METHODS AND MODELS FOR ASSESSING ENERGY RESOURCES

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OPENING REMARKS

M. King Hubbert*, Chairman

One of the most important developments in contemporary scientific and technical thought is the growing awareness of the significance of energy in human affairs. The universality of energy in terrestrial activities can be appreciated when we consider that the earth is a nearly closed material system through whose surface environment occurs a continuous influx, degradation, and efflux of energy. As a consequence, the mobile materials of the earth's surface undergo either continuous or intermittent circulation. These statements encompass just about everything that happens on the earth, including our being here today at this Conference.

This flux of energy is a continuing process that, with only minor variations, has persisted throughout the span of geologic time. The principal sources of energy influx are but three: the solar radiation intercepted by the earth, geothermal energy from the earth's interior, and tidal energy from the potential and kinetic energy of the earth-moon-sun system.

Measured in units of 10^{12} thermal watts (Wth), the rates of influx from these sources are solar, 174,000; geothermal, 32; tidal, 3. It is thus seen that the solar influx is about 5000 times the sum of the other two.

Of the solar influx, about 30%, or $52 \cdot 10^{12}$ Wth, is reflected and scattered into outer space as visible short-wavelength radiation. This fraction is ineffective with respect to terrestrial processes. The remaining 70%, or $122,000 \cdot 10^{12}$ Wth, warms the earth, drives the circulation of air and water, and a small fraction, stored chemically by the process of photosynthesis, becomes the basic energy source for the physiological requirements of the plant and animal kingdoms of the earth's biological system. With one small exception, this energy undergoes a series of

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degradations until it reaches an end state of heat at the lowest ambient temperature of the earth's surface. This is then re-radiated to colder outer space as long-wavelength thermal radiation.

The minor exception pertains to the minute fraction of plant and animal materials that become deposited in peat bogs and other oxygen-deficient localities where they cannot completely decay. When these became buried under great thicknesses of sedimentary sands and muds during the geologic past, they were preserved and converted into the earth's present supply of fossil fuels.

These processes are occurring now, and they also have been occurring during at least 600 million years of geological history. The oldest gas field of which I am aware has been found in Australia in late Pre-Cambrian rocks--perhaps 600 to 700 million years ago. In the USA and other parts of the world, oil and gas accumulations have been found in rocks of all geological ages from the Cambrian, nearly 600 million years ago, to the last million years in the Mississippi delta of coastal Louisiana.

The oldest major coal deposits are the bituminous and anthracite coals of the Carboniferous Period, about 280 to 350 million years ago. Then there are younger subbituminous coals of Mesozoic age (65 to 200 million years ago), Tertiary lignites, and finally peat which is accumulating at present.

The energy stored in the initial supply (before human exploitation) of recoverable fossil fuels is estimated to amount to $2.3 \cdot 10^{23}$ thermal joules (Jth). Other static stores of energy within mineable or drillable depths beneath the earth's surface are represented by earth heat, and by the nuclear energy obtainable from the heavy elements uranium and thorium by fissioning, or from the lightest element, hydrogen, by fusion.

An informative comparison can be made between the magnitude of the stored energy of the fossil fuels and the rate at which energy impinges upon the earth from sunshine. The energy obtainable from the fossil fuels, as we have noted, amounts to about $2.3 \cdot 10^{23}$ Jth. The effective solar energy influx is at a rate of about $1.22 \cdot 10^{17}$ Wth, or joules per second. This amounts to $1.05 \cdot 10^{22}$ joules per day, and the time required for the energy accrual from the solar influx to equal the stored energy of fossil fuels is only 22 days.

Considering that the solar influx is continuous and has been at about the same rate for hundreds of millions of years, it becomes obvious that the largest source of energy available to the earth, past, present, or future, is that from the sun.

Let us now consider the human historical evolution which I think is pertinent to this Conference. We have noted that the time required for the accumulation of the fossil fuels was about 600 million years. It has been only within the last 2 or 3 million years that man has emerged as the world's dominant animal species. During this period man began to do things with the environmental energy flux that no other animal in geological history had ever done before. Initially, this consisted of the manipulation of the ecological-biological system in such a manner as to increase the food supply. Then, about a million years ago, he did a momentous thing: he learned to build a fire, thus tapping the energy of wood--still a biological source of energy, but one not previously utilized for human purposes. By the time of the ancient Egyptians, he tapped a nonbiological energy channel, namely windpower, and by Roman times, waterpower. The net effect of all such activities was to increase the human population, both in density and in geographical extent, with corresponding adjustments in the populations of all other plant and animal species of the ecological system. However, the energy per capita increased but slightly because these changes occurred so slowly that the growth of the human population was fully able to keep pace with the increase of the energy supply. In fact, it was not until continuous exploitation of the fossil fuels was begun--coal about nine centuries ago and petroleum in 1859--that a supply of energy became available whose rate of increase of exploitation was capable of being greater than the rate of growth of the population.

There is a great contrast between the recent past and the present. Despite the fact that coal has been mined continuously since the eleventh century, the amount of coal mined since 1940 exceeds somewhat the amount mined during the preceding nine centuries. Similarly, the amount of oil produced since 1965 is slightly more than all the oil produced before 1965.

