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# A MODEL OF THE WORLD OIL MARKET WITH AN OPEC CARTEL

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**Abstract**

A world oil market model (WOM) with OPEC treated as a Stackelberg cartel has been developed within the framework of the Generalized Equilibrium Modeling System (GEMS) that is available from Decision Focus, Inc. The U.S. sector of the model is represented by a Liquid Fuels Supply model that was presented previously.

The WOM model is described and results obtained with the model for the period 1980 to 2040 are presented. For comparative purposes, results obtained with the model when OPEC is treated as a competitive producer are also presented. By comparing the world oil price as a function of time from the two calculations, the influence that OPEC may have on the oil market by exploiting all of its market power is quantified.

The world oil price as obtained with the WOM model is also compared with world oil price projections from a variety of sources.

# 1. INTRODUCTION

In a previous paper[1] a liquid fuels supply model (LFS) of the U.S. oil market was presented and discussed. In the LFS model the world oil price, i.e., the price of imported oil into the U.S., was specified exogenously as a function of time. In a second paper,[2] adjoint sensitivity theory was applied to the LFS model and it was found, as expected, that the price of imported oil had a very significant effect on the results obtained with the LFS model. To avoid the difficulties inherent in specifying the world oil price exogenously, a model of the world oil market (WOM) that includes the LFS model as a representation of the U.S. oil market and allows a calculation of the world oil price has been developed and is discussed here.

There are a variety of models available[3*] that attempt to estimate the world oil price as a function of time, but in general these models do not attempt to explicitly account for the presence of a cartel in the world oil market. The model of Salant[6] takes into account the presence of a cartel using a Nash-Cournot approach. In the model described here the OPEC cartel is modeled using a Stackelberg approach similar to that described by Marshalla.[4] The merits of Stackelberg theory compared to Nash-Cournot theory have been described in some detail by Marshalla.[7] The model described here takes full account of the cartel's market power and of the depletability of the resource both within and outside of the cartel.

# 2. DEVELOPMENT OF THE WORLD OIL MARKET (WOM) MODEL

## 2.1 Model description

In Fig. 1 a block diagram of the WOM model is shown. In the model four liquid fuel demand regions are distinguished: U.S., Japan/Asia/ Oceania, Organization of Economic Cooperation and Development (OECD) excluding the U.S., and lesser developed countries (LDC). Seven supply regions are distinguished: centrally planned economies (CPE), Canada, other OECD, LDC, core OPEC, other OPEC, and a backstop source. "Core OPEC" represents that part of OPEC that operates as a cartel while "Other OPEC" represents that part of OPEC that operates as a competitive supplier. This division of OPEC allows a range of possibilities for representing OPEC from that of a complete cartel to that of a completely competitive supplier. The "backstop source" of supply represents some source that will become available after the other sources in the model are depleted. The circle in Fig. 1 represents a market were buyers and suppliers trade for a commodity (oil) at a price.

*See Ref. 4 and the references given therein and Annex C of Ref. 5 and the references given therein.

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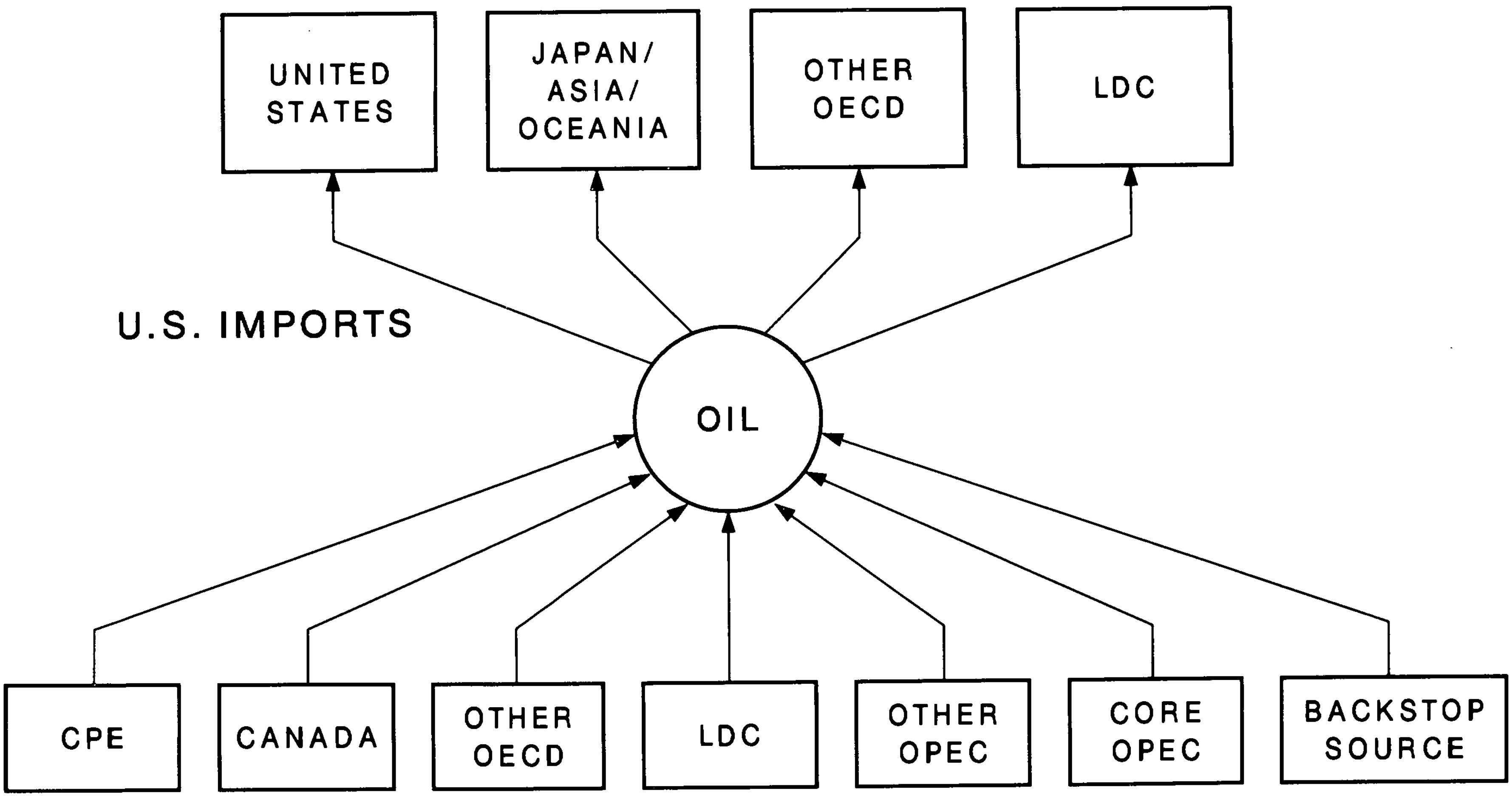


Fig. 1. Diagram of World Oil Market (WOM) model.

The U.S. region in Fig. 1 is represented by the LFS model[1] shown schematically in Fig. 2. This model was described in some detail in Ref. 1 and is used here without change except that the price of imported oil to the U.S., i.e., the world oil price, was specified exogenously as a function of time in Ref. 1, while here it is calculated.

The LFS model in Ref. 1 was constructed using the Generalized Equilibrium Modeling System (GEMS) developed by Decision Focus, Incorporated.[8] The specific features of this modeling system, the equations used to represent the various supply and demand processes, and the numerical methods used to obtain a solution to the equations of a model have been described in detail previously[1,2,8,9,10] so only a brief discussion will be given here.

The basic assumptions of models constructed with GEMS are that the market controls long-term behavior of investment and operating decisions and that agents in the market sense and respond to the discounted stream of future net dollar flows. The model equations are very nonlinear and are fully dynamic in time; i.e., the model equations are coupled in time so that the solution for all times must be determined simultaneously.

