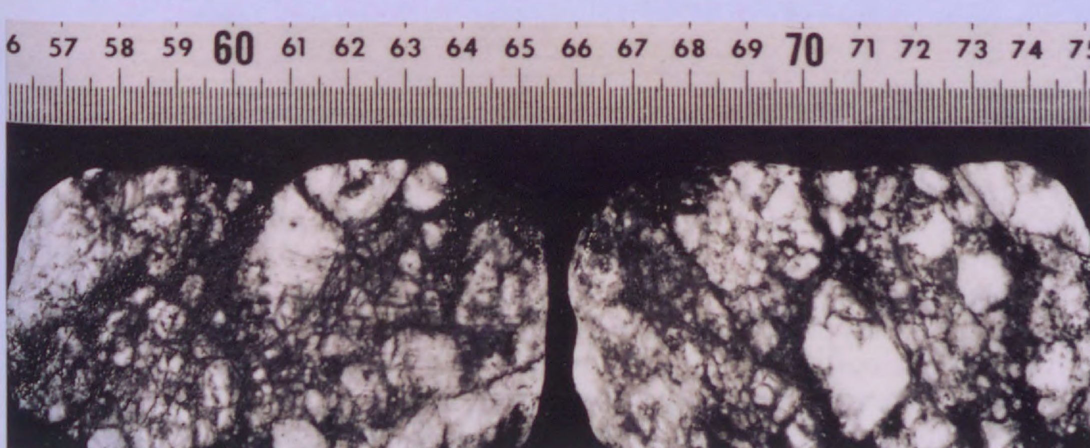
The "lattice of cages" for methane bound among water molecules.

become our major source of energy gas.

Interesting ideas have been proposed to explain the role of gas hydrates in global climate change. Climatologists have suggested that methane from continental gas hydrates contributed to the rapid rise in atmospheric methane and the global temperature rise at the end of the last major glaciation. According to this theory, global warming accelerated methane emissions and ultimately helped to end the ice age. Another suggestion is that falling sea level, due to development of polar ice caps during periods of global cooling, decreased pressure on sediments of the outer continental margin and caused gas hydrates to dissociate, releasing methane into the atmosphere. This theory suggests that the released methane enhanced the greenhouse effect and triggered a period of deglaciation.

Burning synthetic methane hydrate. Original slide courtesy of Morgantown Energy Technology Center, U.S. Department of Energy, Morgantown, W.Va.

Natural methane hydrates (white nodules) in clays (black) in a core recovered during a deep sea drilling project. Scale in centimeters.



CONCLUSIONS—CHALLENGES AND OPPORTUNITIES IN EARTH SCIENCE

The need for a better understanding of energy gases is critical both to the future health of our Nation's economy and to the future health of the entire global environment. Increased use of domestic reserves of natural gas in the United States could cut the costs of importing oil. Increased use of energy gases rather than coal or oil could reduce emissions of atmospheric pollutants—an increasing concern as the world population is expected to grow by 1 billion people each decade for the next few decades. Energy gases offer hope for the future, but is this hope justified for the long term? Is sufficient natural gas available to allow large-scale substitution of coal and petroleum by methane as a fuel for vehicles and electrical generating plants? How can we effectively cut down on carbon dioxide and methane emissions into the atmosphere to prevent or stall the potentially catastrophic effects of global warming without suffering a substantial drop in our living standards? Answers to these questions are essential if we are to make successful long-range policy decisions.

The need for a better understanding of energy gases is critical both to the future health of our Nation's economy and to the future health of the entire global environment.

Like the fabled gold in sea water, an unimaginable wealth of methane lies in the Earth's crust—if only we could afford the unimaginably high price of extracting it all. Obviously the more important question is to accurately predict how much can be produced at a particular price. In an ideal market economy the price of natural gas will be determined by the interaction of the supply and demand. Supply is controlled by the costs of exploration, development, and transport; and costs are clearly going to rise if we must rely on smaller and more inaccessible reservoirs of gas. Demand is determined by the amount of natural gas that consumers are willing to buy at a particular price—to heat their homes and workplaces, fuel their vehicles, and generate electricity—rather than decide to conserve energy or look for some other energy source. Obviously the cheaper the price the higher the demand.

