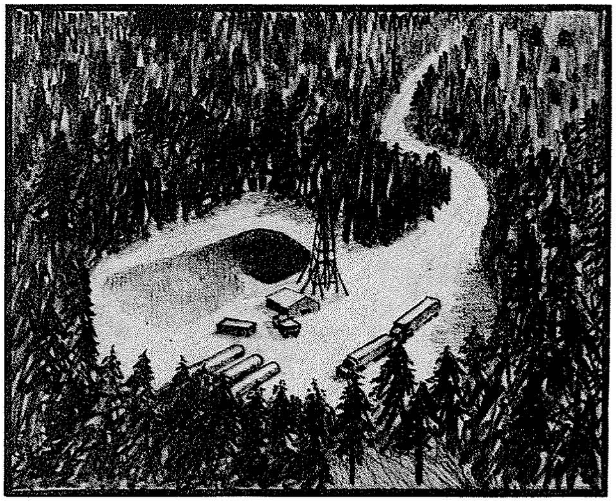
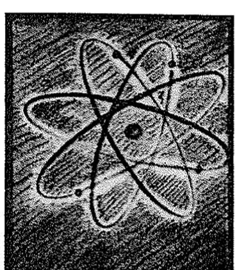
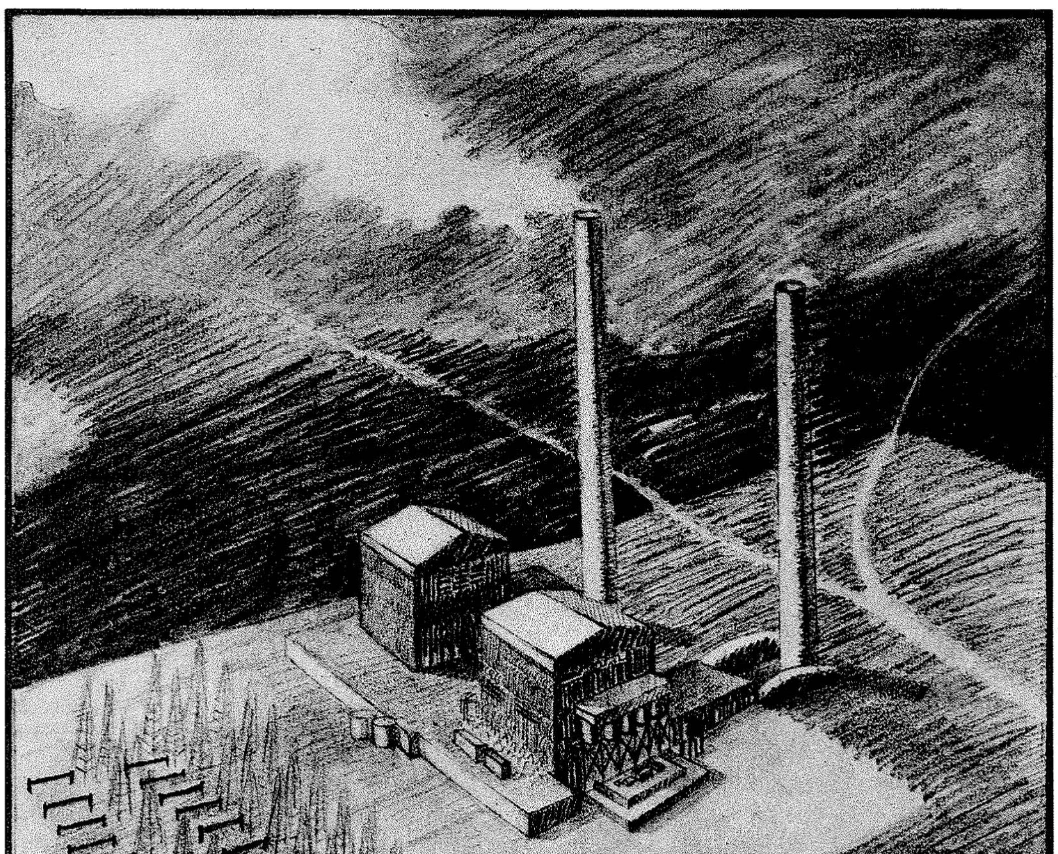
Geological Circular 78-5

Texas Energy Reserves and Resources

by W. L. Fisher







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TEXAS ENERGY RESERVES AND RESOURCES

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This report is based on testimony originally presented to the Texas House of Representatives Interim Committee on Energy Resources, February 16, 1978.

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TEXAS ENERGY RESERVES AND RESOURCES[1]

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Contributing about 25 percent of all the energy ever produced in the United States, Texas has for 50 years led the nation in energy production. Historically, the Texas production has been chiefly from nearly equal amounts of crude oil and natural gas, augmented by smaller amounts of natural gas liquids, uranium, coal, and lignite.

Despite the large and high level of production, the State's endowment of remaining energy reserves and resources is considerable--several times the total production to date. But the future proportions and quantities of energy fuels will not be--indeed cannot be--the same as in the past. Whereas production to date has been largely from conventionally produced oil and natural gas, future production must come in greater percentages from the solid fuels--coal, lignite, and uranium--and from unconventional sources of gas, synthetic gas, enhanced or tertiary recovered oil, synthetic liquids, and geothermal waters. The beginnings of the shift to other fuel sources are already in the making. The production of oil, natural gas, and natural gas liquids has declined since 1972. During this same period both uranium and lignite production in Texas have quadrupled.

Cumulative Production of Energy in Texas

The cumulative production of energy in Texas is just under 500 quads (quadrillion Btu's[2]) (Q) or the equivalent of about 90 billion barrels of oil (table 1). Crude oil has been the leading contributor at 42 billion barrels or approximately 47 percent of the total produced energy. Natural gas produced in Texas has amounted to 212 trillion cubic feet (TCF), the energy equivalent of more than 38 billion barrels of oil. Natural gas liquids have contributed about 9 percent of the total or 8.1 billion barrels. The

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[1]Based on testimony originally presented to the Texas House of Representatives Interim Committee on Energy Resources, February 16, 1978.

[2]Equivalencies for quads are given in table 2.

balance of the historic energy production in Texas, while significant, has been small relative to oil and gas production; 20 million pounds of uranium (U_3O_8), 140 million tons of lignite, and 25 million tons of bituminous coal constitute the equivalent of about 1.2 billion barrels of oil or less than 2 percent of the total historic production of Texas energy.

Table 1. Cumulative production of Texas energy through 1977.

	Conventional Production Units	Barrels of Oil or Oil Equivalent	Quads (Quadrillion Btu's)
Crude Oil	42 billion barrels	42 billion barrels	233
Natural Gas	212 trillion cubic feet	38.2 billion barrels	212
Natural Gas Liquids	8.1 billion barrels	8.1 billion barrels	45
Uranium	20 million pounds	720 million barrels	40
Lignite	140 million short tons	324 million barrels	1.8
Bituminous Coal	25 million short tons	90 million barrels	0.5

Reserves and Resources: Definition of Terms

The terms "reserve" and "resource" are often used interchangeably in casual communication. Yet it is useful, and indeed necessary, to define these terms with some precision if they are to have meaning and utility. Reserves are quantities of energy measured in barrels, cubic feet, British thermal units, quads, pounds, tons, megawatts, megawatt centuries, and the like, which are known to exist with a significant degree of geologic assurance, and which can be recovered with existing technology under current economic conditions. Resources are measured in similar quantities but, in contrast to reserves, (1) are either known with significantly less degree of geologic certainty, (2) or can be extracted only under more favorable economic conditions, (3) or are retrievable only by use of improved technology, (4) or have all three of these characteristics. Resources must move to the reserve category before they can be produced, and can so move only through discovery, through increasing technological feasibility, or through increasing economic feasibility (fig. 1).

Table 2. Texas energy reserves and resources (in quadrillion Btu's).