The GEMS system is composed of a group of process submodels. Each of these submodels represents a particular type of activity; e.g., the resource submodel represents the production of a depletable resource. The equations of a particular submodel contain a large number of parameters and these parameters are used to represent similar but distinct activities such as the production of oil from different geographical regions. When the submodels are linked together into a network such as that shown in Figs. 1 and 2, the equations form a closed set that may be solved simultaneously, by iteration techniques, to determine the equilibrium prices and quantities as a function of time on each link in the network diagram.

The GEMS system, as it is described in Ref. 8, is sufficiently general that it may be used to consider the model of the network diagrams in Figs. 1 and 2, but only if OPEC is treated as a competitive producer. That is, the GEMS system of Ref. 8 has no provisions for the presence of a cartel. The modifications that have been made in the GEMS system to allow for the presence of a Stackelberg cartel are discussed in the next subsection of this paper.

### 2.2 Cartel pricing equation

In this subsection the modifications in the GEMS system that are required to account for the presence of a Stackelberg cartel are presented and discussed. Additional discussion will also be found in the work of Marshalla and Nesbitt.[11,12,13] Since the GEMS depletable resource submodel is already based on a fully dynamic Hotelling model of scarcity rent formation,[1,8,14] it is only necessary to incorporate cartel price setting logic wherein the cartel takes full account of its market position. That is, the cartel takes full account of how a change in the price it sets at any time may affect the entire time trajectories of production by the noncartel suppliers and the entire time trajectories of demand by all consumers.

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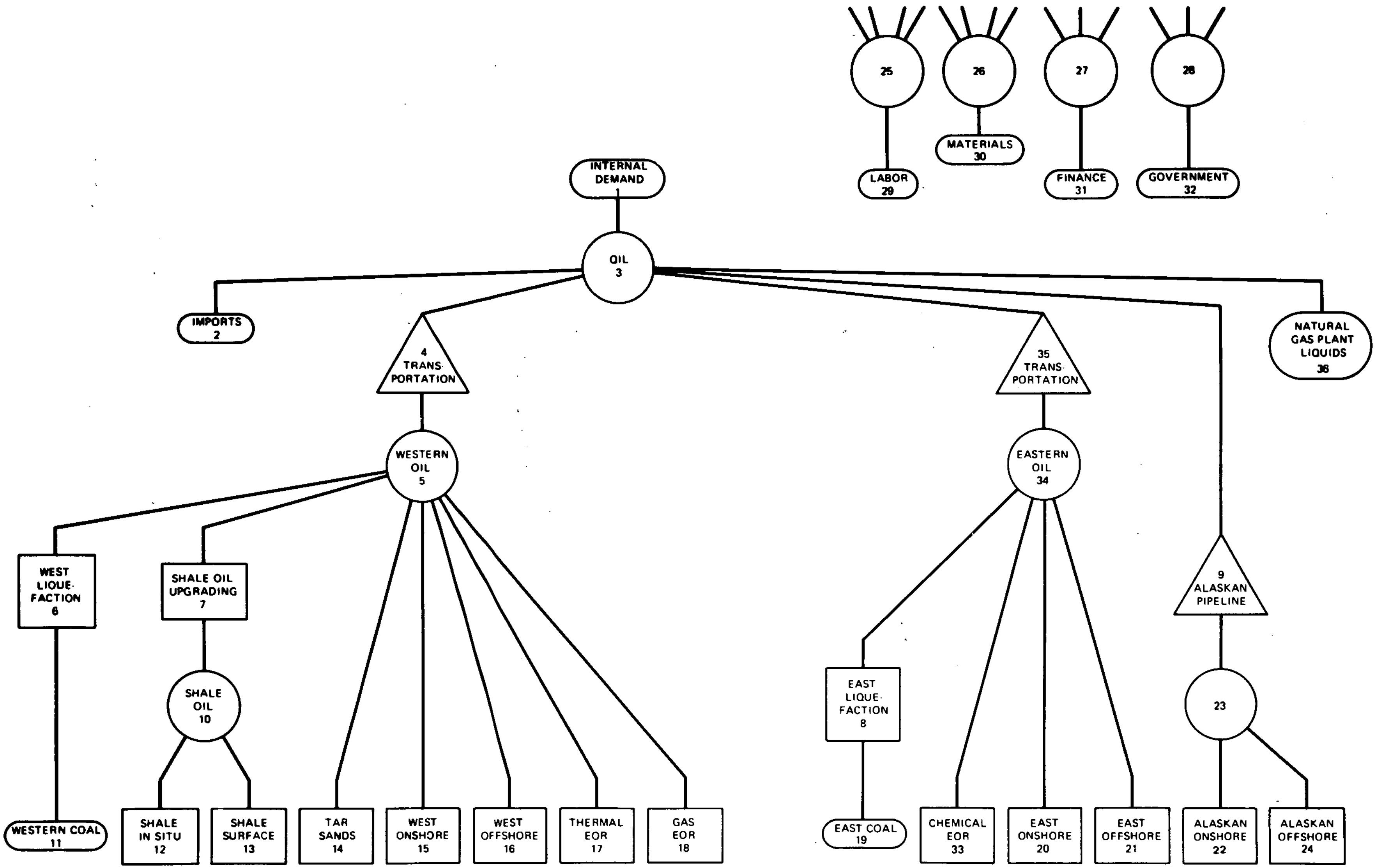


Fig. 2. Diagram of LFS model used to represent the U.S. in the WOM model.

The pricing equation for the cartel may be derived by maximizing the present value of cartel profit. The first-order necessary condition is that at each time point marginal revenue equals marginal cost plus a depletion rent (or "user cost") and may be written as

$$R_n = C_n + S_n \ , \tag{1}$$

where the subscript $n$ is used to denote the discrete time points in the model and

$R_n$ = present value at n of the marginal revenue of the cartel due to committing a unit of reserves at n and producing it out over its lifetime,
$C_n$ = the present value at n of the marginal cost of developing and producing a unit of reserves committed at n,
$S_n$ = the depletion rent required to induce commitments of the next unit of reserves at n.

The present value of the total cartel revenue as of the first model time point, $R$, may be written

$$R = \sum_{k=1}^{\infty} P_k Q_k D_{1k} \ , \tag{2}$$

where

$P_k$ = the price per unit of output at time n,
$Q_k$ = the total production per unit time at k,
$D_{nk}$ = the present value at n of a dollar spent or received at k.

Reserve (or capacity) commitments will be taken to be the cartel's control variable. In terms of this variable the marginal revenue may be written as

$$R_n = \frac{\partial R}{\partial N_n} D_{n1} \ , \tag{3}$$

where

$N_n$ = the number of units of reserves committed at $n$.

The discount factor, $D_{nl}$, is included in Eq. (3) so that the marginal revenue is expressed in current time, i.e., at time n, rather than in present value, i.e., at time 1. By combining Eqs. (2) and (3) one obtains

$$R_n = \sum_{k=1}^{\infty} \left[ P_k \frac{\partial Q_k}{\partial N_n} + \frac{\partial P_k}{\partial N_n} Q_k \right] D_{nk} . \tag{4}$$

The total production per unit time, $Q_k$, is related to reserve commitments, $N_n$, through the equation

$$Q_k = \sum_{n=1}^{\infty} N_n q_{nk} , \tag{5}$$

where

$q_{nk}$ = the production per unit time at $k$ per unit reserves committed at $n$.

