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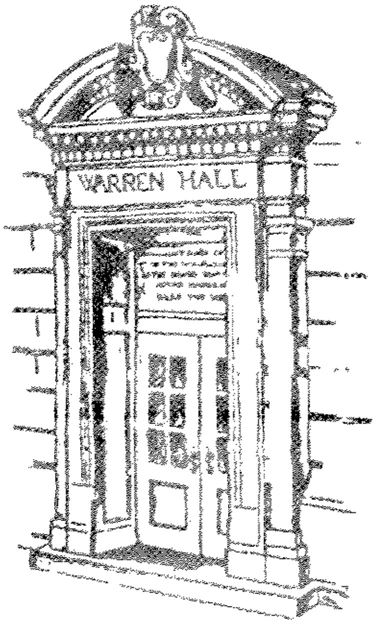

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WORLD OIL: THE GROWING CASE FOR INTERNATIONAL POLICY

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ABSTRACT

Can the economic theory of depletion be reconciled with low petroleum prices? This paper uses a revision of the theory, which reflects demand functions that rise in response to increasing world population and income. The magnitude of producers' and consumers' surplus is estimated under both competitive and monopolistic assumptions; the result indicates a present value comparable to or in excess of today's Gross World Economic Product.

Game theory suggests a framework which explains the interaction between oil pricing and military policy, and the economic incentives which result in a general pattern of recent market equilibrium crude oil prices often fluctuating within a $15-$20 per barrel range. The analysis concludes that the economic incentives for political instability in the Persian Gulf will increase, and more formal methods of setting the international framework for Persian Gulf oil may be expected.

I. ECONOMIC THEORY AND DEPLETION

The theory of depletion is generally excluded from applied analyses of petroleum geopolitics. Generally, the theory is perceived as being counter-factual in several important ways. As usually discussed, the theory assumes constant price or constant demand functions, and projects monotonically declining output and rising prices. These predictions for price and quantity arise from both monopolistic and competitive versions of the theory.

However, the theory can be extended to reflect upwardly shifting demand functions rising in response to growing income and population, and constant, increasing, or declining extraction cost. With these two extensions, depletion theory projects market equilibria where output rises, peaks, and then declines. The price trajectory may decline, stay constant, or rise with the latter part of the path always increasing. With these modifications, the theory can be used to calculate the magnitudes of producer and consumer surplus which may arise from future use of world oil resources.

First, consider Equation (1). It separates the competitive equilibrium trajectory for production and use into two components:

(1) $QE(t) = QC(t) - e^{rt} * SF$

Here, t is the time subscript, QE is the market equilibrium quantity of production and consumption, QC is the quantity which would have been demanded in a competitive market without resource limitations, r is the real discount rate, and SF is a scarcity factor reflecting the amount by which unconstrained production exceeds remaining stock (see Appendix for details).

The associated price path is in Equation (2). MC is marginal cost, P is price, SF is the scarcity factor again, and B1 is a coefficient.

(2) $P(t) = MC(t) + e^{rt} * SF * B1$

Equations (1) and (2) simplify the results of an optimal control solution to the problem of finding maximum producer and consumer surplus in competitive and monopolistic markets where demand curves shift upward as population and incomes rise, and remaining petroleum stock is finite. In addition, the marginal extraction cost may change over time in response to technological or environmental conditions, but remains unaffected by the declining stock of remaining resources. The full problem and solution is summarized in the Appendix[1], showing the basis for these Equations.

Note that in Equation (1) the equilibrium quantity QE would equal the market solution QC if there were no resource limitation, making the scarcity factor SF equal zero. Similarly, in Equation (2), price equals marginal cost if there is no scarcity. Furthermore, if in the presence of scarcity, the marginal cost of extraction were declining over time, the optimal price trajectory may initially decline before ultimately rising.

Figures 1 and 2 show stages of the solution. Figure 1 represents market equilibria with shifting demand and supply functions, and no resource limitation. This trajectory is also shown in Figure 2, as the sequence of triangles. However, with an effective resource constraint, the lower curve shows actual equilibria reflecting scarcity. Note that, even with scarcity, consumption increases for many years.

II. PERSIAN GULF COSTS AND PRODUCERS' SURPLUS

In estimating crude oil production costs, petroleum economics has developed its own applied version of discounting. In a simple form, it is:

$$(3) \qquad \begin{matrix}\text{Adjusted}\\ \text{Investment}\\ \text{in Development}\end{matrix} = \begin{matrix}\text{Total}\\ \text{Initial}\\ \text{Investment}\end{matrix} * \left(\begin{matrix}\text{interest}\\ \text{rate}\end{matrix} + \begin{matrix}\text{risk}\\ \text{factor}\end{matrix} + \begin{matrix}\text{depletion}\\ \text{rate}\end{matrix}\right)$$

Using Adelman's work, the development cost in the Persian Gulf is 55 cents per barrel (Chapman, 1999 and Adelman, 1993). This follows from assumptions of $2.50 per barrel initial investment for exploration, testing, and production equipment, and 10%, 10%, and 2% for the three rates. The result (55¢) is used in Equation (4):

(4)	Illustrative Crude Oil Cost for Saudi Arabia	=	Investment in Development	+	Operations, Lifting	+	Shipping
	\$2.30/barrel	=	\$0.55	+	\$0.25	+	\$1.50

Although this outline of costing will seem simplistic to petroleum engineers, it captures the essence of the method. Generally, the same cost would be expected to produce and deliver Saudi crude oil to Europe, Japan, or the U.S.

The comparable figure for the North Sea or Alaskan oil fields is on the order of \$15 per barrel.[2] This is because geography and climate impose higher technological requirements with higher costs. If we consider geographic and cost data together, it appears that oil production has increased in the regions with higher cost and lower reserves. Simultaneously, production has fallen in the Persian Gulf where reserves are high and costs are low.

Persian Gulf oil is not merely the lowest cost region. It is the region with the greatest remaining reserves, as shown in Table 1. Note the limited resources in the United States and in the North Sea. At some future period, as Alaska and the North Sea begin to decline, OPEC producers may be able to re-establish the price and quantity cartel that existed briefly in earlier periods.

