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NEW THINKING ABOUT NATURAL GAS

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Abstract: This paper is about opening our minds to natural gas. Though conventional wisdom holds that commercial natural gas resources rank third behind coal and oil, recent studies require that this old thinking be challenged. Even today our view of natural gas is permeated by a type of thinking that has grown out of the historical close association of natural gas with oil. This oil thinking has created a generally accepted perception, even among professionals, that often impedes research, development, innovation and implementation of much needed new ideas in the realm of natural gas.

Even though estimates of the natural gas resource base recently have been revised upwards, to the range of 1200 to 1500 Tcf, they are still overly conservative. My estimate of potentially available natural gas resources, based upon accepted theories of the origin of oil and natural gas, forecast the U.S. natural gas resource base to lie within the range of 3,000 to 4,000 Tcf. I believe that this significantly larger natural gas resource base can be developed at prices within reasonable economic limits using both in-hand technology and technological innovations likely to be available soon.

Based upon a large natural gas resource base and other information presented here, I predict: that in the United States natural gas will remain an affordable and reliable fuel beyond the middle of the 21st century; that natural gas will replace oil as the United States’ principal energy source; that the only limits to the use of natural gas will be well in the future when CO_2 emissions from natural gas could possibly begin to exceed limits set by future global warming treaties; and that to use natural gas as a principal energy fuel will be exceptionally beneficial for both developed and developing economies and therefore a great catalyst to the growth of the global economy in a manner that will significantly improve the environment. In developed economies, increased use of natural gas will reduce coal and oil pollution and lower the rate of addition of carbon dioxide to the atmosphere while enhancing economic efficiency and productivity. In developing countries, the use of locally derived natural gas will reduce the capital required to produce the energy necessary for economic growth while allowing these countries to conform to global environmental goals.

The world is now entering The Age of Energy Gases which will progress toward an environmentally benign energy system that will allow civilization, for the first time, to sustain economic growth within a clean global environment.

Introduction

Natural gas, composed principally of methane (CH_4), may well be the world's most abundant hydrocarbon, possibly exceeding in amount both coal and oil (USGS, 1992). Though conventional wisdom holds that commercial natural gas resources rank third behind commercial coal and oil, recent studies of the origin of natural gas, the abundance of methane in the solar system, the pervasive nature of natural gas in the Earth’s lithosphere, and the vast quantities of methane trapped in gas hydrates, require that this old thinking be vigorously challenged.

The thoughts I present here concerning natural gas are both simple and radical. I think that commercial natural gas is vastly more abundant than even our most optimistic estimates suggest, and that our limited view of the potential of this fuel is based in our insistence on holding to the historical mind-set of the association of natural gas with oil. Throughout most of its history in the United States, natural gas has been found principally in geologic and economic association with oil. Up to the 1970’s, natural gas was considered by most a nuisance, or at best, a by-product of oil with little intrinsic value. But understanding the real quantities of economically recoverable natural gas that exist in the Earth lies far beyond accepted concepts of the physical, chemical, technological, and economic limits of oil. Until we break the mental bonds that tie us to these oil-related ideas, we will be unable to foresee the real future of energy gases. To discern that future, we need a radically new paradigm for natural gas resource thinking, and an intense focus upon research and development to test the ideas that arise from this fresh and fertile perspective.

One of the main theses of this paper—that our view of natural gas is permeated even today by thinking that grew out of the close association of natural gas with oil—is based in an historical view of the development of hydrocarbon fuels. During the past decade, this view of natural gas has begun to change. But my purpose here is not to address the cutting edge of natural gas science and technology, it is to speak of the inertia, resulting from decades of focus on oil, that impedes more rapid development and implementation of new ideas in the realm of natural gas. I will also show that thinking from within the realm of natural gas supports a far more optimistic view of the natural gas resource base than is suggested even by the most recent, higher estimates of such agencies as the Department of Energy (DOE), the National Petroleum Council (NPC), and the Gas Research Institute (GRI).

The observations and arguments that support this view come from a lifetime devoted almost exclusively to natural gas exploration and production and, equally important, not to oil. It is a view deeply grounded in experience as well as theory, intuition as well as science, logic as well as fact, and it has been formed in a marketplace where ideas mean little until they have been tested in practice. The ideas contained herein are an outcome of that testing.

Wallace Pratt once said that “oil is found in the minds of men." If this is accurate, and I hold no doubt that it is, perhaps it is time that we recognize that natural gas also is found in the minds of men and women, and that to find more we need to free our vision from the bounds of oil so we can think natural gas. In my opinion, this Professional Paper is a major move in that direction. This contribution is designed to highlight some of the changes in thinking that my experience with natural gas has convinced me we must now make, as well as to inspire new ideas about natural gas in the minds of the men and women in whose hands our energy future lies.

Some Preliminary Observations

Methane—the major component of natural gas—is the simplest and most stable of the hydrocarbon molecules. It is a major component of the atmospheres of Jupiter, Saturn, Uranus, Neptune, and Pluto, and the planetary satellites Titan and Triton. On Earth, large quantities of methane exist in the crust. Of the various known sources of methane, the most abundant occurs in the form of methane hydrates in the sediments of ocean basins and within the permafrost of polar regions (see Kvenvolden, and also Collett, this vol.). Recent estimates of the quantity of natural gas held in these hydrate deposits range from 13 x 10^3 trillion cubic feet (Tcf) to 26 x 10^6 Tcf (Kvenvolden, 1988). Although much of this gas hydrate resource may be non-commercial for the foreseeable future, natural gas has been produced from hydrates on the Yamal Peninsula in Russia (Gustavson Associates, 1992, and Collett, this volume).

While methane is always associated with oil and coal deposits, it is found in many other habitats. Methane leaks from most of the Earth’s surface rocks and oceans. It is found in swamps, landfills, and the stomachs of animals. Methane is found in diamonds (Melton and Giardini, 1974) which form at ultra-high pressures and temperatures, presumably at great depths in the Earth. And it occurs, in quantity, in geologic domains where oil is relatively rare or absent, such as within fold and thrust belts (Howell, et al, 1992), in some large basins such as the West Siberian and San Juan Basins, and at depths below 15,000 feet. Natural gas has been found at 21,000 feet in the granitic rocks of Sweden’s Siljan meteorite impact crater, and at the deepest depths drilled into the Earth, in Oklahoma at 31,441 feet[1], and at over 40,000 feet on the Kola Peninsula in Russia (Oil and Gas Journal, 1991).

Natural Gas—A Distinctly Separate Fuel

In the past, the commonly accepted assumption has been that oil and natural gas are similar substances, traveling together along parallel paths from origin to production. This is neither surprising nor unreasonable as oil is rarely found without associated natural gas and these fuels, in the past, have been explored for, produced, transported, and marketed by what is frequently perceived as a singular and monolithic enterprise—the oil industry. But natural gas and oil *are not the same*; natural gas is as different from oil as oil is from coal. And natural gas occurs in large quantities unassociated with oil. The natural gas industry is now emerging in its own right as completely separate from the oil industry. As this emergence progresses, more people are recognizing the distinct physical, chemical, and geological differences between oil and natural gas which produce equally distinct economic, environmental, technological, and political differences. Let’s look briefly at each of these categories.

Physical Character: Methane is a gas that is lighter than air; oil is generally a viscous liquid that is lighter than water. Oil, as we know it, is virtually destroyed at temperatures that exceed 150 degrees C at low pressure, while methane is found throughout the Earth’s crust at temperatures to at least 800 degrees C. These figures indicate that methane can exist to significantly greater depths in the crust than can oil. Kerogen profiles from deep wells in Oklahoma's Anadarko Basin indicate natural gas could be present at 60,000 feet (Hefner, Kinchloe, and Wheeler, 1973), while little oil is found below 12,000 feet and virtually none below 15,000 feet.