The shape of the time path of production from a unit of reserves is assumed to be a given based on engineering-economic considerations.[1,8*] Then, by differentiating Eq. (5) and utilizing the fact that

$$q_{nk} = 0 \qquad k < n \tag{6}$$

one obtains

$$\begin{aligned} \frac{\partial Q_k}{\partial N_n} &= 0 \qquad k < n \\ &= q_{nk} \qquad k \geqslant n . \end{aligned} \tag{7}$$

It is assumed that demand is fully dynamic in time in the sense that price, $P_k$, depends on the total production per unit time, at all times. That is

$$P_k = P_k(Q_1,\ldots,Q_k,Q_{k+1},\ldots) , \tag{8}$$

and since through Eq. (5) the production rates depend on reserve commitments, one may write

$$\frac{\partial P_k}{\partial N_n} = \sum_{j=n}^{\infty} \frac{\partial P_k}{\partial Q_j} q_{nj} . \tag{9}$$

*It is assumed that the cartel has sufficient foresight not to develop "excess" reserves in the sense that market considerations would call for capacity to be shut down beyond the optimal engineering rate. In the real world so-called "excess" capacities do exist and to the extent that they do, they imply suboptimal behavior.

Finally, by substituting Eqs. (7) and (9) into Eq. (4), one obtains

$$R_n = \sum_{k=n}^{\infty} P_k q_{nk} D_{nk} + \sum_{j=n}^{\infty} \left[ \sum_{k=1}^{\infty} \frac{\partial P_k}{\partial Q_j} Q_k D_{nk} \right] q_{nj} \,, \tag{10}$$

and then using Eq. (1),

$$\sum_{j=n}^{\infty} P_n q_{nj} D_{nj} = C_n + S_n + M_n \,, \tag{11}$$

$$M_n = \sum_{j=n}^{\infty} \left[ \sum_{k=1}^{\infty} \left( - \frac{\partial P_k}{\partial Q_j} \right) Q_k D_{nk} \right] q_{nj} \,. \tag{12}$$

The left-hand side of Eq. (11) is simply the present value of total revenue earned by the cartel per unit of reserves committed at $n$. The term $M_n$ on the right-hand side of Eq. (11) is defined to be the "cartel rent" for it is the term that distinguishes the equation from the equilibrium condition for a competitive regime. Equation (11) states that the cartel will select a pattern of reserve commitments that allows it to earn revenues from each unit of reserves equal to the cost of developing and producing the reserve, $C_n$, plus a standard user cost, $S_n$, that arises from the depletability of the resource and is independent of any market power, plus a cartel rent, $M_n$, that is the extra profit the cartel earns strictly by virtue of its monopoly power.

Equation (11) may be solved for $P_n$ to yield

$$P_n = \frac{C_n + S_n + M_n - \sum_{j=n+1}^{\infty} P_j q_{nj} D_{nj}}{q_{nn} D_{nn}} \,, \tag{13}$$

which expresses the price at time $n$ in terms of future prices. This pricing equation is very similar to that used in the GEMS depletable resource submodel. To obtain the numerical results presented later in this paper, the GEMS depletable resource submodel was modified by adding the cartel rent terms. For computational purposes the infinite sums in Eq. (13) must be truncated; this is done by the same procedure that is used in the GEMS depletable resource submodel as described in Ref. 8.

In principle, all elements of the matrix $\partial \overline{P} / \partial \overline{Q}$ enter into the calculations. For the model considered here, and presumably for other similar models, the matrix has large diagonal terms and decreasingly smaller terms as one moves away from the diagonal. The calculations can be simplified by considering only the diagonal and first off-diagonal terms and this approximation is used in the work reported here. With this approximation Eq. (12) becomes

$$M_n = \sum_{j=n}^{\infty} \left[ \sum_{k=n-l}^{n+1} \left( \frac{\partial P_k}{\partial Q_j} \right) Q_k D_{nk} \right] q_{nj} \ , \tag{14}$$

and this expression is used in Eq. (13).

While the cartel pricing equation is conceptually similar to that used previously in GEMS, it is much more difficult to deal with numerically because of the derivatives that occur. These derivatives could, in principle, be obtained analytically, but this procedure would be formidable. In the work reported here the derivatives were obtained by a numerical procedure that is described below.

Let us assume that there are $N$ discrete time points in the model and let

$\left( \frac{\partial P_k}{\partial Q_j} \right)^i$ = the $i$th estimate of the elements of the $N$ by $N$ matrix $\partial \overline{P} / \partial \overline{Q}$.

Furthermore, assume that with this estimate used in Eq. (13) the model shown in Figs. 1 and 2 has been converged to yield

$P_k^i$ = the $i$th estimate of the elements of the $N$ vector $\overline{P}$,

$Q_j^i$ = the $i$th estimate of the elements of the $N$ vector $\overline{Q}$.

The equations of models constructed with GEMS are such that if the price vector, $\overline{P}$, from a supply node,* e.g., the cartel in Fig. 2, is specified and the node removed from the model, then the new model when converged will yield the quantity vector, $\overline{Q}$, on the link* containing $\overline{P}$. This quantity vector is the "residual cartel demand." With the cartel node removed from the model, specify $\overline{P}$ on the link originally from the cartel to be

$$\overline{P}^{ij+} = \left( P_1^i, \ldots, P_j^i + \Delta P_j, \ldots, P_N^i \right), \tag{15}$$

where $\Delta P_j$ is a constant that must be specified, and then by reconverging the model obtain

$$\overline{Q}^{ij+} = \left( Q_1^{ij+}, \ldots, Q_N^{ij+} \right) . \tag{16}$$

This procedure is repeated for all values of $j$. Similarly, specify

*Node is the term used to describe the geometric elements in Figs. 1 and 2, and link is the term used to designate the line joining two geometric elements.

$$\bar{P}^{ij-} = \left( P_1^i,...,P_j^i - \Delta P_j,...,P_N^i \right) \tag{17}$$

and obtain

$$\bar{Q}^{ij-} = \left( Q_1^{ij-},...,Q_N^{ij-} \right) \tag{18}$$

for all values of $j$. With these quantities an estimate of the matrix element $\left( \frac{\partial Q_k}{\partial P_j} \right)_N^{i+1}$ is given by

$$\left( \frac{\partial Q_k}{\partial P_j} \right)_N^{i+1} = \frac{Q_k^{ij+} - Q_k^{ij-}}{2\Delta P_j} \qquad k=1,N \text{ and } j>1,N \ . \tag{19}$$

The matrix elements on the left-hand side of Eq. (19) could be used directly to obtain the next estimate of the matrix $\partial \bar{P}/\partial \bar{Q}$, but to obtain convergence, relaxation is desirable so the $i+1$ estimate is obtained as

$$\left( \frac{\partial Q_k}{\partial P_j} \right)^{i+1} = \alpha \left( \frac{\partial Q_k}{\partial P_j} \right)_N^{i+1} + \left( 1-\alpha \right) \left( \frac{\partial Q_k}{\partial P_j} \right)^{i} , \tag{20}$$

where $\alpha$ is a constant that must be specified. Finally,

$$\left( \frac{\partial \bar{P}}{\partial \bar{Q}} \right)^{i+1} = \left[ \left( \frac{\partial \bar{Q}}{\partial \bar{P}} \right)^{i+1} \right]^{-1} . \tag{21}$$

This procedure appears to be reasonably straightforward, but it does require appreciable amounts of computing time. It is to be noted that for a model with $N$ time points, a complete iteration, i.e., from one estimate of $\partial \bar{P}/\partial \bar{Q}$ to a new estimate of $\partial \bar{P}/\partial \bar{Q}$ requires that the model be converged $2N+1$ times and a reasonable number of these outer iterations are required before one obtains values of $\bar{P}^{i+1},\bar{Q}^{i+1}$ that are not significantly different from $\bar{P}^i,\bar{Q}^i$.

### 2.3 Model input data

In this subsection some of the important model input data are presented and discussed. The input data used for the LFS model are the same as those used and presented in Refs. 1 and 2 (see also Ref. 15) and therefore they will not be discussed here.

