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A 2-PERSON NON-ZERO-SUM GAME MODEL OF THE WORLD OIL MARKET.(U)
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A 2-PERSON NON-ZERO-SUM GAME
MODEL OF THE WORLD OIL MARKET

by

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1. Introduction.

In the winter of 1973, some major oil exporting countries got together and declared an embargo on oil exports to some western countries for political reasons. Elated by their success and the realization that they controlled a major share of the oil exports, they subsequently raised the price of oil four-fold and cut back production obtaining (in the face of an almost inelastic demand) increased revenues. The major oil importing countries have been trying to work out an optimal energy policy designed to obtain their energy needs at lowest possible prices. Some of the strategies available to the oil importing countries are as follows:

- (i) Decrease the consumption of oil.
- (ii) Increase the domestic production of oil.
- (iii) Invest heavily into research and development of a competitive and alternate source of energy.
- (iv) Form a counter cartel of oil importing countries to coordinate their strategies against the OPEC cartel.
- (v) Attempt to split the oil cartel by bilateral dealings with the individual countries in the OPEC cartel or by playing one member country off against another.
- (vi) Take over the oil fields of the OPEC countries by military force.
- (vii) Stockpile large quantities of oil sufficient to outlast an oil embargo by OPEC over a long period of time.
- (viii) Shut off essential imports of the oil producing countries such as machinery, technology, spare parts for oil extracting and refining plants, food, arms, etc.
- (ix) Block the investment of oil money (earned by OPEC with oil exports) into their economy.

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- (x) Link the economies of the oil importing countries and oil exporting countries together so closely that OPEC nations would have a vested interest in the welfare of the oil importing countries and vice versa.

The strategies available to the oil exporting countries are as follows.

- (i) Raise the price of oil even more for increased revenues from oil exports.
- (ii) Restrict production of oil so as to create a shortage in the oil market enabling them to sustain high prices.
- (iii) Protect itself from world inflation by tying the price of oil to the world wide prices of other goods or reject payment in dollars (or other currency of the oil importing countries) and insist that the oil importing countries use a new 'Arab Dinar'.
- (iv) Use excess capital accumulated from oil exports as a tool in breaking up any cartel of oil consuming nations.
- (v) Declare an embargo on oil exports.
- (vi) Organize other raw material producers under its auspices with the aim of bringing about a further transfer of wealth and goods to the underdeveloped world.
- (vii) Seek help from U.S.S.R. and other communist countries to thwart any embargo or military intervention by the oil consuming nations.

We shall denote the oil importing countries by OPIC and the oil exporting countries by OPEC. We make the following observations regarding the strategies of the OPIC and OPEC nations.

1. Strategy (v) of OPEC can be countered to some extent by Strategies (vii) and (viii) of OPIC.

2. Strategies (vi) and (viii) of OPIC can be counteracted by Strategy (vii) of OPEC.
3. Strategy (vi) of OPIC though feasible under certain circumstances is only effective as a "threat" in extreme circumstances (to prevent the collapse of the social and economic structure of the nation as a result of an extended embargo on oil exports by OPEC). In the same sense Strategy (v) and (vi) are 'threat strategies' for OPEC.
4. Strategy (x) of OPIC is relevant in a "cooperative" solution of the problem.
5. Strategies (iv) and (v) of OPIC and Strategy (iv) of OPEC need to be investigated using the theory of n-person cooperative games.

In short, OPIC is interested in a policy that will ensure an adequate supply of oil at lowest possible prices and OPEC is interested in a policy that will give them the maximum revenues from their finite oil reserves to develop their underdeveloped economy.

2. The Model.

The World oil market is modelled as a 2-person non-zero-sum game. Player 1 called OPIC represents the oil importing nations and player 2 called OPEC represents the oil exporting nations. Implicit in this formulation is the assumption that all major oil importing countries have formed into a cartel and bargain collectively as one unit and that this cartel is the sole market for the oil exported by OPEC. A similar assumption is made about OPEC which monopolizes all the oil imported by OPIC.

