2005 - PEAK IN PETROLEUM PRODUCTION
OR
PINCHING HUBBERT'S PIMPLE

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Introduction

Projecting the future availability and cost of petroleum for 20 to 40 years into the future is an important, but very uncertain task. Periodically various authors project a significant shortfall of petroleum availability in just a few years. One recent March 1998, popular press example is in Scientific American[i]. This information has also been published in professional journals as cited in the article. This information suggests that OPEC has overestimated its reserves by significant amount beginning in late '80's. In addition, the decreasing rate of world wide oil discovery is noted. The purpose of this document is to place these observations in a somewhat different perspective. A unifying theme in these discussions is the frequently observed exponential rise and fall of the rate at which a natural resource is consumed. M. King Hubbert has detailed this observation.[ii] The graph of consumption rate versus time has become known as the Hubbert pimple due to its shape as illustrated in Figure 2.. Another theme is the constant price for petroleum when averaged over a long time period.

Fundamentals

Exponential growth Exponential growth of a quantity Q is a common concept applied to many activities. It simply states that the rate growth is proportional to the amount of the material already present or utilized as shown in the rate and integrated equations below:

$$\frac{dQ}{dt} = rQ \qquad (1) \qquad\qquad Q = Q_{Start}\, e^{rt} \qquad (2)$$

This concept is true for compounded interest. The above equations may be regarded as continuously compounded interest, in contrast to discrete-period compounding, as normally used in business transactions.[iii] The exponential concept is also true for growth of microbes when unconstrained by space, nutrients or toxins. In the microbiology literature, it is referred to as the log-growth phase. The above equations require only two parameters, an initial amount or concentration, Q_{Start} and a growth rate constant, r.

It is another consideration to state that the rate of natural resource consumption is proportional to the amount of that resource previously consumed. This statement is one of assumptions of the Hubbert pimple. Empirically exponential growth has been shown to be true in the early stages of consuming a natural resource. Several supporting statements could be made, which are consistent with this empirical observation of an exponential increase in consumption rate. "Consumption of the resource itself builds the infrastructure that results in increased consumption of the resource." "New technologies build on past technologies." "New technologies also spread from their place and time of origin in an apparent exponential fashion." "Etc." No matter the rational about exponentially increasing natural resource consumption rates, they are empirical observations, not a result of mathematics, as in the case of "interest plus principal" or numbers of microbes/cm^3 , as mentioned in the previous paragraph.

Limits to Exponential Growth Sustained exponential growth does not exist in physically realizable circumstances. There are real world constraints. For this reason, constraints must be added to Equations 1 and 2 above, for the equations to be useful in the real world. In the case of microbial growth, the constraint is frequently depletion of a particular nutrient or its limiting rate of supply, such as access to oxygen. In other circumstances, the exponential growth phase is constrained by accumulation of a toxin. These constraints can be given a mathematical form and have been experimentally verified[iv].

For the consumption of non-renewable resources, constraints to exponential growth must exist, but these constraints are more difficult to demonstrate experimentally. The ultimate constraint on exponential consumption rate increases is the amount of the resource that is economically available for use on the Planet Earth, in a particular circumstance. Another constraint on the rate of resource consumption is just the demand for a particular resource. This demand constraint applies to resources available in very large amounts, such as sand and salt. For the medium-term, this demand constraint also applies to coal and lignite production rates.

The great convenience of petroleum, as a source of both energy and petrochemicals, makes the medium-term constraint on petroleum production rates the amount of the resource that is ultimately available. This situation is in contrast to the present short-term situation, where the supply exceeds demand for petroleum. The medium and long-term constraint for petroleum production is the amount of the resource that is ultimately available, as limited by economics and technologies. This amount has been termed Q_∞. Prior to 1859, the drilling of Edwin Drake's oil well in Titusville, Pennsylvania, Q_∞ for petroleum was essentially zero. This Q_∞-achievable is a function of technologies available to recover the resource, as well as of geology. For this reason, the Q_∞-achievable increases as technology develops. At the turn of the 20th century people would have never considered drilling to 20,000 feet or in water over 3,000 feet deep. Q_∞-achievable is considerably less than the absolute amount of a resource existing on the planet. Several different Q_∞'s will be defined in the later portion of this paper. Given an estimate of the Q_∞-achievable, no matter how uncertain, this limit on petroleum availability must be included in the production rate equation. There is not a unique theoretical way to include this available quantity in the petroleum production rate equation, so a very simple function will be used in the equation below:

$$\frac{dQ}{dt} = rQ_{Start}(1 - \frac{Q}{Q_\infty}) \qquad (3)$$

In this equation, the term in parenthesis starts at a value of 1 and decreases asymptotically to 0, as the resource is consumed. By this means, resource consumption is mathematically limited to the amount of the resource available, and an apparent exponential decay in production rate is observed. This concept is illustrated in Figure 2. The area under the Hubbert pimple in Figure 2 is the numerical value of Q_∞ used to plot the curve. Other more complicated constraints could be included in the rate equation, if desired. More complicated functions are not justified with the limited amount of data available.

Application to historic petroleum production data

This rate equation will now be fitted to a tabulation of cumulative world petroleum production, 1919-94[v] and world production rates, 1960-1996[vi]. Many procedures could be used to fit the constants in Equation 3 to these two sets of data. Obviously, the equation can be integrated analytically, but I choose graphical integration to maintain the real physical nature of the constants in the immediate view of the user. I choose to use an Excel spread sheet to tabulate the data by year, and then to use the "Solver Function" to determine the numerical values for the three constants:

- Q_{Start} at an arbitrarily early date, 1900, (barrels)
- Annual rate production rate increase (fraction per year)
- Q_∞-achievable (barrels)

I choose to minimize the sum of the square of difference between the predicted value and the tabulated value in determining these constants.

(At this point the oral shortcourse presentation will have a live demonstration of the Excel spreadsheet, and its use in determining the three constants will be made. The spreadsheet is available in electronic form. Please inquire of me regarding its internet location.)

When the Excel Solver is used to determine all three constants based on the two oil production data sets, the result is not realistic, Figure 1. Oil production did not peak in 1985 at 22 million barrels per day. Historic oil production rates are not adequate to predict future production rates, at this time, as clearly demonstrated by Figure 1. An independent estimate of Q_∞-achievable is essential, since the computer generated one used for Figure 1, 1.10×10^{12} barrels, is unreasonable. A value of 2.3×10^{12} barrels will be used for Figure 2 and 3. This value is consistent with Figure 12 of Porter[vii]. Figure 2 illustrates the impossibility of fitting events, such as the oil production slump resulting from OPEC embargo, with a simple 3-parameter equation covering a span of 200 years. The cumulative production plot, Figure 3, smoothes out the embargo situation. Figure 2 predicts a peak in world oil production in the year 2005 at 34 billion barrels per year. Petroleum production predictions in Figures 2 and 3 employ three constants, the assumed Q_∞-achievable of 2.3×10^{12} barrels, plus two additional constants, as determined by the curve fitting process.

- Hypothetical cumulative oil production in 1900 — 4.55 billion barrels
- Growth rate term — .0604 fraction/yr.

In these calculations, the constraint on production rate caused by Q_∞-achievable is being noted, even while oil production rates are still increasing. For example in 1994, the last cumulative world production rate data used in the correlation the production rate restraining term, ($1-Q/Q_\infty$-achievable) has a value of 0.664. This quantity is named the restraining factor in the production rate equation

Note the vast extrapolation of a limited amount of data shown in Figure 2. The moderate restraint on exponential growth already experienced allows the whole projection that is shown.

Different authors make different choices for Q_∞-achievable. For example, Campbell's recent choice is lower, 1.7, not 2.3×10^{12} barrels and it is the source of discussion today. His logic for the lower value considers the numerical difference between the petroleum finding rate and producing rate. Since the current finding rate is lower than the production rate, he made an extrapolation as to when we should "run out of oil" and an appropriate Q_∞-achievable determined. There is little rational for difference taking between petroleum finding rate and producing rate. It does not make economic sense to find oil today that will not be needed for 20 or more years, for the international oil industry as a whole. We currently have a 44-year supply of available petroleum at the present rates of usage.[viii] Petroleum exploration and new production activities depend today on perceived local exceptions to the global petroleum supply-demand situation.