Identified Reserves

	Measured		Indicated or Inferred	
Economic	Crude oil	47	Crude oil	47
	Natural gas	62	Natural gas	60
	Natural gas liquids	13	Natural gas liquids	13
	Uranium	24	Uranium	40
	Near-surface lignite	87		
	Near-surface coal	7		
	TOTAL	240	TOTAL	160

Subeconomic Resources

Marginal	Tertiary oil	60	Geothermal water	95
	Near-surface lignite	36	Geopressured methane	55
	Deep-basin lignite	260	Tertiary oil	10
			Asphalt and oil shale	5
	TOTAL	356	TOTAL	165
Sub-Marginal	Tertiary oil	60	Tertiary oil	10
	Deep-basin lignite	390	Geothermal water	95
	Deep-basin coal	47	Geopressured methane	55
	Subtotal	497	Subtotal	160
	Uranium (breeder)	1600	Uranium (breeder)	2800
	TOTAL	2177	TOTAL	2960

Undiscovered Resources

Economic		Subeconomic	
Crude oil	60	Tertiary oil	25
Natural gas	225		
Natural gas liquids	48	Subtotal	25
Uranium	65		
TOTAL	398	Uranium (breeder)	4550
		TOTAL	4575

1 Q = 1 quadrillion Btu's
= 180 million barrels oil and gas liquids
= 1 TCF natural gas
= 77 million short tons lignite
= 50 million short tons coal
= 2500 short tons uranium (LWR)
= 25 short tons uranium (breeder)

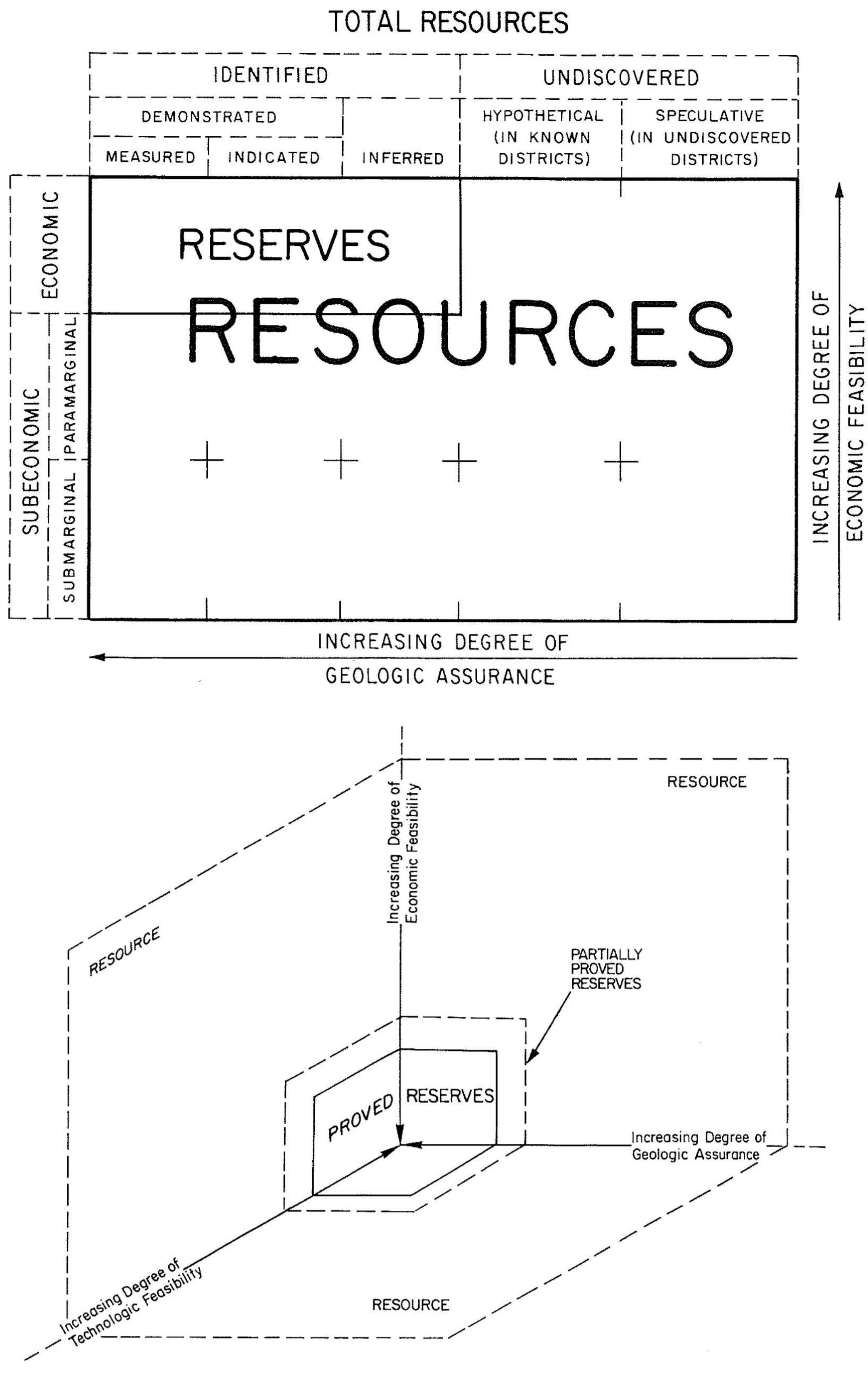

Figure 1. Classification of reserves and resources.

In practice, the terms reserves and resources are variously qualified to reflect varying degrees of geologic certainty, resulting in such common terms as measured, proven, indicated, or inferred reserves, or hypothetical or speculative undiscovered resources; resources are also qualified to reflect varying degrees of economic and technological feasibility.

Calculation, evaluation, and assessment of reserves and resources are essential ingredients both in private planning and in public policy. Nonetheless, it must be emphasized that such calculation is an inexact science. Reserve calculations, the most definitive statement of quantity based on maximum available data, can vary 15 to 20 percent for the same reserve, even when equally competent professionals are making the calculations. Resource estimates can vary an order of magnitude or more, depending on the amount of data available or used or on the specific assumptions made. The numbers in resource calculations have meaning only if assumptions made are explicitly stated. Reserves are analogous to money in the bank or at least to well-secured loans. Resources, in contrast to reserves, are subject to many variables such as geologic knowledge, recovery technology, and economics.

Finally, reserves are not static quantities. Commonly expressed as year-end figures, they are a function of the rate of production and the rate at which resources move through discovery and changing technologic or economic conditions to the reserve category. For example, year-end reserves of Texas oil and natural gas have been declining since the late 1960's because the rate of production has exceeded the rate at which reserves have been added through discovery and through changing economic and technological conditions.

The Reserve and Resource Base of Texas Energy

The following comprises the known elements of the Texas energy reserve and resource base:

(1) Crude oil, recoverable by primary and secondary techniques

(2) Crude oil, recoverable by enhanced or tertiary techniques

(3) Natural gas, conventionally recoverable

(4) Unconventional gas, including methane gas, present in solution in geopressured, geothermal water, and synthetic gas, recoverable by gasification of lignite and bituminous coal

(5) Natural gas liquids

(6) Lignite and bituminous coal

(7) Geothermal waters, in geopressured reservoirs or aquifers with intermediate-temperature waters

(8) Uranium

(9) Synthetic liquids, from coal, lignite, rock asphalt, tar sands, and oil shale

Crude Oil: Reserves and Resources

Approximately 180 billion barrels of oil have been discovered in place in Texas. Of this amount nearly 60 billion barrels will be recovered by primary and secondary production techniques. To date, nearly 42 billion barrels have been produced, leaving a 1977 year-end measured reserve of just under 8.5 billion barrels.[3] Current, measured reserves are at the lowest level since the earliest days of Texas oil history. The history of year-end reserves shows a gradual annual rise in quantity, reaching a peak of 15.3 billion barrels in 1951. From 1951 through 1967, reserve additions generally matched production so that year-end reserves remained essentially stable; 1967 reserves were 95 percent of the peak reached in 1951. Since 1967, reserve additions have averaged only about one-half of production, resulting in a sharp decline in annual year-end reserves; current reserves are barely half of the peak reached in 1951 (fig. 2). The future level of measured year-end reserves of crude oil will depend on the following: (1) the volume of additional, identified reserves classed as inferred and indicated, (2) the volume of oil remaining as undiscovered resources, (3) the rate of drilling and the rate of finding the remaining undiscovered oil, and (4) the extent to which oil in place can be recovered by enhanced technology and methods, in contrast to recovery by primary and secondary methods.

