Resource Constraints in Petroleum Production Potential

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Geologic reasons indicate that the dominant position of the Middle East as a source of conventional petroleum will not be changed by new discoveries elsewhere. The share of world crude oil production coming from the Middle East could increase, within 10 to 20 years, to exceed 50 percent, under even modest increases in world consumption. Nonconventional resources of oil exist in large quantities, but because of their low production rates they can at best only mitigate extant trends. Increased production of natural gas outside the United States, however, offers an opportunity for geographically diversified energy supplies in the near future.

THE DISCOVERY AND PRODUCTION OF MINERAL AND ENERGY resources have always been shrouded in the mystery of the physically unknown and the economically uncertain. The scientist struggles to understand the physical nature of the commodity to better predict its occurrence and volume; at the same time, the economist tries to understand the economic parameters of the commodity in order to predict its role in the market. Commonly, resources originally in large supply have been on the verge of running out just as some new large source has been miraculously discovered or some new process has permitted us to economically extract the resource from a heretofore low-quality source.

In spite of an imperfect knowledge of nature and the limits of technology, we have to make judgments on the basis of current understanding to plan adequately for the future. In this regard, oil and gas are particularly critical commodities because they provide the greatest share of the energy on which our world economy depends. Not all hydrocarbon occurrences are effective sources of fuel for modern industrial societies, in which large volumes of products are essential. Only when oil and gas resources can be produced at a high flow rate are they important to the fuel market.

The world is not, at present, short of oil and gas (as evidenced by quick adjustments in the period from August 1990 to January 1991 associated with the loss of Iraq's and Kuwait's crude oil contributions). Large quantities of oil, amounting to some 50 years at the present rate of consumption, and an even greater volume of gas have already been discovered (Tables 1 and 2). Indeed, we can expect that conventional oil and gas production will continue to increase through the first couple of decades of the 21st century (*1*). But beyond that time, we must expect that the world fuel supply will change fundamentally, because oil will account for a declining fraction of energy consumption. Furthermore, the next several decades will not likely experience just a gradual exhaustion of oil as the primary energy resource. Rather, the supply of oil likely will be periodically disrupted owing to its increasingly narrow geographic distribution into the single dominant area of occurrence—the Middle East (*2*). Stability in the Middle East, as defined by a consistent flow of oil at stable prices, is critical to the modern economic activities in the world. As other parts of the world progressively decline in their capability to produce oil, the Middle East will become increasingly important until substitute sources of fuel energy, with their attendant infrastructures, are developed.

Belief in the above prediction of petroleum availability requires confidence in the professional assessment and analysis of petroleum resources. Petroleum data are incomplete and uncertain, and analogy must take the place of on-the-ground inspection in many remote and deeply buried geologic regions. Conclusions from such professional inquiries have varied substantially over the years. These variations have, in part, stemmed from differences in definitions of the resource, which, for some, also included the unconventional resources of extra-heavy oil, tar sands, tight gas sands, clathrates, and other marginal to noneconomic resource occurrences. Although these unconventional materials may someday supplement conventional fuel resources, the rates of production of unconventional resources alone will likely be too low to satisfy the demands of fuel markets, however valuable they may remain to the petrochemical industry.

Because of the increasing acceptance of hypotheses of the origin of petroleum and our exploration of the entire globe, differences among estimates of petroleum availability are narrowing; the core understanding of resource occurrence has not changed in several decades (*2*). We cannot know where each new discovery will be made, but now we can be substantially confident that new, large occurrences of oil, such as would be necessary to alter the proportional contribution of the Middle East to world petroleum, are not likely to be found; certainly, no such occurrences have been found in the several recent decades of intense worldwide petroleum exploration (*3*).

Although we can see that the remaining crude oil supply is becoming concentrated in a few areas, there are, nonetheless, alternatives on the horizon. As in all energy use, however, change requires infrastructure development, which takes time, costs money, and bears substantial risk because of competing low-cost fuels. The immediate alternative, and it still involves petroleum, appears to be to make full use of the natural gas component of petroleum. The present world geographic distribution of major gas reserves is not conducive to local use in large quantities, but, if gas reserves were converted to liquefied natural gas or to middle distillates, they could be transported readily to market. Extra-heavy oils of Venezuela and tar sands of Canada, so-called unconventional resources, in combination with conventional petroleum, could also make a short-term

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difference as a Western Hemisphere counterbalance to Middle Eastern supply dominance.

World Petroleum Resources

Ultimate resources. Hypotheses of broad characterizations of world paleoclimate, geography, and geology permit us, inductively, to infer the regional petroleum properties useful in making quantitative petroleum resource assessments. These inferences from the hypotheses can then be tested areally and stratigraphically for local concurrence by exploration activities.

The presence of economically recoverable petroleum is essentially a function of five independent variables combining in a satisfactory manner: source rock, reservoir rock, trap, seal, and timing. The occurrence of large resources requires nearly optimum conditions for each of the five variables and is, therefore, a statistically rare event. Owing to the studies over the past 10 years in the World Energy Resources Program of the U.S. Geological Survey and, in particular, to the work of Ulmishek and Klemme (*4*), we can now recognize four areas of the world, or realms, wherein certain germane physical and biological conditions during geologic times have occurred that were either favorable or unfavorable to the occurrence of petroleum throughout the realm. These areas are the Tethyan realm, the Boreal realm, the South Gondwana realm, and the Pacific realm (Fig. 1).