Through the application of Equations (1) and (2), illustrative estimates of the magnitude of producers' and consumers' surplus can be made (see the Appendix). These are shown in Table 2. The first column defines each of the 5 cases. The second column shows the optimal years of use of crude oil into the future for each case. The third column (lambda) is the shadow price, the value in the present of adding an additional barrel to world resources.

The last two columns are the most important. NPV is the net present value of producers' surplus. It is economic rent, the profit above cost, where cost includes a return to investment and to risk as described above. SW is the present value of social welfare, the sum of producers' and consumers' surplus. Consumers' surplus (not shown separately) is the difference between the fourth and the fifth columns. [Social welfare, the sum of producers' and consumers' surplus, is calculated with Appendix Equation (A1). Producers' surplus is calculated with Equation (A2). Consumers' surplus is the difference between SW and NPV. For monopoly cases, the superscript is "m" rather than "c," and the Equation (A10) for monopoly quantity is used in Equations (A1) and (A2).]

Social welfare and consumers' surplus are both maximized by the competitive case. Net present value/economic rent is maximized by the monopoly case. Case 3 assumes a competitive market exists for 40 years, until world use peaks. Then, in the 41st year, monopoly replaces competition.

The 4th and 5th cases in the Table are "backstop" cases. They assume that new fuel feedstock such as biomass or coal-based liquids can become widely available at an equivalent cost of $50 per barrel. (This implies $2 per gallon gasoline: $0.80 per gallon for refining and distribution, and $1.20 per gallon for the $50 per barrel crude feedstock. There are 42 gallons per barrel.)

Since Persian Gulf costs are so much lower than in other producing regions, much of the economic rent in the 4th column goes to those producers. Note that the difference between competition and monopoly (cases #1 and #2) is $6 trillion as a present value. Converted to future value at 5% interest at the end of production (92 years), that value would be $534 trillion. Regardless of the time perspective, there is considerable economic motivation to control Persian Gulf oil production.

III. IS A GAME THEORY EQUILIBRIUM STABLE?

In the early period of the Persian Gulf oil crisis, then-president Bush and Secretary of State James Baker were very explicit about the economic motivations for reversing the Iraqi attempt to dominate the Persian Gulf. Table 1 indicates that Iraq sought control over 55 percent of proved reserves. This quotation was typical: "Our jobs, our way of life, our own freedom and the freedom of friendly countries around the world would all suffer if control of the world's greatest reserves fell into the hands of Saddam Hussein." (New York Times, 1990 and Yergin, 1991, p. 773)

Iraq was defeated (as it had been in Iran), and its world production in the 1990s is reduced to only 20% of its 1989 level. *Nevertheless, there are important unresolved issues that need to be* addressed. They include:

- the political motivation on the part of low cost Persian Gulf producers to offer a price shelter for expensive Northern Hemisphere oil;
- the powerful economic incentive for continuing instability;
- the military cost to the U.S. of guaranteeing access to low cost Persian Gulf oil; and
- the existence or potential for international mechanisms to address the incentives for seizure and the global problems of growing energy use.

If Persian Gulf production costs are as low as the data suggest, why do the Persian Gulf producers not seek monopoly power by first driving high cost competitors out of the industry? Adelman's work leads him to conclude that $5 per barrel could have been an equilibrium competitive price in the 1980s and 1990s (Adelman 1986 and 1993, p. 25. Also see *The Economist*, 1999, pp. 23-25, which also notes $5 as a possible purely competitive equilibrium price.). He had noted that this price would have been profitable for OPEC, and could have led to major increases in OPEC production and world oil consumption. At the same time, a price of $10 or below would reduce capacity in the U.S. and in the North Sea.

It is this latter point which should be given considerable attention. If Saudi Arabia and Persian Gulf governments keep prices in the $15 to $20 range, they support high cost oil production in the countries which provide military security for Persian Gulf governments.

This important point is emphasized by George Bush's meetings with Saudi government ministers and the King in 1986. Bush, then Vice President, publicly and privately sought Persian Gulf support for higher crude oil prices. The price at that time was below $10 (Yergin, 1991, pp. 755-761. Yergin's commentary notes one OPEC oil minister discussing $5 as a possible market price: p. 759.).

The economic logic is as follows. U.S. net imports of petroleum have reached one half of total use.[3] The U.S. production is costly; production cost in the Persian Gulf is not. Consequently, low crude oil prices increase U.S. dependence on imports in two ways. High cost U.S. production has to be shut down when crude prices are near or below $10 on a long term basis. Second, U.S. consumption of oil increases with lower prices. The end result is that crude prices in the $15 to $20 range avoid financial loss for American oil producers, slow the decline in U.S. production levels, and encourage U.S. political support for Persian Gulf governments threatened by Iraq or other forces seeking monopoly power over Persian Gulf oil.

The result of those 1986 discussions was an agreement to set $15 to $18 as a world goal (Yergin, 1991, pp. 755-761). As already noted, that price level has endured. The Persian Gulf War added strength to the existing relationships.

Consider Japan's position in supporting the military defense of Kuwait by the U.S.-led operation. Japan imports essentially all of its petroleum. Three-fourths of its crude oil has originated in the Persian Gulf region (USEIA, 1992, p. 52). In the short run, it would benefit from a

$5 to $10 world price. But, if Persian Gulf oil drives out U.S. and North Sea producers, the resulting monopoly-influenced price would exceed the current $15 to $20 range. With a long run perspective, Japan can depend upon stable prices and political stability for its supply, both supported by the U.S. (Yergin, 1991, pp. 759-760).

Table 3 lays out these and related points in a game theory framework. Both Persian Gulf and OECD governments have been accustomed to the $15 to $20 stable price range. Either group, acting alone, could for a short period force prices in either direction from this range. However, at least for the near term into the next century, both groups have incentives to keep prices in their current range. This is similar to the game theory concept of *Nash Equilibrium:* a status quo where neither side can improve its overall situation by changing its strategy. A game theory approach, then, is intended to represent the interaction of politics, military defense, and economics in world oil markets.