In addition to measured reserves (called proved reserves by the American Petroleum Institute), the U. S. Geological Survey (USGS) reports additional, identified reserves in the categories of indicated and inferred. Indicated reserves include basic, additional reserves from known reservoirs available through fluid injection; extrapolated volume for indicated reserves in Texas is approximately 2 billion barrels. Inferred reserves include quantities that should be eventually added to known fields through extension, revision, and new reservoirs; extrapolated volume for inferred reserves in Texas is approximately 6.5 billion barrels. Inferred reserves represent statistically the volume by which initial discoveries tend to increase with subsequent development and production drilling. Because the average size of new field discoveries is decreasing, it is likely that the increase in reserves through subsequent

[3]As reported by the American Petroleum Institute.

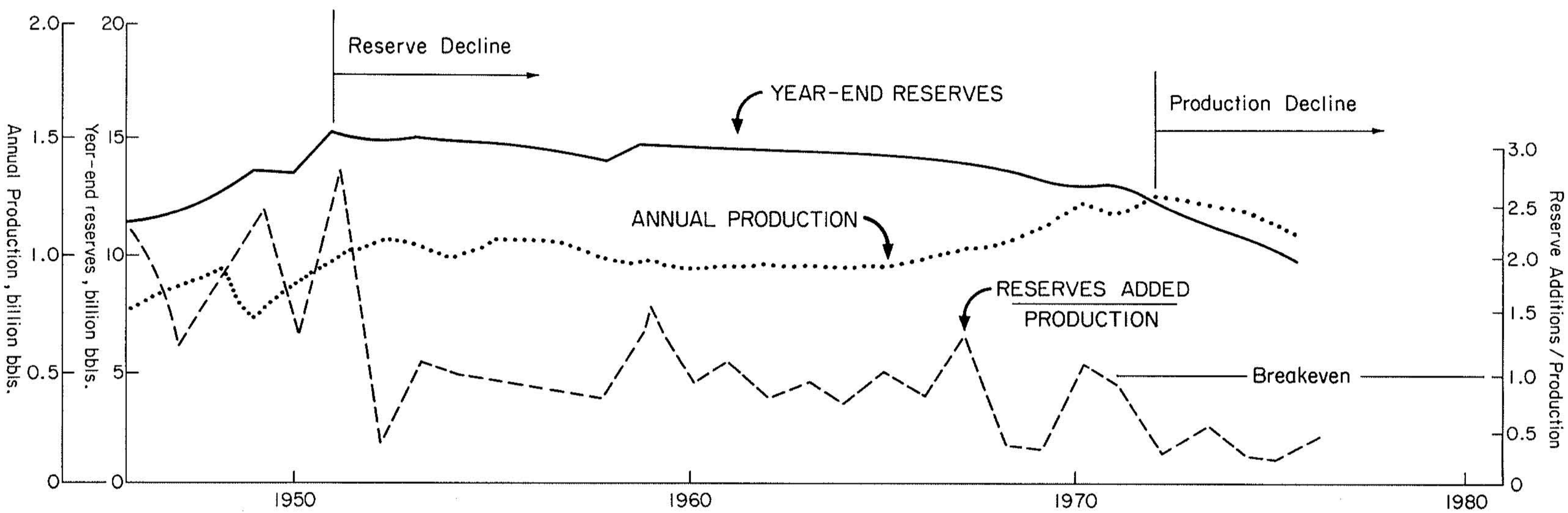

Figure 2. Texas crude oil production and reserve trends.

development and production drilling may be less in the future than it has been historically. Consequently, the reported volume of inferred reserves may be optimistic. But assuming that inferred reserves are at 6.5 billion barrels, that indicated reserves are about 2 billion barrels, and that measured reserves are 8.5 billion barrels, the total identified crude oil reserves would be 17 billion barrels, or 15 times current annual production.

A second major consideration in future reserve levels is the volume of yet-to-be-discovered, recoverable oil. No specific calculations have been reported for Texas, though several estimates have been made for the United States as a whole and for certain subdivisions of the United States. Extrapolated from these calculations, estimates of yet-to-be-discovered, recoverable crude oil in Texas range from about 6 to 20 billion barrels and have a mean of approximately 11 billion barrels (Miller and others, 1975).

Given the extensive drilling that has occurred in Texas to depths at which oil is commonly found, the conservative side of these estimates may be more probable. A total resource figure (measured, indicated, and inferred reserves plus undiscovered resources) thus would range from about 23 to 37 billion barrels and have a mean of about 27 billion barrels. This compares with a historic cumulative production of 42 billion barrels. While an undiscovered resource of approximately 11 billion barrels is yet a substantial exploration target, the rate at which these undiscovered resources can become producible reserves is critical in modifying current production trends in the near future.

For the past five years, Texas production of crude oil has declined an average of about 2.6 percent per year. Measured year-end reserves have declined at an even more drastic rate of about 6 percent annually. Since 1920 an average of about 860 million barrels of recoverable oil have been found each year in Texas; during this same 57-year period, production of crude has averaged about 710 million barrels per year. These historical averages, however, do not reflect the more recent trends. In the heyday of discovery, from 1925 to 1944, average annual reserve additions amounted to 1.5 billion barrels; during the period 1945 to 1953, this average dropped to about a billion barrels per year, roughly equivalent to average annual production during that period. But starting in 1954 and continuing through 1963, average annual discovery of crude oil declined, dropping to only 350 million barrels, roughly one-third of the existing production rates. Then from the early sixties until the present, production climbed to a record 1.3 billion barrels in 1973; average annual discoveries amounted to 60 million barrels, one-twentieth of the average rate of production (fig. 3).

