Second Wallace E. Pratt Memorial Conference
“Petroleum Provinces of the 21st Century”
January 12-15, 2000
San Diego, California

Oil: Are We Running Out? [1]

by David Deming [2]

ABSTRACT

Predictions of imminent oil shortages have been made throughout the 20th century. Although all previous predictions have been false, in recent years a new generation of predictions based on the Hubbert model have become ascendant and attracted media attention. The Hubbert model assumes that a resource is limited and finite. Although conventional oil supplies are finite, it has proven difficult to estimate the size of the ultimate resource. Over the last 50 years estimates of the size of the world’s conventional crude oil resources have increased faster than cumulative production. The estimated size of the ultimate resource base will continue to increase in the future as unconventional fossil fuels come on line. Oil production from Canadian tar sands has already begun.

Unconventional oil resources such as tar sands and oil shales are likely to replace conventional oil and ensure a supply of petroleum for a period of time somewhere on the order of 100 to 1000 years. The only uncertainty concerns the nature of the transition from conventional to unconventional oil resources. The transition may be slow and seamless with no economic disruptions, or it may be characterized by a difficult transition period.

In the long run, nuclear power has the potential to provide large amounts of power for very long periods of time if low-grade uranium is used in breeder reactors. The technology and resources to utilize nuclear power already exist. Limitations on the energy used by our technological civilization are not imposed by finite resources but by social and political attitudes.

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INTRODUCTION

In the past few years, a number of predictions of imminent oil shortages have been made. In a widely publicized Scientific American article, Campbell and Laherrère (1998) wrote: “what our society does face, and soon, is the end of the abundant and cheap oil on which all industrial nations depend”. Writing in the journal Nature in 1997, Craig Bond Hatfield’s short paper was subtitled “a permanent decline in global oil production rate is virtually certain to begin within 20 years”. Ivanhoe (1995) warned of impending economic doom due to an imminent oil shortage:

> “The global price of oil after 1999 should follow the simplest economic law of supply vs. demand—resulting in a major increase in crude and all other fuels’ prices....After the associated economic implosion, many of the world’s developed societies may look more like today’s Russia than the U.S”.

Based on the work of Campbell and Laherrère (1998) and others, science reporter Richard Kerr authored a 1998 article in Science titled “The Next Oil Crisis Looms Large — and Perhaps Close”.

The availability of crude oil is a critical issue. It is hardly an exaggeration to state that crude oil is the lifeblood of the world’s industrial and technological civilization. Although coal and nuclear power can be used for the generation of electricity, there is no ready substitute for petroleum and natural gas in the transportation field. If a permanent decline in oil production is imminent, then some allocation of public and private resources towards the development of alternative energy sources may be a prudent investment. However, if such a decline is not imminent, then the development of alternative energy sources could be a wasteful diversion of valuable resources.

A HISTORICAL PERSPECTIVE

Warnings of oil shortages have been made for most of the 20th century. In 1950, Leonard M. Fanning wrote a monograph titled “A Case History of Oil-Shortage Scares” where he describes seven such episodes up to 1950. These are:

1. The Model T Scare — 1916
2. The Gasless Sunday Scare — 1918
3. The John Bull Scare — 1920-23
4. The Ickes’ Petroleum Reserves Scare — 1943-44
5. The Cold War Scare — 1946-47
6. The Cold Winter Scare — 1947-48

To these we may add two scares brought about by Middle Eastern politics in the 1970s:

7. Arab Embargo Scare — 1973
8. Iranian Revolution Scare — 1979

Both doomsayers and their critics have a long history. Fanning (1950, p. 343) quoted Sir Edward Mackay Edgar in 1922 as stating:

> “Before long there will be a smash. An economic crisis is approaching. American demand for metals, cotton, and oil is so insatiable that a world-wide shortage in these commodities is inevitable. One hundred and fifteen million people are feverishly tearing from the Earth its irreplaceable wealth, using it to maintain a rate of growth unprecedented in all human history..”

As long ago as 1918, A. J. Hazlett (quoted in Fanning, 1950, p. 322) wrote in the Oil Trade Journal that

> “At regularly recurring intervals in the quarter of a century that I have been following the ins and outs of the oil business there has always arisen the bugaboo of an approaching oil famine, with plenty of individuals ready to prove that the commercial supply of crude oil would become exhausted within a given time — usually only by a few years distant”

Hazlett’s words were echoed three years later in 1921 by Thomas A. O’Donnell (quoted in Fanning, 1950, p. 342), president of the American Petroleum Institute who said:

> “We still have with us a rather overproduction of superscientists who are constantly measuring the petroleum resources of the world and point out various kinds of disaster following its exhaustion within a few years”.

In 1920, the US Geological Survey estimated that the world’s supply of conventional recoverable petroleum amounted to 60 billion barrels (Fanning, 1950, p. 331). This proved to be slightly below the mark. By 1998, 800 billion barrels of oil had been produced, with 850 billion barrels in reserve (Campbell and Laherrère, 1998).

Written near the peak of 1979 “Iranian Revolution Scare”, the 1981 edition of a respected and widely used textbook on economic geology (Jensen and Bateman, 1981, p. 6) stated that:

> “The energy crisis has brought home....that oil and gas reserves are finite. Such a situation was given little recognition by laymen even a few years ago, and the mineral economist feared overstating the case because of geological success in locating new petroleum deposits. They had cried “wolf” too many times in the past. Finally, however, the wolves are with us.”

A figure from this text (Figure 1) shows the US entering an incipient 125-year-long “energy gap”, projected to peak shortly after the year 2000. Less than 20 years later, in February of 1999, US gasoline was at a nearly all-time low price. This prompted one editorial cartoonist to picture oil in a race with bottled water to see which could attain the lowest price (Figure 2).

RESERVES, RESOURCES, AND THE ENERGY PYRAMID

Fossil fuels can be broadly categorized as either resources or reserves (Bird, 1989). Resources includes all fuels, both identified and unknown. Reserves are that portion of identified resources which can be economically extracted and exploited using current technology. Reserves grow as technology changes and new resources are discovered through ongoing exploration. It is therefore a fallacy to predict oil shortages by dividing reserves by current consumption rates. McCabe (1998) showed that over the 80 years from about 1915 through 1995, reserves of US crude oil grew at the same rate as consumption (Figure 3). For 80 years, US reserves of crude oil have varied between 10 and 18 years of current consumption. McCabe (1998) concluded that crude oil reserves are comparable to food stocks held in a pantry or warehouse which are constantly replenished.