This $15 to $20 level is far below a true monopoly price. It is also far above a truly competitive world price. The outcome in one narrow facet resembles a competitive market: world price is about at the level where it equals the marginal cost of high cost producers.

In 1998, cash prices for Persian Gulf oil were in the $10 to $15 range. The primary cause may have been a cessation of accelerated growth in petroleum consumption in Asia. Throughout most of that year, futures prices remained in the $15 to $20 range. With this downward pressure of the 1998 cash prices, the 1999 response could be anticipated which would return these crude prices to the usual range.

The second problem affecting the level and stability of prices and supply has already been noted: the Persian Gulf's holdings of extensive amounts of low cost reserves constitute an incentive for continuing political instability. The magnitude of potential gain is evident from the analysis.

With a competitive world market, the economic rent accruing to the owners of the resource had a 1996 present value on the order of fifteen to twenty trillion dollars (see Table 2 again).

If a monopoly were unexpectedly to reassert control, the economic rent estimate would be higher, in the twenty to twenty five trillion dollars range. This petroleum rent, or profit above cost, is comparable in magnitude to the planet's total Gross Economic Product. [World gross economic product was $30 trillion in 1997 (World Bank, 1999).]

On a short run basis, the annual Persian Gulf production is typically in the five billion barrel range in the 1990s. Recalling the discussion of Saudi Arabian crude oil costs, the rent, the difference between price and cost, is typically between $10 and $15 per barrel. We can assert that, with the current market framework, Persian Gulf governments earn at least $50 billion annually in rent above cost.

The tremendous magnitude of these amounts continues to offer incentives for groups outside the current framework to gain some part of this value through arms and political coercion. Consequently, continuing political instability is a possible result of the high levels of economic rent.

This leads to the third issue: what is the military cost to the OECD countries of protecting the current market framework and continued access to the extensive Persian Gulf reserves? Economists generally do not consider this point to be relevant for calculations of external cost. One exception is the work of Darwin Hall. Hall's statistical analysis (19**) finds a relationship between oil imports and U.S. defense spending. Translated into simple terms, each barrel of imported oil adds $10 to defense expenditures. This outweighs a trend variable, which would be reducing military spending by $17 billion annually, in the hypothetical absence of oil imports. Hall also concludes that the U.S. Strategic Petroleum Reserve adds another $2 to Federal expenditures for each barrel of imported oil.[4]

During the Cold War era of competition between the Soviet Union and U.S. allies, there was considerable concern about Soviet influence acquiring a voice in Persian Gulf decision-making. In 1920 and again in the 1940s during World War II, the Soviet Union actively supported short-lived soviet republics in Iran. In 1950, the U.S. Central Intelligence Agency provided short-term leadership to the effort to change Iran's government.[5] The collapse of the Soviet Union ended this competition in the early 1990s.

It must be noted that Hall's approach is not widely accepted amongst environmental economists. Outside the field of environmental economics, energy economists are somewhat more interested. But even among analysts concerned with petroleum and military/political security, there is reluctance to take Hall's literal dollars-and-cents approach.[6]

IV. CAN THE PRICE OF OIL BE PREDICTED?

Economic theory suggested very neat possibilities for projecting future prices for finite resources. In contrast, the preceding discussion introduced the complex world of geopolitics, which created a decade-long era in which crude oil prices were generally in the $15 to $20 per barrel range.

'Oil shocks' which create rapid price increases are dramatic, as occurred briefly in the 1970s, 1980s, and 1990s. However, unexpected events can also reduce petroleum prices. One such surprise took place in 1998. Even though world oil consumption continued to increase, oil prices dropped sharply. Figure 3 helps explain this. [Of course, Figure 3 is not drawn to scale; it shows the economic logic of shifting demand and supply curves causing price reductions while consumption increases.]

First, note that actual oil consumption increases from the first period to the second period:

Q_{2A} is greater than Q_{1A}. (Q_{1A} is actual quantity in the first period, and Q_{2A} is actual quantity consumed in the second period.)

But, actual prices have fallen sharply, and P_{2A} is much lower than P_{1A} in spite of the increase in world oil consumption. How does this happen? It was a result of surprising shifts in both demand and supply curves. The world oil industry had expected the global demand curve to continue to shift upward, to move from D_{1A} (actual first period demand curve) to D_{2E} (expected second period demand curve). Oil production capacity was adequate, and the graph shows the same supply curve for the first period, SC_{1A}, and the expected supply curve for the second period, SC_{2E}. If everything had gone as expected, the expected second period price P_{2E} would have been about the same, and the expected second period market equilibrium for quantity (Q_{2E}) would have increased. Both are shown.

However, there were two major surprises. First, the economic downturn in Asia in 1998 made the actual global demand curve D_{2A} much less than the expected D_{2E}. Second, Iraq nearly doubled its sales in 1998, so more oil was available. The actual global supply curve SC_{2A} was greater than the expected SC_{2E}.

The results? Q_{2A} increased from the previous year's actual Q_{1A}, and actual price dropped sharply from P_{1A} to P_{2A}.

Suppose the low crude oil prices of 1998 were to continue. We know from the preceding analysis that there would be significant reductions in high cost U.S. oil production. There would be a restructuring of the U.S. oil industry as shut-down production required new corporate networks organized around increased use of low cost Persian Gulf oil.

Alternatively, the strategic game theory equilibrium might return crude prices to the $15 to $20 range, as happened in April 1999 (New York Times, April 10, 1999).

It should not be supposed that there is sufficient information here to make a precise forecast of the price of oil at some future date. We do know, however, that we have identified the factors which influence those future prices.