Chemical Composition: Methane, the primary component of natural gas, is the simplest of all hydrocarbons, containing one carbon and four hydrogen atoms (CH_4). Approximately one-half of the energy from burning methane comes from carbon and one-half from hydrogen. Oil, on the other hand, is a mix of very complex long chain, and simpler, hydrocarbons. When burned, oil derives about three-quarters of its energy from carbon and only one-quarter from hydrogen. Coal derives nearly one hundred percent of its energy from carbon.

Geologic Occurrence: Natural gas can be, and seems to be, ubiquitous in the Earth’s rocks, occurring in commercial quantities in strata as old as, and occasionally older than, six hundred million years. Though frequently found in traps of limited extent, natural gas virtually permeates the deeper parts of some basins, such as the Anadarko Basin (see page 19, this paper) and the Alberta Basin (Masters, 1979). Oil, on the other hand, is geographically, geologically, and physically limited in its occurrence and commonly accumulates in unique traps under normal pressures at depths less than 10,000 feet in relatively young rocks. More than one-half the world’s oil,

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[1] The Lone Star—GHK Bertha Rogers #1 well was spud on November 25, 1972, and completed on August 14, 1974. The well was drilled to a total depth of 31,441 feet.

for instance, occurs in rocks younger than Jurassic, or less than 180 million years old. About sixty percent of the world's known oil reserves lie beneath less than one percent of the Earth's surface in the Middle East (World Oil, 1992); 7 percent is concentrated in the Ghawar field alone. Many of the world's largest natural gas fields contain relatively small amounts of oil, while all of the world's large oil fields contain significant quantities of natural gas.

Economic Considerations: Until the early 1970's, except in a few limited cases, natural gas was considered at best a marginally economic by-product of the oil industry. Only during the past twenty years has natural gas achieved independent economic value, whereas oil has maintained significant intrinsic value as an important, easily traded, and readily transported energy commodity since the 1920's. Conversely, no large-scale natural gas transmission systems were built in the U.S. until after World War II. Today, however, natural gas is the fastest growing fuel in the world, while oil use has barely fluctuated over the past ten years[2].

Environmental Differences: Natural gas is the cleanest burning hydrocarbon, a reflection of its simple chemical composition and low carbon content. Though usually grouped with coal and oil as a "fossil fuel" by those concerned with the environment, the use of natural gas produces significantly fewer of the atmospheric pollutants associated with these other hydrocarbon fuels. The burning of natural gas, for instance, produces 25 percent less carbon dioxide than oil and 50 percent less than coal. Indeed, a natural gas-fueled vehicle, compared to an average gasoline-fueled vehicle, emits 24 percent less carbon dioxide and nearly ninety percent less reactive hydrocarbons and carbon monoxide (American Gas Association, 1991), together the main contributors to the photochemical smog that pollutes most of our cities. An advanced, natural gas-fueled, combined-cycle electrical generation plant emits 50 percent less carbon dioxide, and 80 percent less nitrogen oxides, than a conventional oil-fueled plant, and 65 percent less carbon dioxide and 99 percent less nitrogen oxides, than a scrubbed, coal-fueled plant (Flavin, 1992). And, unlike coal and oil fired electrical plants, a natural gas plant emits no sulfur dioxide, eliminating a major cause of acid rain.

At the same time, methane is a greenhouse gas and leakage from the natural gas production and distribution system must be taken into account in any calculation of the contributions that increased use of this resource will have on problems of atmospheric contamination. However, as the intrinsic value of natural gas to the economy increases, the new infrastructure that develops will have insignificant leakage, especially compared to the loss of methane from production and handling of oil and oil products, and from coal mining operations. Controls for the prevention of methane leakage from oil and coal sources are meager or non-existent because the need for such controls has been largely ignored. Methane is also added to the atmosphere from natural surface seeps, ocean vents, rice paddies, wetlands, landfills, and the stomachs of animals.

Technological Possibilities: Historically, during the initial years of economic development of an energy source, the technology associated with it experiences exponential growth, economic efficiency is enhanced, productivity increases, and a new long wave of economic growth is unleashed. In the 1840's, exponential growth of coal-related technologies (the steam engine, the substitution of coke for charcoal, coal-related innovations in the steel industry, etc.) and the resulting increase in economic efficiency and productivity became the catalyst for the Industrial Revolution. In the late 1920's, a similar period of technological innovation related to oil (rotary drill bit, advances in exploration and refining, improvements in the internal combustion engine, etc.) fueled the economic growth that led to the developed economies we know today. Oil technology has now reached the mature phase. But natural gas is just beginning its wave of exponential technological innovation, a result of the relatively recent recognition of its intrinsic value. As natural gas continues to increase in value to the economy and gain an increasing share of the energy market, we can expect an acceleration of natural gas technological innovation at all stages, from exploration to end-use ("non-conventional" production of natural gas, natural gas vehicles, fuel cells, etc.). This may soon lead to a 50 percent or greater increase in overall efficiency in the exploration to consumption cycle for natural gas (Nakicenovic, 1990, and this volume; Mills, this volume) which, in turn, will bring extraordinary economic and environmental benefits to society, many of which we cannot yet even conceive. As natural gas use increases, our economy will move further toward the ability to sustain growth.

Political Aspects: In the United States, natural gas has been significantly more regulated than oil and coal. For decades, governmental policy has heavily favored oil and coal over natural gas. This government intervention has caused natural gas to be the only fuel used in smaller quantities in the United States today than in the early 1970's (see Fanelli, this volume). Primary Energy Substitution curves (fig. 1 and 1a) for the United States clearly show how for nearly one century, market forces drove the orderly transition of energy sources from wood to coal to oil. Notice, however, the diversion from this pattern beginning in the 1970's. At that time, government intervention, which favored coal, oil and nuclear power, created artificial

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[2] World consumption of natural gas has grown steadily over the past decade, increasing some 40% during that time. In that same decade, oil consumption first decreased and then rebounded, with a total change of plus 3% during that same period (Int. Energy Statistics Sourcebook, 1992).

shortages of, and disrupted the historically predictable transition to, natural gas. In 1978, Congress, overreacting to the artificial shortage, legislatively prohibited the use of natural gas for new electrical generation plants and discouraged the use of natural gas in all markets. As a result, most U.S. citizens believed that natural gas was no longer a viable fuel and nearly all of the increasing demand for electricity was generated from less efficient, dirtier, and costlier new coal and nuclear fueled power plants.

Taking 1973 as a baseline, the total amount of additional electricity produced from coal and nuclear plants could have been generated by using 40 Tcf of natural gas[3], a quantity that was readily available as shown on the Primary Energy Substitution Charts (figs 1 and 1a) by the 59 Tcf cumulative decline in natural gas consumption. The misperception of a limited natural gas resource base, resulting principally from the direct association of natural gas with oil, led to an energy policy that caused the U.S. to become the only developed economy in the world to reduce its use of natural gas. Between 1970 and 1989, U.S. natural gas use declined by 11 percent. During this same period, countries as diverse as England[4] and Bangladesh[5] increased their natural gas usage by over 20 percent. These policies cost the American economy more than a trillion dollars in unnecessary capital expenditures to generate more costly electricity, creating, as well, significantly greater environmental damage than would have resulted from the use of natural gas. This wasted capital, which was used to convert less efficient coal, oil, and nuclear fuel to electricity at higher overall costs and additional external expense, lowered U. S. economic productivity and reduced our potential to increase and sustain economic growth.