Finally, the fossil fuels are absolutely exhaustible. When coal or oil is burned the material constituents remain on the earth, but the energy content, after a series of degradations, eventually leaves the earth by outward radiation. According to the best present estimates of the world's ultimate crude oil supply--which I think are reasonably accurate--the world will probably reach the peak in its rate of oil production before the end of the present century. Disregarding the first and last 10-percentiles of the ultimate production each of which will require a longer period of time, the time required to consume the middle 80% of the world's ultimate oil supply will probably be close to the 60-year period from about 1970 to 2030. Thus, a child born within the last decade, if he lives a normal life expectancy, will see the world consume most of its oil during his lifetime. In the case of coal, the time span for the middle 80% is somewhat longer, but, according to one of the papers to be given at this Conference, it is possible that recent estimates of the world's coal resources may have been too large. In that case the peak in the rate of coal production may be reached within about a century from now. The time required to produce the middle 80% of coal may be as short as 200 years.

Hence, if we regard the period of exploitation of the world's supply of fossil fuels in the context of a period of human history extending from about 5000 years in the past to 5000 years in the future, the curve of the rate of production of energy from the fossil fuels would appear as a Washington Monument-like spike of about two or three centuries width for the middle 80% of the ultimate production. It would thus be evident that the epoch of the fossil fuels is but a transient and ephemeral event in the totality of human history, an event nevertheless that has exerted the most profound influence upon the human species that it has experienced during its entire biological existence.

In the light of these circumstances, it is hoped that the world's resources of the fossil fuels to be reviewed in this Conference may be perceived in their proper relation to the world's total energy system.

HUBBERT ESTIMATES FROM 1956 TO 1974 OF US OIL AND GAS

M. King Hubbert

The study of US petroleum resources, whose totals have been reported by Rose, represents perhaps the most important development in the US Geological Survey (USGS) during the last 15 years. As Rose has pointed out, official estimates by the USGS made during the period 1961-1974 have been about 650 billion barrels of crude oil for the entire USA and adjacent continental shelves, or about 600 billion barrels for the conterminous States, whereas my studies from 1956 to 1974 have given consistent estimates of about 170 to 175 billion barrels for the lower 48 States and adjacent continental shelves.

The results of the recent intensive study made by Rose and his staff in the Oil and Gas Branch of the USGS have given estimates of the ultimate amount of crude oil to be produced in the entire USA and adjacent continental shelves in the range of 224 to 301 billion barrels (the published report, Miller et al., 1975, Table 1, gives 218 to 295 billion barrels), the lower figure having a 95% probability and the higher one only 5%. This lower figure is in substantial agreement with my estimate of 1974 (Hubbert, 1974, Table 7, p. 155) of 213 billion barrels.

Since my methods are totally different, I am giving the following summary of my methods of analysis and of the results obtained.

Figure 1 (Hubbert, 1962, Figure 21; 1974, Figure 23) is reproduced from a paper given before an audience of petroleum engineers in 1956 (Hubbert, 1956). At that time, in the 97 years since the initial discovery of oil, the USA had produced 52.4 billion barrels of crude oil. Contemporary estimates by leaders of the petroleum industry of the ultimate amount of oil to be produced in the lower 48 States and adjacent continental shelves ranged from about 150 to 200 billion barrels.

In my analysis, I showed that the area beneath the curve of annual production versus time is a graphical measure of cumulative production. One grid square in the figure corresponds to 25 billion barrels. Hence, for 150 billion barrels, the complete-cycle curve would encompass six grid squares; for 200 billion barrels the area would be eight grid squares. The two curves in Figure 1 are drawn accordingly. For 150 billion barrels the peak in the production rate would have to occur about 10 years after 1956; for 200 billion barrels about 15 years. Therefore, the peak in production should probably occur within the interval 1966-1971.

This prediction proved to be somewhat startling to the petroleum industry and a source of some dismay. It also inspired a succession of much higher estimates, but based upon negligible new information. These are shown in Figure 2 (Hubbert, 1962, Figure 21; 1974, Figure 24). These escalated to about 400 billion barrels, and finally after five years, the USGS trumped them with 590 billion barrels for the conterminous States.

A comparison between the Hubbert 1956 estimate and that of the USGS of 1961 is shown in Figure 3 (correction of Hubbert, 1974, Figure 25). The USGS estimate is equivalent to a prediction that the peak of crude oil production in the USA would not occur until about the year 2000.

Because the foregoing estimates were all in some measure subjective, development of a method of analysis based solely upon the publicly available data of the US petroleum industry was sought. Available data included cumulative production, Q_p, from 1860 to date,

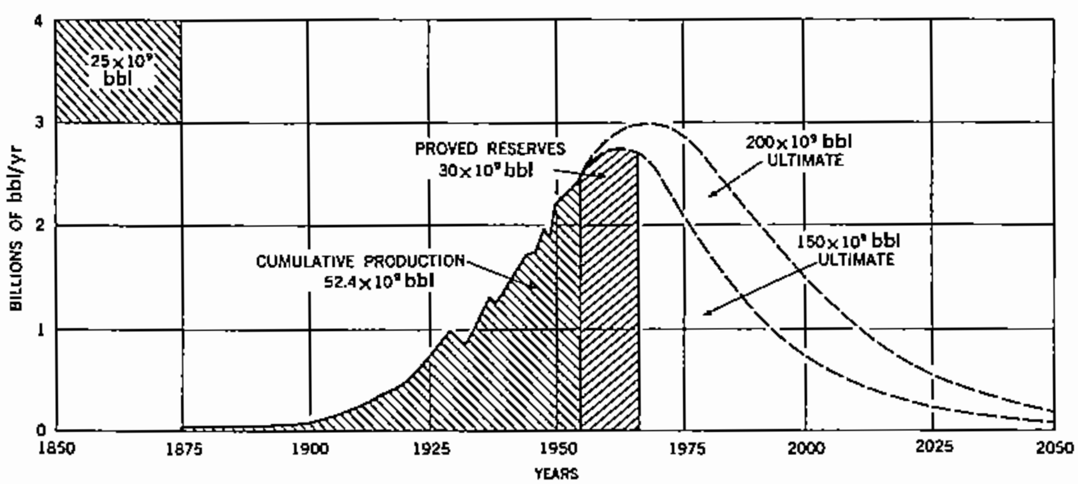

Figure 1. Hubbert prediction of 1956 of future production of crude oil in the conterminous United States and adjacent continental shelves (Hubbert, 1956, Figure 21; 1974, Figure 23).