Personally, we expect continued low crude oil and gasoline prices (in real dollars) in the early beginning of the 21st Century. Very much further into the future, we might see the emergence of continuously growing real prices for petroleum products and ultimately the emergence of new energy sources to substitute for today's petroleum technologies.[7]

V. POLICIES: MILITARY; TAXATION; ADMINISTRATION

The long period of low gasoline and oil prices in association with growing world and U.S. consumption seem persuasive evidence for the absence of any economic problems associated with the concepts of scarcity or depletion. However, an application of economic theory (incorporating upwardly shifting demand functions) projects a long period of rising output and stable prices, followed by declining output and rising prices.

Current cost of production and transport of Persian Gulf oil to Europe, Japan, and the U.S. is low, on the order of $2.50 per barrel. Comparable figures for the North Sea and Alaska are on the order of $15 per barrel. The geographic distribution of crude oil is such that current world production comes disproportionately from high cost, lower reserve regions.

Economic theory related to competition and monopoly helps explain some dimensions of the policies of OPEC and OECD countries, but game theory helps incorporate the political factors which support a stable status quo in the near term. It is one possible description of current markets: the term reflects the interactions of economics, politics, and military considerations.

Given the magnitude of economic rent and geological resources in the Persian Gulf region, the incentives for the use of military force to gain or defend access will continue. As the region's share of remaining petroleum resources continues to rise, the potential for armed conflict will increase.

George Bush articulated a view that international military force is appropriate to defend this world resource against monopolistic control by aggressive invaders. However, the combination of the growing economic importance of Persian Gulf oil and the increasing importance of petroleum as a source of greenhouse gases will define a new challenge. At some future period, international taxation as well as military protection may be considered for application to Persian Gulf oil.

One form of international administration already exists, the status quo. UN-authorized military forces were still in place in 1999. For Iraq, the Security Council continues to limit oil production and foreign trade. As a consequence of the war, U.S. military forces remain significant in several countries, and bombed Iraqi oil facilities in early 1999. Naval power in the Gulf continues as well. In the short run, this de facto international administration will continue.

A second type of international administration is the management of production and pricing goals by OPEC. OPEC itself is evolving into a broader organization with the inclusion of Mexico, Russia, and Norway into the production quota process. [*Wall Street Journal,* June 26, 1998. The Saudi oil minister reaffirmed the price range goals outlined here, and argues for a broader global organization to handle production planning.] This emerging producer organization may play a role in international policy.

Taxation, particularly, may become relevant. The basis may be Persian Gulf exports, or international trade in crude, or world crude production. Consider for illustration a $5 per barrel tax. For Gulf producers with about $12.50 per barrel in economic rent above cost, the tax would transfer 40%. The revenue could be used to finance UN-authorized peacekeeping activities, or climate change programs. The consumer impact would be an increase in gasoline prices of 12 cents per gallon.

Variations in the concept would include (a) initiating a very low tax, increasing it gradually, and (b) dividing tax revenue into shares for exporting governments, and international use.

Looking into the future, several points are clear.

- In the next decade, North Sea and Alaskan production will peak and decline;
- The Persian Gulf will increase its share of remaining resources;
- Prices and rents will begin to increase sometime in the first quarter of the 21st Century;
- The economic incentive will increase for military seizures of Gulf oil regions by Iraqi-type military actions;
- Nuclear and missile weapons testing will continue, both by one or more Gulf nations and their neighbors;
- Global production and consumption will continue to rise in the near future before peaking; and
- The Kyoto Protocol and future climate change treaties will develop economic incentives to influence levels of world oil consumption.

Supporters of Morris Adelman's perspective will be comfortable with the emphasis here on low Persian Gulf production costs and the global importance of oil from that region. (They may be less comfortable with the reconciliation of depletion theory with the current era of low prices and growing consumption.) Nevertheless, we share this Adelman conclusion, "Trillions of petrodollars have changed the Middle East from a local hot spot to a world problem....The cycle will continue: meetings, quotas, firm prices, cheating, price declines, threats and promises, meetings, with here and there some drastic political-military moves." (Adelman, 1993, p. 29)

International administration does exist today in a de facto form, with respect to U.N. and

U.S. military control, and OPEC output/price planning. The confluence of trends points towards continued concerns about stability, prices, and climate change. Perhaps the major issue raised here is the future evolution of current aspects of international management of crude oil in the Persian Gulf.

APPENDIX: A MODEL OF OPTIMAL RESOURCE DEPLETION FOR COMPETITIVE AND MONOPOLISTIC MARKETS

This Appendix provides a summary of the model framework from which Equations (1) and (2) in the text are derived. These two equations are compact expressions of Equations (A7) and (A9) below. The values in Table 2 are calculated with the Appendix equations. The model's utilization of dynamic demand and cost functions with explicit solutions can be seen as an extension of the Hotelling (1931) model of exhaustible resources. The parametric assumptions employed in obtaining the results in Table 2 are shown in Table 4.

Consider a perfectly competitive world oil market with a fixed stock, S, of remaining oil resources. Let P_t be the world oil price (per barrel) and C_t be the marginal cost of oil extraction in period t, respectively. Suppose population, N_t, and per capita income, y_t, are both increasing steadily over time. This would imply that the (inverse) demand function would be shifting outward over time. For computational ease, we make the following two assumptions: (i) The inverse demand function is linearly related to world oil production, q_t; and (ii) as a first approximation, the marginal cost of extraction changes over time in response to technological innovation and environmental protection.