We shall assume that OPIC needs a total of 1 million barrels of oil daily (mmbd) assuming consumption required for a maximum growth of their

economy. A part of this requirement can be met by domestic production of oil. By large investment, the domestic production of oil can be increased by finding new sources, or just by working the existing wells harder using improved technology. Alternatively, the demand for oil can partly be satisfied by other fuels such as coal, nuclear fission, shale oil and other new sources that could be developed by large investment in research and development. Furthermore, the consumption of oil could be reduced by voluntary or mandatory methods such as rationing the supply of oil, an energy tax, etc. This may however, result in losses in the nation's economy. In short, the strategy for OPIC is to decide the quantity of oil imports. More formally, we will denote the strategy space of OPIC by

$$\Sigma_1 = \{x \in E^1 : 0 \leq x \leq 1\}$$

Associated with a strategy $x \in \Sigma_1$ is a monetary cost to OPIC, denoted by $f(x)$ for restricting its imports to x mmbd. $f(x)$ does not include the cost of imports. A sketch of a method of computing $f(x)$ is as follows.

Let $h(y)$ denote the total cost in million dollars daily (mm\$d) to ensure that domestic production of oil (or other sources of energy) is at least y mmbd. Let $g(z)$ denote the loss in million dollars daily in OPIC's G.N.P.[†] if the total oil (energy) consumption is restricted to z mmbd. Then, we have

$$f(x) = \min_{0 \leq y \leq 1-x} [h(y) + g(y+x)]$$

[†]Gross National Product. Other indicators of a nation's economy can also be used.

We will assume that $f(x)$ is a non-increasing positive real-valued function defined on the strategy space Σ_1 of OPEC.

Let the total oil reserves of OPEC be R million barrels. It costs OPEC an average of c dollars per barrel to extract the oil from the fields. The strategy for OPEC is to decide the price of oil exported to OPIC. Denote the strategy space of OPEC by

$$\Sigma_2 = \{p \in E^1: c \leq p < \infty\}$$

Let Σ be

$$\Sigma = \Sigma_1 \times \Sigma_2 = \{(x,p): x \in \Sigma_1, p \in \Sigma_2\}$$

denote the set of all possible outcomes. Let $u_i: \Sigma \rightarrow E^1$ denote the utility function of player i , $i = 1, 2$, defined on the set of all possible outcomes.

To complete the formulation, we will have to define the utility function of each player. Neglecting political, psychological and other considerations, we can define the utility functions purely in terms of monetary terms. Assuming that utility is linear in money, define

$$u_1(x,p) = -f(x) - p \cdot x \quad \forall (x,p) \in \Sigma.$$

The monetary payoff to OPEC resulting from the outcomes $(x,p) \in \Sigma$ is $(p-c) \cdot x$ m.m.\$d. We will assume that OPEC's economy is sufficiently developed to absorb all revenues from oil exports. Again assuming that utility is linear in money, we define

$$u_2(x,p) = (p-c) \cdot x \quad \forall (x,p) \in \Sigma$$

However, under a long term policy, OPEC is interested in obtaining the maximum revenue from its finite oil reserves of R million barrels. Assuming that that parameters of the problem (I, f, c) remain constant with time, we could define

$$u_2(x,p) = \begin{cases} 0 & \text{if } x = 0 \\ \sum_{i=0}^{\lfloor R/x \rfloor} (p-c) \cdot x \cdot \beta^i & \text{if } x > 0 \end{cases}$$

where $\lfloor R/x \rfloor$ denotes the largest integer $\leq \frac{R}{x}$ and β is a discount factor < 1 . The sum $\sum_{i=0}^{\lfloor R/x \rfloor} (p-c) \cdot x \cdot \beta^i$ represents the total revenue in million dollars that OPEC would earn from its total oil reserves of R million barrels given that outcome (x,p) is constant during this period (of $\lfloor R/x \rfloor$ days).