Significant data used in the rest of the model are the resource cost curves[1,8] for the various resource suppliers in Fig. 1. These curves were obtained from the work of the Energy Modeling Forum[3] and are shown in Fig. 3 for Canada, other OECD, LDC, and OPEC. In Fig. 3 and throughout this paper, 1983 dollars are used. The resource cost curve for OPEC in Fig. 3

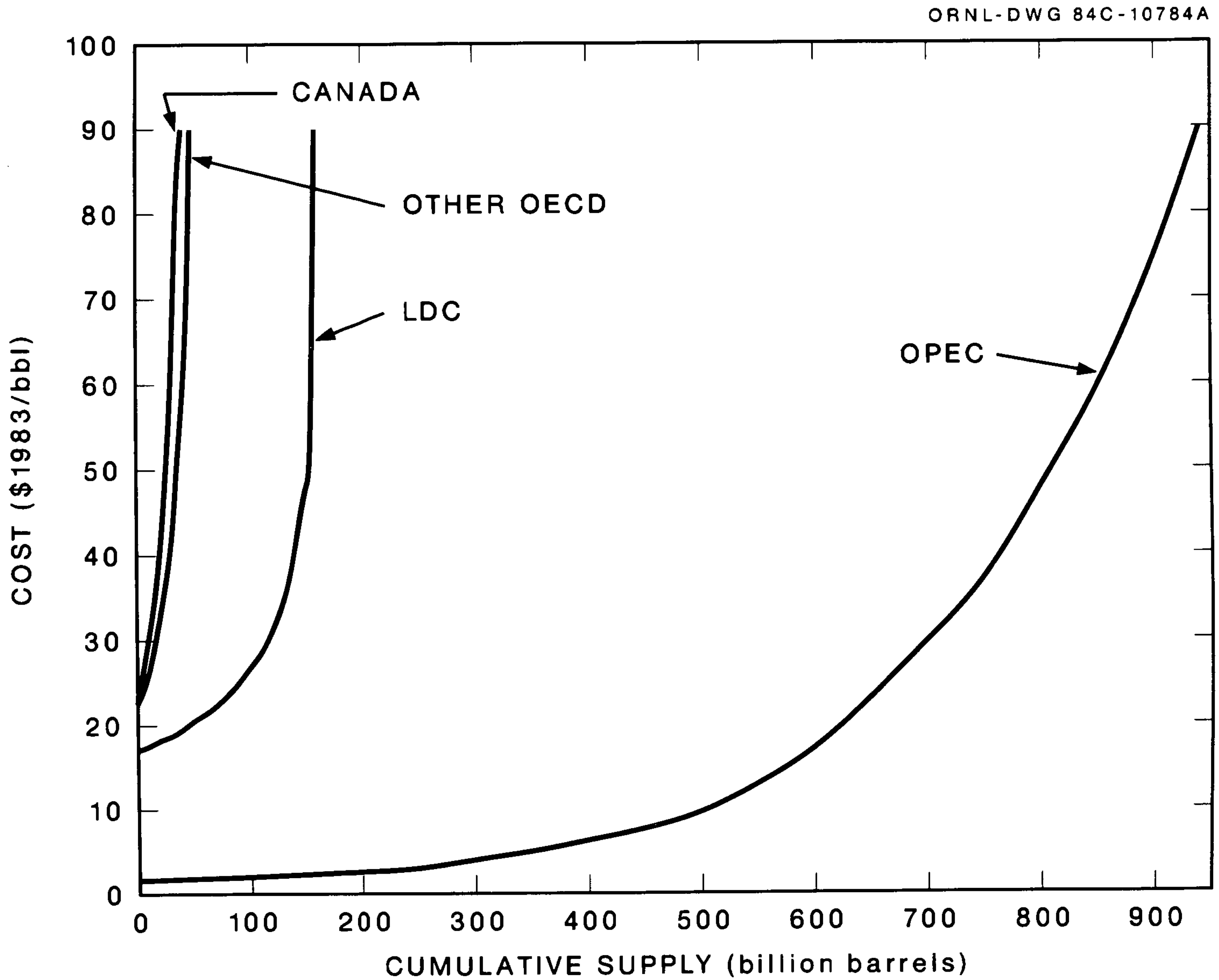


Fig. 3. Resource cost curves used in WOM model.

is for all of OPEC. If part of OPEC operates as a cartel and part operates as a competitive producer then the resource curve must be separated into two parts. This is not done here because only two cases are considered: one in which all of OPEC acts as a cartel and another in which all of OPEC behaves as a competitive producer. A resource cost curve for CPE is not given in Fig. 3 because in the calculations CPE production was not modeled, but the quantity exported by CPE was specified exogenously to be $2.10^6$ barrels/day in 1980 and $1.10^6$ barrels/day in 1990 and thereafter. In addition to the resource cost curves, it is necessary to specify for each supplier the capital cost fraction, i.e., the fraction of the present value of total cost that is not attributable to operating cost, and the deposit decline rate.[1,8] For all suppliers in the WOM model the capital cost fraction was taken to be 0.8 and the deposit decline rate was taken to be 5% per year.

The discount rate for OPEC was taken to be 2% per year in real terms. This value was used for the discount rate when OPEC was considered to be a cartel as well as when OPEC was considered to be a competitive producer. Some results on the effects of varying this discount rate are given in Ref. 11.

Parameter values to determine the demand as a function of time from Japan/Asia/Oceania, other OEDC, and LDC must also be supplied to the WOM model. These demand functions are determined by using a simple lagged response of the form[16]

$$Q_k = Q'_k \left[ \frac{Q_{k-1}}{Q'_{k-1}} \right]^{\alpha} \left[ \frac{P_k}{P'_k} \right]^{\beta} , \qquad (22)$$

$$\alpha = 1 - \frac{\beta}{e_\infty} ,$$

where

| | | |
|---|---|---|
| $Q_k$ | = | the quantity of oil demanded per year at year $k$, |
| $P_k$ | = | the price of oil, i.e., the world oil price, in year $k$, |
| $Q'_k$ | = | reference oil demand per year in year $k$, |
| $P'_k$ | = | reference price of oil in year $k$, |
| $e_\infty$ | = | the long-run price elasticity, |
| $\beta$ | = | the short-run (one year) price elasticity. |

The reference demands as a function of time were taken from Ref. 3 and are shown in Table 1. These demands are several years old and are higher than might be estimated today. Nevertheless, because one of the goals of this paper is to compare the results with those of previously published models, the comparisons have been made on the basis of the demand estimates given in Ref. 3. The results presented in the next section are compared with results

**Table 1**

**Reference Demands and Reference Price as a Function of Time**

| Year | Reference Demand ($10^6$ bbl/day) Japan/Asia /Oceania | Other OECD | LDC | Reference Price ($1983) |
|---|---|---|---|---|
| 1980 | 5.7 | 17.1 | 12.4 | 41.6 |
| 1990 | 6.5 | 19.5 | 12.7 | 37.8 |
| 2000 | 7.9 | 23.7 | 13.3 | 45.1 |
| 2010 | 8.8 | 26.3 | 15.1 | 54.9 |
| 2020 | 10.0 | 30.1 | 18.0 | 65.3 |
| 2030 | 12.2 | 36.6 | 21.9 | 70.2 |
| 2040 | 14.6 | 43.8 | 26.7 | 73.4 |

obtained using a reduced demand, but a somewhat different network diagram in the Appendix. The reference price as a function of time, shown in Table 1, was taken to be an approximation to the world oil prices as calculated here. (The prices in Table 1 are to be compared with the calculated results shown in Fig. 4 of the next section of this paper.) The long-run price elasticity was taken to be $-0.5$ and the short-run elasticity was taken to be $-0.06$.