The world oil market may be represented as maximizing the present value of social welfare (SW), the sum of producers' and consumers' surplus, subject to the appropriate economic, demographic, technological, and geological constraints. Under our assumptions, this may be characterized as follows:

$$\underset{\{q_t,\ T\}}{Maximize}\quad SW = \int_0^T \left[\int_0^{q_t} \left(P_t - C_t \right) dq \right] e^{-rt}\, dt$$

$$s.t. \quad \int_0^T q_t\, dt \leq S$$

$$P_t,\ q_t \geq 0,\ P_t - C_t \geq 0 \qquad \text{(A1)}$$

where

$$P_t = P(q_t, N_t, y_t) = \beta_2^* N_t^{\nu_1} y_t^{\nu_2} - \beta_1 q_t$$

$$C_t = C(t) = C_0 e^{\phi t}$$

$$N_t = N_0 e^{\theta_1 t}$$

$$y_t = y_0 e^{\theta_2 t}$$

and

$\beta_1 < 0$ is the slope of the inverse demand function with respect to quantity;

$\beta_2^* > 0$ defines the intercept of the inverse demand function;

$\nu_1 > 0$ is the elasticity of the inverse demand function intercept with respect to world population; it represents the responsiveness of oil price and quantity to N_t;

$\nu_2 > 0$ is the elasticity of the inverse demand function intercept with respect to per capita income; it represents the responsiveness of oil price and quantity to y_t;

$\theta_1 > 0$ is the population growth rate;

$\theta_2 > 0$ is the growth rate of per capita income;

$\phi \leq \geq 0$ is the growth rate of the marginal cost of extraction;

$r > 0$ is the discount rate;

$S > 0$ represents remaining oil resources.

Since under our assumption of perfect competition, social welfare maximization is equivalent to the maximization of the present value of profit (Chapman 1993), we may restate the problem as follows:

$$\underset{\{q_t,\ T\}}{Maximize} \quad NPV = \int_0^{T^c} \left[\left(\beta_2 e^{\theta t} - \beta_1 q_t \right) - C_0 e^{\phi t} \right] q_t^c e^{-rt} dt$$

$$\begin{aligned} s.t. \quad \dot{X}_t &= q_t^c \\ X_0 &= 0 \\ X_T &\leq S \\ \text{where} \quad X_t^c &= \int_0^t q_t^c dt \\ \theta &= \theta_1 v_1 + \theta_2 v_2 \\ \beta_2 &= \beta_2^* N_0^{v_1} y_0^{v_2} \end{aligned} \tag{A2}$$

Note in this non-stochastic optimal control problem, there are two control variables: q_t^c, the quantity of oil produced at time t, and T^c, the terminal period of the planning horizon. (The superscript c denotes the optimal solution in a competitive market.) The state variable is cumulative production through period t, X_t^c. The Hamiltonian, H^c, associated with the competitive oil market case is

$$H^c = \frac{\left[\left(\beta_2 e^{\theta t} - \beta_1 q_t \right) - C_0 e^{\phi t} \right] q_t}{e^{rt}} - \lambda_t q_t \ ; \quad \frac{\partial P_t}{\partial q_t} \equiv 0 \tag{A3}$$

where $\lambda_t \geq 0$ is the costate variable. The first order conditions for the optimal solution are:

$$(i)\quad \frac{\partial H^c(\bullet)}{\partial q_t} = 0$$

$$(ii)\quad \dot{\lambda}_t = -\frac{\partial H^c(\bullet)}{\partial X_t} = 0 \text{ (i.e., } \lambda \text{ is constant)} \qquad \text{(A4)}$$

$$(iii)\quad \dot{X}_t = \frac{\partial H^c(\bullet)}{\partial \lambda_t} = q_t$$

Solving the first order conditions gives us the following:

$$q_t^c = \frac{1}{\beta_1}\left[\beta_2 e^{at} - C_0 e^{\phi t} - \lambda e^{rt}\right] \qquad \text{(A5)}$$

When the constraint implied by the finite remaining stock of oil resources is non-binding, $X_T < S$ and $\lambda = 0$. In this situation, throughout the period,

$$q_t^c = \frac{\beta_2 e^{at} - C_0 e^{\phi t}}{\beta_1} = QC_t. \qquad \text{(A6)}$$

I.e., the optimal production trajectory would be identical to that produced by a competitive oil market without any resource limitations. However, when the constraint is binding, $\lambda > 0$ and $\int_0^T q_t dt = S$. Under these conditions we obtain

$$\lambda^c = \frac{\beta_1}{M(r)}\left(\beta_4^c - S\right); \text{ and}$$

$$q_t^c = QC_t - \frac{e^{rt}}{M(r)}\left(\beta_4^c - S\right) \qquad \text{(A7)}$$

where $\beta_4^c = \int_0^{T^c} QC_t\, dt$, i.e., the cumulative production through T^c that would have occurred in a perfectly competitive market in the absence of a resource constraint, and $M(r) = \int_0^{T^c} e^{rt} dt$ is an accumulation factor. Note that $(\beta_4^c - S)$ represents the amount by which unconstrained production exceeds the remaining stock and thus represents scarcity. Therefore, the optimal oil production trajectory may be written as:

$$q_t^c = QC_t - e^{rt} SF \tag{A8}$$

where $SF = \dfrac{\beta_4^c - S}{M(r)}$ is a scarcity factor. The corresponding optimal price trajectory is:

$$P_t^c = \beta_2 e^{\theta t} - \beta_1 q_t = C_0 e^{\phi t} + \beta_1 e^{rt} SF \tag{A9}$$

Following the logic of the above optimization, it can be shown that the solution to the optimal depletion problem in the case of an oil market characterized as a pure monopoly is:

$$q_t^m = \frac{1}{2} QC_t - \frac{e^{rt}}{M(r)} \left[\frac{1}{2} \beta_4^c - S \right] \tag{A10}$$

The optimal value for T, T^*, may be obtained by substituting the expression for the optimal oil production trajectory in Equation (A1) and solving the condition $\dfrac{\partial SW}{\partial T} = 0$. This results in

$$T^* = \min \begin{cases} T_1 : q_{T_1} = 0 & \text{if the resource constraint is binding} \\ T_2 : \beta_2 e^{\theta T_2} = C_0 e^{\phi T_2} & \text{if the resource constraint is non-binding} \end{cases} \tag{A11}$$

Note, in the text, $QE(t)$ refers to q_t^c and $P(t)$ refers to P_t^c. For the numerical values shown in Table 2 of the text, the parameter values in Table 4 were assumed.