If the function f is completely known then the formulation of the problem as a 2-person non-zero-sum game is complete. Determining an accurate nature of the function f is no trivial task. However, several studies have been made in the United States to determine the function $f(x)$ for the case of United States alone. See the Appendix for more details.

In the next section, we exhibit the "solution" of the game in the non-cooperative sense. In this case, the non-increasing assumption for the function f suffices to find the solution. In Section 4, assuming an exponential model for $f(x)$, we solve the game in a cooperative sense and indicated the von Neumann-Morgenstern negotiation set, and the Nash's bargaining point solution of the game.

3. The Non-Cooperative Solution of the Game.

By a non-cooperative game is meant a game in which absolutely no preplay communication is permitted between the players.

$$\begin{array}{ccc}
 & & \text{OPEC} \\
 & & c \leq p < \infty \\
 \text{OPIC} & 0 \leq x \leq 1 & [u_1(x,p), u_2(x,p)]
 \end{array}$$

Figure 1. Representation of the game in normal form. Each player has a continuum of strategies.

First we shall find all the equilibrium pairs of the game.

$$u_2(x,p) = (p-c) \cdot x \quad \forall (x,p) \in \Sigma.$$

Let (x^*, p^*) be an equilibrium. Then we have

$$u_2(x^*, p^*) = (p^* - c) \cdot x^*.$$

Since $u_2(x^*, p^*) \geq u_2(x^*, p^* + \Delta p)$ for all $\Delta p > 0$ (by definition of an equilibrium), we have

$$(p^* - c) \cdot x^* \geq (p^* + \Delta p - c) \cdot x^*$$

$$\text{I.e.,} \quad \Delta p \cdot x^* \leq 0 \quad \forall \Delta p > 0.$$

$$\text{I.e.} \quad x^* = 0.$$

Now, we have $u_1(0, p^*) = -f(0)$. Also $u_1(0+\Delta x, p^*) = -f(\Delta x) - p^*\Delta x$. Since $u_1(0, p^*) \geq u_1(0+\Delta x, p^*) \quad \forall \Delta x > 0$ we have,

$$-f(0) \geq -f(\Delta x) - p^*\Delta x \quad \forall \Delta x > 0.$$

I.e.,

$$p^* \geq \frac{f(0) - f(\Delta x)}{\Delta x} \quad \forall \Delta x > 0$$

Let

$$p_m = \max_{0 < x < I} \frac{f(0) - f(x)}{x}$$

then $(0, p)$ where $p \geq p_m$ is an equilibrium outcome. All equilibrium outcomes have the same utility, namely,

$$u(0, p) = (u_1(0, p), u_2(0, p)) = (-f(0), 0).$$

$$\text{Case 2. } u_2(x, p) = \begin{cases} 0 & \text{if } x = 0 \\ \sum_{i=0}^{\lfloor R/x \rfloor} (p-c) \cdot x \cdot \beta^i & \text{if } x > 0 \end{cases}$$

A similar analysis shows that $(0, p)$ where $p \geq p_m$ is an equilibrium outcome with utility vector $(-f(0), 0)$.

Since every equilibrium pair of outcomes are interchangeable, the game is solvable in the sense of Nash and since every equilibrium pair has the same utility, $(-f(0), 0)$ is the "solution" of the non-cooperative game.

The non-cooperative solution is for OPIC to restrict its oil imports to zero and for OPEC to charge a 'very high' price for its oil. The Arab oil embargo in the winter of 1973 was an outcome of the game at its equilibrium. I.e. $x = 0, p \rightarrow \infty$. It was forced by OPEC to demonstrate to the OPIC nations

the disadvantage of a noncooperative situation ('noncooperation' here was on a political issue). Because of the large magnitude of $f(0)$, the utility at equilibrium is more distasteful to OPIC than to OPEC (assuming that interpersonal comparison of utilities is meaningful).