The backstop price as a function of time was taken to be so large in the years 1980 through 1990 that the backstop produced nothing and was taken to be constant at $73.4 per barrel in all later years.

## 3. RESULTS AND DISCUSSION

Calculations have been carried out with the WOM model and results are presented for two cases. In one case, all of OPEC is assumed to behave as a cartel and in the other all of OPEC is assumed to behave as a competitive producer. Since all of OPEC acts neither as a cartel nor as a competitive producer, the results of neither case can be expected to be entirely realistic, but a comparison of the results from the two cases gives an indication of how much OPEC could influence the markets by exploiting all of its market power.

In Fig. 4 the calculated world oil price for the two cases considered is shown as a function of time from 1970 to 2040. Calculated results have been obtained using ten-year intervals and are represented by the plotted points in Fig. 4. Prices in Fig. 4 and throughout the paper are given in 1983 dollars per barrel. The price shown in 1980 is the historical value and is therefore the same in both cases.

With OPEC acting as a cartel, the world oil price is relatively flat until 1990 and rises thereafter, attaining a value of $76.7/bbl in 2040. This value of $76.7/bbl is slightly higher than the backstop price of $73.4/bbl. With OPEC as a competitive producer, the world oil price decreases between 1980 and 1990 and does not return to the 1980 value until approximately the year 2000. In the later years the prices for the two cases are comparable because the backstop source is having a significant influence on the market. From Fig. 4 it is clear that OPEC can have a very substantial effect on the world oil price for many years.

In Fig. 5 the world oil price projections to the year 2010 are compared with the projections from a variety of other sources. The solid lines in Fig. 5 show the results obtained with the WOM model and are the same as those given in Fig. 4. The dashed lines indicate the results presented in the National Energy Policy Plan (NEPP) of 1983.[17] The three different dashed curves represent three different scenarios that were considered in NEPP. The three scenarios represent different economic assumptions with scenario B representing a "mid-range" group of assumptions. There are substantial differences, particularly in the later years, between the

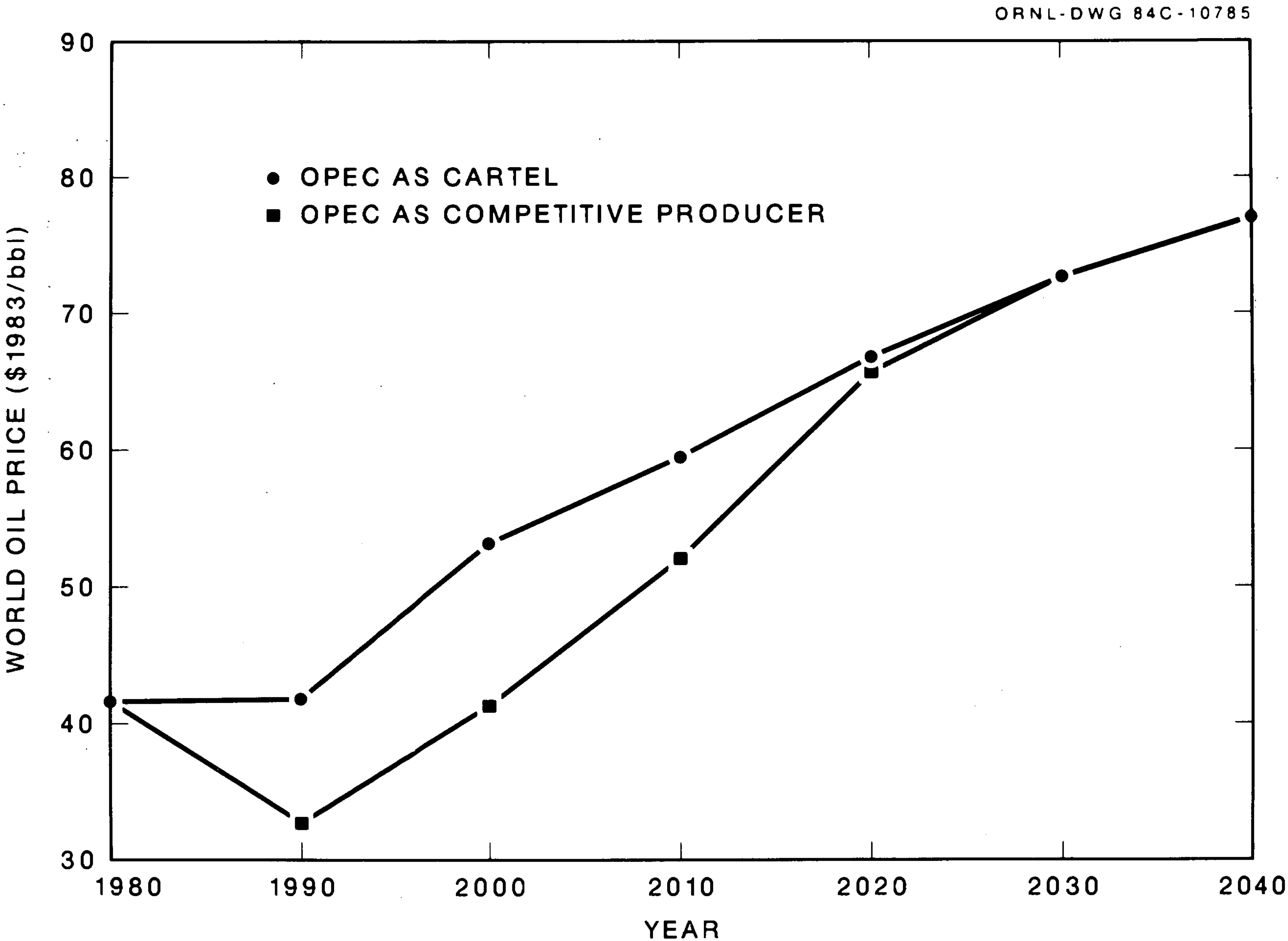


Fig. 4. World oil price vs. time.