About two-thirds of the world's petroleum is associated with the Tethyan realm (Fig. 1), which is named for Tethys, an approximately equatorial seaway that, from time to time, separated Laurasia (the northern paleocontinent) from Gondwanaland (the southern paleocontinent) (*5*). This warm water marine seaway, lying approximately between the 30° latitudes, north and south, was ideal for source rock deposition and permitted the development of carbonate bank petroleum reservoirs that do not form extensively in colder waters at higher latitudes. Salt is also deposited in warm, shallow water, and it provided excellent seals to prevent leakage from the trap and in some areas produced structures to entrap oil by flowing and mounding. Trap formation was further enhanced by the continental collisions associated with the frequent plate tectonic openings and closings of the Tethyan seaway over geologic time. The maintenance over much of geologic time of the ideal conditions for the origin and entrapment of petroleum ensured that trap formation and reservoir development would generally be coincident with oil formation and migration.

The Boreal realm, to the north of Tethys, contains about one-quarter of the world's petroleum, whereas its counterpart south of Tethys, the South Gondwana realm, contains only about one-twentieth of the world's petroleum. The relatively good petroleum

Table 1. Crude oil production, reserves, and undiscovered resources (*3, 9, 18–20*). Data are reported in bbo (bbo = 0.159×10^9 m^3). Data smaller than 0.05 bbo are reported as 0.0. The column numbers identify the following: (1) cumulative production through 1988; (2) 1988 production; (3) identified reserves; (4) reserves/production; (5) lower bound of a 90% confidence interval for undiscovered resources; (6) mean undiscovered resources; (7) upper bound of 90% confidence interval for undiscovered resources; (8) futures [(3) + (6)]; (9) ultimate resources [(1) + (3) + (6)].

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
North America	182.8	4.4	83.0	19	67	121	197	204	387
Canada	14.3	0.5	7.0	14	9	33	57	40	55
Mexico	15.7	0.9	27.4	29	15	37	75	64	80
United States	152.7	3.0	48.5	16	33	49	70	98	251
Other	0.1	0.0	0.1	20	1	1	3	2	2
South America	57.9	1.4	43.8	30	18	44	86	88	146
Argentina	4.9	0.2	2.3	14	1	2	5	5	10
Brazil	2.5	0.2	2.8	13	3	9	18	11	14
Venezuela-Trinidad*	43.9	0.8	34.4	46	8	20	36	54	98
Other	6.7	0.3	4.3	13	5	14	30	18	25
Western Europe	15.7	1.4	26.9	19	11	28	56	55	70
Netherlands	0.5	0.0	0.2	6					
Norway	3.1	0.4	11.0	26	5	13	25	24	27
United Kingdom	8.6	0.8	13.5	16	4	11	23	25	33
Other	3.5	0.2	2.2	14	1	4	10	6	10
Eastern Europe	6.8	0.1	2.0	15	1	2	4	4	11
Soviet Union	103.6	4.5	80.0	18	46	101	187	181	285
Africa	46.4	2.0	58.7	29	20	48	92	106	153
Algeria*	9.1	0.4	8.4	22	1	2	5	11	20
Angola	1.3	0.2	2.0	12	1	2	4	4	5
Egypt	4.4	0.3	4.6	15	1	5	12	9	14
Libya*	15.9	0.4	22.4	59	4	8	15	30	46
Nigeria*	12.4	0.6	16.0	29	4	9	18	25	38
Other	3.2	0.2	5.3	24	9	21	41	27	30
Middle East	160.2	5.1	584.8	114	66	122	199	706	867
Iran*	36.1	0.6	63.0	105	11	22	35	85	121
Iraq*	19.9	1.0	99.0	99	15	45	80	144	164
Kuwait*	23.3	0.5	96.0	204	1	3	7	99	123
Saudi Arabia*	55.8	1.8	255.0	142	20	41	65	296	351
United Arab Emirates*	11.0	0.6	56.2	98	3	7	13	63	74
Other	14.2	0.7	15.6	23	2	4	8	20	34
Asia-Oceania	36.8	2.2	42.8	19	37	81	148	124	160
Australia–New Zealand	3.0	0.2	2.4	12	2	5	11	8	11
China	13.0	1.0	22.0	22	20	48	93	70	83
India	2.6	0.2	4.5	19	1	3	7	8	11
Indonesia*	13.3	0.5	8.4	17	5	10	18	18	32
Malaysia-Brunei	3.9	0.2	4.6	19	3	6	10	10	14
Other	0.9	0.0	1.0	22	4	8	15	9	10
World	610.1	21.3	922.1	43	275	547	945	1469	2079

*OPEC member (note Trinidad is not in OPEC).

potential of the Boreal realm developed because, during Paleozoic time, the continents now composing the Boreal realm were for the most part located south of 30°N (in the vicinity of Tethys). This location permitted the development of good source rock, carbonate bank reservoirs, and evaporite salt seals. Only in Mesozoic and Cenozoic times was this continental block dominantly in the northern high latitudes; at those times, conditions favored natural gas accumulation. Gondwanaland, on the other hand, the mirror image of continents in the Northern Hemisphere, was clustered around the South Pole during early and middle Phanerozoic time (about 500 million to 200 million years ago); only the northern boundaries of the South American and African blocks of Gondwanaland extended into the Tethys region. Thus, the extraordinary petroleum provinces of Venezuela, Algeria, Libya, and the Arabian-Iranian Gulf lie in the Tethyan realm.