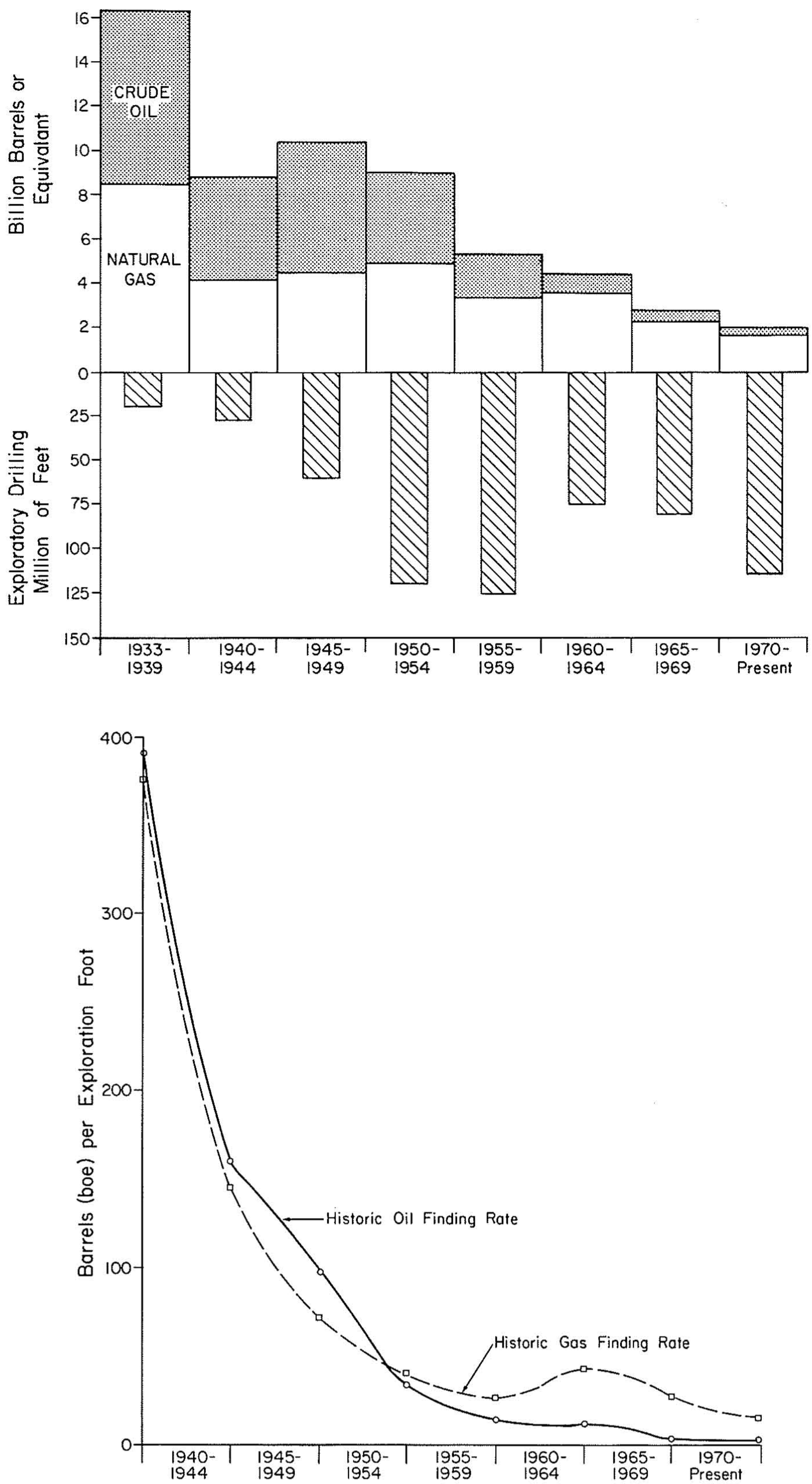

Figure 3. Historic relationship: exploration drilling, oil and gas discoveries, and oil and gas finding rates, Texas.

The substantial reduction in volume of reserves added each year, starting in the 1950's and continuing to the present, is due primarily to a decrease in discovery rate, and not to a major decrease in current exploration activity relative to early years. In recent years the amount of oil discovered per foot of exploratory drilling has been approximately four barrels per foot. If only that portion of exploratory drilling credited to oil well completions and a prorated portion of the recorded dry holes are considered, the oil finding rate is about 10 barrels per foot. Although low, the recent rate of finding has remained relatively stable and should remain so into the immediate future. There is little basis for projecting a significant decline in the rate of finding over the next few years. Increased drilling will thus increase the volume of oil discovered, assuming the finding rate remains stable, but discovery alone will most likely not be sufficient to modify significantly the generally declining trend in crude oil production.

To date, approximately 180 billion barrels of oil have been discovered in place; if the yet-to-be-discovered recoverable volume of crude oil is 11 billion barrels, an additional 35 billion barrels will be discovered in place. (Assuming a 32-percent recovery by primary and secondary recovery techniques, a total of approximately 70 billion barrels will be recovered, leaving about 145 billion barrels in place.) This volume, obviously, constitutes a major potential target for recovery. Enhanced recovery techniques are available to recover a significant portion of this oil, but such techniques cost substantially more than can be offset by existing oil prices. A recent analysis published by the National Petroleum Council (NPC) (1976) concluded that a significant volume of oil could be recovered by using advanced recovery techniques. At a price of $25 per barrel (1976 dollars), an estimated additional 9 billion barrels of Texas crude could be recovered from known fields between now and year 2000 through enhanced oil recovery (EOR) techniques. Under these assumptions, approximately 80 million barrels a year could be produced in 1980, 300 million barrels in 1985, 570 million barrels in 1990, and up to 590 million barrels in 1995. Thereafter, production through EOR would decline to about 540 million barrels in 2000.

Clearly, the volume in oil remaining in place is huge. There are, of course, physical limits to recovery even with enhanced techniques. A subeconomic resource base at approximately 30 billion barrels is calculated here, assuming that an additional 20 percent of the existing and to-be-discovered oil in place, not recoverable by primary and secondary methods, can ultimately be recovered by enhanced methods. The volume actually to be recovered is heavily dependent on price and future technology. For example, under provisions of the National Energy Plan, 1977 (NEP), which prices tertiary oil at current world price, a little less than one-half the amount projected by NPC through 2000 would be recovered (Fisher and others, 1978).

Texas oil production will continue to decline at least for the immediate future. Since decline began in 1973, it has averaged 2.6 percent annually; the largest decline was last year (1977) and amounted to 4.3 percent. Continued increased drilling may slow somewhat the rate of production decline, but barring a significant, yet unlikely, improvement in the rate of finding, new discoveries and reserve additions probably cannot stabilize production at levels comparable to current production. Stabilization of production, possibly at a level of about 80 percent of current production, could occur, but such stabilization would require tertiary production at levels projected by NPC at a price of $25 per barrel (1976 dollars) and, as well, a continued, aggressive drilling program.

Natural Gas: Reserves and Resources

By the end of 1977, approximately 330 TCF of natural gas had been discovered in Texas; 212 TCF or nearly 65 percent of that discovered to date has already been produced. Identified measured reserves are reported by the American Gas Association (AGA) at about 62 TCF; to this amount the USGS assigns an additional 60 TCF carried as identified, inferred reserves.

Whereas the recovery of oil by conventional methods averages about 32 percent of the original oil in place, recovery rates of natural gas are much higher, commonly up to 85 percent or higher. As a result, there is less opportunity to apply enhanced recovery techniques--beyond conventional methods--to natural gas as there is to crude oil. Exceptions are certain tight geological formations such as the Devonian shales, the sandstones in the Rocky Mountain basins, as well as certain Texas formations.

As with oil, the year-end identified reserve quantity of natural gas is dynamic and changing. It is the trend in reserve volume and the factors controlling this trend that assume importance even greater than the absolute reserve number. Texas year-end reserves of natural gas gradually increased from the early days of oil and gas exploration and reached a peak of 125 TCF in 1967. Current reserves of 62 TCF are the lowest in long-term history and are less than 50 percent of peak reserves existing 10 years ago (fig. 4). This rather drastic decline in measured reserves is due simply to the rate of production outpacing the rate of reserve addition. Until the early 1950's, additions to reserves substantially exceeded production. From 1952 through 1967 reserves were added at a rate generally equal to production, even though production