Geologists have traditionally calculated energy reserves by estimating the size of the resource that is currently economic to extract. By contrast, geologists in the future need to estimate the size of the

RESEARCH QUESTIONS ON THE NATURE OF ENERGY GASES

What types and amounts of organic matter are important in generating usable accumulations of energy gases?

In what sedimentary basins will we find major accumulations of gas?

What physical and chemical conditions in the geologic setting favor the generation and trapping of energy gases?

How can reservoirs be better characterized to help exploration and development of unconventional gas resources?

Can the newer seismic applications of bright-spot technology and 3-D seismic reflection be used, and improved, to locate and evaluate undiscovered gas prospects?

What is the nature of natural fractures (for example, in what rocks and at what depths do they occur; how do they form; what is their extent and how can we determine it); and can an understanding of their distribution be better used in the recovery of gas from unconventional reservoirs?

What is the potential of gas hydrates as an energy resource?

resource that would be available for various price scenarios. By combining this more detailed understanding of the factors controlling the supply of energy gases with an understanding of demand, economists should be able to make better predictions about the use of energy gases in the Nation's future. Another benefit of such models would be better prediction of the result of taxes imposed on energy—whether used to raise revenue or to encourage lower emissions of pollutants or greenhouse gases. To be effective and usable our future models of the interaction of supply and demand must consider *all* energy sources, because it is the *complex interaction* of the supply curves of various energy sources that will determine the future energy mix. We must also see supply and demand curves within a global context. An increase in natural gas consumption in the United States does not necessarily equate to an increase in domestic production. We need to consider the price level at which it will be economic to build new pipelines to import gas from Canada, for example, or to start importing large volumes of liquefied natural gas (LNG) by tankers.

If we decide that it is environmentally sound and economically feasible to rely more on energy gases as a fuel source, we must delineate substantial new reserves—which may well require some new and innovative exploration methods and recovery techniques. Large reserves of natural gas are found associated with many petroleum reservoirs, and until about 10 years ago most natural gas was found as part of

We need to know the full impact of any future development and find the most cost effective way of reducing emissions.

petroleum exploration programs. Large amounts of gas also occur in areas containing little or no liquid petroleum. This *nonassociated gas* is common in the deeper parts of sedimentary basins where temperatures and pressures are so high that liquid petroleum would break down and convert to gas. Fracturing certain types of tight (low-permeability) rocks may yield usable amounts of gas. The vast deposits of gas hydrates under the Arctic permafrost and in sediments of the oceans could potentially also be a source of commercial methane if we can develop suitable technologies as well as solve the environmental problems of extraction. These *unconventional* sources of gas will only become more

RESEARCH QUESTIONS ON THE AMOUNT OF ENERGY GASES

How much conventional natural gas remains to be discovered in the U.S.?

What methodologies need to be developed to evaluate the potential of unconventional resources?

Will natural gas reserves continue to "grow" in the next decade as they have in the past 10 years?

What are the resources of natural gas on a worldwide basis?

Can we develop realistic pictures of price versus supply of energy gases, to compare quantities and availability of natural gas from various sources in a global energy mix?

RESEARCH QUESTIONS ON THE ENVIRONMENTAL ASPECTS OF ENERGY GASES

What will be the effect of emissions into the atmosphere with a changing energy mix—one that might contain a larger percent of energy gas, for example?

What are the environmental consequences associated with additional drilling required for increased natural gas production?

How do the rates of natural emissions of methane compare with the rates of emissions from human-related sources associated with energy extraction and use?

What are the potential environmental impacts of global warming on releasing methane from gas hydrates into the atmosphere?

economic if the price of energy rises and (or) future technological advances reduce the costs of exploration and development. However, a sound understanding of the nature and distribution of these potential resources is necessary before we can plan for their future use.