Surprisingly, estimates of both U.S. and world crude oil resources (Figure 4) have also increased over time (McCabe, 1998). The increase of resources through time can be explained by the concept of the energy pyramid (Figure 5). There exists a relatively small quantity of high-quality, low-cost hydrocarbons. These resources constitute the top of the energy pyramid. However, there are larger quantities of lower-quality, higher-cost hydrocarbon resources. At the present time, the top of the energy pyramid contains conventional oil and gas resources. Simply put, these are hydrocarbons which can be extracted by drilling holes in the ground and pumping them out. However, even if coal is excluded, conventional oil and gas constitutes less than 5 per cent of sedimentary hydrocarbons (Dusseault, 1997). As time passes, man moves lower in the

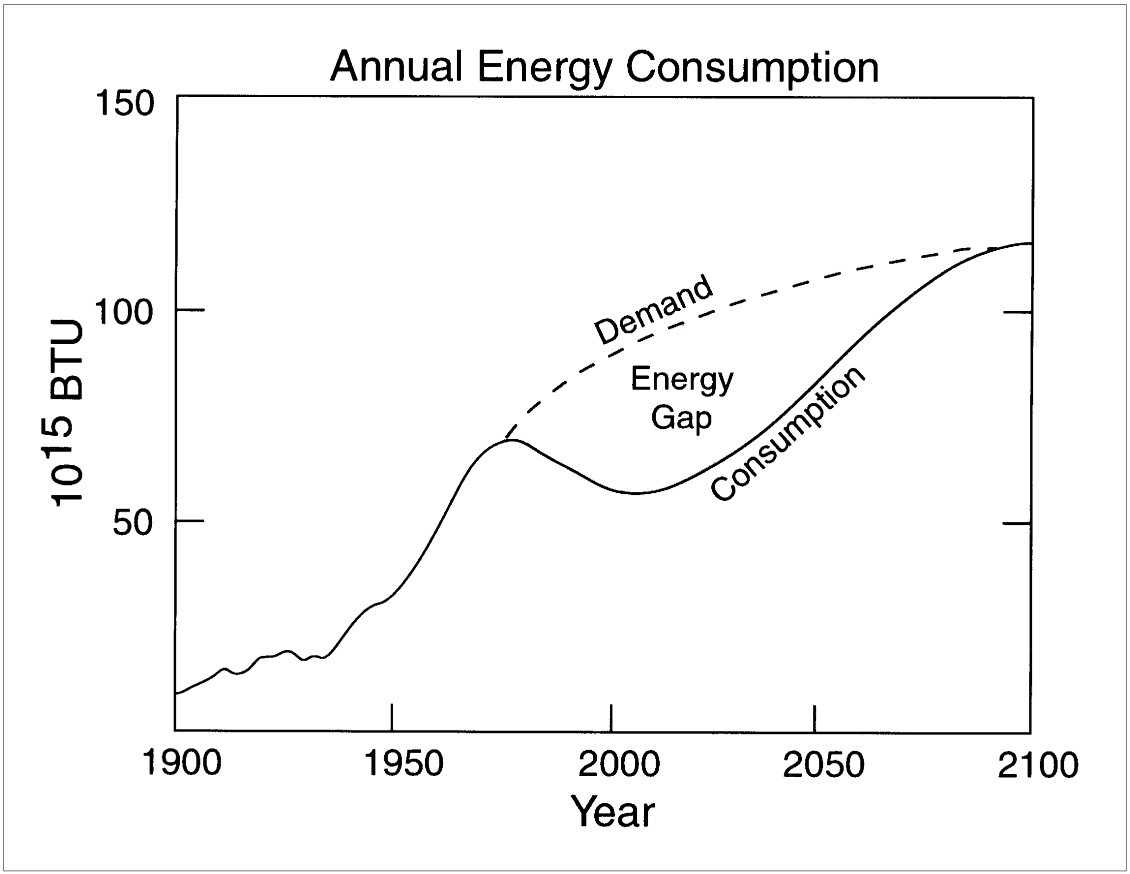

Figure 1 – Past and predicted U.S. energy consumption from the 1981 edition of a textbook on economic geology (after Jensen and Bateman, 1981, p. 10).

energy pyramid and resources which were formerly unknown or considered uneconomic are added to the resource base.

Unconventional hydrocarbon resources include tar sands, oil shale, coal, and methane hydrates. The inclusion of limestone and water at the base of the hydrocarbon pyramid (Figure 5) illustrates that as a last resort synthetic hydrocarbons could be assembled from the carbon in limestones and the hydrogen and oxygen in water (Dusseault, 1997). Manufactured hydrocarbons would not be an energy source so much as a means of storing and transporting energy. With present day technology the process would be expensive and impractical. However, if a large scale source of cheap energy such as nuclear power were available if might eventually become economically feasible to engage in the mass production of synthetic hydrocarbons.

UNCONVENTIONAL HYDROCARBON RESOURCES

Tar Sands

In all probability, the next cut lower in the hydrocarbon pyramid will be the exploitation of tar sands. Large-scale mining of tar sands in Canada began in 1967. Extraction technology was updated in 1992 by the Canadian oil company Suncor (George, 1998). George (1998) reported that Suncor has been producing oil from Canadian tar sand deposits profitably for five years. In 1998, the International Energy Agency (IEA, 1998) estimated the cost of producing Canadian tar sands to be in the range of $12. to $15. a barrel.

The size of the tar sand resource is large (Table 1). George (1998) and the IEA (1998, p. 113) estimated that 300 billion barrels of oil could be recovered from Alberta tar sands using present day technology. Although

Figure 2 – BARREL RACERS – Cartoon illustrating that in February of 1999, crude oil in the U.S. was cheaper than bottled water (Copyright © February 13, 1999, *The Daily Oklahoman*).

consumption rates are not constant with time, it is sometimes more intuitive to express resource size in terms of years of supply[1] . The 1997 US consumption of crude oil was about 6 billion barrels (BP, 1998). Based on this rate, the Alberta tar sands contain crude oil equivalent to a 50-year supply. Another well-known tar-sand resource is the Orinco deposit in Venezuela. The IEA (1998) estimated that 300 billion barrels of oil could be produced from the Orinco deposits at a total extraction cost of $15. to $17. a barrel. Worldwide, Meyer and Schenk (1985) estimated world heavy crude oil and bitumen resources to be 6,200 billion barrels with 890 billion barrels being “recoverable”. These numbers are equivalent to 1033 and 148 years of 1998 US crude oil consumption, respectively.

Oil Shale

The extraction of crude oil from oil shales is somewhat more difficult and expensive than the processing of tar sands. However, the size of the potential resource is huge. Smith (1981) estimated that the Green River Formation in Colorado, Utah, and Wyoming contains 1,500 billion barrels of oil, equivalent to 250 years of 1998 US consumption. Duncan and Swanson (1965) estimated that if all oil shale in the US is considered, the size of the potential resource is 160,000 billion barrels, or 26,667 years of US consumption. Suncor corporation is currently developing an oil shale demonstration project in Australia. The Suncor technology involves baking oil out of crushed rock in a giant, drum-shaped kiln (George, 1998).

Gas-to-Liquids

Worldwide, there are large gas resources which cannot be exploited because of a lack of a delivery system (pipeline). The IEA (1998, p. 112) estimated that there are 1488 trillion cubic feet (TCF) of “stranded” gas which cannot reach markets. 1488 TCF of gas is equivalent to 150 billion barrels of oil, or 25 years of US supply at a 1997 consumption rate. Gas-to-liquids (GTL) technology allows these gas resources to be converted