Campbell notes that this difference taking procedure is consistent with historic domestic petroleum finding and production rates. To meet domestic petroleum requirements, the choice is to import more oil. Domestic petroleum resources remain to be utilized, but few are economically competitive with imported oil. With regard to the whole world, there is no option to import more oil.

Q_∞-achievable at a Constant Price for Petroleum

Relative to industrial construction costs, oil prices have remained constant for the past 70 years. This fact can be demonstrated by using the refinery construction cost index and refinery fuel cost index as published in the Oil and Gas Journal. They were extrapolated back to 1930, by the Oil and Gas Journal staff. Other choices of fuel cost and industrial construction cost indices could have been made, and they would have yielded similar results. Least squares fitting of these data results in a slope of 1.0, as shown in Figure 4. This one-to-one relationship between fuel cost and industrial construction costs exists for the entire period as a whole.

There is a significant price perturbation, as an apparent result of the OPEC oil embargo, which began in October, 1973. It should stressed, however, that the real price of petroleum had started to increase earlier, after 1969, as shown in Figure 4. In 1984, it would have appeared that the price of oil relative to industrial construction cost had increased permanently, but not so. The price of energy fell in 1985 and remains low relative to industrial construction costs.

The actual oil production rate data used in Figure 2 and 3 were taken during this long period of relatively constant oil prices, as discussed above. As a result, that assumption of constant relative petroleum price is a part of its extrapolation from 1996 to 2120. Adequate petroleum producing capacity has been maintained in spite of producing petroleum from more extreme circumstances. This fact has come as a surprise to the oil industry, and it has been explained as being the result of improved exploration and production technologies. This circumstance has been discussed recently for domestic petroleum reserves.[ixx]

At some point the real price of petroleum will have to increase with respect to industrial construction costs. The straight line shown in Figure 4 will not continue forever. Predicting when this real price increase for petroleum will occur is a very difficult task. Petroleum exploration and production technology improves in unpredictable ways. Increased petroleum prices will increase industrial construction costs, so construction costs will tend to rise with petroleum prices. For these reasons, predicting the year for real long-term increases in petroleum prices to occur is very difficult. When the real price of petroleum increases, several responses can be anticipated.

Q_∞-achievable With Increasing Petroleum Prices

When the price of petroleum increases relative to industrial construction costs several responses will be made. Some responses will sustain the rate at which petroleum can be produced:

- Application of significantly more expensive exploration and production technologies.
- Application of advanced enhanced oil recovery processes.
- Major increases in the production of heavy oil.

Application of more expensive exploration and production technologies At relatively constant oil prices the technologies for exploration and production of petroleum have improved to an extent that was not expected. The success of exploratory wells has been sustained, and the capabilities to produce petroleum in very hostile environments has been demonstrated. The fraction of oil produced before field abandonment has been further improved. Real increased petroleum prices, or even a confident expectation of increased petroleum prices, will result in further improvements in petroleum exploration and production technologies.

Application of advanced enhanced oil recovery processes. Sophisticated enhanced oil recovery processes have been developed in laboratory and field tested to a limited degree. These technologies include surfactants, in situ combustion, microbial, caustic and alcohol flooding etc. Some of these technologies may become attractive with increased petroleum prices. Present day enhanced oil recovery techniques can be further improved and applied in circumstances that are not now economic, when there is a real increase in petroleum prices.

Major increases in the production of heavy oil Most estimates of petroleum availability are for conventional petroleum, and so exclude heavy crudes and tars. This is true of the Q_∞-at-a-constant-price used in Figures 2 and 3 of 2.3×10^{12} barrels. Tars and heavy oils are estimated to be approximately that amount of oil too. Tar and heavy crudes are currently being produced in Canada and Venezuela.

Other responses to increased petroleum prices will moderate the demand for petroleum:

- Increased liquid fuel yields at refineries.
- Alternatives to liquid hydrocarbon fuels.
- Displacement of liquid fuels from stationary usage to transportation usage.
- Reduced transportation fuel requirements by consumers.