Throughout geologic time methane has been released into the atmosphere and reabsorbed into the oceans and rocks. Understanding this complex natural cycle is essential if we are to determine the impact on the global environment should human activities continue to increase the amount of methane released to the atmosphere. Increased use of energy gases as a substitute for coal and petroleum would appear to be sound from an environmental perspective, as it should result in lower

As we come to a better understanding of the geologic setting of these gases, in all their forms, we will be able to make more educated decisions for the future at the local, national, and global level.

emissions of greenhouse gases and other pollutants. However, we need to know the full impact of any future development and find the most cost effective way of reducing emissions. For example, organic decay in refuse dumps produces methane, which instead of being allowed to leak into the atmosphere could be extracted and used to fuel power plants with lower emissions than a coal-powered plant. The problem is that most dumps are not large enough to cost effectively install the necessary extraction processes. Cheaper and more effective ways of reducing global methane emissions may exist—perhaps repairing leaking pipelines or recovering and utilizing the emissions of methane from coal mines.

We also must continue to investigate the role of gas hydrates in the environment. It is possible that natural release of methane from hydrates could either accelerate or decelerate global warming or cooling trends. A better understanding of the role of hydrates in climate change is important because, if global warming should take place and permafrost melt, then large volumes of methane could be released into the atmosphere. It has also been suggested that sudden release of gas hydrates from marine sediments could result in huge submarine landslides that would cause considerable damage in coastal areas, to shipping, and to offshore drilling platforms.

What role will energy gases have in our future? What role will they play in our economy and what impact will they have on our environment? As we come to a better understanding of the geologic setting of these gases, in all their forms, we will be able to make more educated decisions for the future at the local, national, and global level.

GLOSSARY OF TERMS RELATED TO ENERGY GASES

As with any other field of science or technology, there are many words and phrases used by those who study energy gases that can be confusing to the nonspecialist. We hope this glossary of terms helps demystify some of the jargon.

GENERAL TERMS

Abiogenic gas. Hydrocarbon gas that is not derived from the decomposition of organic matter by methanogenic microorganisms or thermal processes. Usually, this gas is considered to be from below the Earth's crust and represents gas originally trapped during the formation of the planet.

Anticline. The crest of folded rock layers.

Associated gas. Natural gas that occurs in the same reservoir with petroleum. The gas may occur as a free state or may be dissolved in the petroleum (see *dissolved gas*).

Biogenic gas. Methane gas that was generated by microorganisms at the Earth's surface or at shallow depths within sedimentary basins.

Bright spot. A term used in reflection seismology to describe a high contrast in rock properties, which sometimes is a result of natural gas accumulations.

Btu. British thermal unit—a unit to measure energy. One Btu is the amount of energy required to raise the temperature of one pound of water from 60 to 61 °F (15.56 to 16.11 °C) at standard atmospheric pressure.

Butane. A hydrocarbon gas consisting of 4 carbon atoms and 10 hydrogen atoms.

Conventional reservoirs. Rock layers that allow sufficient flow of natural gas to be produced by traditional methods. Contrast *conventional resources*.

Crude oil. See *petroleum*.

Dissolved gas. Natural gas occurring in solution in oil within a reservoir.

Energy gases. Combustible gases found in natural gas that burn sufficiently to yield energy. Examples of these gases include methane, ethane, propane, butane, and molecular hydrogen.

Ethane. A hydrocarbon gas consisting of two carbon atoms and six hydrogen atoms.

Exploration. The search for economic accumulations of natural gas.

Fault. Fracture in which rock layers on opposite sides of the fracture have moved relative to one another.

Flaring. The indiscriminate burning of natural gas at a wellsite or refinery. No energy is collected from this burning.

Greenhouse gas. One of the gases in the atmosphere that absorb and re-emit infrared radiation emitted from the Earth's surface. As some of this radiation is directed back down to the Earth it helps warm the surface and the lower atmosphere.

LNG. Acronym for liquefied natural gas, which is natural gas that has been converted to a liquid by lowering its temperature to –250 °C.

LPG. Acronym for liquefied petroleum gas, which includes propane and butane. These gases may be liquefied at room temperature by placing them under high pressures. They are also known as LP gas and bottle gas.