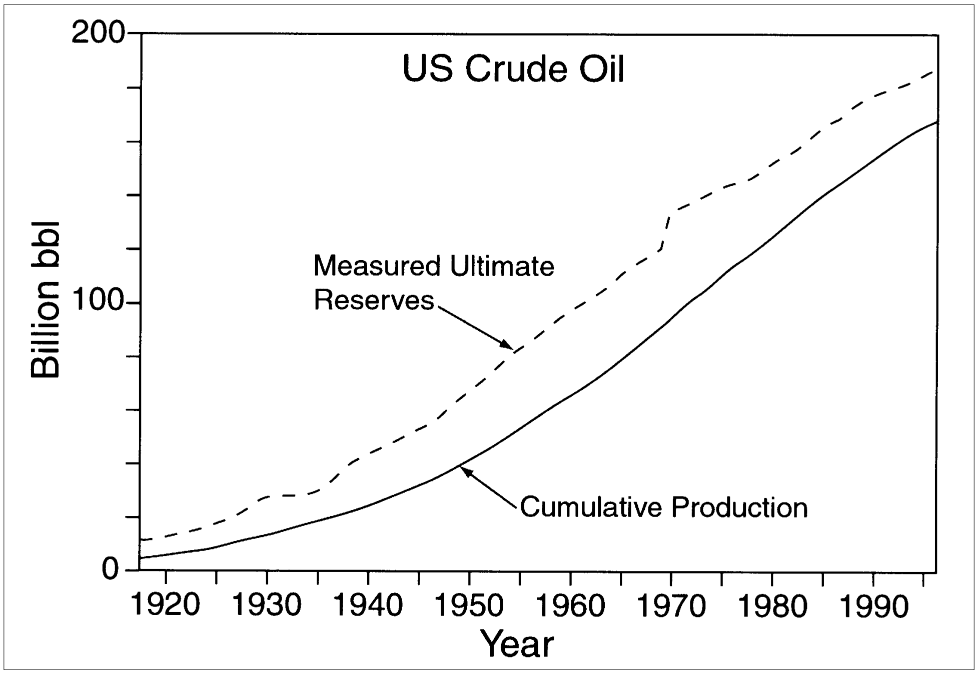

Figure 3 – Reserves of U.S. oil versus cumulative production (after McCabe, 1998, p. 2114).

into a transportable form. The IEA (1998) described GTL technology as dating to 1923, but only recently “coming of age”. Fouda (1998) reviewed several different GTL technologies under development, and notes that even with existing technology natural gas can be converted into liquid fuels at prices “only about 10 percent higher per barrel than crude oil”.

Methane Hydrates.

Methane hydrates are ice-like mixtures of methane (CH_4) and water in which the gas molecules are trapped within a framework or clathrate of water molecules. Methane hydrates are found in polar regions where temperatures are cold enough for permafrost to be present and offshore on the continental margins where cold water is found at depths greater than 300 to 500 meters (Kvenvolden, 1993).

Methane hydrates are of interest for two reasons. Many estimates of the size of the hydrate resource are very large (Figure 6). Kvenvolden (1993) estimated the amount of methane in gas hydrates throughout the world to be about 700,000 trillion cubic feet. As of 1997, the US consumption rate for natural gas was 22.3 trillion cubic feet per year (BP, 1998). Thus the potential size of the methane hydrate resource is equivalent to 31,390 years of 1997 US consumption. Second, methane is a proven and relatively clean-burning fuel which can be used in motor vehicles as well as for electricity generation and home heating.

At the present time, it is uncertain if economic production of methane hydrates will occur at any time in the foreseeable future. Laherrere (1999a, b) points out that the size of the methane resource and its nature (concentrated versus dispersed) is very uncertain. Direct evidence of methane occurrences in thick, concentrated deposits is rare to nonexistent, and indirect indicators are “unreliable and highly speculative” (Laherrere, 1999a, b).

To produce natural gas from hydrates, the hydrate must be dissociated or broken down into gas plus water or gas plus ice. At the present time, there is no technology for the economic extraction of methane from hydrates. Methane hydrates are mostly viewed in the petroleum industry as a production nuisance which can clog pipelines and well bores. Three potential production methods are recognized in the literature. These

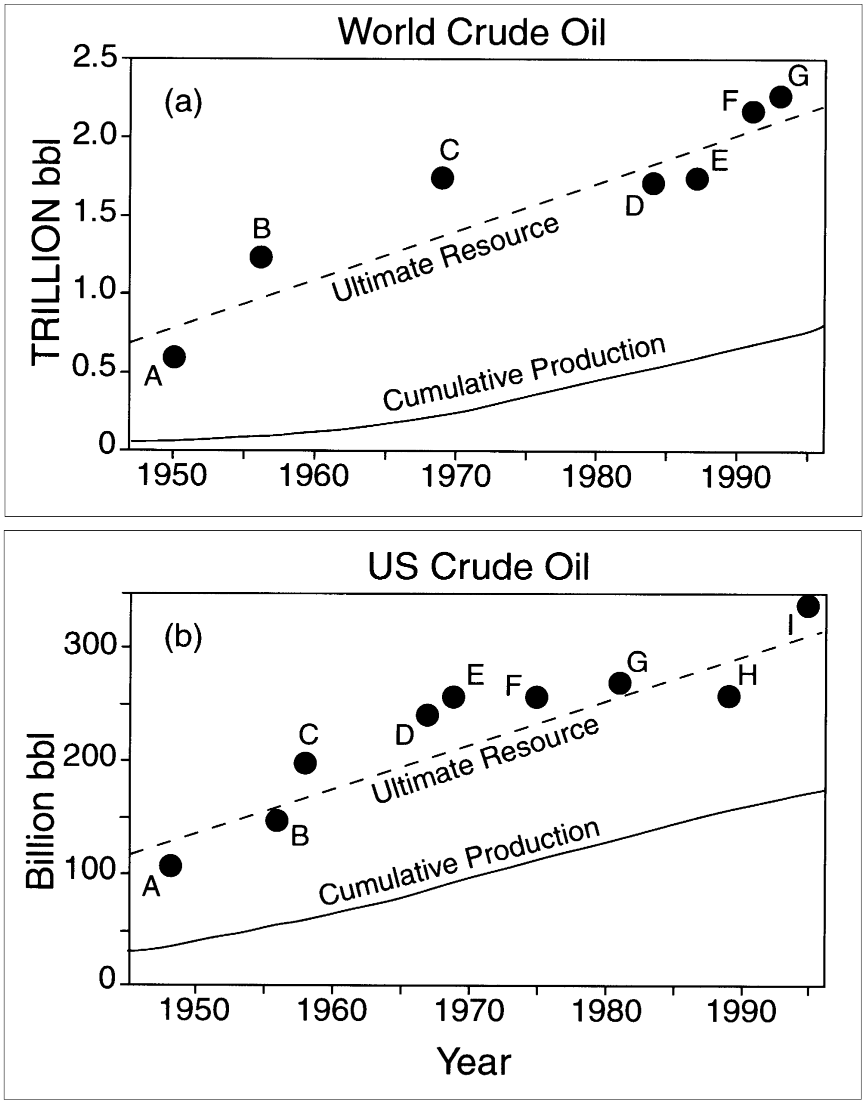

Figure 4 – (a) Historical estimates of the total size of the world's crude oil resource versus cumulative world production. Resource estimates are those selected by McCabe (1998) and are keyed as follows: A (Weeks, 1950), B (Hubbert, 1956), C (Hubbert, 1969), D (Masters et al., 1984), E (Masters et al., 1987), F (Masters et al., 1991), G (Masters et al., 1994).