It is worth noting that Stiglitz (1976) showed that in the presence of constant elasticity demand functions and zero extraction costs, the competitive and monopoly cases yield identical price trajectories. However, if either one, or both, of these conditions are not met, the monopoly price is initially higher and the optimal production horizon is longer. Furthermore, Stiglitz argued that these two price paths diverge only slightly. This result was reexamined by Pindyck (1978) who showed that degree to which a monopolist is able to exercise his monopoly power depends on his ability to take advantage of the short term adjustment lags in the demand for output. This was specifically true in the case of OPEC. Our model is congruent in detail with both.

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FOOTNOTES

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1. This paper is in part the basis for Chapter 9, "World Oil: A Strategic Limited Resource?" in Chapman (1999). Also see Chapman (1983). This second article was the basis for the Appendix, which describes the optimal control framework for Equations (1) and (2). Further discussion of the results is available in Rowse (1988 and 1990).

2. Again as illustration, use Adelman's (1993) UK value of $14,400 per daily capacity. Now assume this includes exploration cost. For the 'oil discount factor,' use 10 percent interest, 10 percent risk factor, and 5 percent decline. Assume $5 per barrel each for operations and delivery to a European port refinery. The result is $15 per barrel production cost for crude oil for the UK.

3. There is some disagreement on the point as to whether import dependency should be measured by imports alone, or net imports defined as imports less exports. On the net import basis, the U.S. percentage is about 50 percent of the 6-7 billion barrels of annual consumption. Both U.S. annual consumption and the net import percentage are slowly increasing. The Persian Gulf has supplied about 20 percent of imports over a quarter of a century.

4. The Strategic Petroleum Reserve is maintained at nearly 600 million barrels. Hall's

estimates were in 1985 dollars (Hall, 1992); the text values are in 1995 dollars. An analysis by Green and Leiby implies military cost at about $5 per imported barrel (see Kahn, 1998, p. 238). Michael O'Hanlon at the Brookings Institute estimates a very high Persian Gulf military cost for the United States: $50 billion annually. See *New York Times*, December 30, 1995, and September 18, 1996.

5. Kermit Roosevelt coordinated this effort. Roosevelt (1979) is very informative. A brief economic history of the Cold War in oil is in Chapman 1983, pp. 83-86.

6. Some other sources on the economics of petroleum and national security are Adelman (1993, pp. 27-28), Bohi and Quandt (1984), Broadman and Hogan (1988), Lichtenblau (1994, pp. 329-346), Lovins and Romm (1992/93), Ravenal (1984 and 1985). Shibley Telhami and Michael O'Hanlon attribute $50 billion annually to U.S. military spending related to the Persian Gulf (see *New York Times*, December 30, 1995, and September 18, 1996).

7. New technologies may bring such sources as tar sands, oil shale, and coal liquefaction into commercial gasoline production. Much higher prices would bring these sources into production. Backstop technologies are part of the depletion theory used in this discussion; see Chapman (1993).

ABBREVIATIONS

FSU	Former Soviet Union
GNP	Gross national product
na	Not applicable
NPV	Net present value
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of Oil Producing and Exporting Countries
SW	Social welfare
U.N.	United Nations
U.S.	United States

JEL Classification Code

C61, Q32, Q41, Q43, Q48

TABLE 1
Geologists' Upper Probability Estimates of Regional and World Crude Oil
(billion barrels)

	Identified Reserves	**Estimated Undiscovered Resources**	**Estimated Total Upper Probability Remaining Resources**
Persian Gulf	660	217	877
Former Soviet Union	57	234	291
United States	23	55	78
North Sea - Western Europe	17	34	51
World	1,000	938	1,938

Note: On identified reserves: Iraq 100; Iran 89; Kuwait and Neutral Zone 99; Saudi Arabia 259. World totals include other regions. Total four countries: 547; or 55 percent. See U.S. Geological Survey and other sources discussed in Chapman (1993 and 1999). For 1995 production, the amounts were: Persian Gulf 7; FSU 2.5; U.S. 2.5; North Sea-Western Europe 2; world total 22; all in billion barrels. Also see Campbell and Laherrère (1998, pp. 78-83).

TABLE 2
Producers' Surplus and Social Welfare: Present Values

CASE	T (years)	λ[a] ($/bl)	NPV[b] (in billion $)	SW[c] (in billion $)
1. Competition	69.44	$7.46	$15,659	$31,561
2. Monopoly	91.78	$4.02	$21,469	$27,980
3. Shift from competition to monopoly, year 41	80.80	na	$16,153	$31,224
4. Competition with backstop	47.67	$2.63	$5,519	$29,365
5. Monopoly with backstop	55.20	na	$14,876	$17,522

a. Lambda is the shadow price, the present value of an additional barrel of oil.

b. NPV is the net present value of producers' surplus or rent.

c. SW is social welfare, the present value of consumers' and producers' surplus.

na = not applicable.

Note: See Appendix for model structure and Table 4 for parameter values.

TABLE 3
General Economic Impact of Crude Oil Price Decision in Game Theory Framework

Price Per Barrel	OECD Countries	Persian Gulf Oil Producers
$10 or less	-higher GNP growth -shut domestic production -greatly increased oil consumption -much more imports -more pollution, climate change -end Persian Gulf political support	-loss of OECD political support -lower revenue, greater volume -higher market share -faster depletion
$15 - $20	-stable GNP growth -stable near-term oil production -slow growth in oil consumption -slow growth in import share -stable prices -continued Persian Gulf support	-continued OECD political support -stable revenue, profit, rent
$30	-decline in GNP growth -rapid near-term growth in production -stable or declining consumption -end Persian Gulf support	-loss of OECD political support -less market share -less production, more profit, rent -greater payoff to successful Iraq-type action

TABLE 4
Parametric Assumptions

Parameter	Numerical Value Assumed
β_1	1.8
β_2	60
ν_1	1.0
ν_2	0.5
θ_1	1.37% per year
θ_2	1.60% per year
ϕ	1.61% per year
C_0	$10 per barrel (1989 prices)
N_0	5.3 billion (in 1990)
y_0	$4000 (1989 prices)
r	5% per year
S	2100 billion barrels (upper 5% probability of estimated resources)