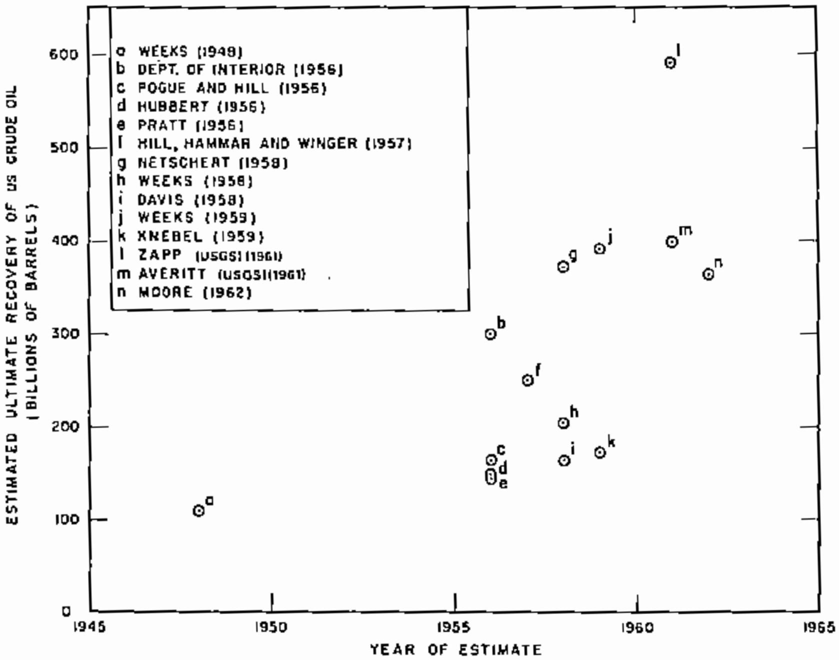

Figure 2. Estimates of ultimate crude oil production in conterminous United States published between 1948 and 1962 (Hubbert, 1962, Figure 21; 1974, Figure 24).

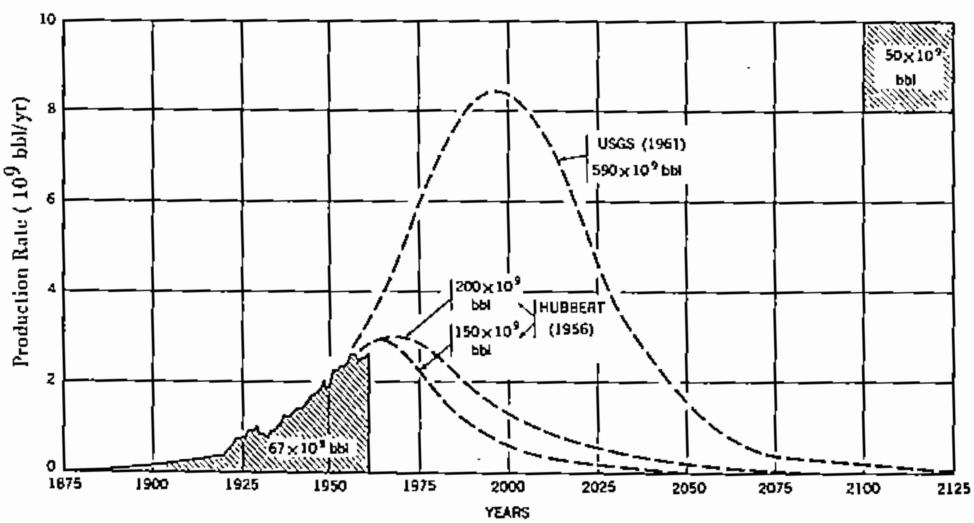

Figure 3. Comparison of complete cycles of US crude oil production based upon estimates of 150-200 and 590 billion barrels for Q_∞ (correction of Figure 25, Hubbert, 1974).

proved reserves, Q_r, since 1937, and approximate data annually since 1900. Finally, cumulative proved discoveries, Q_d, are defined by

$$Q_d = Q_p + Q_r \quad . \tag{1}$$

The approximate behavior of these three quantities during the complete production cycle is shown in Figure 4 (Hubbert, 1962, Figure 22; 1974, Figure 26). The actual data as of 1972 are shown in Figure 5 (Hubbert, 1974, Figure 36). Here it is seen that by 1972 proved reserves were 10 years past their peak, and cumulative discoveries had passed their inflection point at about 1957. The best mathematical fit for these curves gave 170 billion barrels for Q_∞, the ultimate cumulative production--the same figure obtained by a similar analysis in 1962.