(b) Historical estimates of the total size of the U.S. crude oil resource versus cumulative U.S. production. Resource estimates are those selected by McCabe (1998) and are keyed as follows: A (Weeks, 1948), B (Hubbert, 1956), C (Weeks, 1958), D (Hubbert, 1967), E (Hubbert, 1969), F (Miller et al., 1975), G (Dolton et al., 1981), H (Mast et al., 1989), I (U. S. Geological Survey National Oil and Gas Resource Assessment Team, 1995, and Minerals Management Service, 1996).

are (1) thermal stimulation, (2) pressure reduction, and (3) inhibitor injection. In brief, the only one of these three methods which can lead to large-scale economic production is thermal stimulation. This is because hydrate dissociation involves an endothermic phase change. It is thermodynamically feasible to supply the necessary energy if freed methane is burned, because the heat of dissociation is only about 10% of the heat released by methane combustion (Holder, 1984). The primary production challenge will be to devise a technology for delivering heat throughout hydrate reservoirs.

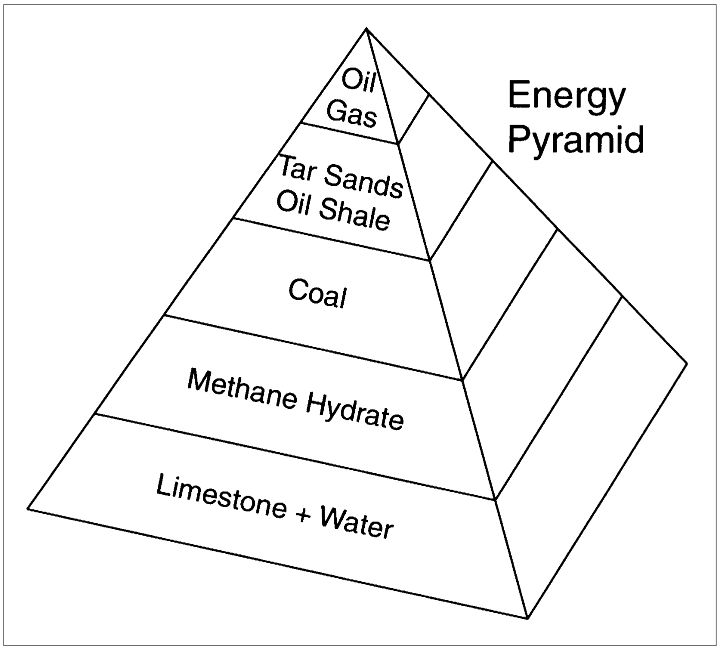

Figure 5 – Hydrocarbon energy pyramid.

HUBBERT'S MODEL AND PREDICTIONS

M. K. Hubbert made two valuable contributions to the understanding of fossil fuel production and depletion. First, he pointed out that production and consumption tend to increase exponentially during the initial phase of a resource's development. In 1950, it was common to calculate years of total supply by dividing reserves or resources by current production or consumption rates. Hubbert pointed out that such a method was likely to drastically underestimate the time over which adequate fuel supplies would be available, because consumption and production rates would increase in the future. Secondly, Hubbert pointed out that problems arise not when total supplies are exhausted, but when demand exceeds supply. If the production curve is symmetric, this point is reached when half of the ultimate production is reached.

Hubbert's model is based upon two assumptions. First, that the supply of any resource is finite. Second, that the production rate of a resource will grow exponentially, peak, and then decrease exponentially as the resource is depleted. Hubbert applied these assumptions to make predictions of both US and world oil production. The most famous of these predictions was made in a 1956 paper published in the American Petroleum Institute's "Drilling and Production Practice" titled "Nuclear Energy and the Fossil Fuels". Based upon ultimate oil reserves estimates of 150 and 200 billion barrels, Hubbert (1956) predicted that oil production in the US would peak as early as 1965, but no later than 1970. Oil production in the conterminous U.S. peaked in 1970 at 3.44 billion barrels.

In his earlier works, Hubbert was somewhat obscure regarding the mathematical formulae he used to produce his bell-shaped production curves. Although the "Hubbert Curve"is bell-shaped, it is not the Gaussian curve seen in probability theory (Laherrere, 1999c). A complete explanation of Hubbert's methods is found in a somewhat obscure symposium volume published by the National Bureau of Standards (Hubbert, 1982). In this work, Hubbert (1982) derives an expression for cumulative production Q (Hubbert, 1982, p. 49) and identifies it as the "logistic equation" originally derived by the Belgian demographer Verhulst. The more familiar plots of production rate (dQ/dt) follow immediately by taking the derivative with respect to time. Although the logistic equation seems to have been favored by Hubbert as the most logical approach, Hubbert (1982, p. 139) claimed that his prediction of 1956 was drawn by hand. In response to a question, he stated:

> "In my figure of 1956, showing two complete cycles for U.S. crude-oil production, these curves were not derived from any mathematical equation. They were simply tailored by hand subject to the constraints of a negative-exponential decline and a subtended area defined by the prior estimates for the ultimate production. Subject to these constraints, with the same data, I suggest that anyone interested should draw the curves himself. They cannot be very different from those I have shown".

Whatever the case, in reality there is no unique Hubbert curve. Hubbert himself (1949, p. 105) wrote that:

> "Thus we may announce with certainty that the production curve of any given species of fossil fuel will rise, pass through one or several maxima, and then decline asymptotically to zero. Hence, while there is an infinity of different shapes that such a curve may have, they all have this in common: that the area under each must be equal to or less than the amount initially present".

In fact, the production curves shown by Hubbert for coal (1949, p. 107) and for petroleum (1950, p. 104) are not bell-shaped, but are strongly asymmetrical with post-peak production declining more slowly than pre-peak production increased. In his 1956 paper and after, Hubbert seems to have exclusively used symmetrical production curves.

Despite the fame of Hubbert's 1956 prediction and the widespread acceptance of his model, some pointed criticisms of the Hubbert model can be made. McCabe (1998) demonstrated that there is no inherent reason that production of an energy resource should necessarily follow a Hubbert-type curve, and cited examples which did not. He also pointed out that the production history of some resources (e.g., Pennsylvania anthracite) have followed a Hubbert-type curve, but are far from exhaustion. In some historical cases, production dropped because of substitution of alternative energy sources. For example, in the 20th century coal was largely replaced by oil and natural gas (Figure 7). McCabe (1998) showed that energy markets tend to be "open" as opposed to "closed". That is, the history of energy use is one of substitution. It is not clear, however, if this can be the case for petroleum. Coal and nuclear power can replace gas and oil for electricity generation, but at the present time there is no ready substitute for petroleum in the transportation sector.

Advocates of the Hubbert model (e.g., Ivanhoe, 1995; Campbell and Laherrere, 1998) often cite the accuracy of Hubbert's 1956 prediction of US oil production as substantiation for the correctness of the Hubbert method. Ivanhoe (1995) characterized Hubbert's 1956 prediction as the "only truly valid scientific projection of future oil production", and claimed that since the 1970 production peak, oil production from the 48 conterminous US states declined within 5% of Hubbert's 1956 prediction. Campbell and Laherrere (1998) in reference to Hubbert's 1956 prediction said "He was right: production peaked in 1970 and has continued to follow Hubbert curves with only minor deviations". However, McCabe (1998) objected that "the conclusion that Hubbert's methodology and assumptions must have been correct because his predictions were accurate is not logical". Furthermore, claims of predictive accuracy appear to be overstated. Hubbert's (1956) prediction of gas production proved to be grossly in error. As of 1998, U.S gas production was more than twice as high as Hubbert predicted in 1956 (Figure 8).