Blinders of the Past

To quote from Daniel Yergin's epic account of the oil industry: "Oil is the world's biggest and most pervasive business, the greatest of the great industries that arose in the last decades of the nineteenth century...The expansion of the business in the twentieth-century embodies the twentieth-century evolution of business, of corporate strategy, of technological change and market development, and indeed of both national and international economies." (Yergin, *The Prize*, 1991). The immense influence of the oil industry on the development of our society and culture has been institutionalized in academics, policy-making, and the collective mind of the general public. Without question, until the 1970’s natural gas was a “by-product” of oil exploration, oil drilling, and oil production. Unfortunately, natural gas continues to be perceived in that context. Even today, university degrees are granted in *petroleum*[6] geology, *petroleum* engineering, and *petroleum* land management. Petroleum, originally defined as “rock oil”, signifies oil and only oil in the minds of most people, and we must recognize that many universities, oil companies, and natural gas companies even today educate and train people to be oil engineers, oil geologists, and, most unfortunately, oil thinkers.

In the past, oil thinking has so dominated the natural gas extraction industry that it has distorted the process of natural gas exploration, production, and, particularly, past and present estimates of the remaining natural gas resource base. Until recently, most of the respected and accepted estimates of the natural gas resource base rather accurately approximated the quantity of natural gas that would be produced in association with future oil production within the economic and technological parameters that were predicted for the oil industry. Those estimates excluded most of the natural gas that will be found and produced, in very large quantities, outside the geologic, economic and technological domains of oil. Let me share with you six quite typical examples of oil bias and misunderstandings about natural gas that have led to very real though unintended distortions of the U. S. natural gas resource base.

1. In 1957, with a degree in petroleum geology from the University of Oklahoma, I joined Phillips Petroleum Company as a trainee, spending time in the Economic Analysis Section where each drilling proposal was closely reviewed. At the time, natural gas prices were fixed by the government at only a fraction of the equivalent BTU value of oil. As a result, the price of natural gas was of no significance in risk analyses of drilling proposals or the calculation of future revenue and rate of return on investment. Natural gas was to be used, at best, as a “plus factor” that might pay for the overhead of operating an oil well. Throughout the 1950’s and ’60’s Phillips, and I presume most major oil companies, analyzed geology and forecast economics strictly by using geologic and economic factors appropriate to oil. Natural gas discovered during this period of oil exploration was found largely by chance, and had little relationship to the amount that might have been found if the emphasis had been on natural gas rather than oil. As a result, all econometric projections, such as the one in the example below, that used these data to predict the future of natural gas had little bearing on the actual amount of natural gas in the ground. Rather, these models, based

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[3] Based on figures from the Energy Statistics Sourcebook, 1991.

[4] Based on figures from the International Energy Statistics Sourcebook, 1992, and Jenkins, 1977.

[5] Personal communication, Janet Rains (The GHK Co.) with an official of the U. S. State Department, June 1992.

[6] Petroleum—as late as 1979 the primary definition of petroleum in the Glossary of Geology clearly stated that the word petroleum refers to liquid oil. The secondary definition, a more general one, includes all liquid and gaseous hydrocarbons.

principally upon oil-based economics and geology, estimated only the amount of natural gas that would reasonably be found and produced in the future by the United States oil industry during its search for oil.

2. Oil thinking has had a major impact on the econometric modeling of gas resources even by natural gas companies and associations. An estimate of future natural gas supplies and production made by the American Gas Association in the mid-1970's provides a classic example. Having already become the principal public advocate for a large natural gas resource base, the "optimistic" scenario of the AGA appeared to me to be ultra-conservative to pessimistic, and I became curious about the sources of information upon which the study had been based. It turned out that the AGA economists had followed a highly logical approach; wanting to project the highest, reasonably possible quantities of natural gas that would be found from estimates of future drilling, they had used the historically highest natural gas finding rates per well drilled. The limitation of this study was inherent in the information, because the historically high finding rates were achieved during the 1950's when oil companies, based solely on oil economics, with no thought of natural gas as a commodity with intrinsic value, were exploring and drilling mainly in the rather shallow geologic environments where their geologists expected to find oil. Though the AGA projection was indeed more optimistic than most other forecasts for natural gas, it had little relevance to future natural gas extraction as it included no consideration of natural gas to be found not in association with oil, or in domains in which natural gas is prolific and oil does not exist, such as the vast volume of rocks in overthrust belts and at depths below which oil is generally absent (see T. Woods, this volume).

3. The artificially created shortages of natural gas production which appeared in the early 1970's as a result of decades of unrealistic government price controls led to an equally artificial shrinkage of America's proven reserves by the late 1970's. This exceptionally telling example of the effect of perception upon prediction is the essential thesis of this article. Spurred on by the common misperception that the U.S. was rapidly running out of natural gas, John O'Leary, head of the Federal Energy Administration, declared, and often repeated, that "Natural gas has had it." That perception became the official government view and soon most prognosticators, including the major integrated oil companies as well as many natural gas companies, were forecasting "grave" shortages and espousing their concerns. The shortage mentality was seized upon by the nation's coal and nuclear industries, so natural gas, of course, became an "unreliable" source of energy. In 1977, as a result of the perception of shortages, the Secretary of the Interior ordered a study of six major offshore natural gas fields in the Gulf Coast to determine if they had reserves as large as were currently estimated by the field operators. Though these six fields were selected for their large size and with the expectation that they might have a high potential for increasing production, the study, conducted by the Committee on Gas Production Opportunities of the National Research Council (1978) found that all six fields had significantly less natural gas than had been originally estimated. This finding essentially "confirmed" the official government position that our nation indeed had a critical shortage of natural gas and suggested that the United State's natural gas resource base was both limited and scarce. Since 1977, however, these six fields have produced 4.7 Tcf which exceeds the Committee's estimate of remaining reserves by 65 percent. This 65 percent may be a reliable factor by which we should increase our current estimates of proven producing reserves in order to achieve a more realistic idea of the quantities of natural gas available from existing fields.

4. In 1984, a senior executive of Exxon and I were called before Congress to testify about the nation's natural gas future. The Exxon representative[7] testified that, "We estimate the volume of yet undiscovered natural gas from conventional sources in the U.S. to be about 300 Tcf.... This is very close to our last published assessment of the volume of resources in 1976." Based upon this limited and pessimistic view of our natural gas supplies, he went on to predict that "Future demand for [natural] gas will exceed the supply available from the domestic resource base. Requirements for natural gas will significantly outstrip domestic supply capability by the late 1980's." He concluded with Exxon's dim view of the natural gas future of the United States saying, "We project a shortfall of economically available gas from any source." Unfortunately, this overly negative view, coming from the nation's largest oil company, had a detrimental effect upon other industry and government estimates of America's natural gas future.

At these hearings, I made the point that Exxon's estimates, and all the other comparably small estimates, were founded upon oil thinking and that a more realistic number, based upon a great deal of experience in natural gas exploration and production, would be the natural gas resource base estimate I originally presented in 1978 at the Aspen Institute (Hefner, 1978 and fig. 2) of from 1,000 to 1,500 Tcf, three to five times Exxon's figures. At the time, Exxon, other oil companies, and policy makers gave little weight to estimates made by a small independent natural gas producer. However, as in the example above, time has been on the side of new natural gas understanding—the National Petroleum Council, an advisory committee to the Secretary

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[7] Charles B. Wheeler, Senior Vice President, Exxon Co., U. S. A. Quotes from testimony before the Committee on Energy Regulation, Subcommittee of the Full Committee of Energy and Natural Resources, April 26, 1984, Washington, D. C.

of Energy composed mainly of representatives from the oil industry, has recently estimated the natural gas resource base to be 1295 Tcf. This is a significant step forward for an organization dominated by oil, and an affirmation of the validity of my estimates, made 15 years ago, based on natural gas experience and thinking outside the confines of conventional oil-based wisdom—the type of thinking I hope to stimulate with this article and upon which we need to base our energy future.