The time derivative of equation (1) is

$$dQ_d/dt = dQ_p/dt + dQ_r/dt \quad . \tag{2}$$

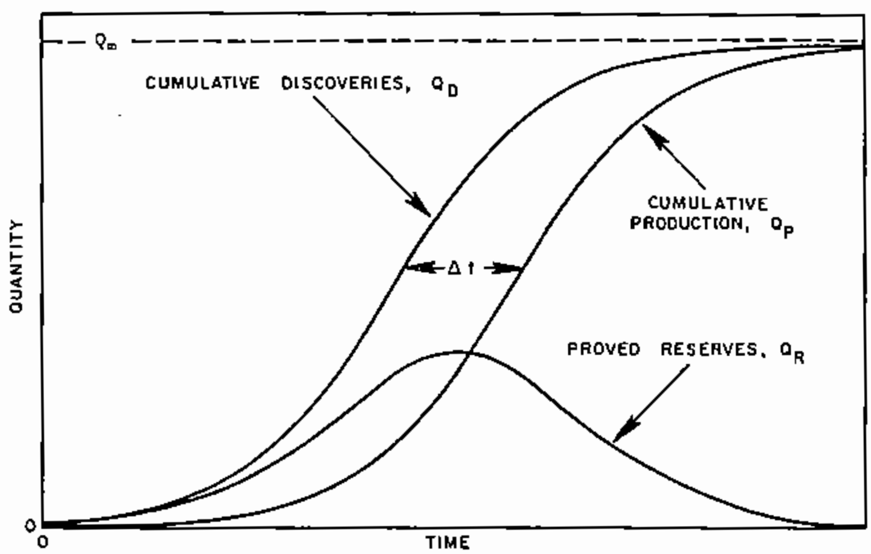

Figure 4. Variation with time of proved reserves, Q_r, cumulative production, Q_p, and cumulative proved discoveries, Q_d, during a complete cycle of petroleum production (Hubbert, 1962, Figure 22; 1974, Figure 26).

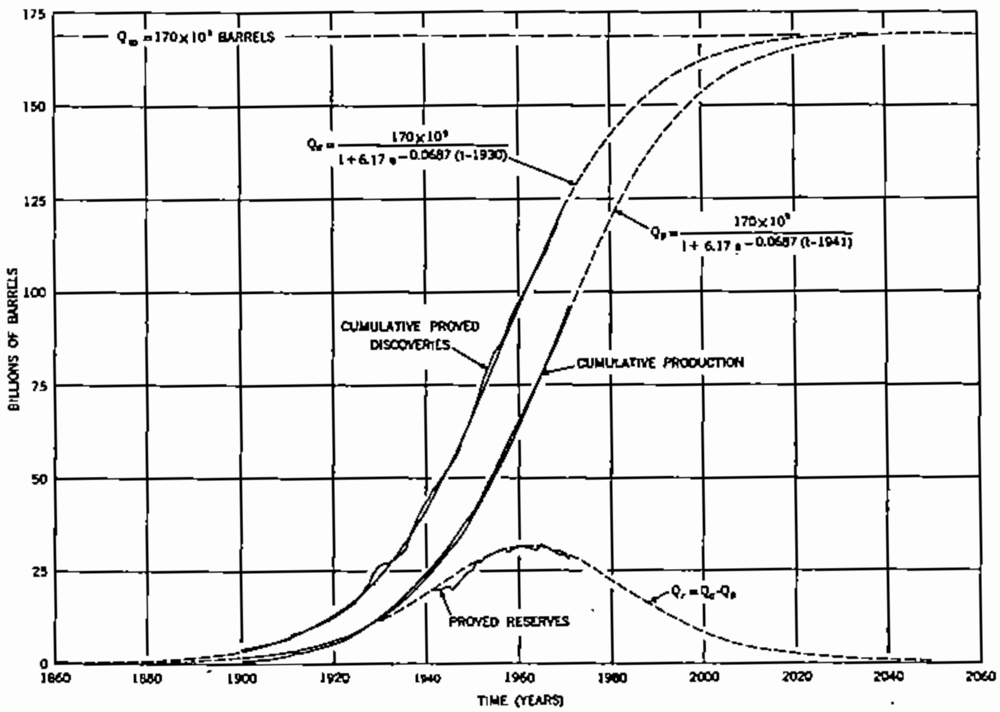

Figure 5. Logistic equations and curves of cumulative production, cumulative proved discoveries, and proved reserves for crude oil from the conterminous United States 1900-1971 (Hubbert, 1974, Figure 36).

The derivative curves are shown graphically in Figure 6 (Hubbert, 1962, Figure 24; 1974, Figure 27). It will be noted that when proved reserves reach their peak

$$dQ_r/dt = 0 \qquad (3)$$

and

$$dQ_d/dt = dQ_p/dt \quad . \qquad (4)$$

Hence, when the dQ_r/dt curve crosses the zero line, the curves dQ_d/dt and dQ_p/dt cross one another.

The curve of the computed mathematical derivative, dQ_d/dt of the discovery curve with actual data superposed, is shown in Figure 7 (Hubbert, 1974, Figure 38). It is seen that the