To correctly evaluate the accuracy of Hubbert's 1956 predictions, it is necessary to consider the context of his writing. In 1956, Hubbert made what he considered to be a "best" estimate of the total size of the U.S. crude oil resource (given the symbol Q_∞ by Hubbert). This estimate was $Q_\infty = 150$ billion barrels and included offshore areas of the conterminous U.S., but excluded Alaska. Hubbert (1956) then proceeded to consider an exaggerated estimate of the largest possible size of the U.S. crude oil resource in order to set an outer limit. Hubbert (1956, p. 18) set this at $Q_\infty = 200$ billion barrels, noting that the addition of 50 billion barrels to the resource base was "an amount equal to 8 East Texas oil fields".

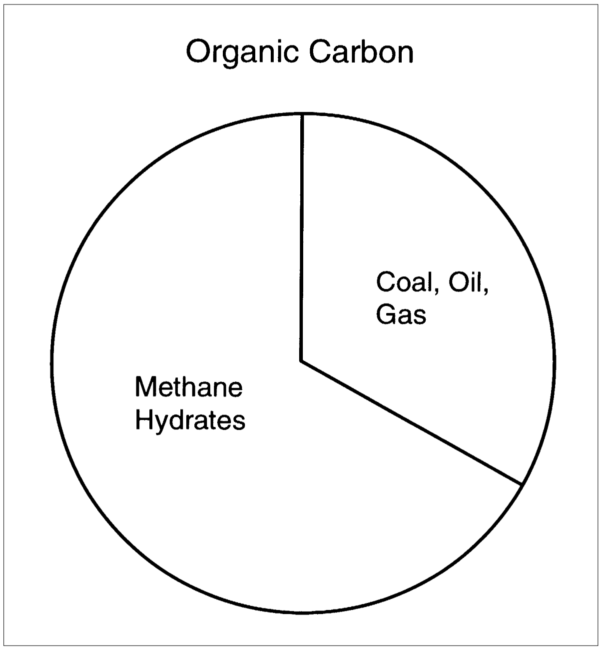

Figure 6 – Relative amounts of organic carbon in methane hydrates compared with coal, oil, and gas (after Kvenvolden, 1993).

Claims regarding the predictive accuracy of Hubbert's predictions appear to be largely based upon the upper curve derived from Hubbert's upper limit of Q_∞ = 200 billion barrels, (Figure 9). This curve was presented by Hubbert not as a best prediction, but as an absolute upper limit. Even so, as early as 1970, actual production of U.S. crude oil had exceeded Hubbert's upper limit by 13%, and Hubbert's best estimate of future U.S. crude-oil production was badly in error. From about 1975 through 1995, Hubbert's upper curve was a fairly good match to actual U.S. production data (Figure 9). However, in recent years U.S. crude-oil production has been consistently higher than what Hubbert (1956) considered to be the highest possible future levels. In light of this, it is strange that Hubbert's predictions have been characterized as a remarkable success. Ironically, Hubbert's subsequent revisions to his U.S. crude-oil predictions ultimately proved to be less accurate than the upper curve he drew in 1956, because he finally settled on a number for the size of the ultimate resource Q_∞ in the neighborhood of 170 billion barrels. Hubbert's last prediction of U.S. crude oil production was made in 1980 and published in 1982 (Hubbert, 1982, p. 89). This prediction (Figure 10) is based upon an estimate of Q_∞ = 170 billion barrels, and thus is intermediate between the two curves published by Hubbert in 1956 (Figure 9). As of 1998, Hubbert's 1980 prediction was 39% too low.

Hubbert's primary success was his prediction that oil production in the U.S. would peak "at about 1965" (Hubbert, 1956, p. 18). Hubbert (1956) went on to claim that even if Q_∞ proved as large as 200 billion barrels, the peak would be "retarded only until about 1970". The actual peak occurred in 1970. Hubbert's best estimate (1956) of peak production in 1965 was in error by 5 years, with the actual production peak occurring at the outer limit of his uncertainty range. However, adherents to Hubbert's methods tend to present the peak-production prediction in the best possible light. For example, both Ivanhoe (1995) and Campbell and Laherrère (1998) claimed that Hubbert (1956) predicted U.S. oil production would peak in 1969, plus-or-minus a year. This is only true if Hubbert's (1956) upper curve (Figure 9) is used, and Hubbert's actual prediction of 1965 ignored.

The primary problem with Hubbert-type analyses is that they depend on an estimate of the total resource size. The greater the size of the resource, the longer the Hubbert peak is delayed. The history of resource assessments (Figure 4) shows that over the last 50 years estimates of ultimate oil reserves have risen as fast or

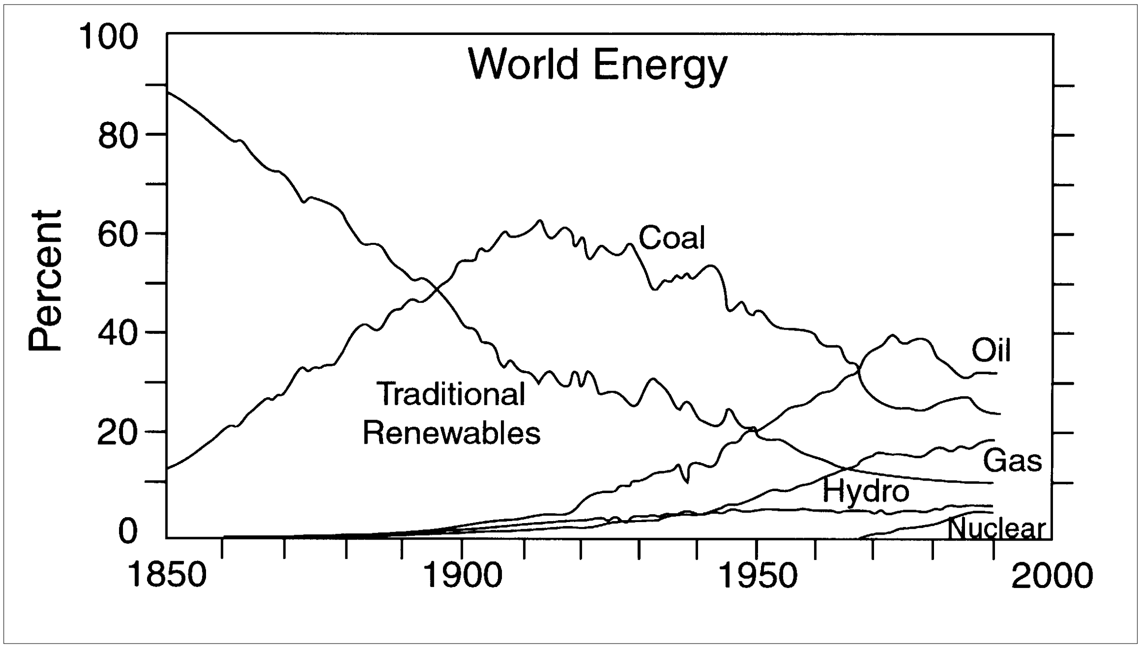

Figure 7 – World energy consumption, 1850 through 1990 (after: Nakicenovic et al., 1998).

faster than cumulative oil production. For a Hubbert-type model to work, there must be some assurance that the estimated size of the resource base is accurate and will not increase in the future. McCabe (1998, p. 2122) points out that "all (resource) assessments have a strong subjective component and, at best, only identify those resources that appear to have some economic potential within the foreseeable future". McCabe (1998) goes on to state that "a finite resource cannot be realistically be measured". As time proceeds, each succeeding assessment cuts down further into the resource pyramid, thus each succeeding assessment is larger than the previous. If this is true, then it is impossible to make an accurate or stable assessment of the size of the resource base and all predictions based on a Hubbert model will fail. Lynch (1999) noted out that "the Hubbert method has consistently produced bad forecasts", and cites predictions made by Campbell (1989, 1991).