Increased liquid fuel yields at refineries Refinery configurations and operating conditions are adjusted to minimize the production costs of their primary product, transportation fuels. Low petroleum prices have resulted in extensive usage of processes such as coking. Much of the resulting coke has only boiler fuel value. Refinery upgrades now frequently include the sale of electric power as a byproduct. This circumstance results in the under utilization of the organic carbon from petroleum. With significant increases in petroleum prices, processes such as hydrocracking will become favored, resulting in increased transportation fuel yields. If natural gas prices increase in parallel with petroleum prices, gasification of coal to supply hydrogen and energy to petroleum refineries will be justified. In these circumstances, a refinery might produce a larger volume of transportation fuels than they purchase as petroleum. These changes in refinery configurations and operating conditions will occur gradually, without great notice by the public. Increased prices for conventional petroleum will also justify the more expensive processing of very abundant heavy, sour crudes. Until many of these options for increased refinery yields have been implemented, there is little incentive to extensively develop non-petroleum sources of liquid hydrocarbons.

Displacement of liquid fuels from stationary uses. For stationary usage, natural gas is the fuel of choice. Where a distribution infrastructure for natural gas is available, there is little reason to consider any other fuel for stationary usage. In cases where 100% reliability is essential, liquid fuel backup may be required. It should be noted that delivery of natural gas is frequently more reliable than either water or electricity.

Liquid fuels are then used for stationary uses in circumstances where natural gas distribution networks are not available. This usage of liquid fuels for heating is considerable in older metropolitan areas where natural gas lines are costly to install, and in rural areas where the population density does not justify the cost of a natural gas distribution network. Propane is an example of the displacement of liquid fuels from stationary uses to transportation usage. The amount of propane that is available relative to the total domestic transportation fuel consumption is very limited. With propane being defined as an alternative fuel, its usage for transportation can be expected to increase, leaving less propane for available for stationary usage, largely in rural areas. The decision then becomes a political issue with advocates of non-hydrocarbon fuels and rural consumers joining against the extensive usage of propane as an alternative transportation fuel. The GAO has determined propane availability and price will not be a short-term problem.[xi] The conflict among users does not exist between diesel transportation fuels and light fuel oil, since diesel and fuel oil is a primary refinery products. Increased prices for fuel oil and diesel will discourage its use in stationary applications.

Displacement of natural gas and liquid fuels by solid fuels for stationary usage is not a probable activity, because liquid fuels offer many major advantages over solid fuels. Some of these advantages for liquid and gaseous fuels over solid fuels are as follows:

- Lower investment and maintenance requirements by the user.
- Much greater consumer convenience.
- Less difficulty in meeting emissions standards.

The availability of free solid fuel is inadequate to cause significant usage of solid fuels on a small scale or even a medium-scale. Municipal incinerators and recycling operations have to charge a tipping fee,. This number, frequently 15 to 25 dollars per ton, quantifies the actual negative value of municipal solid waste as a fuel relative to fossil energy. Sawmills and paper mills are an exception to this usage of solid fuels.

In many cases, the substitution of solid fuels for liquid fuels in stationary applications is best accomplished indirectly, via the use of electricity. Coal can be burned to produce electricity economically in an environmentally acceptable manner. The electricity is then available as needed for heating, cooling and mechanical power. Solar, wind, nuclear and geothermal are also options for production of electricity. Currently natural gas and cogeneration facilities are the least costly source for incremental electric power generation capacity.

Reduced transportation fuel requirements by consumers Reducing transportation fuel requirements requires changes in life-style. Such changes in life-style come very slowly to the American public unless there are regulatory constraints. Many people regard increased transportation fuel costs as just an increase in the cost of living, not as a reason to reduce transportation fuel usage.

Q_∞ With economic competition from other liquid fuels

Non-petroleum sources of hydrocarbon liquids will become more attractive as the real cost of petroleum increases. Conversion of natural gas to liquid fuels may be the next source of liquid fuels, particularly for natural gas in remote locations. This conversion is already being accomplished by Shell, and other companies, such as Exxon, are considering the opportunities.[xii] If and when natural gas prices rise in parallel with petroleum, other fossil fuels will become attractive sources of liquid fuels. South Africa has demonstrated gasification of coal followed by Fischer-Tropch synthesis of liquids. Currently, Tennessee Eastman is gasifying coal for production of "petrochemicals" at Kingsport Tennessee. Synthesis gas, from gasification of coal and/or reforming natural gas, provides options for two non-hydrocarbon fuels, methanol and dimethyl ether. Pyrolysis of coal to recover hydrocarbon liquids prior to the combustion of the residual char for generation of electric power is another potential source of hydrocarbon liquids.[xiii] Several other coal liquefaction processes have been developed. Oil shale is a very large resource of liquid hydrocarbons that may prove difficult to implement due to environmental constraints.