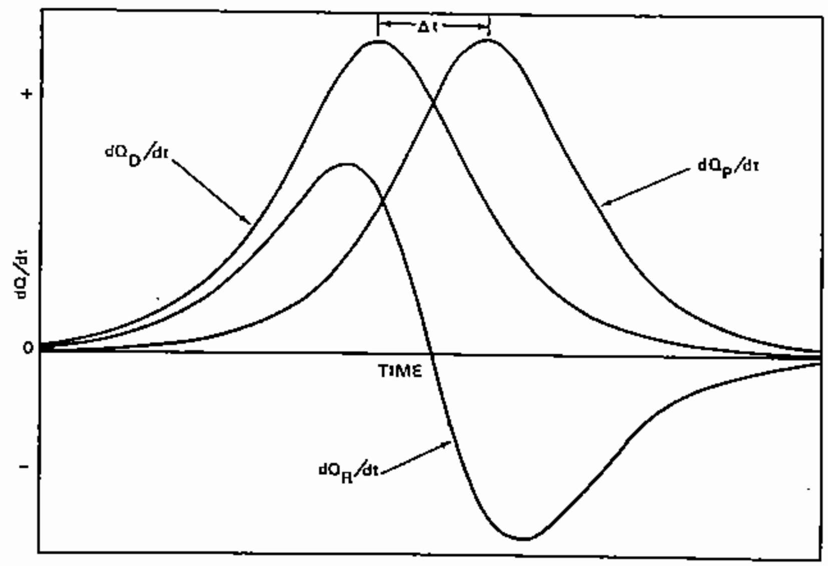

Figure 6. Variation of rates of production, of proved discovery, and of rate of increase of proved reserves of crude oil or natural gas during a complete production cycle (Hubbert, 1962, Figure 24; 1974, Figure 27).

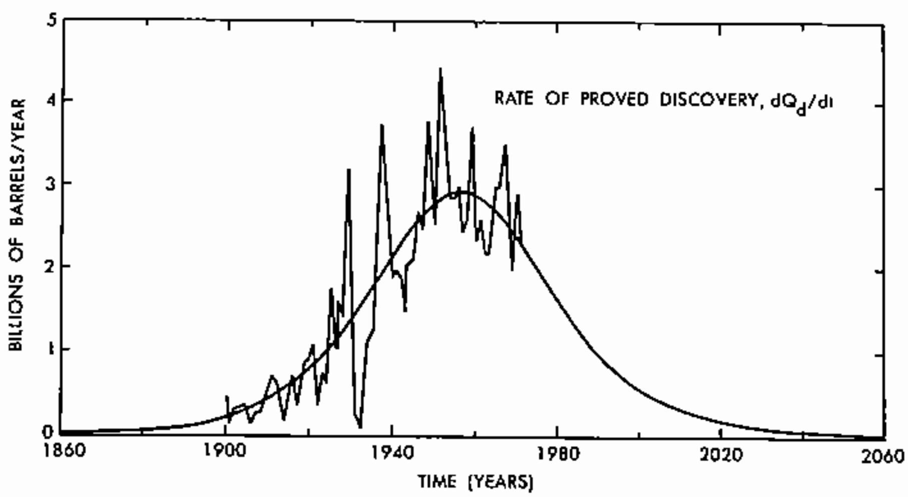

Figure 7. Comparison of annual proved discoveries of crude oil in the conterminous United States, 1900-1971, with corresponding theoretical curve derived from logistic equation (Hubbert, 1974, Figure 38).

rate-of-discovery curve passed its peak in the second half of the 1950 decade, and has been declining ever since.

The curve of the rate of increase of proved reserves is shown in Figure 8 (Hubbert, 1974, Figure 40). This curve crossed the zero line in 1962 and is now near the bottom of its negative loop.

Finally, the curve of the rate of production, dQ_p/dt, is shown in Figure 9 (Hubbert, 1974, Figure 39). This has an aberration owing to successive Middle East disturbances since 1956. The peak production rate, slightly eccentric with respect to the mathematical curve, occurred in 1970. The mathematical curve reached its maximum about 1968.

Based upon the foregoing analysis, the curve of the complete cycle of crude oil production in the conterminous states is shown in Figure 10 (Hubbert, 1974, Figure 51). Here, the 67-year period from 1932 to 1999, is the time during which the middle 80% of Q_∞ will be consumed. A child born about 1930 will see the US consume most of its oil during his lifetime.

A different method of analysis is shown in Figure 11 (Hubbert, 1974, Figure 50). This consists in plotting the discoveries per foot of exploratory drilling, dQ/dh, versus cumulative feet of drilling, h. In the figure, the separate columns are averages for each 10^8 ft of drilling. Cumulative discoveries to about 1972 by $17 \cdot 10^8$ ft of drilling amounted to 143 billion barrels. Extrapolation of the negative-exponential decline curve approximating the actual data gives an additional 29 billion barrels of crude oil, or a total of 172 billion barrels for Q_∞--a result in close agreement with that obtained earlier by other methods.

ESTIMATES FOR THE WORLD

I have not personally made world estimates for petroleum, but those shown in Figure 12 (Hubbert, 1974, Figure 67) made by Richard Jodry of Sun Oil Company are in substantial agreement with other recent estimates. The Jodry estimates total 1952 billion barrels. Rounding this off to 2000 billion barrels, and computing the complete cycle of world production gives the results shown in Figure 13 (Hubbert, 1974, Figure 68). This is based upon the assumption of an orderly evolution of petroleum production. Should production be constrained at near present levels, the area under the top part of the curve would be displaced to the declining phase.

According to this curve, the peak of world production rate will probably occur about 1995, and the period for the middle 80% will be the 56-year interval from about 1965 to 2021. A child born now will see the world consume most of its oil during his lifetime.