Methane. The smallest and simplest naturally occurring hydrocarbon molecule, consisting of four hydrogen atoms in coordination with a single atom of carbon: CH_4.

Molecular hydrogen. Gas consisting of two bound hydrogen atoms.

Natural gas. Naturally occurring gases found in *sedimentary basins*. Natural gas typically is enriched in *energy gases*, especially *methane*, but includes small amounts of *noncombustible gases*.

Nonassociated gas. Natural gas that is not trapped with petroleum in the same reservoir.

Noncombustible gases. Gases that do not burn. Common examples in natural gas include carbon dioxide, nitrogen, and hydrogen sulfide.

Offshore. Exploration or production activity that occurs in areas covered by the sea.

Onshore. Exploration or production activity that occurs on land.

Organic matter. Material derived from living organisms. These materials typically consist of a carbon-to-carbon bonded framework with bonded hydrogen, oxygen, nitrogen, phosphorus, and sulfur.

Petroleum. Naturally occurring liquid oil in the Earth's crust consisting primarily of hydrocarbons but also including nitrogen, sulfur, and oxygen. Also called *crude oil*.

Play. A set of geographically related gas accumulations with similar or identical geologic origins.

Propane. A hydrocarbon gas consisting of three carbon atoms and eight hydrogen atoms (C_3H_8). Commonly used in some kinds of heaters and in outdoor grills.

Prospect. A geologic feature having the potential for trapping and accumulating gas.

Reservoir. A porous or highly fractured rock that contains natural gas.

Seal. An impermeable barrier or rock layer that prevents or restricts the flow of petroleum or natural gas in sedimentary basins.

Sedimentary basin. A depression in the Earth's crust that has been infilled with sediment, which turned into sedimentary rock after burial.

Seismology. The study of sound waves transmitted through the Earth.

Stratigraphic trap. A rock layer that laterally changes from a porous rock to an impermeable rock and prevents upward movement of natural gas.

Thermogenic gas. Natural gas formed by the thermal decomposition of organic matter in rocks as they are buried in *sedimentary basins*.

Unconventional reservoirs. Rock layers that have restricted flow of natural gas, and therefore require special methods and technologies to produce. Contrast *unconventional resources*.

TERMS DEALING WITH THE AMOUNT OF GAS

Terms such as **reserves** and **resources** are constantly included in discussions of energy and environmental issues. However, heated arguments often ensue, in which the principal issues are definitions and subtle semantic distinctions. Common usages of some of these terms are listed.

Conventional resources. Those discrete concentrations of natural gas and natural gas liquids that exist in known reservoirs and that can be extracted using traditional development practices. Contrast *conventional reservoirs*.

Crustal abundance. The total amount of natural gas in the Earth's crust. This quantity, while of scientific interest, is, like the abundance of gold in the ocean, largely irrelevant to human activity.

Cubic foot of gas. Unit of measure—the amount of natural gas that can occupy the volume in a 1×1×1 foot cube at room temperature at atmospheric pressure. **Mcf, MMcf, Bcf, Tcf** are abbreviations meaning thousand cubic feet, million cubic feet, billion cubic feet, and trillion cubic feet of natural gas, respectively.

Cumulative production. The total amount of gas that has been produced in a specified reservoir or play.

Estimated ultimate recovery (EUR). The total amount of gas that will have been produced from a reservoir or play on the day it is abandoned and removed from any further production. EUR is only known with certainty after production ceases but is ordinarily estimated by summing the *cumulative production* and the *proved reserves*.

Inferred and indicated reserves. See *reserve growth*.

Proved reserves. The estimated quantities of natural gas that engineering or geologic analyses demonstrate to be producible under current economic and operating conditions.

Reserve growth. As a play is developed the *estimated ultimate recovery* usually grows. There can be many reasons for this, but it is commonly due to the discovery of new reservoirs or by the application of new technologies. Estimates of the amount of reserve growth are called *inferred or indicated reserves*, depending on the confidence of the estimate.

Resources. Known or hypothetical concentrations of gas which, in the opinions of various geologists, analysts, or engineers, can now or in the future be developed as energy sources.