Contrary to Exxon's projections, during the entire decade of the 1980’s natural gas supplies have so outstripped demand that the average wellhead price, instead of continually rising as Exxon and most others predicted as a result of their pessimistic estimates of the resource base, actually has declined from an average of over $3.50 per Mcf in constant dollars in 1984 to a spot price of less than $1.00 per Mcf in February 1992.

5. The influence of oil thinking on estimates of the future of natural gas continues today. An excellent current example of this effect is the Ouachita overthrust belt in Western Arkansas and southeastern Oklahoma. The northern limit of the Ouachita overthrust belt is defined by the location, at the surface, of the large regional Choctaw fault. Conventional oil wisdom has always suggested that significant amounts of oil, and natural gas, should not be present south of the Choctaw fault because the sediments had been subjected to temperatures and pressures that would destroy any oil and reservoir pore space that had originally been present. As a result of this belief, prior to 1988, few exploratory wells had been drilled within the Ouachita overthrust province. However, beginning in 1988, a number of large new natural gas discoveries, including several wells that rank among the world’s largest[8], were made south of the Choctaw fault, at progressively deeper levels. Some 125 wells have now been drilled, discovering approximately 1 Tcf of new gas reserves in an area once thought to be virtually barren. The average ultimate production of each of these new wells will be well over the equivalent of 1 million barrels of oil. The natural gas industry is currently drilling 12 deep wells (below 15,000 feet) to further test the large potential of this fold and thrust belt. Already, several completed deep wells have paid back their complete investment in one year or less, and have established new reserves at a cost of about $.25 per Mcf. Unfortunately, as of the date of this paper, the large potential of this geological province, which I predict to be in the range of 30 to 50 Tcf, is not yet included in official estimates of the country’s natural gas resource base. In spite of the fact that the province now contains its first new giant field that I call the South Choctaw field[9], the “official” estimate remains at only 5 Tcf, in part because of the lag time in “official” estimating and reporting, and in part due to the natural hesitancy of experts to predict the potential for new and large discoveries of natural gas in areas where many people, including myself, were originally taught no oil or gas could occur.

6. Oil is a viscous, non-compressible fluid that could not be economically produced from many excellent natural gas reservoirs even if it were present. Methane is a highly compressible gas with negligible viscosity which leads to significant differences between oil and natural gas production. One highly important factor not well understood by economists and policy makers is the difference between the recovery of usable energy (Btus) from an oil reservoir and a natural gas reservoir at increasing depths below the surface. Below 8,000 feet a natural gas reservoir will nearly always produce more usable Btus than an oil reservoir and at 15,000 feet over one and one-half times the usable energy could be recovered from a natural gas reservoir (fig. 3). A barrel of oil at 20,000 feet, for instance, equals a barrel of oil at the surface, but a barrel volume of natural gas at 20,000 feet in an overpressured basin such as the deep Anadarko, equals as many as 500 barrels of natural gas at the surface. The compressibility[10] and negligible viscosity of natural gas are generally taken into account in economic analysis, drilling, and production practices; however, decades of experience focussed on non-compressible oil and only slightly compressed (“normally pressured”) natural gas has led frequently to oversight of the effects of compression and flow characteristics unique to natural gas on both the drilling for deep natural gas and the ultimate volume of natural gas production. The following examples illustrate my point.

Oil-dominated thinking, for instance, has caused most of the blowouts I am aware of in my career, and has added much largely unnecessary risk, time, and expense to drilling in high pressure natural gas regions. I have been made aware many times (and even recently), that drilling engineers with decades of “oil drilling” experience overlook the fact that an inflow of natural gas from a high pressure reservoir at depth, hardly noticeable in pit volume at the surface, undergoes an enormous rate of expansion as it approaches the surface. In the Anadarko example above, 50 percent of the expansion would take place in the last 1,000

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[8] These include the Zipperer, with initial flows of 40 MMcfd and Estimated Ultimate Reserves of 35 Bcf; the Baumann, with initial flows of 60 MMcfd and EUR of over 40 Bcf, and the recent Windingstair, with initial flows of 50 MMcfd and EUR of 50 Bcf.

[9] I define the South Choctaw field to include all Spiro-Wapanucka production south of the Choctaw fault from T3N-R15E Pittsburg County to what is now called the South Panola field in T4&5N-R20E Latimer County.

[10] Defined by Boyle’s Law and called the “Z Factor” in estimates of natural gas reserves.

feet, a rate that would easily cause a blowout if overlooked and unsuspected.

The misunderstanding of deep, high pressure, natural gas reservoirs on the part of reservoir engineers was poignantly illustrated one day in 1982 when I presented a core from 18,000 feet in the deep Anadarko Basin to the senior engineer of one of the world's largest banks specializing in petroleum financing. Thinking that it was the finest-looking clastic reservoir rock I had ever seen from the deep Anadarko, I was shocked when he took one look at the core and pushed it away with the curt comment: “that rock will never produce any oil!” It didn’t, but the well completed for 35 million cubic feet of natural gas per day and has produced over 20 Bcf of natural gas; it will eventually produce the energy equivalent of 6 million barrels of oil.

Engineers maintain that the unique characteristics of a gas, including compressibility, have been taken into full account in estimates of deep, high pressure, natural gas reserves and therefore their estimation of ultimate reserves should be viewed generally with “a high level of confidence.” But my experience suggests that we do not fully understand what is happening in these high pressure reservoirs, particularly the mechanisms of movement of high pressure natural gas through the various types of connected pore space found at these depths. We must remember that petroleum reservoir engineering is founded on the work of Henri-Philibert-Gaspard Darcy (1803-1858), a French engineer who in his study of the sewers of Paris measured the flow of various liquids through sand packs. Darcy’s early simple equations, still in use today with little modification, were suitable to normally pressured liquid oil moving through sand, the most prevalent oil reservoir. I believe, however, that Darcy’s equations are significantly lacking in their ability to describe and predict the movement of natural gas through the broad variety of natural gas reservoirs that exist. We simply do not yet understand the dynamics and rates of flux of natural gas moving through the complexity of microfractures, micro and macro vugs, primary and secondary porosity, natural macrofractures, and induced and propped fractures that occur in deep, high pressure, natural gas reservoirs. As a result, procedures used to estimate natural gas reserves in shallow, low pressure, reservoirs do not give an accurate picture of the quantity of natural gas resources available at depth. Engineering technology and techniques for the estimation of particularly deep, high pressure, natural gas reserves did not keep pace with the industry’s ability to produce natural gas from these complex reservoirs particularly during the drilling and production boom of the late 1970’s and early 1980’s [11]. I am confident that this is one cause of the general underestimation of proven reserves in the deeper, higher pressure domains. The production decline curves shown in figure 4, typical of the U. S. mid-continent region, graphically demonstrate this point.

The Natural Gas Resource Base of the United States

A number of circumstances have arisen recently that have caused many estimates of the natural gas resource base to be revised upward. These reassessments have been forced by a variety of factors including: new prolific discoveries in places long ago written off by oil explorationists; new views of existing natural gas reserves; a growing awareness of the differences between oil and natural gas; a wave of recent exploration and production technology enhancement specifically related to natural gas; and the recent recognition that the overall decline of many natural gas reservoirs is hyperbolic rather than straight line (fig. 4).