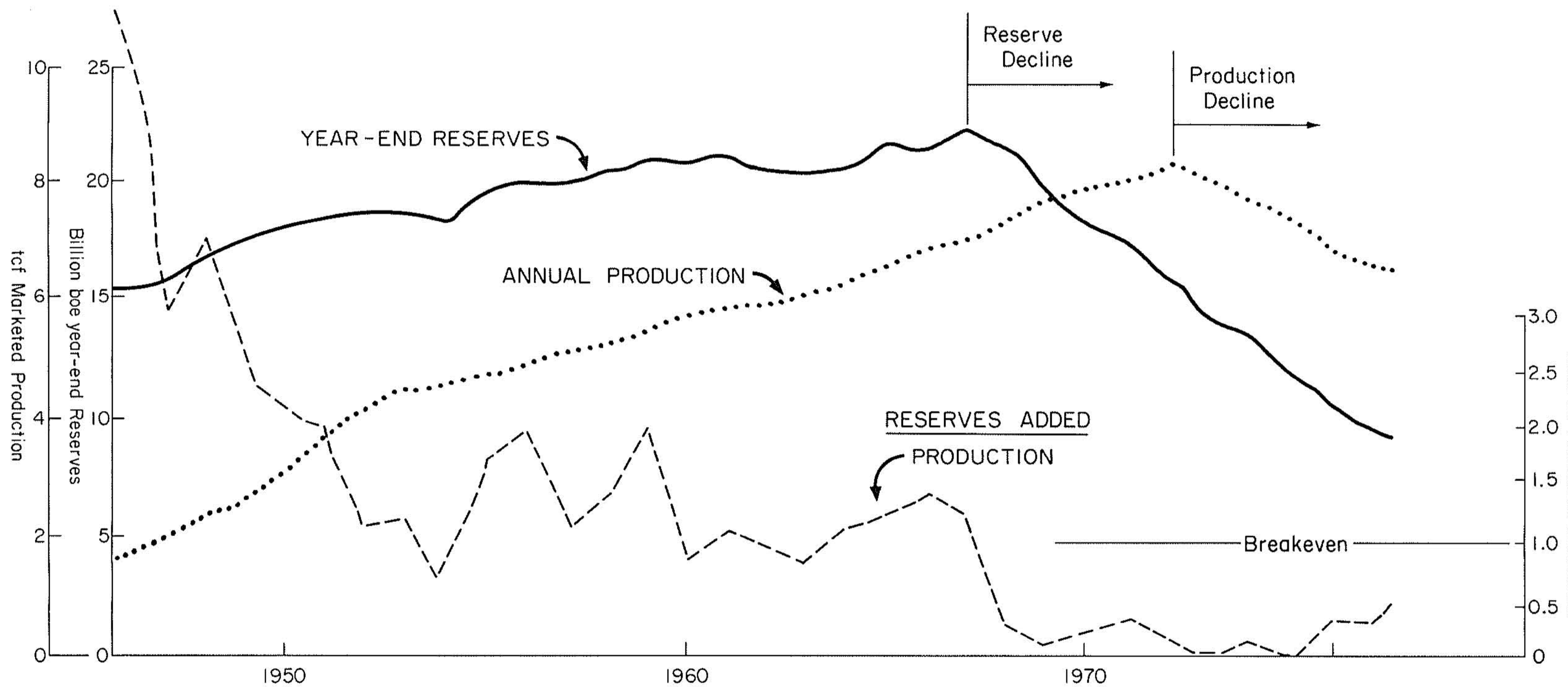

Figure 4. Texas natural gas production and reserve trends.

doubled during that period. Since 1967, however, reserve additions have averaged no more than 15 percent of production. Because of this drop in reserve addition, further worsened by two years (1973 and 1975) of negative revisions amounting to nearly 2.5 TCF, the significant decline in production that began in 1973 was inevitable (fig. 4). Since peak production in 1972, Texas production of natural gas has declined 24 percent, or an annual average of 4.8 percent.

Although recent declining trends in year-end reserves and in production are drastic, several factors relative to Texas natural gas could arrest these trends and even lead to stabilized or increased levels of future production. Indeed, the future of Texas natural gas seems considerably brighter than the future of Texas crude oil production.

For one, the substantial increase in drilling in Texas over the past five years has led to a 26-percent increase in the number of gas wells (35,231 in 1972 compared with 44,432 in 1977) and a 20-percent increase in number of producing fields (9,406 in 1972 compared with 11,317 in 1977), according to the 1977 Annual Report of the Texas Railroad Commission Oil and Gas Division. Furthermore, recent increases in drilling activity are beginning to show in reserve additions, which in 1977 amounted to 4.3 TCF, the highest addition posted since 1967 and better than half the total reserve addition of 8.3 TCF posted for the period of 1968 to 1976.

Secondly, the identified reserves (measured plus inferred) are larger for natural gas than for oil (21.5 billion barrels of oil equivalent of gas versus 16.5 billion barrels of oil), and the percent of total identified reserves already produced is less for gas than for oil (64 percent for gas, 72 percent for oil).

Thirdly, estimates of yet-to-be discovered natural gas are higher than those for oil. According to figures extrapolated from USGS (Miller and others, 1975) estimates, an undiscovered resource ranging from 90 to 225 TCF, with a statistical mean of about 150 TCF, exists in Texas. These figures are approximately 2.5 times greater in oil equivalency than similar estimates for oil. National estimates made by the Potential Gas Agency (1977) are about twice the national estimates of the USGS, and at least some basis exists for characterizing the USGS estimates as conservative. The average depth of exploration wells is about 6,000 feet; currently, only about 1 percent of all exploratory drilling is at depths greater than 15,000 feet. While hydrocarbons in the liquid state (crude oil) occur almost exclusively at depths where most of the historical drilling has taken place, hydrocarbons in the gaseous state may exist to depths in excess of 25,000 feet. Consequently, even in areas extensively drilled at shallow depths, such as the Texas basins, a significant part of the potentially gas-prone section in oil and gas basins is relatively untested. Accordingly, an estimate of 225 TCF of undiscovered gas, the higher USGS estimates, seems reasonable. Certainly, the frequency of potential reservoir rock is less at greater depths (due to lower permeabilities) in certain basins like the Texas Gulf Coast. Furthermore, at depths in excess of 15,000 feet, costs of drilling and completion are significantly higher. For example, cost of the average deep well in Texas in 1976 (below 15,000 feet) was about $2.24 million, whereas cost of the average well between 5,000 and 7,500 feet was approximately $175,000 (American Petroleum Institute, 1977).

Finally, although the rate of finding for natural gas, as for oil, is substantially lower than in earlier years, the gas finding rate has stayed at higher levels--about twice that of oil (fig. 3). Furthermore, while a future increase in the oil finding rate does not seem likely, an improved gas finding rate is possible with deeper drilling.

In addition to conventional gas sources, other potential sources of gas include methane in solution in geopressured geothermal waters and synthetic gas derived from lignite and coal. These potential sources are considered in following sections of this report on lignite and geothermal resources.

Therefore, the volume of remaining reserves (62 TCF) plus expected resources (approximately 225 TCF) and a reasonable finding rate that possibly could improve offer a potential basis for arresting production decline in conventionally recovered natural gas, thus stabilizing production at a substantial level, or even increasing the current level of production. Obtaining any of these possibilities will require significant increases in the volume and depth of exploratory drilling, which are both highly sensitive to natural gas prices.

Natural Gas Liquids: Reserves and Resources

Natural gas liquids (NGL), largely liquid petroleum gas, ethane, natural gasoline, and isopentane, are products separated as liquids from produced natural gas. Cumulative Texas production of NGL through 1977 has amounted to about 8.1 billion barrels from a total natural gas production of 212 TCF. Reserves and resources of NGL are directly a function of natural gas reserves and resources. Assuming that the historic as well as the recent NGL/gas ratio of 26 barrels per MMCF holds, NGL reserves and resources are as follows:

Identified Reserves	Gas	NGL
Measured	62 TCF	2.4 billion barrels
Inferred	60 TCF	2.3 billion barrels
Undiscovered Resources	225 TCF	8.7 billion barrels
	TOTAL	13.4 billion barrels

Lignite Coal: Reserves and Resources

Lignite or low-rank coal occurs extensively in the Coastal Plain portion of Texas and is principally concentrated in East Texas. Lignite is found mainly in three geologic formations: the Wilcox, the Yegua, and the Jackson. The most extensive and better grade deposits are in the Wilcox of East Texas.