The remainder of Gondwanaland constitutes the South Gondwana realm and is generally characterized by the absence of good source rocks, carbonate bank deposits, and evaporitic salt seals. After the breakup of Gondwanaland, which occurred in Late Jurassic and Early Cretaceous times (some 150 million years ago), the various continental blocks migrated sufficiently north to permit favorable petroleum geology conditions, as evidenced today by petroleum reservoirs, mostly in coastal areas, found in eastern South America, West Africa, India, and southeasternmost Australia. Even in these later times, however, continental blocks in the South Gondwana realm were mostly above sea level, and had only limited access to the marine depositional conditions that might have provided high petroleum potential.

The Pacific realm contains only about one-twentieth of the world's petroleum. Subduction and the dragging down of the continental margin have served to metamorphose all but the most recent sedimentary rocks and have left only Neogene rocks with petroleum potential. But even the Neogene rocks are affected secondarily by the results of subduction, because they commonly are inundated with volcanic debris that destroys reservoir properties and hence the potential for large petroleum accumulations.

Within the Pacific realm, as in all other realms, the few windows of anomalous petroleum abundance have been successfully exploited. Nonetheless, there now is sufficient understanding of regional geologic history and processes to be able to postulate with confidence the expected geologic conditions within each realm and to infer their particular petroleum geology properties. From that understanding, and using analogs developed for the most part within each realm, we have assessed undiscovered petroleum poten-

Table 2. Natural gas and natural gas liquids (NGL) production, reserves, and undiscovered resources (*3, 18, 21, 22*). Liquid data reported as billion barrels (0.159×10^9 m^3), gas reported as tcf (28.9×10^9 m^3). The column numbers are the same as those in Table 1.

	Natural gas									NGL	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(3)	(6)
North America	826.5	21.2	440.2	21	581	926	1378	1366	2193	11.5	19.4
Canada	73.1	3.2	94.8	30	153	367	646	462	535	2.2	8.4
Mexico	21.9	1.1	73.4	66	70	157	291	231	252	1.1	2.4
United States	731.5	16.9	272.0	16	307	399	507	671	1403	8.2	8.6
Other			0.0		1	3	6	3	3	0.0	0.0
South America	36.4	2.3	168.9	73	95	210	387	379	415	2.5	3.1
Argentina	9.3	0.8	27.3	36	10	37	75	64	74	0.4	0.6
Brazil	1.8	0.2	3.8	19	10	53	100	57	59	0.1	0.8
Venezuela-Trinidad*	17.2	0.9	118.8	134	20	65	140	184	201	1.8	1.0
Other	8.1	0.4	18.9	43	26	55	99	74	82	0.3	0.8
Western Europe	120.3	6.0	219.4	37	121	206	320	425	545	3.3	3.1
Netherlands	52.0	1.9	61.1	32	5	10	20	71	123	0.9	0.1
Norway	9.3	1.1	93.1	88	55	157	240	251	260	1.4	2.4
United Kingdom	23.3	1.6	42.2	27	8	20	46	62	86	0.6	0.3
Other	35.7	1.4	23.0	16	11	18	27	41	77	0.3	0.3
Eastern Europe	46.8	0.0	22.1					22	69	0.3	
Soviet Union	332.2	27.5	1450.0	53	739	1582	2861	3032	3364	21.8	23.7
Africa	29.9	2.1	206.2	98	216	444	784	650	680	3.1	6.7
Algeria*	15.0	1.6	104.2	67	6	26	53	131	145	1.6	0.4
Angola			1.7		2	6	11	7	7	0.0	0.1
Egypt	1.4		9.4		8	30	60	40	41	0.1	0.5
Libya*	5.4	0.2	25.6	127	7	27	55	52	58	0.4	0.4
Nigeria*	5.9	0.1	47.3	479	80	182	340	229	235	0.7	2.7
Other	2.3	0.3	18.0	72	84	173	306	191	193	0.3	2.6
Middle East	54.6	2.6	1247.2	481	623	1125	1826	2372	2427	18.7	16.9
Iran*	17.1	0.6	595.0	947	300	567	1000	1162	1179	8.9	8.5
Iraq*	3.2		34.8		60	120	200	155	158	0.5	1.8
Kuwait*	5.3	0.2	37.8	210	3	6	10	44	49	0.6	0.1
Saudi Arabia*	13.1	0.9	181.3	200	200	360	600	541	554	2.7	5.4
United Arab Emirates*	7.1	0.3	187.1	609	30	60	100	247	254	2.8	0.9
Other	8.8	0.6	211.2	369	6	13	22	224	233	3.2	0.2
Asia-Oceania	76.8	4.8	288.3	60	365	723	1248	1011	1088	4.3	10.8
Australia–New Zealand	7.0	0.7	40.8	57	35	102	219	143	150	0.6	1.5
China	17.1	0.5	30.0	60	122	260	467	290	307	0.5	3.9
India	1.6		21.0		9	28	62	49	50	0.3	0.4
Indonesia*	13.0	1.2	85.6	69	47	95	167	181	194	1.3	1.4
Malaysia-Brunei	4.7		65.0		30	74	150	139	143	1.0	1.1
Other	33.5	2.3	45.9	20	86	164	276	210	243	0.7	2.5
World	1523.6	66.5	4042.2	61	2897	5216	8448	9258	10782	65.6	83.8