Significant increases in petroleum prices and/or international political unrest will make some of these technologies for non-petroleum liquid fuels attractive. At some point in the future, liquid fuel needs will be most economically supplied by these non-petroleum sources. This competition with alternative fuels will place an upper bound on petroleum prices. Petroleum production rates will decrease rapidly when this limiting price for petroleum is reached. The decreased production rates will not mean we have run out of petroleum on the Planet Earth. It means that we have run out of petroleum that is price competitive with non-petroleum sources of liquid fuels.

Conclusions

"Projecting the future availability of petroleum for 20 to 40 years into the future is a important but very uncertain task." is the first sentence of this paper. That sentence also serves well to start summarizing and drawing conclusions. Current historic production rate data were shown inadequate to predict a future peak in petroleum production. An independent assumption of the economically available petroleum available on the Planet Earth is essential. Several of these Q_∞'s have been considered in this study, and have resulted in several cost regimes for petroleum production. This circumstance is shown in Figure 5, which plots relative price for petroleum as a function of the amount produced. History is documented only up to 1994. The remainder of the curve is extrapolation. First, we extrapolate how much petroleum will be produced at a constant price. In today's terms, how long the oil price will stay low? This amount of petroleum is a complex function of geology, international politics, and improved technology. For this reason it is almost impossible to predict when the true price of petroleum will increase. When true price for petroleum increases the Q_∞-at-constant-prices will have been largely consumed. This quantity is the 2.3×10^{12} barrels as used in Figures 2 and 3.

Petroleum will then be produced within an increasing price circumstance; so more expensive exploration and production technologies will be justified. This rising price circumstance can not continue indefinitely. At some point, the cost of petroleum as a liquid fuel will approach the cost of alternative fuels. At this time, the petroleum in Q_∞-with-rising-prices of will have largely been produced.. It should be obvious that this quantity can not be extrapolated from existing data. It is guessed to be one-half of Q_∞-at-constant-prices or 1.65×10^{12} barrels for Figure 5. This $Q\infty$-with-rising-prices is a function of the several factors mentioned in the previous paragraph, plus an additional factor, the price of alternative fuels. This alternative fuel price is very difficult to predict. Developers of new processes are notoriously optimistic as to the price at which their new products can be produced. Some of these factors are detailed in my previous paper on the subject.[xiv] This developer optimism can not be quantitatively discounted, so the price at which alternative fuels will be available in large quantities remains uncertain. In some cases, such as liquid fuels from natural gas, large energy companies and engineering contractors should be able to calculate a reasonably accurate price for alternative liquid fuels. Without great confidence, I suggest 2 to 5 times the present relative price of petroleum, as the price at which large amounts of alternative liquid fuels will be available from solid fossil fuel resources such as coal and oil shale. A value of 4 times the present cost for petroleum is used in Figure 5.

When cost competitive alternative fuels become available, world petroleum production rates will decline, since more expensive exploration and production methods for petroleum will no longer be justified. This observation regarding declining petroleum production rates suggests that Q_∞-with-competition is a strong function of alternative liquid fuels costs, as well as geology and technology. So Q_∞-with-competition is even more difficult to estimate than Q_∞-with-rising prices. Again it will be guessed that Q_∞-with-competition will be half of the value for Q_∞ at constant price or 1.65×10^{12} barrels for Figure 5.

It should be stress that the X-axis is the cumulative quantity of petroleum produced, not time. Various times are noted on the figure for the convenience of the reader. The actual rate of petroleum production will be determined by demand as well as petroleum availability. Even so, petroleum availability will ultimately determine its production rate, at some rather distant point in the future, perhaps 40 years from now, as shown in Figure 6. For this figure, $Q_{\infty\infty}$ is the sum of the three Q_∞'s discussed above, plus heavy oil, for a total of 6.9×10^{12} barrels.