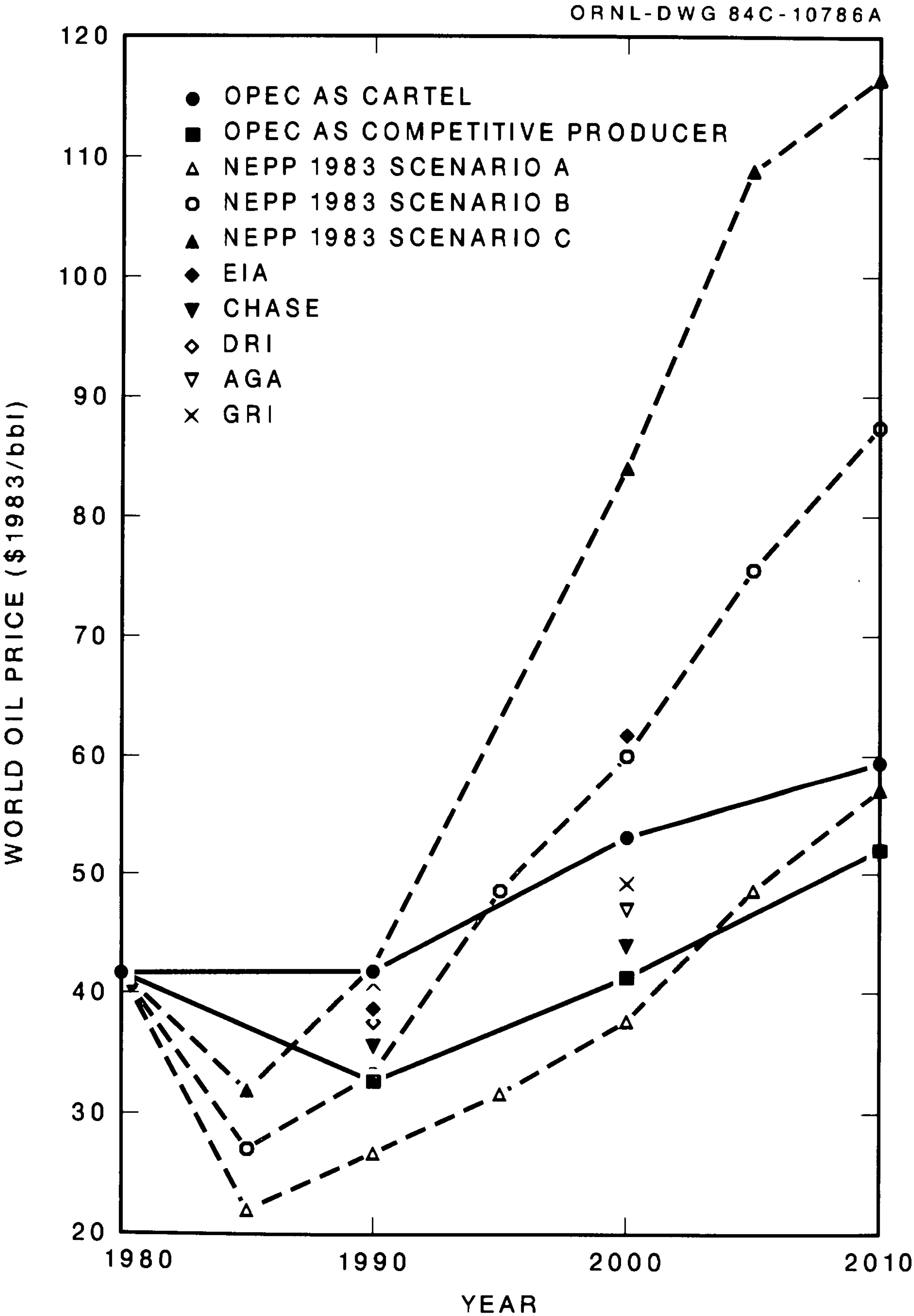


Fig. 5. World oil price vs. time. (The sources of the data are: NEPP scenarios A, B, and C, Ref. 17, EIA Ref. 18, Chase Ref. 19, DRI Ref. 20, AGA Ref. 21, GRI Ref. 22.)

prices obtained with the WOM model and those given for scenarios A and B in NEPP. It should be noted that since prices here are calculated only at ten-year intervals, the present calculation could not give the minimum in 1985 that is shown by all of the NEPP scenarios. The use of ten-year intervals in the WOM model is merely an artifice to avoid long computing times. The length of the time interval is a parameter in the WOM model so the calculations can, in principle, be carried out using smaller time intervals.

The world oil price projections shown in Fig. 5 from other sources are in approximate agreement with the results obtained here, in the sense that the values in general lie between the two solid curves.

In Fig. 6 the U.S. oil import quantity is shown as a function of time for the two cases considered. In the case when OPEC acts as a competitive producer the world oil price is quite low in the 1980 to 2010 years (see Fig. 4) and, as a consequence, U.S. oil imports are high. When OPEC acts as a cartel, the world oil price is high and U.S. imports are low.

Also shown in Fig. 6 for comparative purposes are the U.S. oil imports given in the 1983 NEPP. The three NEPP scenarios in Fig. 6 are the same as those considered in Fig. 5. The NEPP does not project a substantial increase in the 1980 to 1990 period even though the world oil price in all three NEPP scenarios is quite low in 1985 (see Fig. 5). U.S. imports in NEPP scenario B are quite similar to the U.S. imports obtained with the WOM model when OPEC is treated as a competitive producer. It should be noted, however, the world oil prices for NEPP scenario B and from the WOM model with OPEC competitive (see Fig. 5) are quite different.

In Fig. 7 the total demand, i.e., the quantity imported by the U.S., Japan/Asia/Oceania, other OECD and LDC, is shown as a function of time for the two cases considered here. This total demand is different in the two cases because U.S. imports are different and because the differences in the world oil prices over time have some effect [see Eq. (22)] on the demand for oil from Japan/Asia/Oceania, other OEDC, and LDC. Also shown in Fig. 7 is the production from OPEC, from the backstop source, and from all other producers, i.e., from CPE, Canada, other OEDC, and LDC. In GEMS models supply always equals demand, so the sum of the three solid production curves in a given year equals the solid demand curve in the same year, and likewise for the sum of the three dashed production curves. In the case when OPEC is considered to be a competitive producer, OPEC production is very large in the year 1990 to 2000 in response to the large demand in these years. In general, OPEC production is high by today's standards because of the relatively high demand from Ref. 3 that is used in the calculations. The backstop source produces relatively small amounts in the early years, but has a very substantial share of the market in the last years considered.

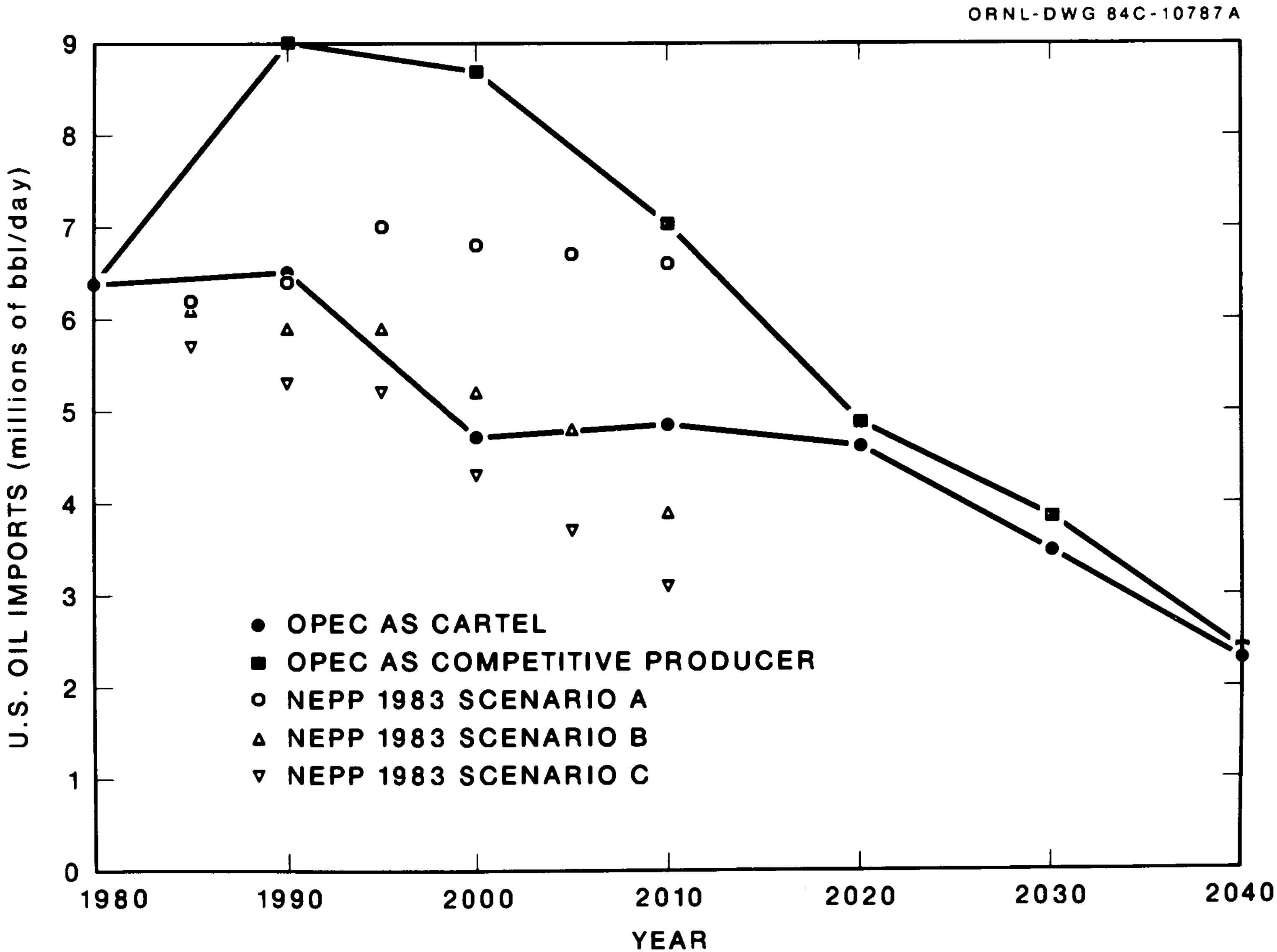


Fig. 6. U.S. oil imports vs. time.