*OPEC member (note Trinidad is not in OPEC).

tial by basin and country (Tables 1 and 2) (*6*). Even though oil and gas are distinctly different commodities that can be generated in widely differing ways, their origins have many similarities and in large measure they occur together. This is so because the giant occurrences of natural gas dominate the total resource volumes, and these tend to be located where the giant resources of oil also have been discovered. An exception to this generalization appears to be the Barents and Kara seas, where large dry gas resources recently have been discovered without significant companion oil deposits. Generally, good sealing rocks, such as salt, are required to secure the trapping of gas, but these rocks are geologically excluded in high latitudes; the large gas resources of the West Siberian basin are sealed by permafrost. The large gas occurrences in the Kara and Barents sea areas, however, deprived of both salt and permafrost, are sealed with a fine-grained shale having low permeability.

Field growth and the identified reserve. The petroleum resources, from which one can estimate future daily production, include undiscovered and discovered resources (Tables 1 and 2). The quantity of undiscovered oil and gas resources is uncertain and is expressed in Table 1 by the reporting of a probability range of values. The quantity of reserves in known fields is uncertain as well. In the United States and Canada the amount of producible oil and gas from discovered fields has been consistently underestimated (*7*). As the fields are developed and produced, their estimated size usually increases. This increase in the estimates of ultimate field recovery is called field growth.

Two reasons that field estimates are conservative are (i) the economic penalties for underestimation are much less severe than those for overestimation and (ii) reservoirs can be discovered or extended in known fields or both. In the United States, the estimate of the remaining growth of oil recovery in discovered fields beyond proved reserves is comparable in magnitude to proved reserves.

The growth in a field's estimated size continues for decades after the field's discovery. For example, estimated recovery for pre-1920 U.S. fields grew about 400 mmbbl (million barrels, 1 mmbbl = 1.59 $\times$ 10^5 m^3) per year from 1977 to 1988 and accounted for about 15% of the total additions to U.S. reserves (*8*). In the United States during the period from 1978 through 1988, approximately 83% on average of the additions to proved reserves came from growth of fields that were more than 6 years old (*8*). Estimates of reserves in fields outside the United States and Canada are not as well documented but appear to show similar trends with regard to growth of discovered fields. Specifically, annual additions to world reserves appear to be much larger than can be accounted for by new field discoveries (*3*).

Our estimates (Tables 1 and 2) of reserves for the United States include 22 bbo (billion barrels of oil, 1 bbo = 1.59 $\times$ 10^8 m^3) of expected field growth. The corresponding figure for gas is 100 tcf (trillion cubic feet, 1 tcf = 2.8 $\times$ 10^{10} m^3). We believe that the oil reserves in the Soviet Union (Table 1) also include a significant component beyond the strict definition of proved reserves. For most of the other non-OPEC (Organization of Petroleum Exporting Countries) members, our estimates do not include the expected growth of discovered fields; most of the reserve estimates for oil and gas came from *World Oil* (*9*). The understatement of gas reserves (Table 2) is likely even greater than that for oil because gas is far less developed than oil as an energy source in most areas of the world.

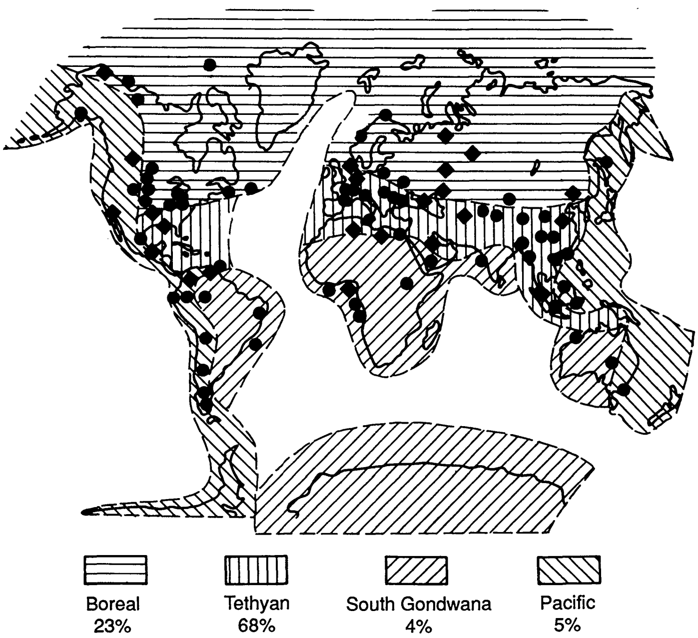

Fig. 1. Geographic distribution of the four petroleum realms of the world and the oil and gas content of each as a percentage of world discovered oil and gas. Also shown are the locations of the major (◆) and moderate (●) occurrences of world petroleum. Adapted from (*4*).