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About the author

Dr. Parker has been involved in energy related research at many levels:

- Phillips Petroleum Company, 1956-1969, Enhanced oil recovery, oil shale, & drilling fluids.
- Engineering Societies Commission on Energy, Washington, DC, 1979-81, Evaluation of processes for alternative fuels.
- Director - Office of Agricultural Materials in USDA/CSREES, Washington , DC, 1993-95, Facilitation of agricultural crop usage as energy sources and industrial materials.

Since 1970 he has been Associate and Full Professor in the Department of Chemical Engineering, Texas Tech University. His research and teaching interests include energy matters, environmental remediation, and materials science. He consults for various energy and environmental companies.

He is the inventor on 83 US patents.

Harry W. Parker received his BS in Chemical Engineering with Honors from Texas Tech University in 1953, and continued at Northwestern University earning his MS and PhD degrees in 1954 and 1956.

He is a member of the American Institute of Chemical Engineers, and the American Chemical Society.

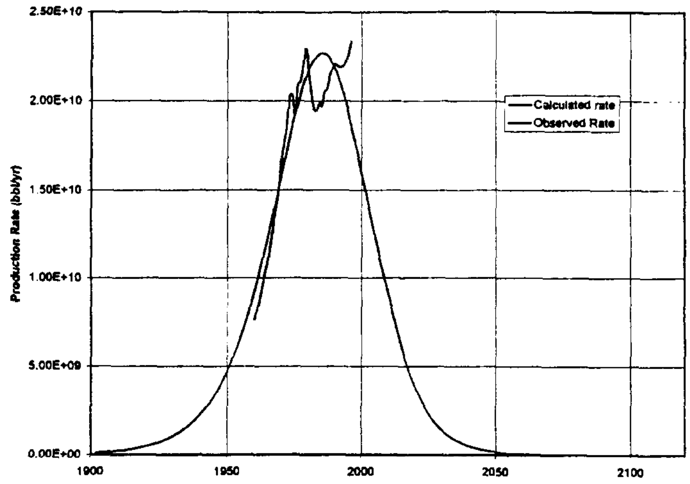

Figure 1 - Curve Fit for Q-Infinity (not realistic)