The three most prominent groups of estimators are the Potential Gas Committee (PGC)[12], the U.S. Department of Energy (DOE), and the United States Geological Survey (USGS). Recent estimates by the DOE (EIA, 1990) and PGC (1990) are 1,370 and 1,033 (with proved reserves added) Tcf, respectively. Though it is sometimes difficult to compare estimates because they are based on different definitions and categories of resources, the DOE and PGC estimates suggest a sufficient supply of natural gas to meet significantly increased demand for 30 to 40 years. The most recent USGS study (1989), based on data available as of January 1987 and considering conventional resources only, estimates supplies of natural gas at 399 Tcf, a number comparable with the oil thinking estimates of the past.

In 1991, Enron, the United State’s leading integrated natural gas company, revised upward its estimate of the remaining economically recoverable resource base from 805 Tcf in 1989 to approximately 1,200 Tcf in 1991, and increased it again to 1303 Tcf as of January 1993. In 1991, Enron stated that “A major reason for our optimism, ... is the development and rapid diffusion of technology.... These developments portend both an increase in the economic viability of new resources...and an upsurge in the yields from traditional producing regions” (Enron, 1991). In 1993, Enron noted the close similarity of its 1993 estimate with the NPC estimate of 1295 Tcf as of January 1991, and agreed with the NPC statement “Natural Gas is an abundant domestic resource and can be produced and delivered at prices that allow both expansion of market and continued

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[11] Personal communication, Dr. Jack Krug to Robert A. Hefner III, March 1993.

[12] The Potential Gas Committee consists of volunteer members from the natural gas industry, government agencies, and academic institutions who are concerned with natural gas resources. The PGC functions independently but with the guidance and assistance of the Potential Gas Agency.

development of the resource."[13] In addition to these estimates, the Gas Research Institute (GRI) has recently released a figure of 1585 Tcf (Fisher, 1993).

Though these new estimates are a significant step toward a more realistic assessment of our real recoverable natural gas resources, I believe they are still overly conservative. My position is based on new information and my experience in natural gas exploration and production, particularly in the Anadarko Basin where the history of development suggests that natural gas reserves are significantly larger than most of us imagine, much less calculate. The history of the Anadarko Basin indicates that the distinction between conventional and unconventional sources of natural gas is largely one of perception, controlled by a combination of the state of our technology, our estimates of future prices, our familiarity with a particular source, and politics. The Anadarko Basin also provides a striking example of the fundamental differences in the occurrence of oil and natural gas that continue to affect the methodology of estimation of resources.

The Anadarko Basin. In the early 1960's, The GHK Company decided to explore for non oil-associated natural gas in the Anadarko Basin, recognizing that this would require searching at depths well below known oil reservoirs. At that time, the oil industry utilized models that indicated deep drilling would be totally unproductive: accepted geochemical models taught that all hydrocarbons would be burned off by high temperatures, and shallow drilling experience combined with theoretical models indicated that porosity would decrease with depth and disappear entirely at about 20,000 feet, collapsed by overburden pressure (fig. 5). And even if porosity and hydrocarbons were preserved at these depths, in 1960 few believed that the technology for drilling and production of such deep wells existed.

Nevertheless, in a series of deep wells drilled in the Anadarko Basin in the late 1960's and early 1970's by The GHK Company and others, we discovered that both porosity and natural gas do exist even to depths of over 30,000 feet (Hefner, 1980). We found that conventional thinking no longer applied below a zone I call the transition zone, usually encountered near 15,000 feet and characterized by rocks that have been strongly affected by pressure solution, recementation, and fracturing. Below this zone, pressures jumped beyond their normal gradient and porosity actually increased (Hefner, 1980). In 1969, GHK's historic #1 Green discovery was the first well to prove the misconception of porosity disappearing with depth. In this well, porosity of up to 18% was measured at 21,600 feet in a reservoir containing a surface shut-in pressure of 15,130 psi. (fig. 6)[14]. The well produced at a rate of over 19 Mcf of gas per day and on an annual basis was capable of producing an amount of energy equivalent to one-third the energy produced by a nuclear plant. It soon became evident that below the transition zone we generally encountered a rapid shift in the pressure gradient from the normal 0.465 pounds per foot of depth to near 0.60 pounds per foot of depth, which continued to increase to gradients as high as 1.0 pounds per foot of depth at 31,441 feet in the Lone Star-GHK Rogers well. The transition zone proved to be a pressure barrier below which porosity is enhanced and held open by high pressure natural gas. At first my colleagues thought the excellent porosity of the #1 Green would only be found in carbonate reservoirs due to greater rock strength as compared to sandstone reservoirs. By 1982, however, approximately 380 wells had been drilled to below 15,000 feet in the Anadarko Basin and porosity in sandstone reservoirs had been found to range frequently from fifteen to twenty percent, a large number of which were capable of production rates similar to the #1 Green. As large quantities of natural gas were extracted from these deep, prolific reservoirs and the pressure lowered in the vicinity of wellbores, reservoir rocks would indeed collapse, requiring artificial fracturing for continued high rates of production. Below the transition zone, traditional fracturing with silica sand or glass beads proved detrimental to production because crushing of both these materials at the extreme overburden pressures actually reduced permeability and flow rates, thus limiting the quantity of commercially recoverable reserves. However, at this time, Exxon had developed sintered bauxite as a proppant with two to three times the compressive strength of silica beads, and four to five times that of sand. Once the problem of the extremely abrasive nature of the material was overcome, sintered bauxite fracturing proved to be a highly effective treatment and is a prime example of how new natural gas-related technology increases the availability and quantity of natural gas resources. The flow rates and commercially recoverable ultimate reserves were usually increased several fold and sometimes by nearly an order of magnitude (fig. 7). This breakthrough in fracture treatment proved to be as important to deep, high pressure, natural gas production as the introduction of hydraulic fracturing was to oil in the 1950's.

After drilling several hundred wells to depths of four to five miles, with reservoir pressures ranging beyond 20,000 psi, in my view deep gas is no longer an unconventional

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[13] Quoted in cover letter for Enron booklet "The Outlook for Natural Gas / Technology Marches On", dated March 22, 1993.

[14] The #1 Green was spud in October, 1967, and completed in the spring of 1969 after being drilled to a total depth of 24,473 feet, at that time the second deepest well bore ever drilled into the Earth. The well produced 19 MMcfd at a flowing tubing pressure of 7,010 psi, without stimulation, from perforations between 21,604 and 21,644 feet. When shut-in, the well measured 15,130 psi at the surface, which at the time was the highest pressure ever measured in the world.

source, at least within the context of technological understanding and ability. Perhaps the only remaining truly unconventional source of natural gas lies in the methane hydrates of the ocean and polar regions. Because we have seen how perceptions significantly influence resource estimates, changes in the perception of what is technologically feasible within the limits of foreseeable economics will almost certainly lead to continued increases in most estimates of the natural gas resource base.

Perhaps a more immediate and striking example of the limitations on our view of natural gas resources is provided by the history of development of the Anadarko Basin and what this reveals about the nature of occurrence of oil and natural gas. Historically, oil developers followed trends along which unique but similar oil pools would be found. One technique of estimating future oil reserves that arose from this process involves the analysis of a basin by "trends" and "plays" that could be forecast reasonably on the basis of the location, character, size, and production history of existing oil fields. In the past, this analysis has worked well in oil basins of the United States, most of which contain many small to medium sized oil pools.