Like other models, the Hubbert model is based upon assumptions and its validity should be judged by comparing predictions with facts. However, amongst not only its adherents, but the larger world as well, the Hubbert model is dogmatically regaraded as being absolutely correct almost to the point of religous zealotry. In a posthumous tribute to Hubbert, the National Academy of Sciences (1990) referred to Hubbert's model — an empirical model based upon assumptions — as a "mathematical proof". In reference to the Hubbert method, Lynch (1999) pointed out that all previous applications had systematically underestimated actual production and suggested:

> "Since persistent errors in one direction are proof that a theory and/or parameters need revision (if not discarding), reviewing existing work is an important aspect of scientific discovery. Scientists are supposed to produce theories that are reproducible and verifiable. If not, they are practicing religion."

Hubbert apparently never considered that the size of the finite resource base might be a moving target, thus invalidating his entire approach. In an interview published in 1983 (Clark, 1983, p. 22) he proved himself to be both a doomsayer and a strict malthusian:

> "We are in a crisis in the evolution of human society. It's unique to both human and geo-

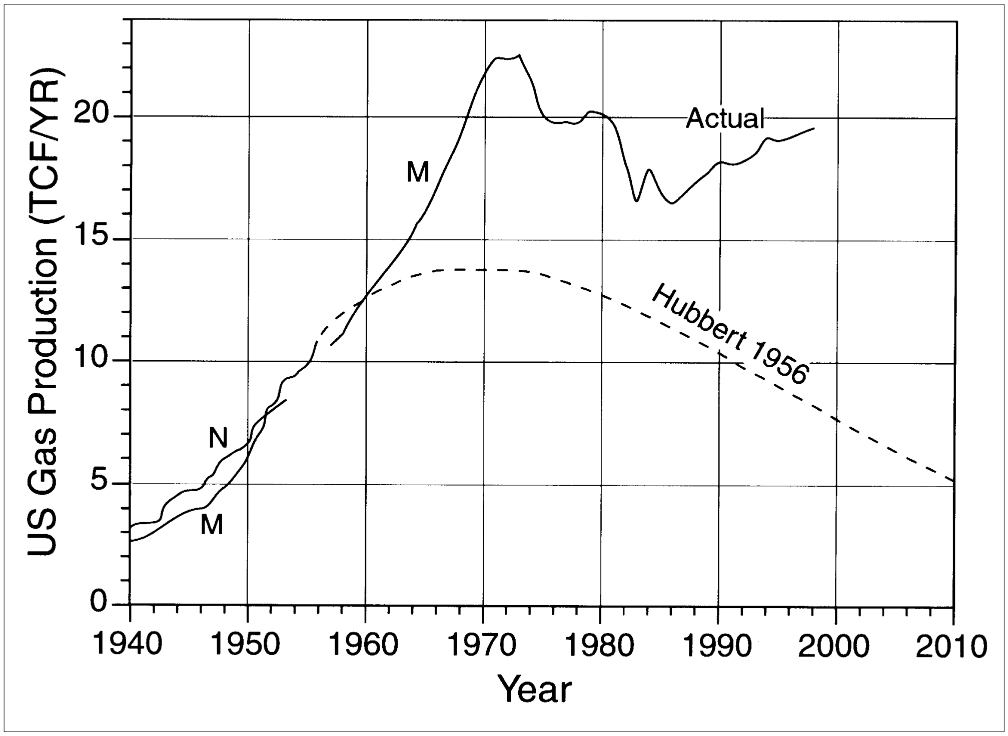

Figure 8 – Production of natural gas (solid lines) in the United States (excluding Alaska) compared with Hubbert's 1956 prediction (dashed line) of future gas production. "M" indicates marketed gas, which is about 1% lower than net or total gas production ("N"). Data prior to 1957 are from Hubbert (1956, p. 18) and were obtained by digitizing his figure 22. Data from 1957 through 1998 are from annual estimates of marketed gas made by Oil and Gas journal.

> logic history. It has never happened before and it can't possibly happened again. You can only use oil once. You can only use metals once Soon all the oil is going to be burned and all the metals mined and scattered....I think the world is seriously overpopulated right now. There can be no possible solutions to the world's problems that do not involve stabilization of the world's population".

Despite Hubbert's 1983 prediction of imminent shortages, the average price (in terms of wages) of non-ferrous minerals (oil, coal, zinc, lead, platinum, tin, etc) in the U.S. fell by more than 50% from 1980 to 1990 (Moore, 1995, p. 112).

Hubbert had strong views on the nature of society and its relationship to science. He was intimately involved with technocracy, a political and ideological movement which reached its zenith in the U.S. during the 1930s (Akin, 1977). Technocracy is defined as "a government and social system controlled by scientific technicians". Under a technocratic system, all production and pricing would be under the control of a small cadre of scientists and engineers. Human relations were also to be administered "efficiently" and "scientifically" by a experts in the same manner as production. The technocratic society envisioned by Hubbert and his colleagues was to be highly authoritarian. Akin (1977, p. 145) described technocratic utopia as:

> "Under a technocracy, a sizable amount of things deemed good would be given up. For those who desired a new society, the concern for the commonweal minimized outdated concepts of individual conscience, free choice, and self-expression—the whole liberal belief in the dignity and worth of the individual. There would be no nonsense about individual liberty"

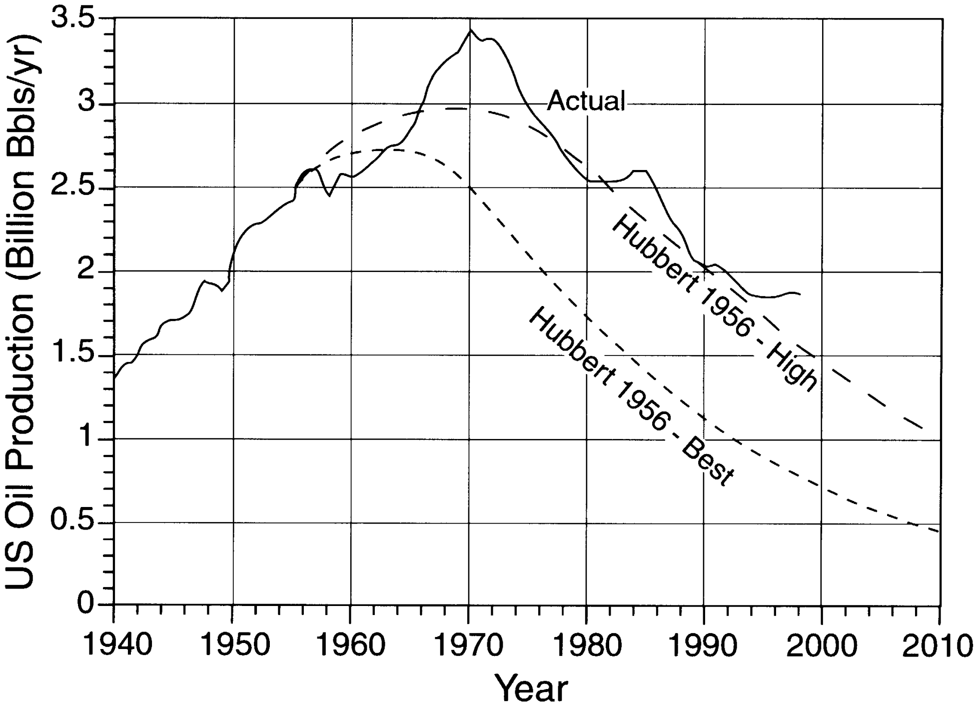

Figure 9 – Crude oil production (solid line) in the United States (excluding Alaska) compared with predictions (dashed lines) made by Hubbert (1956). Production data prior to 1955 are from Hubbert (1956, p. 17) and were obtained by digitizing his figure 21. Data from 1956 through 1998 are from annual estimates made by Oil and Gas journal.