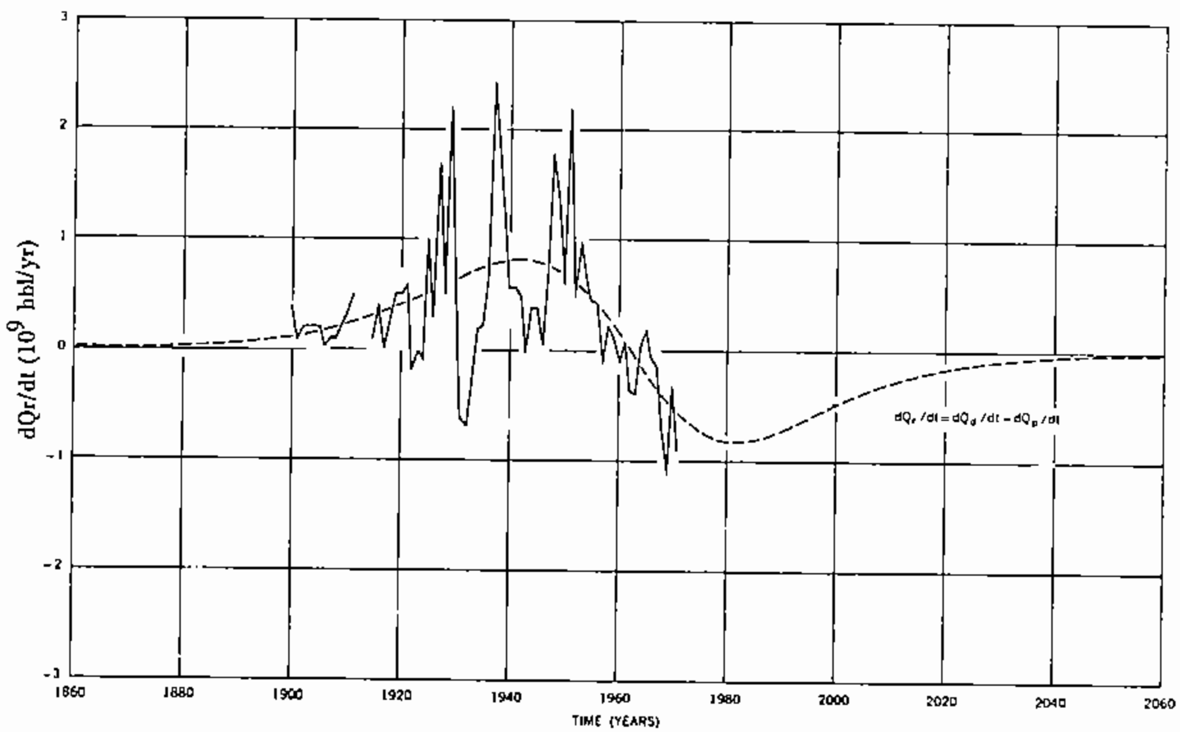

Figure 8. Comparison of annual increases of proved reserves of conterminous United States, 1900-1971, with theoretical curve derived from logistic equations (Hubbert, 1974, Figure 40).

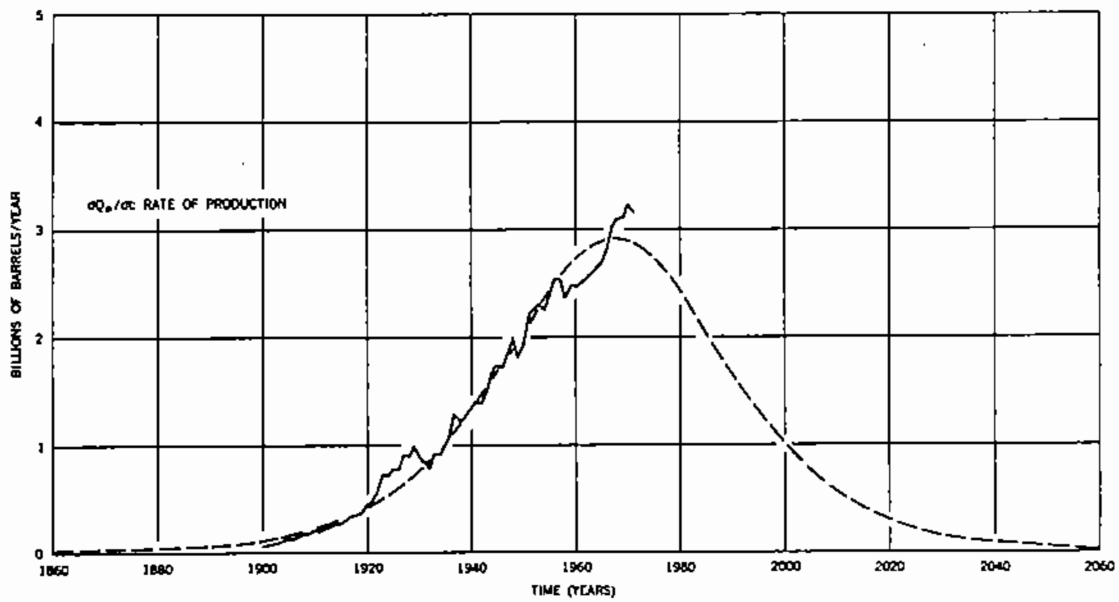

Figure 9. Comparison of annual crude oil production in conterminous United States, 1900-1971, with corresponding theoretical curve derived from logistic equation (Hubbert, 1974, Figure 39).