Analysis of Resource Quantity and Geographic Location

Maturity of nonrenewable resources. Economists are wont to argue that nonrenewable resources are inexhaustible because decreases in supply will cause price increases that adjust demand and promote marginal production and substitutions. We do not contest the theoretical tenets of that position; all those reactions will surely occur. They might not, however, prevent declining production of crude oil and a loss of significant parts of the fuel market.

By concluding that the petroleum industry is mature we mean that it is unable to maintain production of conventional oil within the limits of historical prices. A number of factors affect production, principally the drilling rate and the size and geologic quality of the geographic area where petroleum can be produced economically. When prices, over the range of historical experience, limit entry of the industry into frontier or high-cost areas or prevent sufficient drilling to maintain production, the industry is mature.

By this definition, the U.S. petroleum industry in the lower 48 states is mature. Production is declining under current economic conditions, and during the recent times of much higher prices the United States was not able to increase production, even including Alaskan production, to the peak level of 1970. In areas having roughly uniform drilling costs (per well), a maturation pattern similar to that of the onshore lower 48 states can be expected: initial discoveries result in a buildup of reserves and increasing production and are followed by declining discovery rates (1945 to 1955), stable reserves (1960s), and declining production (1970 to date). The time periods delineating any of these stages can be shortened or lengthened by fluctuating prices or other economic instabilities. This maturation pattern of the U.S. oil industry has also been followed by the gas industry, but it has lagged by several years.

Recent world production history. By 1988 OPEC, the United States and the Soviet Union jointly, and the other non-OPEC producers each accounted for about one-third of world oil production (Fig. 2). In 1973 OPEC had accounted for 55% of world production, representing their historical maximum, which they were able approximately to maintain until 1979. After 1979, however, there was a sharp decline in OPEC production because of reductions in world demand for oil associated with the 1979 major price increases. The price increases permitted continued development of high-cost areas such as the North Sea and the U.S. North Slope and encouraged marginal developments, all of which eventually limited the OPEC market share. This price response produced an expectation that price increases would bring on major new oil discoveries as needed. Studies by workers in the World Energy Resources Program of the U.S. Geological Survey, however, suggest that no new major basins (that is, with 20 billion barrels of recoverable crude oil) are likely to be discovered (*3*).

During the period of 1960 to 1988 (Fig. 2), the combined production of the United States and Soviet Union grew at a rate of 2.6% per year irrespective of major price fluctuations. We know from the component parts that the flattening of the joint U.S. and U.S.S.R. production curve would have been a production decline if the price escalation during this period had not supported the North Slope development. U.S.S.R. production increased steadily to 1979, but since 1980 it has been relatively flat. The growth in production of other non-OPEC producers from 1960 to 1988 increased at an annual rate of 7.6%, which reflected the development of new provinces in the North Sea and Mexico and increases in production in China, Egypt, Oman, Brazil, Malaysia, and dozens of smaller producers. The rate of production increase was established before the price increases, but the price increases permitted development in the North Sea and other high-cost areas to contribute to the maintenance of that rate of increase of production in the other non-OPEC countries.

Because of U.S. and U.S.S.R. production declines resulting from industry maturity, it seems clear that non-OPEC production will become inadequate and that OPEC's dominance in world production will return. The geographic concentration of OPEC futures (identified reserves plus mean undiscovered resources) (Table 1) suggests that future OPEC production will increasingly be concentrated in the Middle East. In order to predict the time period when OPEC can be expected to regain dominance in world crude oil production, one must develop scenarios of the production capabilities of non-OPEC countries.

Scenarios of non-OPEC crude oil production capabilities. Currently, two-thirds of world oil production is from non-OPEC countries, but these countries account for only 25% of the world's identified reserves. The geographic distribution of world oil production has been changing and will continue to shift toward the Middle East. The conventional resources shown in Table 1 permit inferences about future production capabilities. This analysis leads to the conclusion that under generally stable economic and political conditions, the market share of non-OPEC producers could decline to below 50% of world oil production during the next 20 years.