Unconventional resources. Resources whose technical development is in a relatively early stage; they generally do not occur in discrete accumulations. These resources commonly require development practices different from traditional production methods employed. Examples include coal-bed gas, tight gas, and shale gas. Contrast *unconventional reservoir*.

FEDERAL AGENCIES WITH REGULATORY OR RESEARCH RESPONSIBILITIES FOR ENERGY GASES

U.S. Department of the Interior, 1849 C Street N.W., Washington, D.C. 20240
U.S. Geological Survey (303 236 5711)
Bureau of Mines (202 501 9290)
Bureau of Land Management, Office (202 208 3435)
Minerals Management Service (703 787 1113)

U.S. Department of Energy, 1000 Independence Avenue S.W., Washington, D.C. 20585
Program for Energy Research (301 353 4944)
Program for Fossil Energy (301 353 2617)
Energy Information Administration (202 586 1181)
Federal Energy Regulatory Commission (202 357 8300)

U.S. Department of Agriculture
Forest Service, Public Affairs Office, Box 96090, Washington, D.C. 20090-6090 (202 447 3760)

Department of Transportation
Office of Pipeline Safety, 400 Seventh Street S.W., Washington, D.C. 20550 (202 366 4595)

Environmental Protection Agency, 401 M Street S.W., Washington, D.C. 20460 (202 382 2090)

United States Congress, 600 Pennsylvania Ave. S.E., Washington, D.C. 20510-8025
Office of Technology Assessment (202 224 9241)

United States Senate, 508 Dirksen Senate Office Building, Washington, D.C. 20510
Committee on Commerce, Science and Transportation (202 225 5115)
Committee on Environment and Public Works (202 224 6176)
Committee on Energy and Natural Resources (202 224 4971)

United States House of Representatives, 2322 Rayburn House Office Building, Washington, D.C. 20515
Committee on Energy and Commerce (202 225 3641)

National Laboratories
Lawrence-Berkeley National Laboratory (510 486 4000)
Los Alamos National Laboratory (505 667 5061)
Lawrence-Livermore National Laboratory (510 422 1100)
Sandia National Laboratory (505 844 5678)

FURTHER READING

Introduction—Energy Gases In Our Future

General background

Grübler, A., and Nakicenovic, N., 1988, The dynamic evolution of methane technologies, *in* Lee, T.H., Linden, H.R., Dreyfus, D.A., and Vasko, T., 1988, The methane age: Dordrecht, Kluwer Academic Publishers, Geojournal Library, v. 9, p. 13–44.

Lee, T.H., Linden, H.R., Dreyfus, D.A., and Vasko, T., 1988, The methane age: Dordrecht, Kluwer Academic Publishers, Geojournal Library, v. 9, 204 p.

Melvin, A., 1988, Natural gas—Basic science and technology: Bristol, U.K., British Gas plc, 221 p.

Environmental concerns

Berger, A., Schneider, S., and Duplessy, J. Cl., 1989, Climate and geo-sciences—A challenge for science and society in the 21st Century: NATO ASI Series, Series C, Mathematical and Physical Sciences No. 285, Kluwer Academic Publishers, Dordrecht, 724 p.

Gore, A., 1993, Earth in the balance: New York, Plume, Penguin Books, 407 p.

Jäger, J., and Ferguson, H.L., eds., 1991, Climate change—Science, impacts and policy: Proceedings of the Second World Climate Conference, Cambridge University Press.

Energy Gases—Their Composition, Origin, And Occurrence

Generation of energy gases

Beebe, B.W., and Curtis, F., eds., 1968, Natural gases of North America: American Association of Petroleum Geologists Memoir 9, v. 1, 1226 p.; v. 2, 1267 p.

Hunt, J.M., 1979, Petroleum geochemistry and geology, Chapter 5, How gas forms: San Francisco, W.H. Freeman, p. 150–185.

Jenden, P.D., Drazan, D.J., and Kaplan, I.R., 1992, Mixing of thermogenic natural gases in northern Appalachian Basin: American Association of Petroleum Geologists Bulletin, v. 77, p. 980–998.