Lignite and bituminous coal were the principal energy fuels in Texas during the latter part of the 19th century and through the 1920's. With the advent of oil and natural gas, coal was displaced as a significant fuel source. The return to lignite as a fuel began in the middle 1950's, and by the early 1970's, as natural gas became less abundant and more expensive, interest in lignite as a fuel for power generation increased dramatically. To date, about 140 million tons of Texas lignite have been produced, and nearly half that production has been posted since 1970. Based on the capacity of mines and plants now in operation plus those scheduled to be in operation, Kaiser and Cooper (1978) project 1985 production of Texas lignite at about 65 million tons. About 90 percent of this production will go to support an installed power generation capacity of about 12,000 MW, about 30 percent of the State's 1985 projected electrical demand; the balance will be used in the industrial sector. The significant shift toward lignite as a power generation fuel is rather directly a function of the abundance of the resource, the price of natural gas in the intrastate market, the availability of natural gas, and the existing State policy as articulated in Texas Railroad Commission Docket 600, effective December 1975.

Calculations and estimates of Texas lignite reserves and resources historically have been made by The University of Texas at Austin Bureau of Economic Geology (BEG). These figures have been the source or basis of calculations also reported by the

U. S. Bureau of Mines (USBM), the U. S. Geological Survey (USGS), and the U. S. Department of Energy (DOE). The first significant calculation was made in 1955 (Perkins and Lonsdale) followed by calculations made by Fisher (1963), Kaiser (1974), and most recently by Kaiser (1978). The Bureau of Economic Geology is currently (1978) conducting detailed reserve and resource calculations, based in part on industry drilling data, for the Texas Energy Advisory Council.

Trends of these estimates have been toward an upward revision of reserve volume, largely due to the availability of more data and greater geologic synthesis with time. Recent estimates (Kaiser, 1974, 1978) have distinguished between near-surface lignites, those under less than 200 feet of cover, and deep-basin lignites, those at depths greater than 200 feet. Values reported for the near-surface lignites are considered identified resources, based on actual measurement and reliable geologic inferences. A portion of these (to depths of 150 feet) are designated as reserves based on current recovery factors, land availability, and economics. The deep-basin lignites, likewise, are identified but are not designated as reserves because their recovery depends on more favorable economics and improved technology. In the future, it is likely that lignite now classed as resources, including both deep-basin and certain near-surface deposits, will move to the reserve category.

Near-surface lignite, as noted previously, is that lignite under less than 200 feet of cover. An excellent understanding of regional geology combined with tangible evidence of lignite occurrences (outcrops, earlier and current mine workings, and boreholes) provides the basis for reserve estimates. Estimation rests on such geologic evidence as stratigraphic occurrence, sand-body geometry, ancient depositional environments, regional dip, and projection up-dip from the deep basin. These data allow determination of potential acreage underlain by lignite; where a large amount of data exists, actual productive acreage may be calculated. The ratio of productive to potential acreage is then applied to potential acreage in similar geologic settings. Lignite thickness assigned is typical for the area under consideration. In all cases 1,750 tons/acre-foot is used.

The most recent BEG estimate of near-surface lignite resources was published in January 1978 by Kaiser. In-place lignite resources amount to 12,197 million short tons (158 Q), excluding lignites in seams less than 3 feet thick. Reserves, lignite that can be economically recovered today, are estimated assuming surface mining to 150 feet, an illegal fraction[4] of 10 percent, and a recovery factor of 85 percent. Under

[4]Includes such unavailable lignite as that beneath urban areas, highways, and rivers.

these assumptions, statewide reserves are set at 6,740 million short tons (87 Q). Inclusion of lignite beneath 150 and 200 feet of cover would increase current reserves by 2.8 billion short tons (36 Q). Heating values assigned to the Wilcox, Jackson, and Yegua lignite-bearing geologic units are 7,000, 5,000, and 6,000 Btu/lb., respectively. Deep-basin lignites are those that occur at depths greater than 200 feet. These occur extensively throughout the Texas Coastal Plain and have been mapped using logs and records from more than 3,000 oil and gas wells. These deep-basin lignites were first delineated by the BEG in 1974 (Kaiser) and are calculated to represent approximately 100,000 million tons.

These lignites will be recoverable only by in situ recovery methods; underground or deep-mining is possible but unlikely due to inherent problems in underground mining in unconsolidated sediments. The kind of recovery closest to near-term commercialization is in situ gasification. Current technology limits the process to 2,000 feet, and consequently the resource base is set at 40 billion tons or that portion of the resource occurring at depths ranging from 200 to 2,000 feet. In situ gasification requires gasification of a lignite seam underground to recover the products as a low-Btu gas (carbon monoxide and hydrogen diluted with nitrogen). The heating value assigned is 6,470 Btu/lb., a weighted average based on near-surface lignite values by geologic unit. Thus, a ton of lignite so burned will yield the equivalent of about 130 MCF of gas. If 50 percent of the approximately 40 billion tons of deep-basin lignites in place at depths from 200 to 2,000 feet were recovered, total yield would be 2,600 TCF of synthetic gas. As such, synthetic gas has a Btu value about one-tenth that of conventional natural gas; the gasified coal resource base is the energy equivalent of about 260 TCF or 260 Q of conventional gas. The development of advanced techniques to gasify lignite in place down to depths of 5,000 feet would increase this resource to the energy equivalent of 650 TCF of conventional natural gas.

In conclusion, recoverable reserves of Texas lignite, calculated to be 6.7 billion tons, are considerable. Lignite resources potentially recoverable at higher prices or with improved technology could increase the reserve volume eightfold and, of course, provide an even greater ingredient in the energy future of Texas.

As a measure of the volume of Texas lignite reserves and the energy production they will support, we may consider the volumes needed to support the 12,000 MW of projected, installed, lignite-generating capacity by 1985. The generation of 1,000 MW of electricity requires about 5.5 million tons of lignite per year. Maintenance of 12,000 MW of capacity through normal 30-year plant lives will require just under 2.0 billion tons of lignite, or about 30 percent of the presently identified reserve.

Bituminous Coal: Reserves and Resources

Bituminous coal occurs in the north-central part of the State and at a few localities along the Rio Grande in South Texas and in Trans-Pecos Texas. Although not nearly as abundant, the Texas bituminous coals are higher in heat value than Texas lignites, occur in relatively thin seams, and are commonly high in sulfur content.

Total historic production of bituminous coals in Texas has amounted to about 25 million tons. None has been mined in recent years, nor is any bituminous coal now being mined in the State. However, a mine which will produce about 300,000 tons per year is now opening in South Texas near Laredo where bituminous (so-called cannel coals) will be produced for industrial use. Kaiser and Cooper (1978) project a total 1985 bituminous coal production of about 3 million tons, which will be used in the industrial sector specifically for rotary kiln heating in cement manufacture.

Bituminous coals are not as well delineated as Texas lignites; estimates herein are based on reports of the USGS (Mapel, 1967) and the BEG (Evans, 1974). Near-surface statewide resources (0 to 200 feet) are set at 790 million tons and are calculated by taking 20 percent of the resources to depths of 1,000 feet. Reserves are estimated assuming surface mining to 150 feet, an illegal fraction of 10 percent, a recovery factor of 80 percent, and 20 percent lost in washing. Under these assumptions reserves are set at 330 million tons (6.5 Q). Heating value assigned is 10,000 Btu/lb. The deep-basin resource in place is 4,700 million tons, of which 50 percent or 2,350 million tons (47 Q) is potentially recoverable, most probably by in situ or in place recovery methods.

Given the relatively small resource base of Texas bituminous coals, their occurrence in thin seams, and their high sulfur content, near-surface mining of the coals will most likely be for relatively small volume industrial use where a heat value higher than those obtained from lignites is required. The potential for recovery, whether by deep mining or by in situ recovery, of the deep-basin bituminous coal is severely restricted by seam thickness.

Uranium: Reserves and Resources

Uranium, the fuel for nuclear reactors, occurs in three known areas of the State: the Coastal Plain (mainly concentrated in South Texas), Trans-Pecos Texas, and North Texas. Sustained commercial production has been limited to South Texas where a cumulative State production of about 20 million pounds or approximately 10,000 tons has been produced.