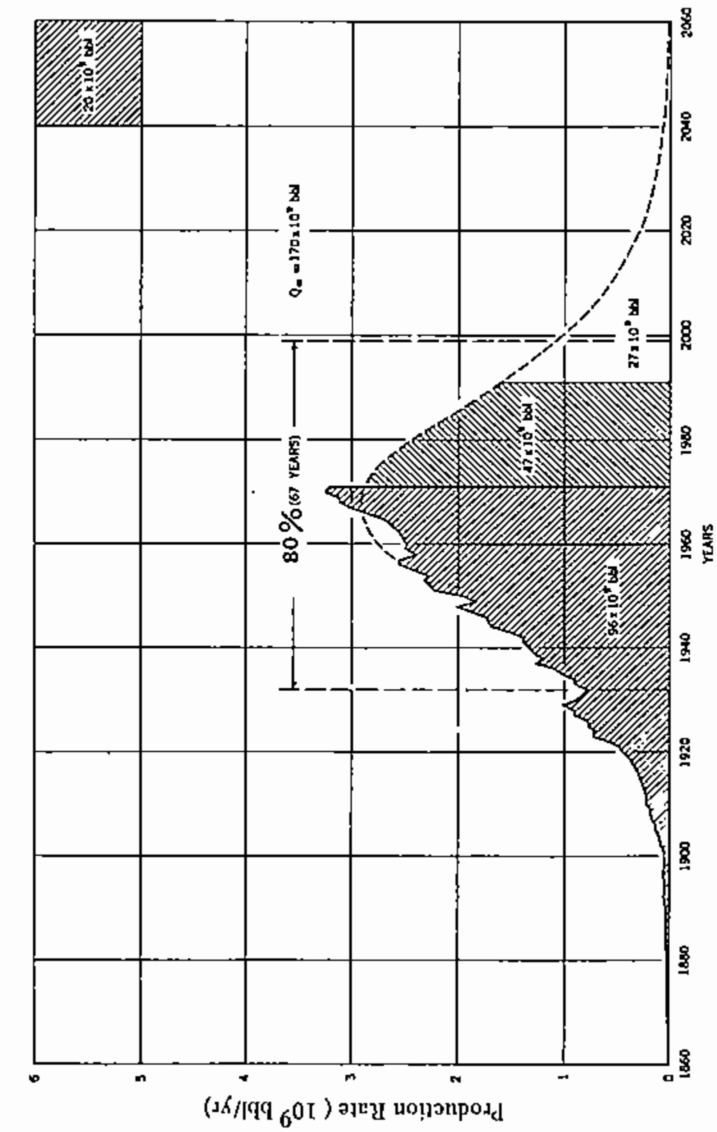

Figure 10. **Complete cycle of crude oil production in conterminous United States as of 1971 (Hubbert, 1974, Figure 51).**

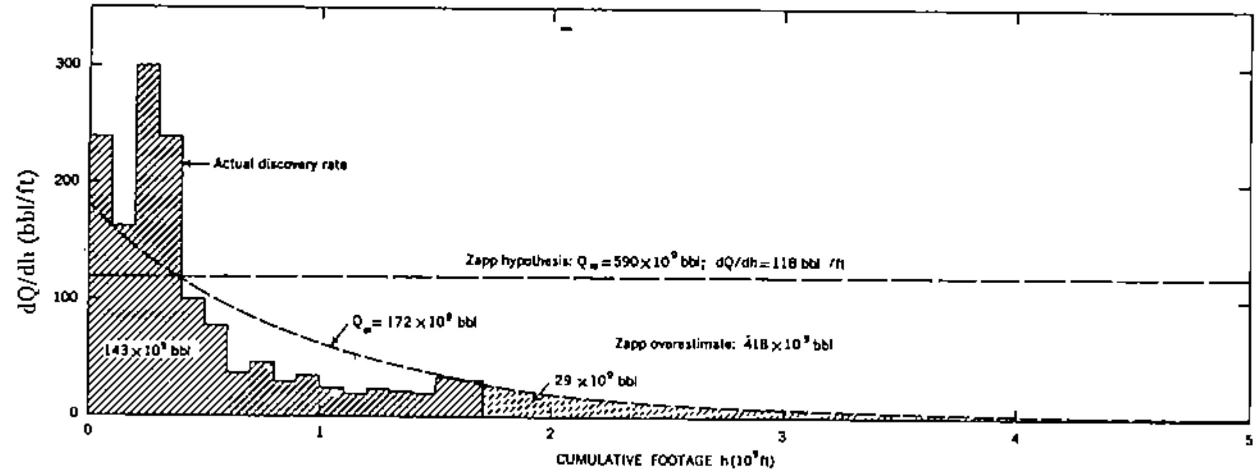

Figure 11. Estimate of ultimate crude oil production of conterminous United States by means of curve of discoveries per foot versus cumulative footage of exploratory drilling, and comparison with Zapp hypothesis (Hubbert, 1974, Figure 50).