Schoell, M., 1983, Genetic characterization of natural gases: American Association of Petroleum Geologists Bulletin, v. 67, p. 2225–2238.

Schoell, M., ed., 1988, Origins of methane in the Earth: Chemical Geology, v. 71, no. 1/3, p. 1–266.

Tissot, B.P., and Welte, D.H., 1984, Petroleum formation and occurrence, Second edition (especially Part I, Chapter 5, and Part II, Chapter 6): Berlin, Springer Verlag, 699 p.

Vially, R., ed., 1992, Bacterial gas: Paris, Editions Technip, 242 p.

Whiticar, M.J., Faber, E., and Schoell, M., 1986, Biogenic methane formation in marine and freshwater environments; CO_2 reduction vs acetate fermentation—Isotope evidence: Geochimica et Cosmochimica Acta, v. 50, p. 693–709.

Reservoirs and gas fields

Flint, S.S., and Bryant, I.D., eds., 1993, The geologic modelling of hydrocarbon reservoirs and outcrop analogues: International Association of Sedimentologists Special Publication 15, 269 p.

Halbouty, M.T., ed., 1992, Giant oil and gas fields of the decade: American Association of Petroleum Geologists Memoir 54, 526 p.

Levorsen, A.I., 1967, The reservoir, *in* Geology of petroleum: San Francisco, W.H. Freeman, p. 49–96.

How Much Energy Gas And At What Price?

Gas assessments

Mast, R.G., Dolton, G.L., Crovelli, R.A., Root, D.H., Attanasi, E.D., Martin, P.E., Cooke, L.W., Carpenter, G.B., Pecora, W.C., and Rose, M.B., 1989, Estimates of undiscovered conventional oil and gas resources in the United States—A part of the Nation's energy endowment: U.S. Geological Survey and Minerals Management Service, 44 p.

National Petroleum Council, 1992, The potential for natural gas in the United States: Washington, D.C., in five volumes plus summary, unpaginated.

U.S. Geological Survey, 1993, USGS Assessment Papers (a series of 6 papers by various USGS scientists): American Association of Petroleum Geologists Bulletin, v. 77, p. 452–508.

Unconventional gas resources

Collett, T.S., 1993, Natural gas hydrates of the Prudhoe Bay and Kuparuk River area, North Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 77, p. 793–812.

Kvenvolden, K.A., 1993, Gas hydrates—Geological perspectives and global change: Reviews of Geophysics, v. 31, p. 173–187.

Masters, J.A., ed., 1984, Elmworth—Case study of a deep basin gas field: American Association of Petroleum Geologists Memoir 38, 316 p.

Rightmire, C.T., Eddy, G.E., and Kirr, J.N., 1984, Coal bed methane resources of the United States: American Association of Petroleum Geologists Studies in Geology 17, 378 p.

Schwochow, S.D., Murray, D.K., and Fahy, M.F., eds., 1991, Coalbed methane of western North America: Rocky Mountain Association of Geologists, 336 p.

Spencer, C.W., and Mast, R.F., eds., 1986, Geology of tight gas reservoirs: American Association of Petroleum Geologists Studies in Geology 24, 299 p.

In association with this Circular, the USGS has published a Professional Paper:

Howell, D.G., ed., 1993, The future of energy gases: U.S. Geological Survey Professional Paper 1570, 892 p.

A video, also titled, "The Future of Energy Gases," has been produced.

☆U.S. GOVERNMENT PRINTING OFFICE: 1994- 573-038/86022

Petroleum production well on the North Slope of Alaska. Although this area is well known for its oil reserves, it also has a tremendous wealth of energy gases trapped in conventional reservoirs and as gas hydrates occurring below the permafrost. In the future, these energy gases could be as important as North Slope oil is today, but only if they can be produced in a cost-effective manner while mitigating environmental impact. Original slide by Tim Collett.

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

McCabe and others—THE FUTURE OF ENERGY GASES—U.S. GEOLOGICAL SURVEY CIRCULAR 1115