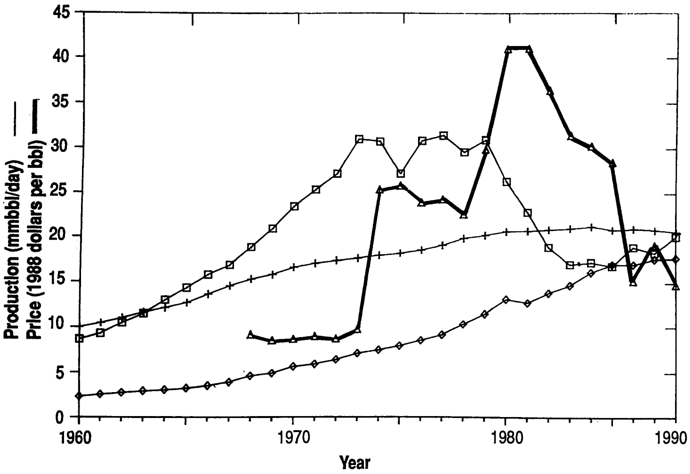

Fig. 2. A record of world crude oil production, 1960 to 1988, compared to U.S. import price (△) (in 1988 dollars) since 1968 of three component parts—OPEC (□), the United States and the Soviet Union (+), and other non-OPEC countries (♦), where 1 barrel = 0.159 m^3. Adapted from (*2*).

The elements of the analysis of future production potential are (i) the annual additions to reserves from new discoveries and from growth of discovered fields and (ii) the fraction of proved reserves produced annually. Calculations were done for individual countries and summed. In calculating the production capabilities we assumed that political and economic factors will permit the non-OPEC countries to develop their conventional resources at rates similar to those of the early 1980s.

Projected additions to reserves from new discoveries were based on extrapolations of each country's past discovery rate. The projections were constrained so that by 2010 at least half of the mean undiscovered oil shown in Table 1 would be in discovered fields, although not necessarily yet credited through growth to proved reserves. Projected additions to proved reserves from growth in the estimated recovery of discovered fields were based on field growth factors calculated from U.S. data (*10*).

Three scenarios were calculated: the low scenario, having growth of proved reserves plus cumulative production (for both new and older fields) at one-third of the U.S. rate and one-twentieth of the proved reserves produced annually; the middle scenario, having growth at one-half of the U.S. rate and one-sixteenth of the proved reserves produced annually; and the high scenario, having growth at two-thirds of the U.S. rate and one-twelfth of the proved reserves produced annually. However, if a country was already producing its reserves at a greater fraction than assumed in a scenario, then that country's fraction remained constant.

The Soviet Union and the United States account for about half of non-OPEC production, and in all scenarios the production of both countries is projected to decline (Fig. 3). U.S.S.R. production is projected to decline from 11.7 mmbbl of oil per day in 1988 to between 7.3 mmbbl per day and 7.8 mmbbl per day in 2010. By 2010, U.S.S.R. proved reserves are projected to decline by 22 bbo to 24 bbo even though 49 bbo to 53 bbo are added to proved reserves. U.S. production is projected to decline from 8.1 mmbbl per day in 1988 to 4.4 mmbbl per day in 2010. By 2010, U.S. proved reserves are projected to decline by 12.5 bbo even though 33.5 bbo are added to proved reserves.

Production from other non-OPEC producers is projected in 2010 to range from 0.4 mmbbl per day less than that in 1988 to 4.1 mmbbl per day more (Fig. 4). By that time, the non-OPEC producers outside the United States and Soviet Union are projected to have added 135 bbo to 154 bbo to reserves through discovery and development, although their proved reserves will decline from 122 bbo to about 100 bbo.

The net result is that by 2010 non-OPEC production, in all scenarios, will be below the 1988 level (Fig. 4). By 2010, non-OPEC production is projected to decline from 38 mmbbl per day in 1988 to 29 mmbbl to 34 mmbbl per day. Total additions to

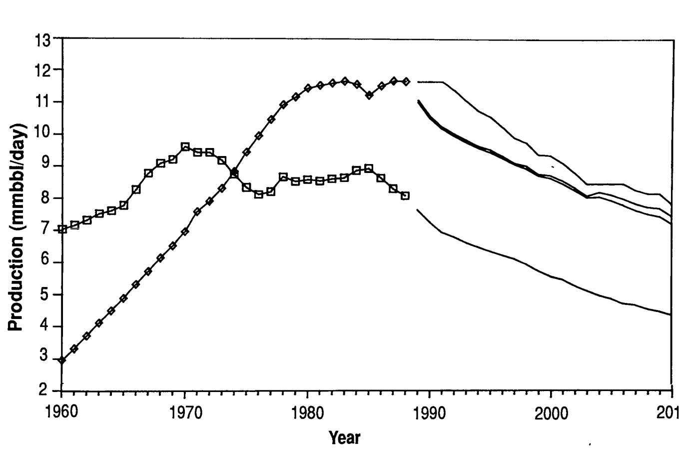

Fig. 3. Historical crude oil production with future projections for the Soviet Union (♦) and the United States (□) (*19, 20*). Adapted from (*2*).

non-OPEC proved reserves during this period are 241 bbo under the high scenario and 218 bbo under the low.

An annual world oil consumption growth of 1% implies, under the low non-OPEC production scenario, that by 2010 OPEC would be required to supply 43 mmbbl per day; under the high scenario, 38 mmbbl per day would be required of OPEC. For a 2% annual consumption growth, the corresponding OPEC production requirements would be 61 mmbbl per day and 57 mmbbl per day. Under the assumption of 1% consumption growth and the high scenario, OPEC would achieve 50% of world production in 2009. Under the assumption of 2% consumption growth and the low scenario, OPEC would achieve 50% of world production in 1998. OPEC's highest crude oil production was 32 mmbbl per day in 1973 and 1979.