Figure 1. World Oil Markets if Demand Shifts and Costs Increase

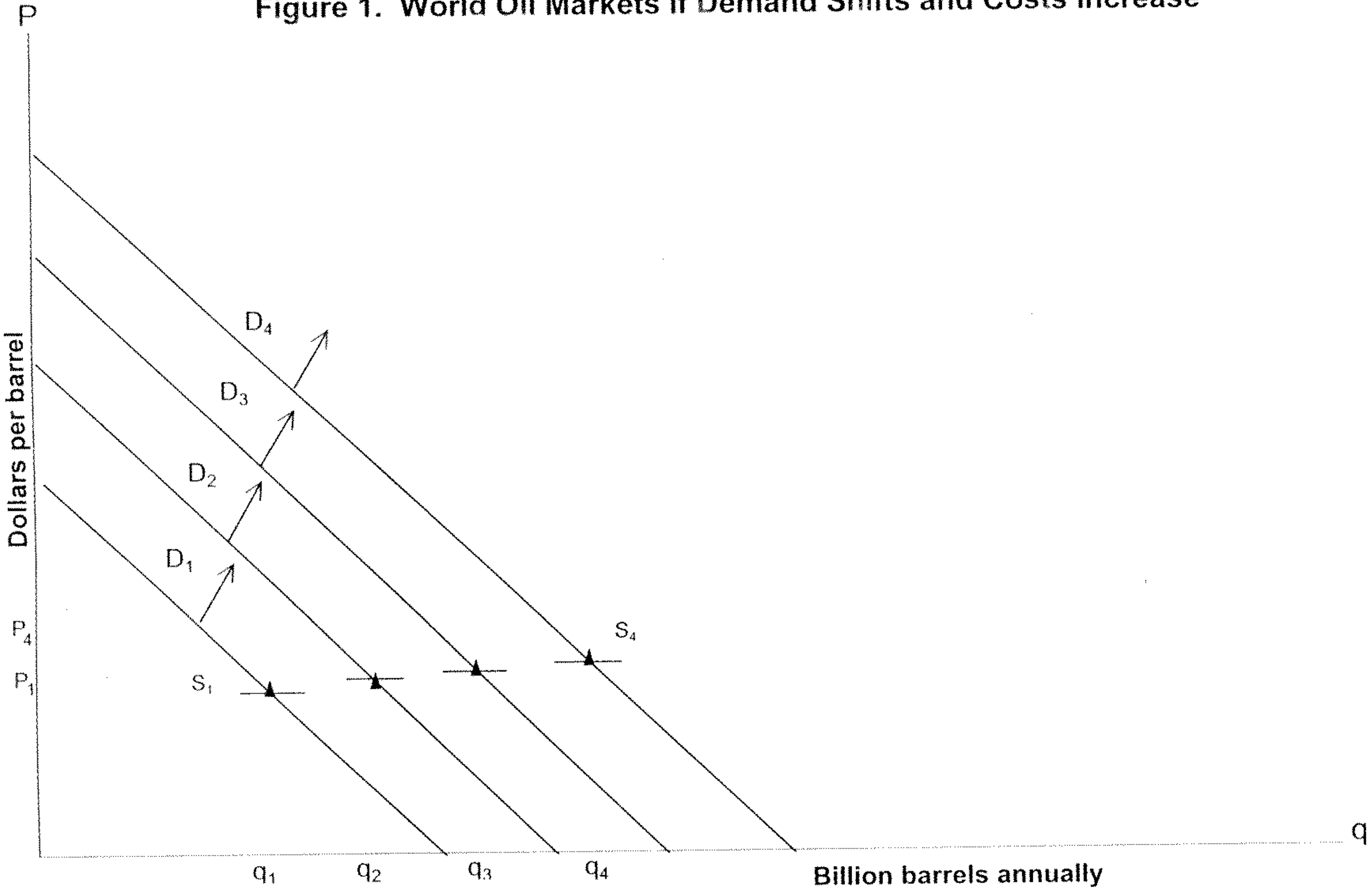


Figure 2. World Petroleum Market Projections: Growing Population, Income, Cost, Competitive Market