When the shallow flanks of the Anadarko Basin began to develop in the 1950's, it looked very much like an oil basin, with scattered, small oil and gas pools separated by areas of no production (fig. 8). But as time passed, and more wells were drilled to increasing depths, producing areas began to change to gas fields, and the gas fields began to merge, creating a pattern indicating that the Anadarko Basin, at depths generally below the main level of oil production, is actually one gigantic natural gas field (fig. 9), approaching the size, by volume of resource, of the large gas fields of Siberia. Production in the Anadarko is from multiple horizons, beginning in Permian rocks near the surface and extending to the worlds deepest natural gas production at 26,566 feet from the Arbuckle Formation of Cambrian Age[15]. I think a similar pattern of natural gas distribution will appear in other areas—as deeper wells are drilled, we will begin to see that natural gas accumulations, below the zones that are predominantly oil, are essentially continuous over very large areas.

Given this type of pervasive distribution, the old but often used practice of estimating potential natural gas reserves using the oil technique of "play" and "trend" analysis based on fields and individual structures only limits our ability to achieve an accurate estimate of the real resource base of natural gas. Because of this thinking, during the 1970's and 1980's my estimates of the natural gas resource base were often challenged on the basis that we were not finding any more "giant" fields and very few "significant" fields. My reply was that the Anadarko Basin was indeed a “giant” field in continuing development that actually contained at that time some 300 individual wells each capable of ultimately producing over 6 Bcf of gas, the equivalent of 1 million barrels of oil.

Perhaps the most important lesson from the Anadarko is contained in estimates of the total quantity of natural gas present in this region. Below the transition zone, rocks of the Anadarko Basin form an overpressured envelope within which porosity is held open largely by the presence of methane. This overpressured envelope has recently been described as a "mega compartment complex" by Al-Shaieb et al (1992, and fig. 10). The rocks of this pressure complex are by volume primarily Pennsylvanian and Mississippian shales. We have calculated the quantities of methane in place within these shales to be in the range of 2,000 Tcf (Appendix 1). This estimate does not include local overpressured compartments present outside the mega compartment complex in many stratigraphic intervals, particularly in rocks of the Hunton and Simpson Groups (Al-Shaieb, et al, 1992, and fig. 10). Most of this natural gas occurs in shales with significant porosity but, other than microfractures, little or no permeability. The amount of natural gas that may be ultimately available is thus uncertain and would depend upon the economy, technology, and the rate of flux through the fractured shales and coals.

In general, natural gas wells produce significantly more natural gas than indicated by original estimates. In my experience, this has nearly always been true for wells producing from below the transition zone in the Anadarko Basin. The decline curves and ultimate reserve forecasts for the wells shown in figures 4 and 7 are typical examples of engineering underestimation of natural gas wells in the Anadarko and Arkoma basins. These figures show that early estimates of ultimate production, based on initial flow rates, pressure decline, and volumetric calculations, are almost always overly conservative. This is particularly true for larger, more prolific, natural gas wells that frequently produce several times the quantity of natural gas indicated by early estimates. These underestimates of reserves are the result of several factors including new technology (fig. 7). I suspect, however, that the major contributor to significantly low estimates of reserves, even in the light of apparently adequate production and reservoir data, is the continuing failure to recognize the complex multiple flow and drainage regimes of these reservoirs. In the recent past, this oversight has resulted in forecasts, based on straight line decline, that tended to be extremely low. Unfortunately, the low estimates in a well, a field, or a producing region then became generally accepted and reservoir engineers were commonly reluctant to increase their low forecasts until

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[15] The deepest production in the Anadarko Basin and the world is Chevron's #1 Ruth Ledbetter, completed in 1977. Drilled in Wheeler County, Texas, the #1 Ledbetter flows from Arbuckle production (Ellenburger Formation in Texas) from perforations as deep as 26,566 feet (Petroleum Information Corp. 1982; Personal communication, Alan Petzet, Oil and Gas Journal, April 19, 1993; and Dwight's Database).

forced to by increased production of natural gas. In addition, I believe that high pressure natural gas is able to flow at commercial rates from reservoirs with porosities as low as 5 percent or less, far beneath that which is generally accepted. This would also add to natural gas production in excess of original estimates, as would additional natural gas flows that enter the reservoir from adjacent overpressured and fractured shales.

A More Optimistic View of the Natural Gas Resource Base

Considering the degree of inaccuracy of past natural gas resource base estimates, and the large quantities of natural gas that we know exist in such habitats as deep gas reservoirs and methane hydrates, I am led to believe that natural gas, recoverable with present technologies and at prices within reasonable future estimates, is immensely more abundant than even the recent, more optimistic, calculations suggest. The analysis that follows is both general and speculative in nature, and is included here to stimulate discussion and promote the research and development that is necessary to achieve a fuller understanding of the natural gas resource base. This discussion assumes the validity of generally accepted ideas concerning the origin and stability of oil (which, as I explain below, I have many reasons to doubt) and does not take into account the newest information that may bring these established ideas into significant question (see Lewan, this volume, and Gold, this volume).

Most petroleum scientists believe that oil forms from the breakdown of biological materials deposited in lakes, marshes, swamps, and along the flanks of continents. During burial, when temperatures reach about 95 degrees C., the biological material kerogen begins to convert to bitumen, oil, and natural gas. This process continues to about 175 degrees C, above which it is thought that oil can no longer exist and will partially break down to methane and other light hydrocarbons. At higher temperatures, with sufficient hydrogen, oil and kerogen are converted to methane. Specialists in the field of maturation of organic material estimate that 50 to 70 percent of total kerogen is converted to oil and natural gas. In the absence of hydrogen, graphite is the end product. Oil generation thus takes place geologically at relatively low temperatures and pressures, so, unlike natural gas, the physical and geological limits of the oil window are narrow.

The window of generation for natural gas, on the other hand, seems to have no practical physical limits within, and even beyond, the confines of known sedimentary basins. Natural gas is generated biogenically, through the action of microorganisms, at ambient, and quite possibly much higher, temperatures and pressures. Thermogenically, generation of methane occurs throughout the “oil window”. Above 175 degrees C. methane can be generated from oil and other hydrocarbons to temperatures that may exceed 600 degrees C (Hunt, 1975). Moreover, after the process of oil and gas generation and migration from source rocks has taken place, significant amounts of kerogen, bitumen, and oil remain at or near the place of origin, available for conversion to additional quantities of natural gas. My rough calculations (appendix 2), experience, and intuition, as well as some research by others (Comer and Hinch, 1987), indicate that the quantity of natural gas ultimately generated from the original biological material can be assumed to be by mass approximately four times that of oil.

For this to occur, a large source of additional hydrogen must be available, as the original organic material does not contain enough for efficient conversion to take place. The availability of hydrogen is always the main limiting factor for the generation of oil and natural gas as well as the continued generation of methane at temperatures and pressures beyond the oil window. A number of factors suggest that ample hydrogen is available to drive the process: 1) Hydrogen is one of the most abundant elements in the solar system and is found throughout the Earth’s sediments; 2) Hydrogen may diffuse upward through the crust as a result of subduction of water under the continents and/or continued outgassing from disassociation of hydrogen-rich compounds associated with the Earth's origin; 3) Hydrogen is found in many of the deepest test wells drilled (Behr and Raleigh, 1988; Kozlovsky, 1986) and is often vented from volcanoes and mid-ocean rifts (Krauskopf, 1982; Lilley, et al, 1982); and 4) At higher temperatures, in the absence of hydrogen, any remaining oil and unconverted kerogen would be converted to graphite. But the presence of graphite in sedimentary and metasedimentary rocks is low compared to the volume of oil and gas, which suggests that sufficient quantities of hydrogen have been available to allow conversion to hydrocarbons.