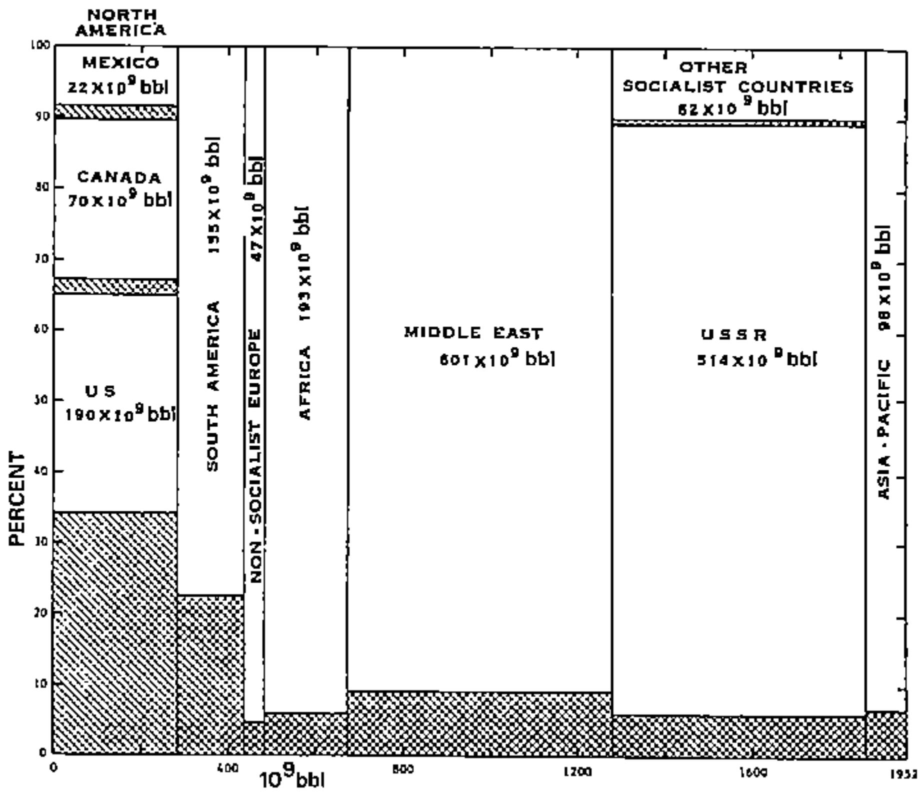

Figure 12. Graphical representation of Jodry estimate of world ultimately recoverable crude oil. The shaded areas at the foot of each column or sector represent quantities consumed already (Hubbert, 1974, Figure 67).

Finally, to appreciate the brevity of the epoch of the totality of fossil fuels in human history, consider Figure 14 (Hubbert, 1972, Figure 20; 1974, Figure 69). Here, on a background of human history from 5000 years ago to 5000 years in the future, the epoch of the fossil fuels comprises principally the brief interval of only about three centuries, and is hence but an ephemeral event in the totality of human history, an event nonetheless that has exercised the most disturbing influence experienced by the human species during its entire biological existence.

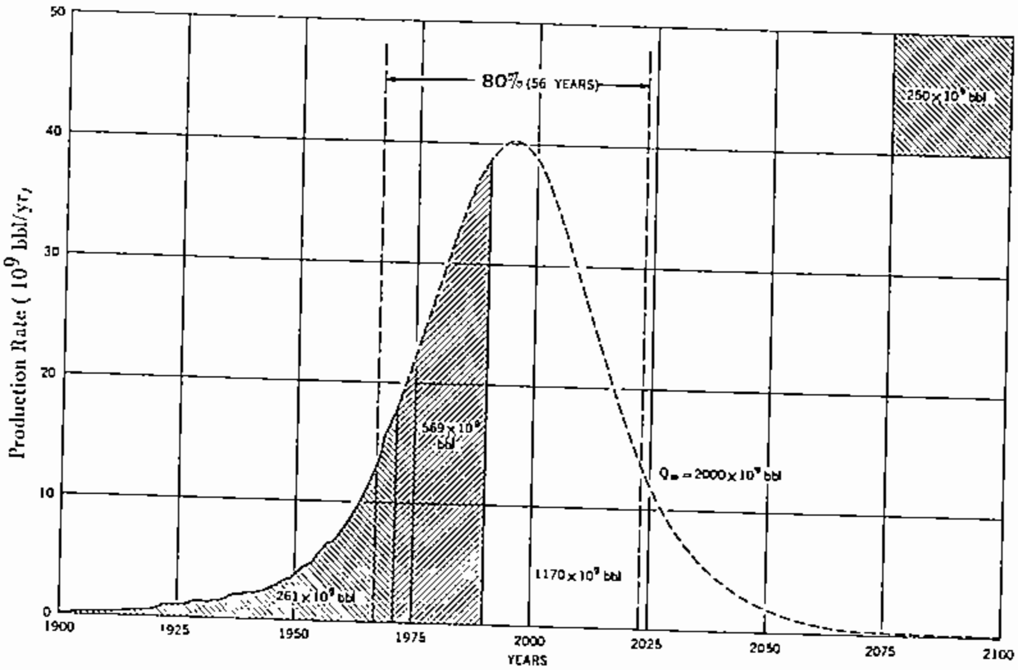

Figure 13. Estimate as of 1972 of complete cycle of world crude oil production (Hubbert, 1974, Figure 68).

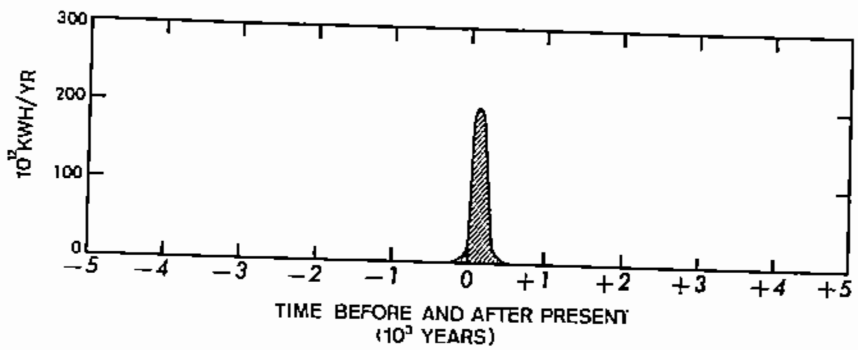

Figure 14. The epoch of fossil fuel exploitation as seen on a time scale of human history from 5,000 years ago to 5,000 in the future (Hubbert, 1972, Figure 20; 1974, Figure 69).

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