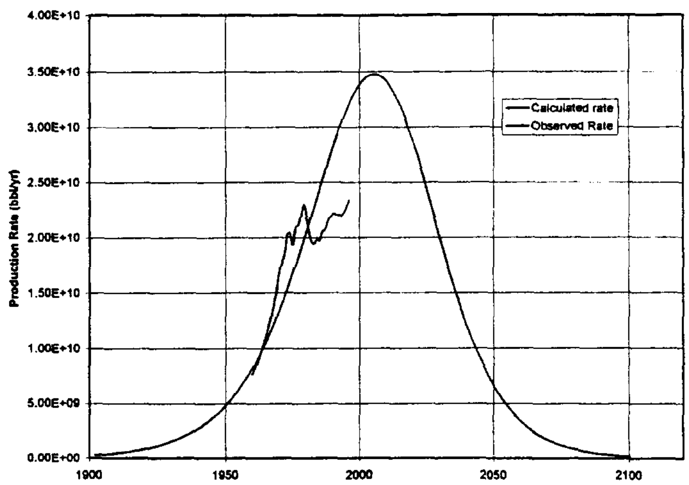

Figure 2 - Actual and Calculated Petroleum Production Rate

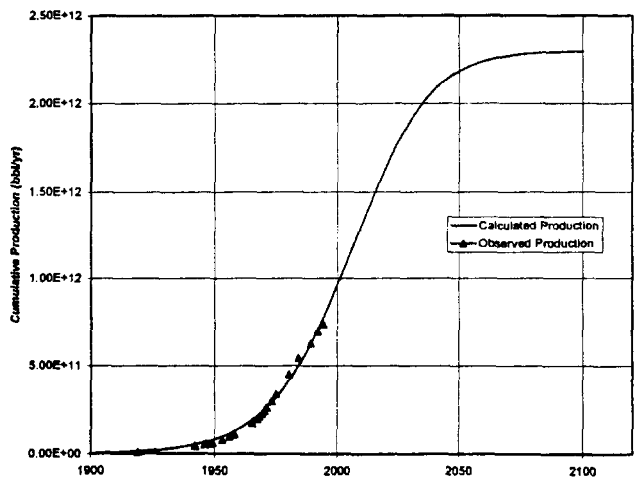

Figure 3 - Cumulative World Petroleum Production

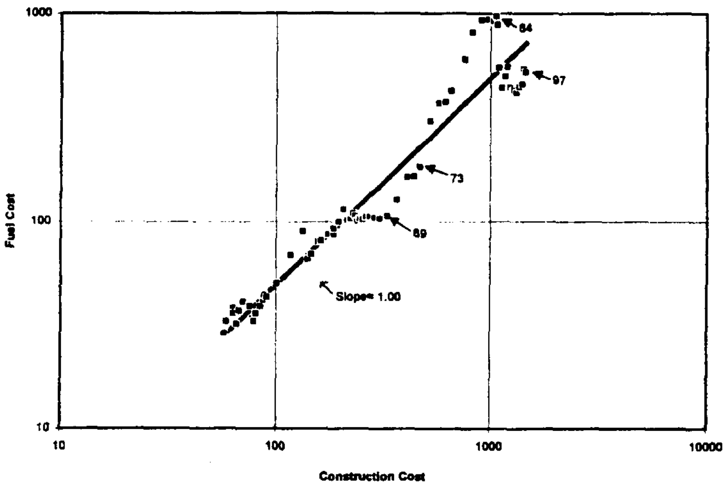

Figure 4 - Construction vs. Fuel Index

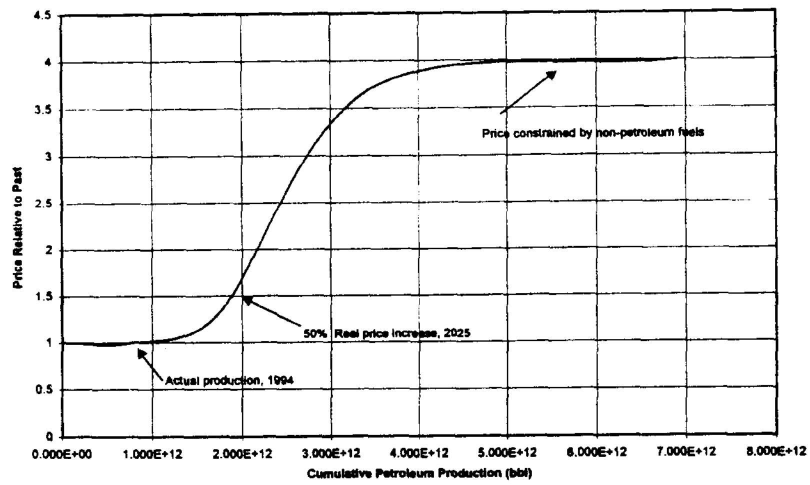

Figure 5 - Price vs. World Petroleum Production

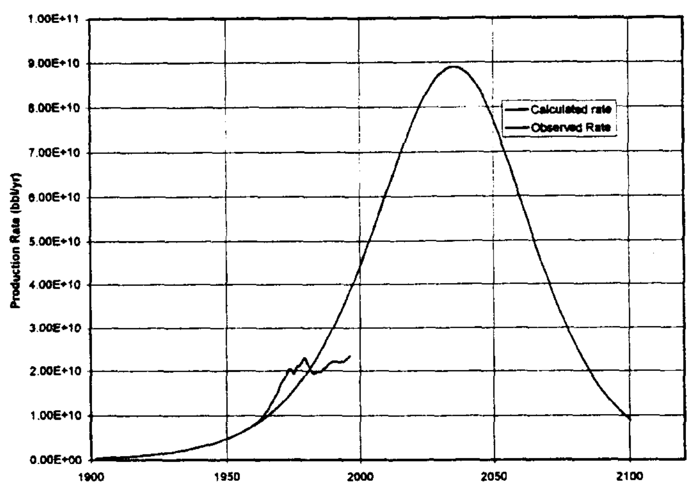

Figure 6 - Curve Fit for Q-Infinity-Infinity