Technocracy flourished in the depths of the 1930s Great Depression, when it appeared as though the American economic system had failed. During the latter two-thirds of the twentieth century, authoritarian governments in Nazi Germany, the Soviet Union, and Communist China, murdered tens of millions of their own citizens under the guise of promoting utopian ideals. By 1990, the Soviet system in Russia and its satellites had collapsed and was an economic basket case. In contrast, the United States weathered the economic depression of the 1930s and went on to provide its citizens with high levels of material prosperity combined with economic, political, and personal freedoms. With the benefit of this retrospective, Hubbert's political ideas appear to have been dangerously wrong. What is not clear is to what extent these beliefs may have influenced his scientific conclusions regarding mineral resources.

NUCLEAR ENERGY

The history of energy utilization is one of substitution (Figure 7). Up to about 1895, wood was the primary energy source for the world. Coal was the dominant source of the world's energy from 1895 through 1965. The age of oil began in 1965, and it remains the largest single energy source in the world today. Where will energy for the civilization of the future come from?

Wood is a largely renewable resource, but its energy density is inadequate for a technological civilization. The world contains large amounts of oil and gas, both conventional and unconventional. Barely a fraction of the world's coal resources have been depleted. However, the potential nuclear energy resource is so large that it is virtually unlimited when measured in terms of today's energy demands.

Uranium consists of three natural isotopes in the following proportions: U-238 (99.3%), U-235 (0.7%), and U-234 (0.005 %). The only isotope which may be readily utilized in fission reactors is U-235. The much more

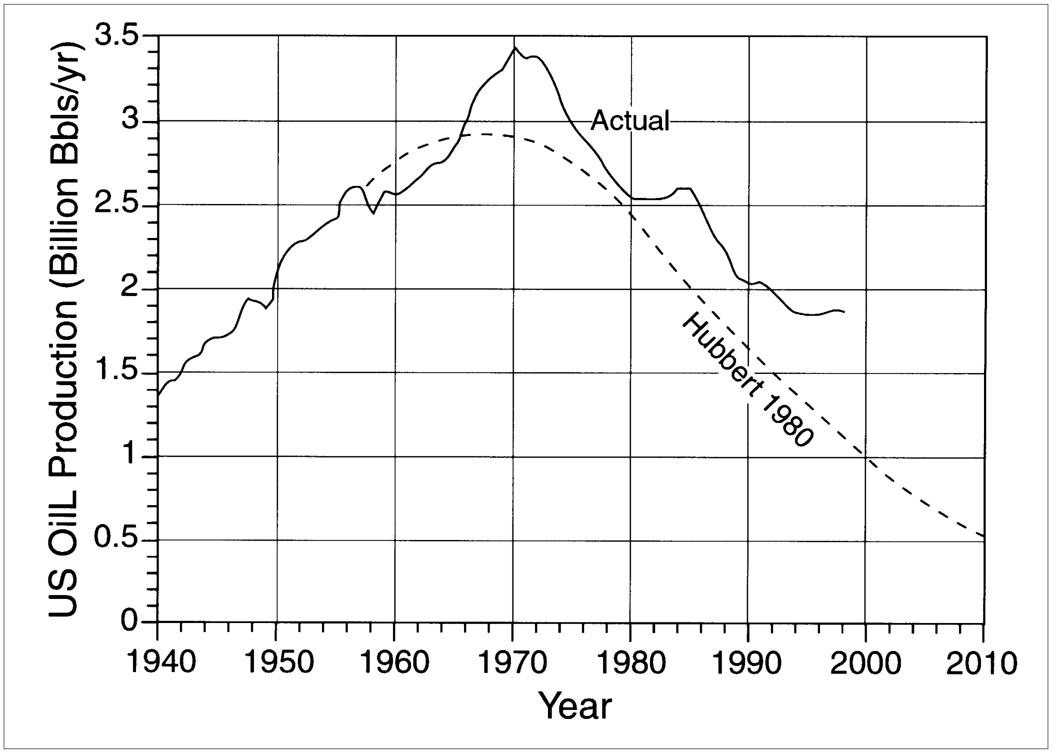

Figure 10 – Crude oil production (solid line) in the United States (excluding Alaska) compared with prediction (dashed line) made by Hubbert (1982) in 1980. Production data prior to 1955 are from Hubbert (1956, p. 18) and were obtained by digitizing his figure 22. Data from 1956 through 1998 are from annual estimates made by Oil and Gas journal.

abundant U-238 isotope is not fissionable, but may be converted into fissionable Plutonium under neutron bombardment by U-235 fission. Nuclear reactors may be burner or breeder reactors. Burner reactors fission the high-grade isotope, U-235. Breeder reactors use U-235 to produce fissionable Plutonium from the more abundant U-238 isotope. More fissionable material is produced than used in a breeder reactor. This does not violate the conservation of energy, because a breeder reactor simply unleashes the potential energy inherent in the relatively stable U-238 isotope.

Finch (1997) estimated that at current use rates, the size of the world's U-235 resource was sufficient to supply 500 years of use. However, if U-238 is utilized in breeder reactors, the size of the resource becomes almost unimaginably large (Figure 11). Hubbert (1969) pointed out that the continental crust contains large amounts of low-grade uranium. For example, the Chattanooga Shale found in the states of Tennessee, Kentucky, Ohio, Indiana, and Illinois, contains a unit about 15 feet (4.6 m) thick which contains 0.006 percent uranium by weight. The energy density is such that 20 square kilometers of this unit would provide the same energy as 200 billion barrels of oil (Hubbert, 1969, p. 227). Hubbert (1969) noted that the energy potentially obtainable from low-grade uranium obtained from crustal rocks is easily hundreds or thousands of times larger than all other fossil fuels combined. More recently, Cohen (1983) pointed out that uranium could be extracted from sea water at a cost of only $1000./lb. This cost, although high compared to a 1983 market price of $40./lb, would add only 0.03 cents per kW-hr to the cost of generated electricity. Uranium is also being constantly added to seawater through erosion of the continental crust. Cohen (1983) calculated that 16,000 tonnes of uranium per year could be drawn from seawater continuously for hundreds of millions of years without depleting the oceans. If breeder reactors are utilized, this amount of uranium would be sufficient to provide energy at a rate 25 times the world's electricity usage in 1983, or twice the world's total energy consumption in 1983.