By accepting the assumption that the quantity of methane generated from organic materials is at least four times that of oil, we may then estimate the natural gas resource base as a multiple of known quantities of oil in the United States. These calculations for natural gas utilize a simple multiple of the original oil in place, adjusted for differences in recoverability of oil and natural gas. I assume here an average recoverability for oil of 30 percent and for natural gas of 80 percent. These figures are both approximations. Though oil field recovery may reach 40 percent or more in some fields, in others it may be as low as 20 percent and in a few cases even as low as 10 percent. On an historical basis, then, the assumption of 30 percent recoverability is perhaps reasonable.

Estimate of all U. S. conventional oil reserves:

(1) Proven reserves (Howell, et al 1993)	45.0 BBO*	
(2) Undiscovered resources (Mast, et al 1989)		49.4 BBO

(3) Already produced reserves[16]	149.6 BBO
Ultimate recoverable resources	244.0 BBO
Original oil in place (assuming ultimate recoverable reserves equal 30 percent of OOIP)	813.0 BBO
Conversion to natural gas:	
Assuming 4 to 1 ratio of gas in place to oil in place	
813.0 x 4 = 3252 BBO =	18,906.2 Tcfg**
Ultimate recoverable reserves estimated to be 80 percent of gas in place: 18,906.2 Tcfg x .80 =	15,125.0 Tcfg
Minus cumulative production to date (PGC, 1990)	(730.0 Tcfg)
Gives Amount Possibly Available,	
U.S. Natural Gas Resource Base=14,395 Tcfg	

* BBO = Billion Barrels of Oil

** Tcfg = Trillion Cubic Feet of Gas

This speculative estimate of methane originally generated and potentially recoverable is ten times higher than the conventional resource base estimates that now hover between 1,200 and 1,500 Tcf. And because the calculations are based solely upon proven amounts of oil entrapped and in place, they do not take into account early, biogenically derived methane or methane hydrates nor the vast quantities of oil that may have leaked away during geologic history.

We can reconcile the conventional estimates with the 14,400 Tcf figure only by assuming that: 1) trapping mechanisms for natural gas are not as effective as those for oil and large quantities of natural gas have leaked, and continue to leak, into the atmosphere; or 2) much gas is located in reservoirs that have not yet been tapped (some of which may not be commercially producible, such as the high pressure fractured shales of the deep Anadarko Basin, and the tight gas reservoirs of the Green River Formation).

At present, little data is available on the methane flux either in deep high pressure regions or at the surface, and though some work is now in progress to establish what surface flux might be (see Clayton, et al, this volume), considerably more research is needed in this area. We do know that natural gas accumulates in solid waste landfills and swamps without effective “caprocks”, and that flows of natural gas streaming upward through the sediment column tend to form their own barriers to migration. This, along with my experience in natural gas exploration, indicates to me that trapping mechanisms for natural gas are effective, though perhaps not as efficient as those for oil.

If this is true, then there must be a vast quantity of natural gas still in the crust that we have not yet located. The analysis above suggests that the original natural gas resource may have been easily four times that of oil on an energy equivalent basis. I suggest that after leaking, the amount of recoverable natural gas remaining is likely to be, at a minimum, equal to the original amount of oil. Assuming that sedimentary basins contain at least as many reservoirs for gas as for oil (and they may well contain more), the recoverable natural gas resource base for the United States is thus likely to be in the range of 3,000 Tcf to 4,000 Tcf, rather than the 1,200 to 1,500 Tcf predicted today. This higher estimate is much more compatible with the enormous amounts of natural gas known to exist in the form of gas hydrates (see Kvenvolden, this volume) and in habitats such as the Anadarko Basin overpressured mega-complex.

The focus here is not on the absolute accuracy of the larger estimates. Rather, I am suggesting that there exists a reasonable and supportable view of our natural gas resource base that is significantly higher than the one presently held by most oil and gas professionals. That many will disagree with this new view is understandable; whenever a paradigm shifts, new ideas seem uncomfortable and drastically out of line with what is held to be true. But I have shown in a variety of ways that the view of natural gas resources that has resulted from oil thinking reflects a model that no longer fits the data. Though oil thinking applied to the realm of natural gas has held our creativity, our ingenuity, and our technological innovation in check, that old paradigm is now crumbling. We are in a time of fundamental reevaluation and some bold new thinking has begun.

The Gold Hypothesis

Although the very large quantities of methane calculated above, and the much greater amount that could be estimated similarly for the world, can be explained generally by calling on conventional ideas about oil and natural gas, I question seriously whether the large quantities of oil and natural gas found in the earth are of biological origin. Early in my career, I wondered why oil is usually found around the shallow edges of basins at depths less than 10,000 feet, while natural gas, which is less dense and found above oil when they occur together, occurs in abundance below oil, down to the deepest levels drilled. Later, when deeper wells revealed the region of high pressure natural gas and enhanced porosity below the transition zone at about 15,000 feet, I questioned the origin of this gas, and wondered what mechanisms had created the large zone of abnormally high pressure lying below normally pressured oil and natural gas. And as I began to develop my own conviction of vast natural gas resources, I wondered if the original organic content was indeed sufficient to provide the raw materials necessary to generate these potentially enormous reserves.

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[16] Personal Communication, Janet Rains (The GHK Company) with a representative of the American Petroleum Institute, Feb. 1992.

When I first read an article in 1977[17] concerning Thomas Gold's theory of the origin of hydrocarbons through outgassing of carbonaceous compounds from the mantle, I was immediately struck by how well Gold's abiogenic hypothesis fit my experience in drilling for, and producing, deep, high pressure, natural gas. Gold, for instance, discusses in detail the origin and effect of the "critical layer", a zone below which higher pressure regimes are encountered. Gold's critical layer is the transition zone I have described, below which all deep Anadarko wells encounter abnormal pressures. Under Gold's hypothesis, these abnormally high pressures are readily accounted for by the trapping of higher pressure gas from the mantle on its way toward lower pressure domains. Gold's ideas are presented in detail elsewhere in this volume.

Though I recognize that few geologists give credence to Gold's hypothesis, I have had personal communication with several physicists and petroleum geologists who do. But most importantly, I can't escape the fact that my knowledge and experience of natural gas, gained from operating many of the world's deepest and highest pressure natural gas wells, are accounted for more clearly by Gold's ideas than by conventional theories of biological/thermogenic origin of natural gas. Because its enormous implications to the economy and the environment, the Gold Hypothesis is an area of new thinking about natural gas that undoubtedly needs significantly increased study and research, in spite of the pressures of conventional wisdom.

Conclusions

In the context of the broad review of energy gases presented in this Professional Paper, we should remember that our knowledge of the Earth is still exceptionally limited, particularly as we move deeper into the crust, into the realm of deep, high pressure, natural gas. While a number of papers in this volume reflect the new and exciting research that is taking place in the realm of energy gases, they also remind us of the present limits to our understanding. Compared to the hundreds of billions of dollars that have been spent on research and development of coal, oil, and nuclear energy systems and technology, for instance, pitifully little has been spent on the basic research necessary to understand the real potential of natural gas as a long term energy source. As a result, our educational system, our national energy policy, and our economy have traditionally focussed on oil, coal, and nuclear energy. Though this focus is slowly changing, we continue to sustain the momentum in our society for the use of these less efficient, environmentally-degrading energy technologies, even though their external economic and social costs have placed significant limits upon U.S. economic growth, particularly over the last decade. While debate over the role of various fuels during the next several decades will undoubtedly continue, the world-wide increase in use of natural gas clearly reflects the growing demand for a significantly cleaner, more efficient, fuel. Even within the limitations of oil-based thinking, recent estimates of the resource base reflect a changing view of the abundance of natural gas. And the size of the natural gas resource base is likely to continue to grow in proportion to the degree to which we are able to free our thinking from the comfortable limits of outdated perceptions and accept the many new physical and chemical facts that surround the field of geology and the origin of our solar system.