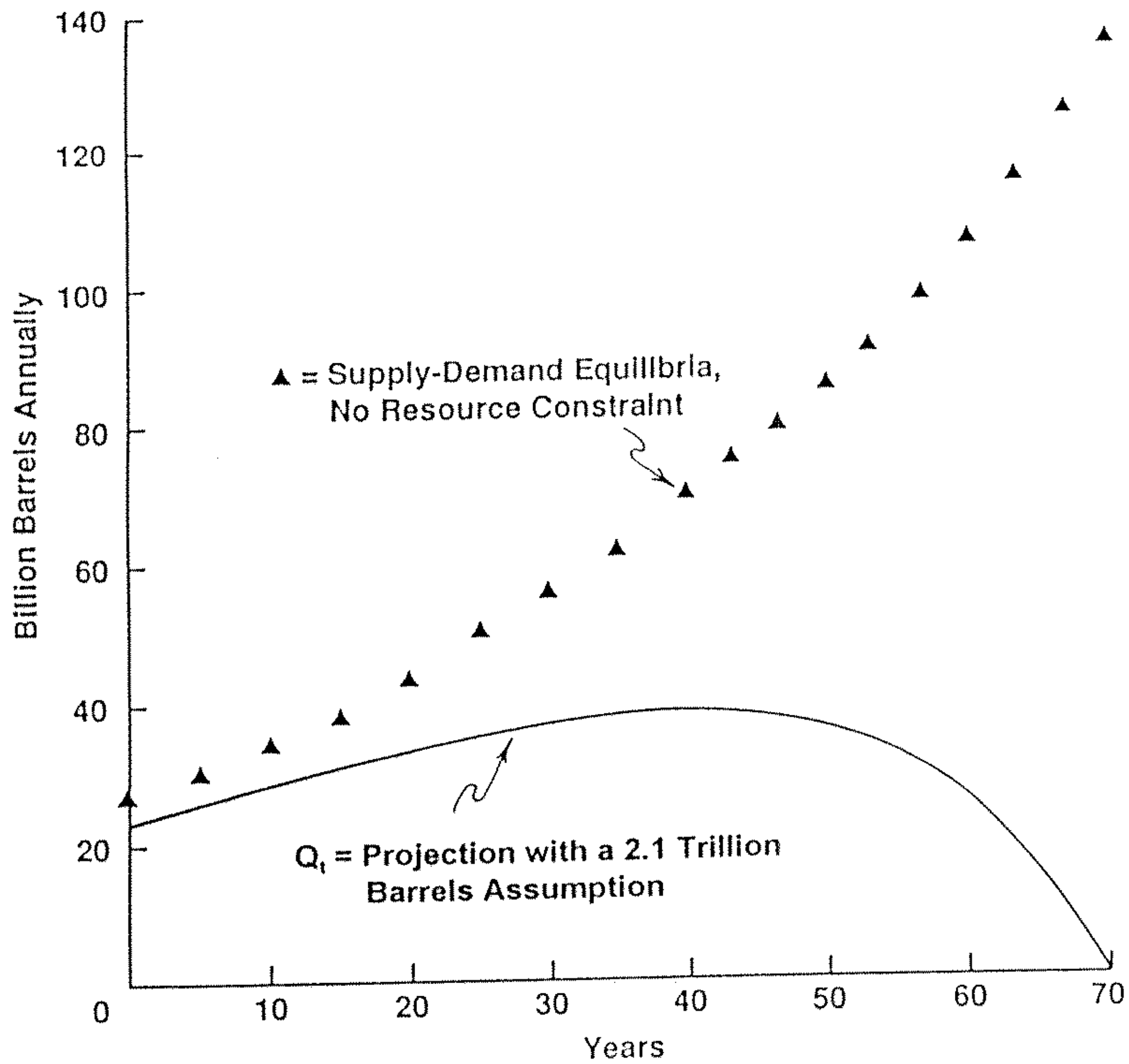
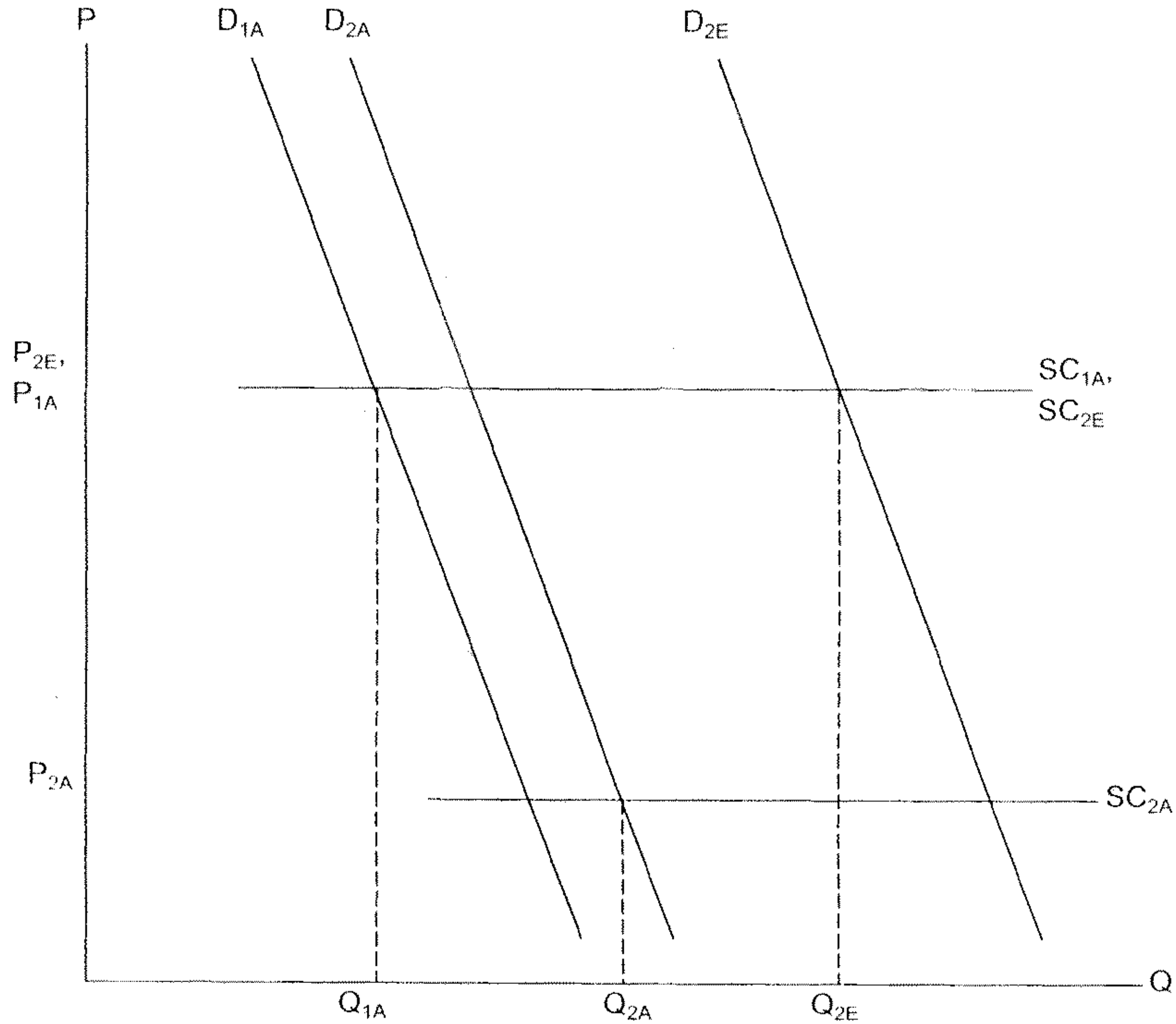


Figure 3. Expectations and Market Equilibria



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