Estimates of national reserves and resources are compiled by the Department of Energy (formerly Energy Research and Development Administration and Atomic Energy Commission) and are based on different cost levels (most recently \$15.00, \$30.00, and \$50.00) per pound of U_3O_8.[5] Historic uranium reserves and resources have been divided into the following categories: (1) ore reserves, based on actual measurement data and equivalent to identified, measured reserves; (2) probable resources, quantities in known districts based on geologic inference, (3) possible resources, and (4) speculative resources.

Ore reserves for Texas (identified, measured reserves) are given as 54,000 tons of U_3O_8 by DOE (1978), based on a \$50.00 per pound cost level. This figure compares with unofficial industry estimates ranging from 50,000 to 75,000 tons. The DOE figure includes reserves recoverable by solution mining. The rate of exploratory drilling for uranium continues high; in 1971, 5.8 million feet, equal to 25 percent of the 1977 oil and gas exploratory footage, was drilled.

Basing calculations on an analysis of ERDA figures, Dickinson (1976) reported 100,000 tons as probable resources, a value here included as inferred reserves. In addition, an undiscovered (possible and speculative resource) quantity of uranium is estimated at approximately 160,000 tons.

No uranium reserves are attributed at this point to areas of North Texas and Trans-Pecos Texas. Assessment is now underway in those two areas as well as other areas of the State by the BEG in cooperation with the USGS and DOE. It should be emphasized that the estimates of possible and speculative resources are just that--possible and speculative. If exploration programs in the frontier areas of Texas--North Texas Permian and Triassic, East Texas, South Texas Carrizo and Wilcox, and Trans-Pecos volcanics--prove successful, current estimates would be quickly outdated; likewise, poor results from exploration in these areas would leave current possible and speculative resource estimates inflated.

All reserve and resource values assume utilization of uranium in light-water reactor (LWR) technology. If, however, a breeder technology is employed the energy yield from Texas uranium would be increased about 60 to 80 fold.

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[5]Estimated operating and forward capital costs are used; profits and sunk costs are excluded and, accordingly, cost categories are not representative of prices.

Geothermal Resources

Potentially significant sources of energy in Texas are geothermal waters, subsurface formation waters occurring at temperatures above the normal geothermal gradient. These range from the low- to intermediate-temperature waters associated with hot springs in the Trans-Pecos and Central Texas areas to the higher temperature waters in abnormally pressured (geopressured) zones in the Texas Gulf Coast Basin. The low- to intermediate-temperature geothermal waters (generally between 45° and $100^{\circ}C$) have potential utilization largely restricted to local space heating. Average temperatures of the geopressured geothermal waters, by contrast, range from 140° to $180^{\circ}C$, thus they have the potential for steam energy (through flash separation or through use of binary systems) as well as for at least some mechanical energy because of high pressures associated with such waters. In addition, the geopressured geothermal waters of the Gulf Coast Basin contain methane gas in solution, which is also a potentially recoverable energy source.

The Trans-Pecos and most of the Gulf Basin resources have been recently assessed by the BEG, and a program is currently underway to assess the Central Texas geothermal resource. However, at this time preliminary resource estimates are established only for the Texas Gulf Basin area, and until test well data are obtained, resource volumes for this area must be inferred from geologic evidence. (Drilling of a test well in Brazoria County began in late June, 1978.)

Low- to Intermediate-Temperature Geothermal Waters

Geothermal resources of Trans-Pecos are located along the Rio Grande between El Paso and Presidio where there are about 20 hot springs or wells in Texas and Mexico. The hot waters result from circulation of ground water to depths of 1 to 3 kilometers in an area of high thermal gradient. Maximum temperatures are $47^{\circ}C$ ($117^{\circ}F$) and $80^{\circ}C$ ($176^{\circ}F$) for hot springs and wells in Texas and $90^{\circ}C$ ($194^{\circ}F$) for hot springs in Mexico within 5 kilometers of the border. Subsurface temperatures estimated from chemical composition of the hot waters range from $60^{\circ}C$ ($140^{\circ}F$) to $160^{\circ}C$ ($320^{\circ}F$). Still higher temperatures may exist but cannot be proven without more subsurface information (Henry, 1977). Preliminary assessment of geothermal resources of the Trans-Pecos area have recently been completed by the Bureau of Economic Geology (Henry, 1977).

Presently identified temperatures of these hot waters are too low for established electrical generation methods. Development of heat-exchange systems that employ low boiling temperature fluids would be necessary before the hot waters could be used for power generation. The hot water could now be used for space or process heating, but the low population density and high annual temperature of the most promising area, which is around Presidio, limit this use.

In Central Texas, along the Balcones and associated Luling-Mexia-Talco fault systems, which trend northeast to southwest across Central Texas, abnormally hot waters have been produced for decades. Waters, such as those that flow from wells at Marlin, Texas, are highly saline (3,770 ppm) and exhibit surface temperatures of about 65°C. Well depths are from generally 2,500 to 3,000 feet.

Undoubtedly, hotter waters occur at greater depths. For example, temperatures of 116°C have been reported from deep, saline aquifers in the Luling fault zone in Atascosa County. Other hot wells have been reported from the Balcones zone in the Waco and Austin areas. These hot waters occur within aquifers of Cretaceous age (Trinity Sands, Edwards Formation), but the ultimate source of the thermally anomalous waters may be from deeply buried Cretaceous and Jurassic rocks in the East Texas Basin, or from older, structurally complex rocks of Paleozoic age within the deeply buried Ouachita foldbelt system that lies beneath the fault zones, or from both.

The potential low-temperature geothermal fairway defined by the Cretaceous aquifers, the complex faulting, and the zone of abnormally hot and saline water, is about 500 miles long and 75 miles wide. It extends from Grayson, Fannin, and Lamar Counties along the Red River southwestward through the vicinities of Hillsboro, Waco, Temple, Austin, and San Antonio to the Mexican border in Kinney and Maverick Counties. If this geothermal resource can be accurately defined in area, depth, and thermal levels, its use in space heating systems by cities within the fairway could be specifically evaluated. Approximately 40,000 square miles across Central Texas are potentially underlain by anomalously hot waters. Assessment of these resources is currently underway by the BEG in cooperation with the DOE; results of this study are scheduled for publication in 1979.

No resource estimates are presented at this time for the low- to intermediate-temperature geothermal waters of Central Texas and Trans-Pecos Texas; such estimates are awaiting further study and assessment. In this area potential use of geothermal waters is restricted to local space heating and cannot be used to generate electrical energy that could be stored or transported.

Geopressured-Geothermal Waters: Thermal Energy and Methane Gas

Several geologic formations in the Texas Gulf Coast Basin contain zones of waters that have abnormally high temperature and pressure. These zones have an areal extent of more than 25,000 square miles and are up to 8,000 feet thick. Occurring at depths of 10,000 to 20,000 feet and greater, they constitute the geopressured geothermal resource of the Texas Gulf Coast. Average temperatures of these waters are approximately 300^{o}F; average reservoir pressures are about 10,000 psi; average salinities range from 25,000 to 50,000 ppm.

Methane gas appears to occur in solution in the waters, the saturation levels depending on salinity, temperature, and pressure. Average concentrations of methane gas are judged to range from 34 to 47 cubic feet per barrel of water.

Energy is potentially recoverable from these geopressured reservoirs in three forms: (1) thermal energy resulting from elevated temperatures, (2) mechanical energy as a function of reservoir pressures, and (3) methane gas in solution in the geothermal waters.

Published estimates of onland Gulf Basin geothermal resources, of which about 65 percent are assumed to occur in Texas, vary widely; in several instances exceptionally high estimates--up to 105,000 Q or 105,000 TCF of methane gas alone--have been reported. These estimates bear little or no relation to technical facts as now understood.