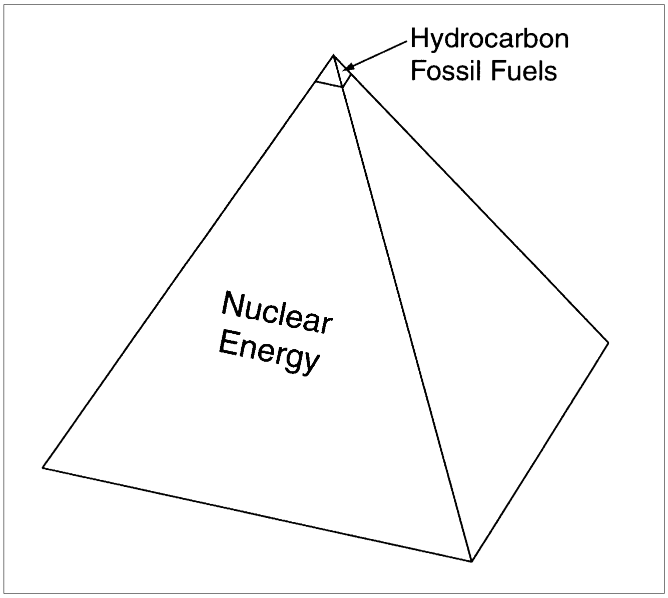

Figure 11 – Energy pyramid. Potential nuclear energy resources dwarf all hydrocarbon fossil fuels.

Although nuclear power has great promise, it is being phased out in the U. S. As of 1995, uranium accounted for 23 percent of electricity generated in the U. S. (Finch, 1997). No new nuclear power plants have come on line in the U.S since 1993. Commercial nuclear power plants have operating lifetimes of 40 years. Starting in 2012, there will be a steady decrease in the amount of electricity generated through nuclear power if new plants are not built. If the present situation continues, nuclear power will cease to exist in the U.S. by the year 2033.

The utilization of uranium for nuclear power generation is controlled almost exclusively throughout the world by government policies and regulations. Government policies in turn are strongly influenced by social and political attitudes. Two well-publicized nuclear power-plant accidents have contributed to the formation of highly negative attitudes concerning nuclear power. In 1979, a nuclear power plant on Three Mile Island, about 10 miles south of Harrisburg, Pennsylvania, released some radioactivity into the surrounding environment. Although the magnitude of the release was inconsequential, public media played on the public's fears. In 1986, a catastrophic nuclear accident occurred at a nuclear power plant in Chernobyl, Ukraine. The Chernobyl disaster cemented opinion regarding the safety of nuclear power, and essentially made further debate moot for perhaps a generation.

If the environmental problems and perceptions surrounding nuclear power plants cannot be overcome, there is no known resource or technology which can supply energy for the civilization of the future. In the long run, however, it may be best if today's generation of burner reactors are phased out. Although the amount of U-238 is very large, fissionable U-235 is scarcer. If we continue on the present course, supplies of U-235 may be depleted in burner reactors before they can be used in a new generation of self-sustaining burner reactors. Hubbert (1969, p. 228) predicted that the failure to make the transition from burner to breeder reactors would constitute "one of the major disasters in human history".

CONCLUSIONS

1. The history of the 20th century is one of repeated false predictions of imminent oil shortages.
2. Although conventional oil and gas deposits may be finite, estimates of their size have grown through

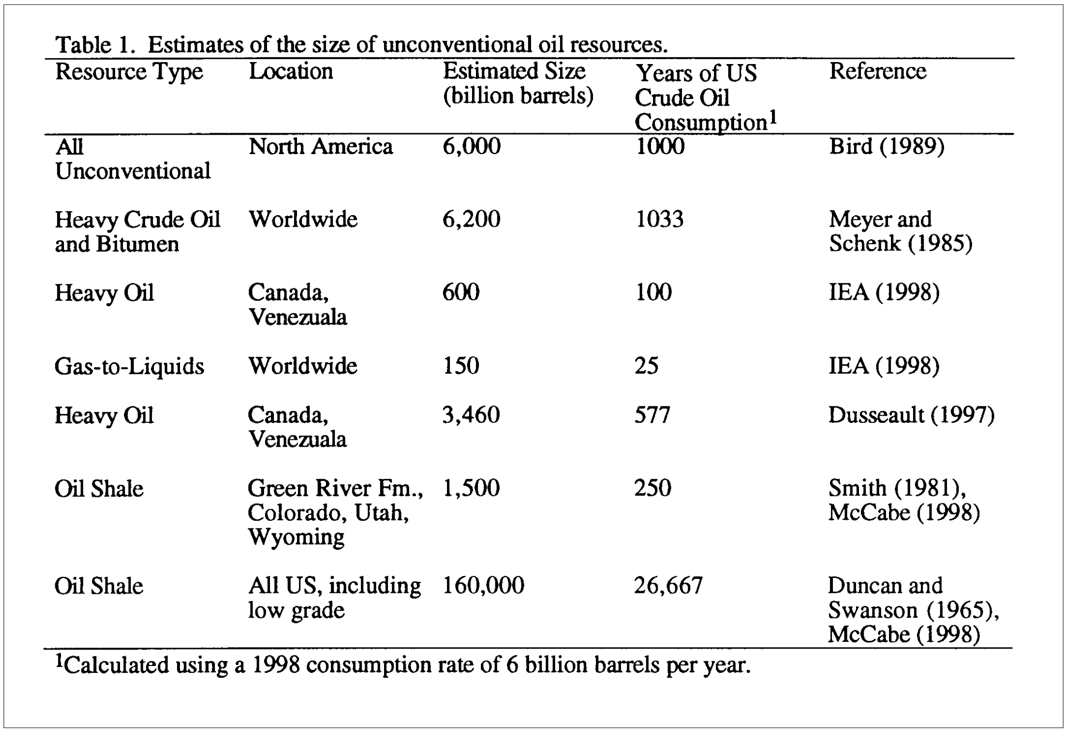

Table 1. Estimates of the size of unconventional oil resources.

Resource Type	Location	Estimated Size (billion barrels)	Years of US Crude Oil Consumption[1]	Reference
All Unconventional	North America	6,000	1000	Bird (1989)
Heavy Crude Oil and Bitumen	Worldwide	6,200	1033	Meyer and Schenk (1985)
Heavy Oil	Canada, Venezuala	600	100	IEA (1998)
Gas-to-Liquids	Worldwide	150	25	IEA (1998)
Heavy Oil	Canada, Venezuala	3,460	577	Dusseault (1997)
Oil Shale	Green River Fm., Colorado, Utah, Wyoming	1,500	250	Smith (1981), McCabe (1998)
Oil Shale	All US, including low grade	160,000	26,667	Duncan and Swanson (1965), McCabe (1998)

[1] Calculated using a 1998 consumption rate of 6 billion barrels per year.

the last 50 years as fast as cumulative production.

3. As production of unconventional oil resources in the form of tar sands has already begun, it becomes increasingly difficult to define the size of the world's oil and gas resource base. Unconventional oil resources such as tar sands and oil shales are sufficient in size to supply the world's petroleum needs for about 100 to 1000 years.

4. As conventional oil resources begin to become depleted they will be replaced by unconventional oil resources. The nature of the transition is unknown at the present time. It may be seamless, with uninterrupted supplies and low prices, or there may be interruptions in oil supplies, high prices, and economic disruptions.

5. Although the Hubbert model was an important advance in the science of resource evaluation, its application over the last 40 years has resulted in depletion estimates that are systematically premature and inaccurate. Current and future application of the Hubbert model will remain problematical so long as resource estimates remain uncertain.

6. At the present time, the only known energy resource which can supply the world's needs for the distant future is nuclear power. Nuclear power is only a long-term solution if breeder reactors are used.

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