In my view, the long term impact of natural gas as a primary component of our national energy mix will have profound and positive effects on our economy, our ability to compete in world markets, our national and global environment, our strategic defense systems, and ultimately our very role in the 21st century global community. By implementing policies that will allow natural gas to displace oil and coal and become America's principal energy source, we will enhance the efficiency, productivity and security of the economic system, reduce the pollution produced from energy consumption, and decrease the potential of future Middle East wars and predictable oil price shocks. The impact of decisions made now concerning our energy future is so important that increased focus on scientific investigation of the origin and occurrence of natural gas has become urgent. I believe that such work will show that the world has more usable Btus in the form of methane than either oil or coal, and that the United States has sufficient quantities of natural gas to sustain the increased use of this fuel as a principal energy source well beyond the middle of the 21st century. Based upon new thinking about natural gas, I predict that:

1. In the United States, natural gas will remain an affordable and reliable fuel beyond the middle of the 21st century.

2. Natural gas will replace oil as the United States' principal energy source within a decade.

3. Natural gas is so abundant that the only limits to its use will be well in the future when CO_2 emissions from natural gas use could possibly begin to exceed limits set by future global warming treaties.

4. Natural gas use will be exceptionally good for the global economy for both developed and developing nations. In the developed countries, the increased use of natural gas will enhance economic efficiency, expand production, and decrease pollution and carbon dioxide. In the developing countries, the use of locally derived natural gas will reduce the capital required to produce the energy necessary for economic growth and, at the same time, allow these countries to conform to global environmental goals. In

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[17] Article in New York Times, June 8, 1977.

China, for instance, the use of its vast supplies of natural gas (Hefner, 1985) will stimulate growth by reducing demand for capital and by removing huge quantities of coal from its already bottle-necked transportation sector. For developed economies such as the United States, increased use of natural gas will eliminate an enormous capital drain on our domestic economy that would be required by the development and continued use of frontier oil, “clean coal”, or advanced nuclear technology.

5. Natural gas is the beginning of the next long term energy transition (fig. 11). Throughout the history of human economy, each transition in a basic energy system has been driven by a new wave of technological innovation and has uplifted increasingly larger segments of the world population to a higher quality of life. The human economy began with a long period during which we relied upon rather crude, dirty, *solid* sources of energy such as animal dung, wood, and coal. More recently, we have been in a period dominated by a more advanced, cleaner energy system based on *liquids*, using principally oil-based fuels. I think history will record this period as being relatively brief. The liquid oil phase is declining even now and being superseded by the next long term transition which will be fueled by energy *gases*, beginning with methane and leading to hydrogen. As in the past, the energy gas transition will continue toward more technologically advanced, more efficient, and cleaner energy inputs to our economy. This transition will move steadily toward an environmentally benign energy system. As the Age of Energy Gases advances, together with revolutionary changes in communications, information transfer, and education, the world economies will become increasingly capable of sustaining economic growth. Toward the end of the 21st century, humankind for the first time will be able not only to lift the entire world population to standards of living and education now known only in the developed nations, and perhaps even beyond, but to do so within a clean global environment. We must begin now to implement policies and economic change that will accelerate our transition into The Age of Energy Gases.

Appendix 1 will appear here

Appendix 2.

Note: This is a very general calculation presented to provide some substantiation of the statement that the amount of recoverable natural gas should equal 1 to 4 times the amount of recoverable oil. It is a highly simplified analysis of a process that is still not well known (see Lewan, this vol. and Price, this vol.). Though it may well raise some questions, I provide it as an example of the ideas upon which the statement is based.

Assume 50% of Kerogen converted to oil
- 30% of oil migrates into reservoir
- 30% of migrated oil is produced from well bore

Therefore 4.5% of original kerogen is produced as oil. This is a high estimate; 1% or 2% is the generally accepted figure.

It follows that:
- 50% of original kerogen is available in some form, probably hydrogen deficient, for conversion to natural gas.
- 70% of oil generated does not migrate and remains in or near the source rock (i.e. 0.7 of original 50% kerogen converted) giving (0.7) (0.50) = 0.35 of original kerogen in place.

Add H_2O, increasing temperature and pressure, and time:
Then 50% of original kerogen plus 35% of original kerogen now in form of oil or bitumen is available for conversion to natural gas. Assuming 50% is converted to natural gas, then 0.85 x 0.5 = 0.425 of original kerogen converted to natural gas.
Assume 60% migrates and 80% is produced from reservoir, then (0.425) (0.6) (0.8) = 0.2 or 20% of original kerogen is available for production as natural gas, or nearly 5 times the amount of oil available (4.5% of original kerogen)

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Figures.

1. United States Primary Energy Substitution Chart shows how successively cleaner, more efficient primary energy sources progressively replace existing sources. Thin lines represent actual consumption. Thicker lines are mathematically fitted to these curves in the historical portion of the chart, and projected into the future.

1a. United State Primary Energy Substitution Close-up focusses upon the large distortion of historical market driven energy transitions as a result of command and control government intervention.

2. United States Natural Gas Projected Production vs. Actual Production Capacity.

3. Recoverable BTUs per 1 Barrel Volume Natural Gas vs Oil from Reservoirs of Increasing Depths.

The following assumptions were used to determine BTU recoveries: 1 bbl. = 5.616 Ft.3; Oil Gravity = 28 degrees API; Gas/Oil Ratio = 300; Gas Gravity = 0.6; 20 % Oil Recovery; 80 % Gas Recovery at Low Pressure increasing linearly to 90 % recovery at 20,000 feet; Temperature gradient = 1 degree F/100 ft.; Surface temperature = 70 degrees F; Pressure gradient =.45 psi/ft.; 1,000 BTU gas. OIL: In the oil case, a temperature shrinkage factor was applied. Therefore a barrel of oil from depth contains slightly less BTUs than a barrel at the surface. GAS: In the case of gas, a formation volume factor (Bg) was used to determine total at-the-surface volumes. OVERPRESSURED ANADARKO BASIN GAS: The normal pressure gradient of 0.45 psi/ft. was used for depths less than 11,000 ft. Below 11,000 ft., the pressure gradient was increased linearly to a 0.9 psi/ft at 20,000 ft.

4. Production decline curves for three natural gas wells: the GHK #1 Green and the Phillips Petroleum Co., Bowers B, both in the Deep Anadarko Basin, and the Amoco Gallagher, in the Arkoma Basin.
5. The pre-1970 Conventional Theory of Porosity vs. Depth.
6. Enlarged photograph of the producing reservoir in the GHK #1 Green illustrating relatively high porosity at 21,600 ft.
7. Production decline curves for the GHK #1-8 Berry.
8. Oil and gas fields, Anadarko Basin, 1965.
9. Oil and gas fields, Anadarko Basin, 1985.
10. Schematic cross section, Anadarko Basin. The area within the thick line indicates the overpressured compartment.
11. Global Energy Systems Transition forecasting the Age of Energy Gases