If the game is played once (i.e., for a period of one day) in a noncooperative sense then the equilibrium point is a viable solution concept. However, we have a situation where the same game (the parameters of the game, in reality, change with time) is repeated every day, every month and every year. In situations like these, even when there is no preplay communication, there is, nonetheless, a form of involuntary communication. The players signal to each other via their choice patterns on previous plays. The situation in the post-embargo period when OPEC increased their price four-fold and the United States reduced their growth in oil imports from OPEC can be explained as a kind of preliminary jockeying before the two players realize the advantages of a cooperative bargaining solution. The long period of time involved in the process is because both the players have sluggish policy-making processes that prevent them from making their policies optimal. Their interests involve numerous considerations. Sorting out those considerations is a complicated process and the result is perhaps a characteristic preference to pursue previous policies rather than switch to new policies unless forced to do so. In recent years the OPEC and the OPIC nations have been bargaining for an outcome which would be mutually acceptable to both the players. The theory of two-person cooperative games indicates the kind of bargaining and "solutions" under these circumstances. This is considered in the next section.

4. The Cooperative Solutions of the Game.

In a cooperative game, we assume that

- (1) all agreements are binding and they are enforceable by the rules of the game, and
- (2) a player's evaluation of the outcomes of the game are not disturbed by the preplay negotiations.

Since the solution depends on the function $f(x)$, we will assume an exponential model for $f(x)$ to illustrate the mechanism of finding the cooperative solutions of the game. Assume that

$$f(x) = (f(0)/(1-e^{-\alpha I}))e^{-\alpha x} - (f(0) \cdot e^{-\alpha I}/(1-e^{-\alpha I})) \quad \forall 0 \leq x \leq I$$

where α is a positive constant. Note that the studies conducted by National Petroleum Council does indicate an exponential type function for $f(x)$ in the case of the United States only. See the Appendix for more details. Hence our assumption may not be far removed from reality.

4.1. The von-Neumann-Morgenstern Negotiation Set.

Let

$$A = \{(u_1(x,p), u_2(x,p)) : (x,p) \in \Sigma\}$$

denote the set of all possible payoffs. Due to the nature of the game, we do not consider randomization of strategies as feasible. Hence, we consider only pure strategies. A point $(u_1, u_2) \in A$ is said to be dominated by a different point $(u_1', u_2') \in A$ if we have $u_1' \geq u_1$ and $u_2' \geq u_2$. The set of all undominated outcomes in A is called the Pareto-optimal set. Denote this set by P . I.e.,

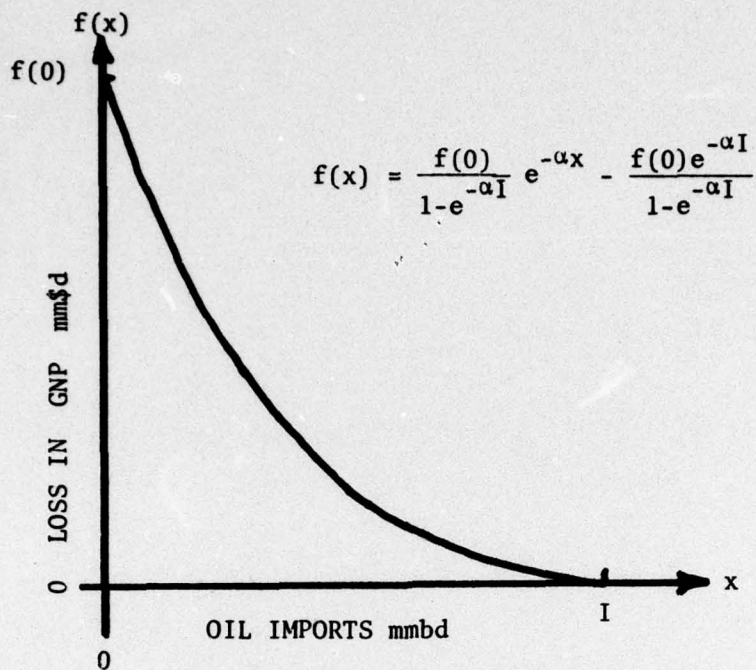


Figure 2. The exponential model of $f(x)$.