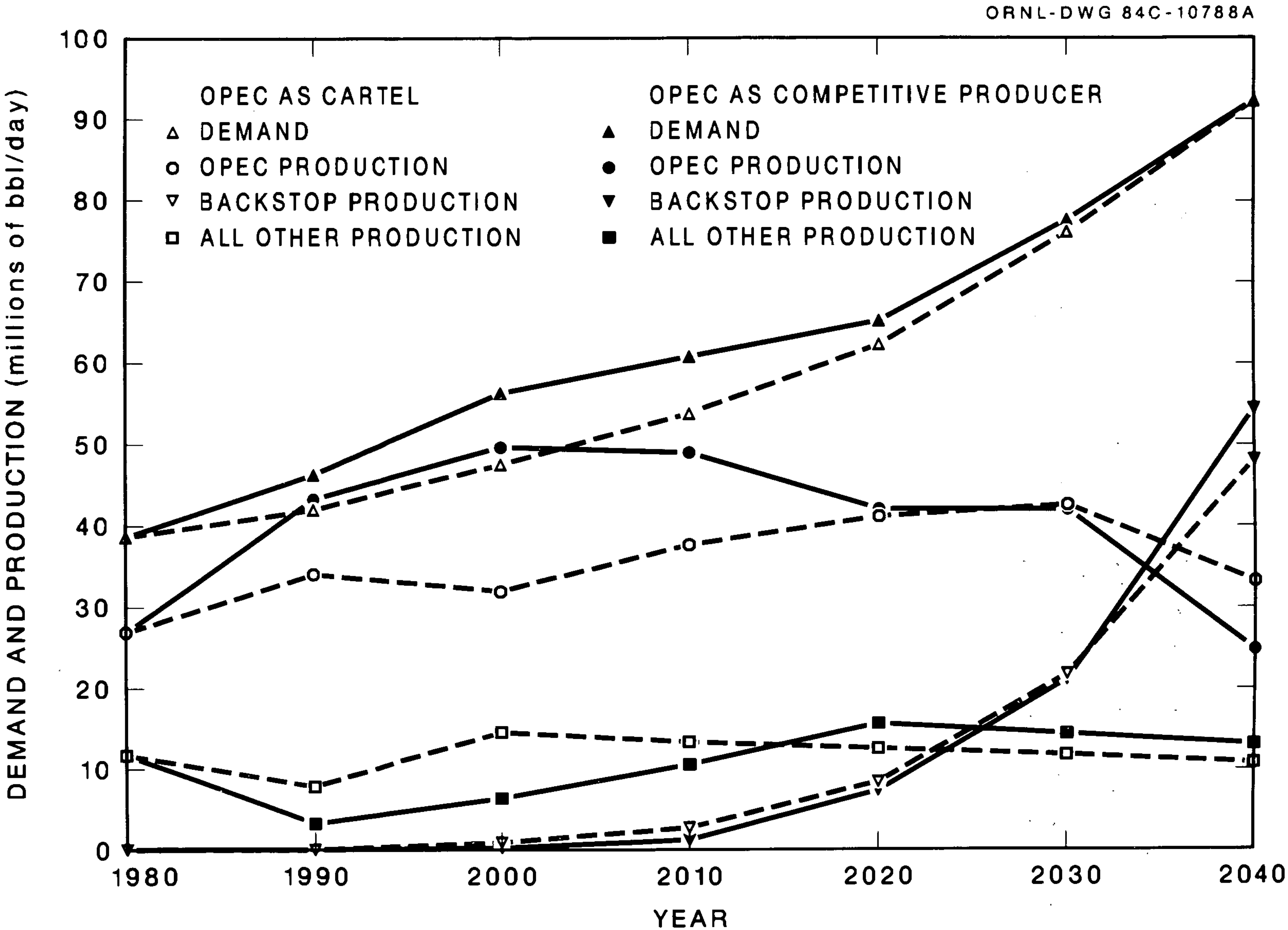


Fig. 7. OPEC production vs. time.

**SUMMARY**

A model of the world oil market that allows OPEC or some portion of OPEC to be represented as a Stackelberg cartel has been developed. The model includes a fully dynamic treatment of scarcity rents for all producers, including the cartel. Results assuming full cooperation among OPEC member states and no cooperation among OPEC member states have been obtained and indicate that full cooperation among OPEC member states could cause a substantial increase (~25%) in world oil prices in the 1990 to 2010 year period.

# APPENDIX

The results presented in the body of the paper are dependent on the reference demands and prices (see Table 1) that were taken from Ref. 3. Marshalla and Nesbitt[12] have done calculations using lower, and, by present day standards, more realistic reference demands and prices, and in this appendix the world oil prices as a function of time (shown in Fig. 4) are compared with the corresponding world oil prices from Ref. 12.

The theory used in Ref. 12 is the same as that used in the present paper, but the network diagram is somewhat different. The diagram from Ref. 12 is shown in Fig. A.1 and is to be compared with the diagrams in Figs. 1 and 2. Because of the difference in the network diagrams, there are a variety of differences in the data used, but one significant difference is in the reference demands and prices for Japan/Asia/Oceania, other OECD, and LDC.[13] The reference demands and prices used in Ref. 12 are shown in Table A.1 and are significantly lower than those in Table 1.

In Fig. A.2 the world oil prices as a function of time as obtained here and as given in Ref. 12 are compared. Because of the lower demands, the world oil prices from Ref. 12 are substantially lower than the prices calculated here, but the relative difference between the prices with OPEC as a cartel and OPEC as a competitive producer are very similar in the two different calculations.