About 10% of the liquid petroleum produced outside of OPEC is in the form of liquids extracted from natural gas and amounts to about 4 mmbbl per day. We projected future gas production by a method similar to that used for oil production. The result was that the production capability for natural gas liquids increased from 4 mmbbl per day to 7.6 mmbbl per day by 2010, with all but 0 to 0.5 mmbbl per day of the increase coming from increased gas production in the Soviet Union (*11*). Even given the optimistic assumptions for gas demand growth, any net increase from liquids produced from gas is unlikely to postpone by more than a year or two the time when OPEC achieves 50% of the world's production of petroleum liquids.

Crude oil alternatives. During the next 20 years, additional crude oil will come from improved recovery of the oil remaining in discovered fields, extra-heavy oil, and bitumen. Recovery from such sources, however, has higher investment requirements than conventional oil production, and the rate of recovery has historically been low. Demand for crude oil could also be dampened by direct substitution of natural gas and the conversion of gas to liquid transportation fuels.

The National Petroleum Council's assessment of possible additions to U.S. crude oil reserves from enhanced oil recovery (EOR) (*12*) amounted to 14.5 bbo (27.4 bbo in the advanced technology case) on the basis of a $30 per barrel oil price in 1984 dollars. The dramatic 1986 price decline resulted in the suspension of many EOR projects such that significant contributions from EOR may not be realized before 2010. Applications of EOR are specific to location and field. Percentage increases in recovery from individual fields with atypical reservoirs cannot be extrapolated nationwide.

Venezuela's Orinoco extra-heavy oil belt contains the world's largest accumulation of extra-heavy oil (denser than water and fluid in the borehole). Of the estimated 1200 bbo remaining in the belt, some 267 bbo are judged to be recoverable. This oil requires upgrading to be used as a refinery feedstock. By the year 2000, 0.5 mmbbl per day of extra-heavy oil are planned to be produced from the Orinoco (*13*); although this planned amount of production is obviously not limited by resources, its modest level suggests some restriction.

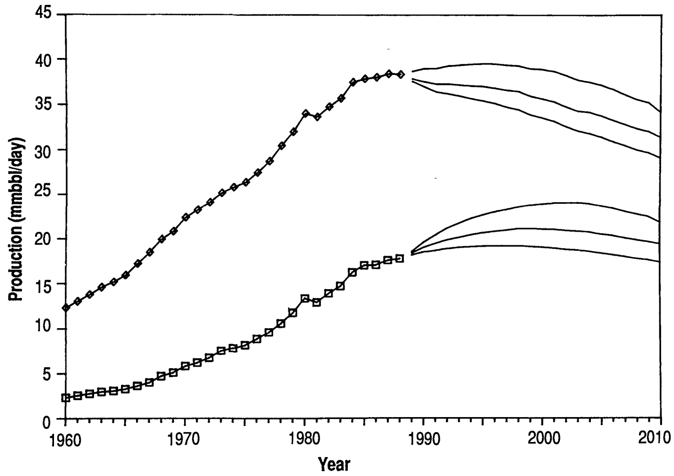

Fig. 4. Historical crude oil production with future projections for non-OPEC countries (♦) and non-OPEC countries excluding the United States and the Soviet Union (□) (*8, 19*). Adapted from (*2*).

For at least 20 years, Canada has aggressively pursued development of bitumen (denser than water and not fluid in the borehole) as an alternative source of crude oil. Canada's 308 bbo of recoverable bitumen accounts for 75% of the world's recoverable bitumen. Production capacity is expected to grow from 0.18 mmbbl per day to 0.35 mmbbl per day by the year 2000 (*14*). Once again, the rate of production, although modest, is not limited by the resources.

Natural gas can displace oil as an energy source in stationary end uses and also can be converted to liquid transportation fuels. It is probably the most important alternative to conventional crude oil because less than 40% of the identified gas reserves are in OPEC countries, and on an energy equivalent basis ultimate gas resources are about equal to those of oil, whereas gas production has been only about half that of oil.

The list of countries (Table 2) with large reserve-to-production ratios, and hence a great capability to expand production, indicates the lack of local gas markets and the difficulty of transporting gas. Only about 10% of the gas produced enters international markets in pipelines, and only 3.3% (some 2 tcf) is converted to liquefied natural gas (LNG). Annual LNG trade is expected to grow, but under present incentives only to about 4 tcf to 6 tcf by 2010 (*15*). Its growth is limited because high capital costs require that it serve a stable market so that the plants can operate near capacity.

Conversion of gas to liquid transportation fuels, such as methanol, middle distillates, or gasoline, offers another means to enhance gas use and to diversify geographically the sources of liquid fuels. The technologies are sufficiently expensive, however, that they are applicable only to low-cost gas that cannot otherwise be marketed. Although it is unlikely without mandated environmental regulations or other incentives that methanol (a natural gas derivative) would gain wide use as a transportation fuel (*16*), the markets for middle distillates and gasoline are already available and follow crude oil prices.