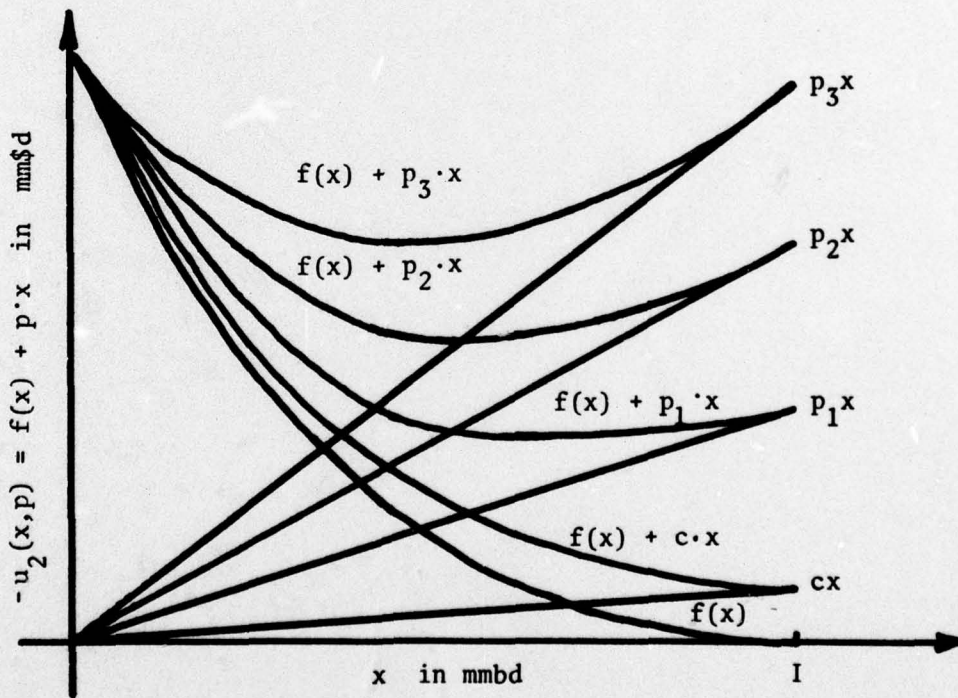


Figure 3: The utility function of player 2.