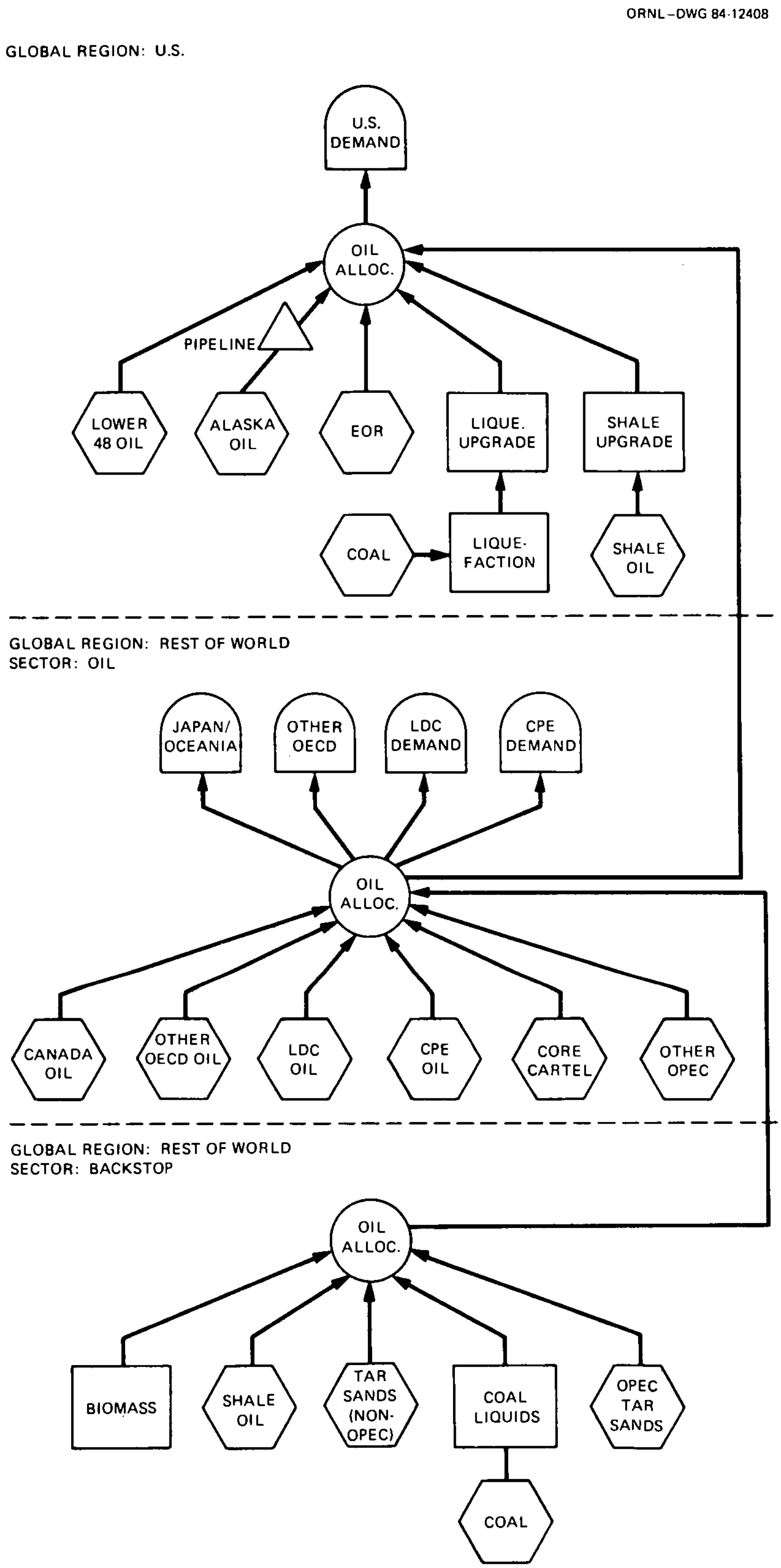


Fig. A.1. Diagram of model used in Ref. 12.

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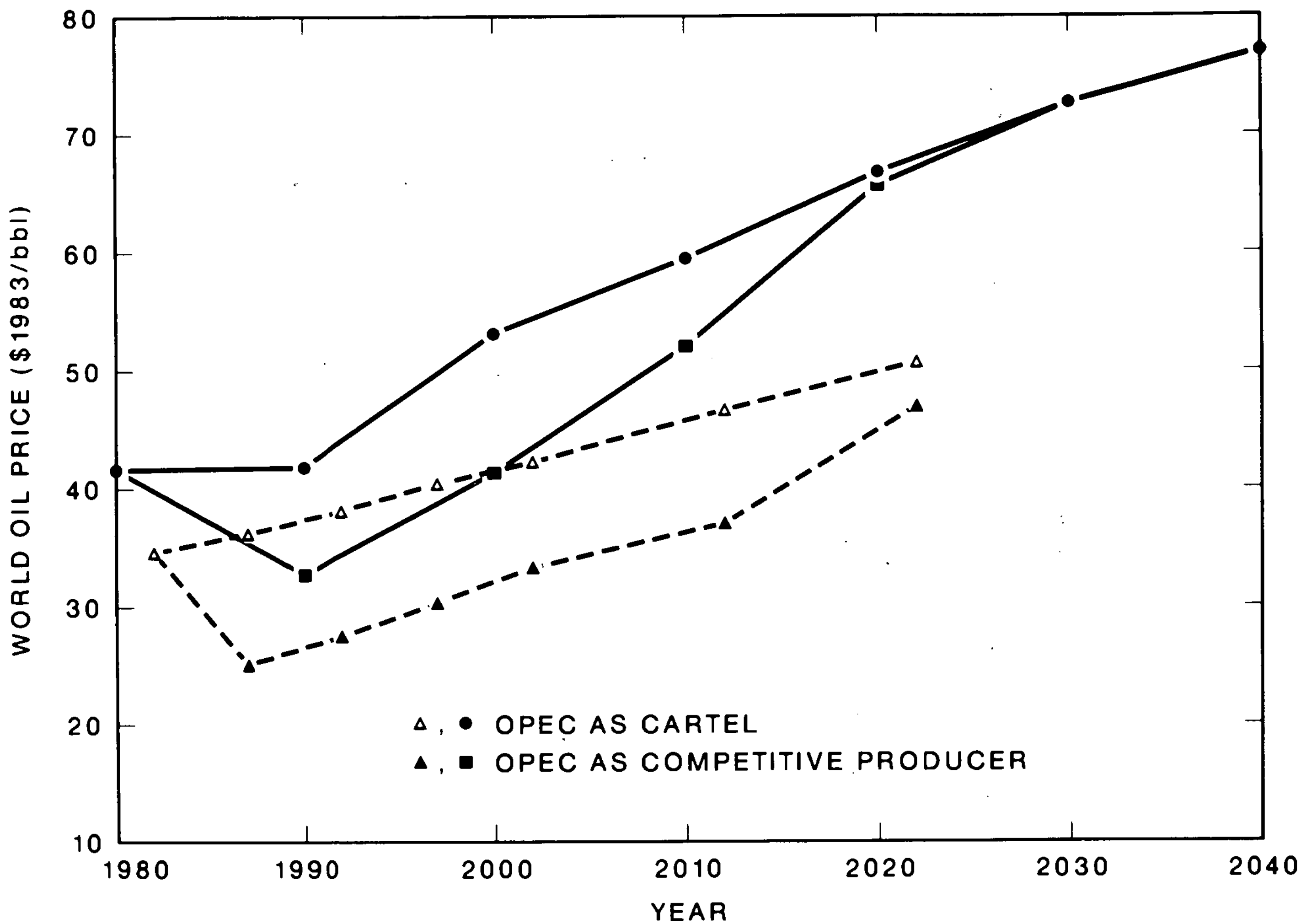


Fig. A.2. World oil price vs. time. The solid line joins the results obtained in the present paper while the dashed lines join the results presented by Marshalla and Nesbitt.[12]

Table A1

Reference Demand and Reference Price as a Function of Time (From Ref. 12)

| Year | Reference Demand ($10^6$ bbl/day) Japan/Asia /Oceania | Other OECD | LDC | Reference Price ($1983) |
|---|---|---|---|---|
| 1982 | 5.5 | 12.8 | 9.9 | 34.6 |
| 1987 | 5.1 | 11.9 | 9.2 | 26.7 |
| 1992 | 5.5 | 12.5 | 9.8 | 30.4 |
| 1997 | 5.8 | 13.2 | 10.4 | 32.5 |
| 2002 | 6.2 | 13.8 | 11.1 | 35.8 |
| 2007 | 6.6 | 14.5 | 11.8 | 39.3 |
| 2012 | 7.1 | 15.3 | 12.6 | 42.6 |
| 2017 | 7.6 | 16.1 | 13.5 | 45.6 |
| 2022 | 8.1 | 16.9 | 14.4 | 48.1 |
| 2027 | 8.6 | 17.7 | 15.3 | 50.5 |
| 2032 | 9.2 | 18.6 | 16.4 | 52.0 |
| 2037 | 9.8 | 19.6 | 17.5 | 54.3 |
| 2042 | 10.4 | 20.6 | 18.6 | 56.4 |

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