In 1975 the U. S. Geological Survey published estimates of the Gulf Coast geothermal resource. The total in-place resource extrapolated for onland Texas was reported as follows:

Thermal energy		26,150 Q
Methane		14,425 Q
Mechanical energy		120 Q
	TOTAL	40,695 Q

The USGS further reported recovery volume of the in-place resource at 3 levels: 3.3 percent recovery based on a well spacing ranging from 1.9 to 2.9 km; 2.1 percent recovery based on a well spacing ranging from 2.3 to 2.9 km; and 0.5 percent recovery based on a well spacing ranging from 4.8 to 7.1 km. It should be pointed out that a 3.3 percent recovery by USGS calculations would require the drilling of 26,000 wells, nearly 10 percent the number of all oil and gas wells ever drilled in the Gulf Coast

Basin, and that these geothermal wells would be substantially deeper than the average, previously drilled oil and gas wells.

As follows, recoverable volume extrapolated for Texas is reported by the USGS in quads:

	3.3%	2.1%	0.5%
Thermal energy	860	550	125
Methane	465	295	70
Mechanical energy	ignored	25	ignored
TOTALS	1,325 Q	870 Q	195 Q

The USGS estimates of recoverable energy from Texas geothermal resources, while conservative compared with certain estimates, are huge, nonetheless. As a point of reference, the 3.3-percent recovery of 1,325 Q reported by the USGS is 2.7 times greater than all the energy ever produced in Texas and is equal to 80 percent of all the energy ever produced in the United States.

Three years ago the Bureau of Economic Geology undertook, under contract with ERDA (now DOE), an extensive geologic assessment of Texas geopressured geothermal resources (Bebout and others, 1978). Most of that geologic assessment is now complete. Records of about 3,000 well logs were studied, hundreds of cores were examined, and numerous water samples were tested; the various geopressured geothermal zones as well as critical parameters were mapped extensively and in detail.

The Bureau of Economic Geology has defined, on the basis of this more detailed assessment, several fundamental factors which are critical to resource assessment yet which differ significantly from assumptions made by the USGS in calculating their estimates. For example, the volume of potential reservoir sand mapped by the BEG is less than half that assumed by the USGS; average temperatures are about 10 percent less; average porosity values are about 15 percent lower; average pressures are about 12 percent less; and average salinities are about 55 percent greater. BEG determinations, based on a much more extensive evaluation of available data, have the effect of significantly reducing the size of this in-place and thus recoverable resource. BEG estimates are as follows:

	In-Place Resource	3.3% Recovery
Thermal energy	2825 Q	95 Q
Natural gas (methane)	1630 Q	55 Q
TOTAL	4,455 Q	150 Q

The BEG currently estimates that both in-place and recoverable resources are approximately 11 percent of those reported by the U. S. Geological Survey in 1975.

BEG estimates assume no significant water will be derived from surrounding shales and that exsolution of gas and gas caps within the reservoir will not occur. However, to the extent that such processes might occur or that recovery might exceed 3.3 percent of the resource in place, an additional 95 Q of thermal energy and 55 Q of methane gas, or a total geopressured geothermal resource of 300 Q, is estimated. It should be emphasized that both the USGS and BEG estimates are based on geologic evidence and inference.

As a part of the BEG assessment, a test-site prospect was delineated in Brazoria County and is now (July 1978) being drilled. This well, which will be tested over a two-year period, is absolutely critical to ascertain better the productive rate and capacity of the geothermal systems and to improve reliability of current resource estimates based on geologic inference. A number of factors will serve either to increase or to decrease the volume of recoverable energy over current estimates. If substantial volumes of water can be produced from the surrounding shales, in addition to water from the aquifer, resource estimates will increase. If gas saturation is higher than anticipated, or if gas exsolves and accumulates as gas caps within the tapped reservoir, the energy yield will be higher. On the other hand, if reservoir permeabilities are lower (and BEG determinations at this point indicate permeabilities throughout much of the resource area to be only a fraction of those assumed by the USGS) energy yields over a given period of time will be lower than current estimates.

Test drilling, therefore, is required to ascertain the potentiality of Texas geopressured geothermal resources. What seems clear at this point is that the exceptionally high estimates earlier reported are not warranted but that a significant resource target is, nonetheless, present.

Concluding Observations: The Future of Texas Energy

While the total production of Texas energy to date stands at just 500 Q, the identified reserve base--measured, indicated, and inferred--stands at about 400 Q (table 2). There also exists an identified, but subeconomic resource base estimated to be about 650 Q. To these two categories an estimated yet-to-be-discovered resource of about 420 Q can be added for a grand total reserve and resource base of about 1,475 Q, or nearly three times the historic, cumulative production. If a breeder reactor technology, which would result in more use of uranium reserves and resources, is perfected, and if as a matter of policy it is utilized, the total reserve and resource base would be increased approximately sevenfold to 10,500 Q, or 20 times the historic, cumulative production.

Despite the significant volume of energy yet to be developed, it is likely that the future level of energy production in the State cannot match the highest levels of past energy production, though under appropriate circumstances it can come close. Without question, the future mix of Texas energy production will differ from the past (tables 2, 3, and 4). For example, petroleum (oil, natural gas, natural gas liquids) makes up nearly 99 percent of the historic production of Texas energy; however, it constitutes only 50 percent of the remaining measured reserves and only 30 percent of the estimated remaining energy resource base.

Lignite, by contrast, has contributed only about 0.4 percent of historic Texas energy production; it represents, however, a staggering 40 percent of both the measured reserve and resource base. Uranium production to date has been only 0.8 percent of cumulative production, but uranium represents 10 percent of the measured reserve and will be substantially more if breeder technology is utilized. Geothermal resources--hot water and methane gas--are yet to contribute to production, but their estimated volume constitutes nearly 20 percent of the resource base.

With substantial efforts in gas well drilling and with major success in enhanced recovery of oil, Texas oil and gas production can stabilize for the near term at levels close to the current levels of production; natural gas production could conceivably increase under appropriate price incentives to encourage deep drilling. However, several recent studies have indicated that deep gas drilling and rapid development of tertiary oil most likely will not occur under present or proposed energy policy. Further maintenance of the role of energy production in the Texas economy will also depend to a great extent on continued, rapid, immediate development of near-surface lignite and uranium reserves. Longer term maintenance of energy production levels

Table 3. Past and future mixes of Texas energy.

	% Cumulative Production	% Measured Reserves	% Total Identified Reserves	% Resource
Crude Oil	46.9	19.1	23.2	14.1
Natural Gas	42.7	25.4	30.3	14.1
Natural Gas Liquids	9.1	5.5	6.6	3.0
Uranium	0.8	10.2	16.2	4.1
Lignite Coal	0.4	36.9	22.0	43.0
Bituminous Coal	0.1	3.0	1.8	2.9
Geothermal Water and Methane	0.0	0.0	0.0	18.8

Table 4. Cumulative production of Texas energy relative to remaining reserves and resources.

	Cumulative Production Quads	Remaining Energy Classed as Reserves, Q	% Total Reserve Produced[1]	Remaining Energy Classed as Resource, Q	% Total Resource Produced[2]
Crude Oil	233	92	71.7	225	42.3
Natural Gas	212	120	63.9	225	38.1
Natural Gas Liquids	45	26	63.4	48	37.8
Uranium[3]	4.0	64	6.0	65	3.1
Lignite	1.8	87	2.0	686	0.2
Bituminous Coal	0.5	7	6.6	47	0.9
Geothermal Water and Methane	0.0	0	---	300	---

1 Includes cumulative production plus remaining reserves.

2 Includes cumulative production plus remaining reserves plus remaining resources.

3 Excludes breeder technology.

will depend on effective development of deep-basin lignite, geothermal resources, and breeder technology for increased uranium utilization, all of which further depend on an immediate and vigorous research and development effort.

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