Technologies for producing these other liquid fuels have been developed and some have been commercially used, but none of the fuels has been produced on the scale required to affect significantly crude oil consumption. For example, Shell Oil in 1989 announced construction of a $660-million plant, the first of its kind, to convert 100 million cubic feet (2.83×10^6 m^3) per day of gas to 500,000 metric tons per year of middle distillate fuels by the use of the middle distillate synthesis process (*17*). Depending on the suite of fuels produced, the plant output could be 10,000 to 12,000 barrels per day. The apparent thermal efficiency of the process is between 62 and 64%. Assuming 5.8 million Btus (British thermal units) per barrel of crude oil (38 GJ/m^3) and 1000 Btus per cubic foot of gas (0.037 GJ/m^3) with a thermal efficiency of 62%, we calculate that 3.4 tcf of gas per year is required to replace 1 mmbbl per day of crude production.

The United States does not have sufficient low-cost gas to replace its declining crude production (*18*). The required increases in gas production for the Soviet Union to so compensate, however, are well within its capability. The non-OPEC producers outside of the United States, Soviet Union, and Middle East account for 661 tcf of gas reserves and 2155 tcf of gas futures but only 15.6 tcf per year of production. It is possible, with massive investments in conversion plants, that a significant part of the projected decline between now and 2010 of between 4.2 mmbbl and 9.2 mmbbl per day of non-OPEC production could be compensated for by expansion of natural gas use in the Soviet Union and other non-OPEC countries.

However, gas conversion, as with all alternative fuels, requires substantial capital investments. Even if the increasing OPEC market share leads to significantly higher prices, capital markets may not judge the price increases to be sufficiently robust or stable for development of substitutes on a large scale.

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23. Background information essential to the preparation of this article was developed in concert with our colleagues in the World Energy Resources Program of the U.S. Geological Survey and the Foreign Energy Supply Assessment Program of Energy Information Administration of the Department of Energy. Basic petroleum data derive primarily from Petroconsultants S.A.

Advances in Helioseismology

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Globally coherent oscillation modes were discovered in the sun about a decade ago, providing a unique seismological probe of the solar interior. Current observations detect modes that are phase-coherent for up to 1 year, with surface velocity amplitudes as low as 2 millimeters per second, and thousands of mode frequencies have been measured to accuracies as high as 1 part in 10^5. This article discusses the properties of these oscillation modes and the ways in which they are adding to our understanding of the structure and dynamics of the sun.

HELIOSEISMOLOGY, THE STUDY OF SOLAR OSCILLATIONS and their use as a probe of the sun's interior, is still a relatively young field. High-degree solar oscillations were first observed in the early 1960s (*1, 2*), and it was just over a decade ago that globally coherent oscillation modes were observed in the sun (*3*). In this short amount of time, however, the quality of the observations has improved greatly, and there have been substantial advances in our theoretical understanding of these oscillations [see the review articles on helioseismology (*4*)]. The observations have allowed us to accurately measure the depth of the solar convection zone as well as the sun's internal rotation profile, and to infer the temperature of the solar core (important for unraveling the solar neutrino problem).

Starting with a model for the overall structure of the sun, one can show with linear adiabatic perturbation theory that small-amplitude oscillations of the model about its equilibrium state can be classified into three types (*4*): (i) p-modes, which have pressure as the dominant restoring force; (ii) g-modes, for which gravity, or buoyancy, is the primary restoring force; and (iii) f-modes, which are nearly compressionless surface waves. Our discussion here will focus on p- and f-modes, for which there is clear and abundant observational data. g-Modes, according to calculation, are predominantly trapped deep in the solar interior, and it seems likely that these modes are not excited to observable amplitudes at the sun's surface. Some possible g-mode detections have been reported, but the observations at this point are still not convincing.

p-Modes are essentially acoustic (sound) waves propagating through the solar interior. For frequencies below a maximum acoustic cutoff frequency, $\nu < \nu_{\mathrm{a,\ max}} \approx 5.3$ mHz, acoustic waves in the interior are reflected near the solar surface, forming an acoustic cavity inside the sun (*4*); for $\nu > \nu_{\mathrm{a,\ max}}$, waves propagate through the surface and their energy is quickly dissipated. Because the wave damping is small inside the sun, interference organizes the reflected waves into the normal modes of the acoustic cavity, which are the p-modes. For our discussion these modes can be thought of as a set of harmonic oscillators, each uncoupled to all the rest, independently interacting with weak driving and damping forces. [Nonlinear coupling between modes has been found theoretically to be quite small (*5*).]

The perturbation of a scalar quantity in the solar interior, such as pressure p, resulting from an oscillation mode, can be written as an eigenfunction

$$\delta p(\mathbf{r},t) = \mathrm{Re}[\delta p_{n\ell}(r) Y_\ell^m(\theta,\phi) \exp(i2\pi\nu_{n\ell m}t)] \qquad (1)$$

with frequency eigenvalue $\nu_{n\ell m}$, where $Y_\ell^m(\theta,\phi)$ is a spherical harmonic. Each mode is labeled with three integer "quantum"

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