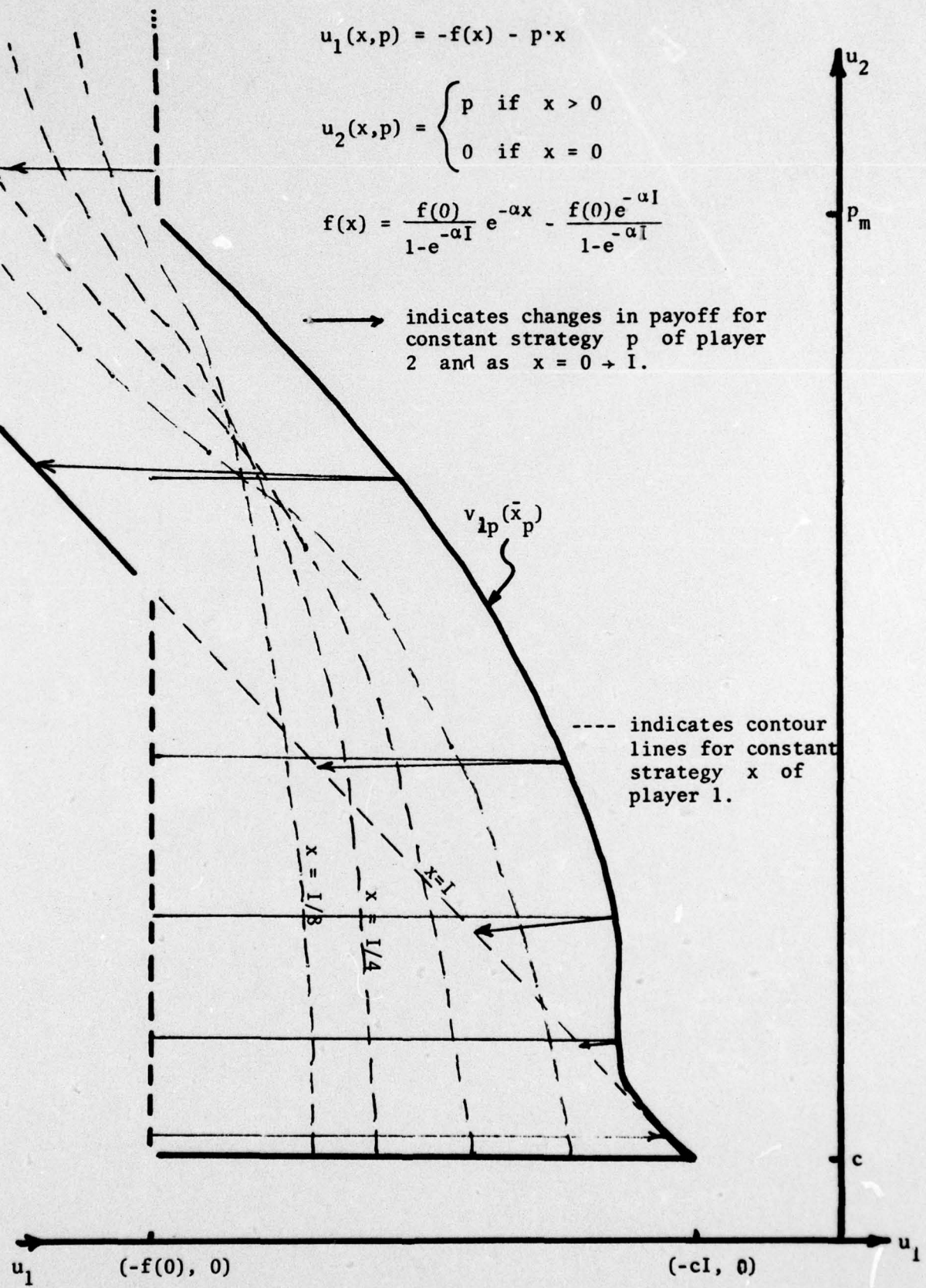


Figure 4. Geometrical Representation of the Game.

$$P = \{(u_1, u_2) \in A: \nexists (u'_1, u'_2) \in A \text{ such that}$$

$$(u'_1, u'_2) \neq (u_1, u_2), u'_1 \geq u_1 \text{ and } u'_2 \geq u_2\}.$$

Let v_1 and v_2 denote the maximin values for players 1 and 2 respectively. These values represent the amount each player can guarantee himself by treating the game in a non-cooperative manner. The negotiation set denoted by N is defined as

$$N = \{(u_1(x, p), u_2(x, p)) \in P: u_1(x, p) \geq v_1 \text{ and } u_2(x, p) \geq v_2\}$$

As shown in the last section, for our game $v_1 = -f(0)$ and $v_2 = 0$. The corresponding maximin strategy for OPIC is $x = 0$ and for OPEC is $p \geq p_m$.

Suppose OPEC chooses a fixed strategy $p \in \Sigma_2$. Then the payoff to OPIC if it chooses strategy $x \in \Sigma_1$ is

$$\begin{aligned} v_{1p}(x) &= u_1(x, p) = -f(x) - p \cdot x \\ &= -K_1 e^{-\alpha x} - K_2 - p \cdot x \end{aligned}$$

where

$$K_1 = f(0)/(1 - e^{-\alpha I})$$

and

$$K_2 = f(0)e^{-\alpha I}/(1 - e^{-\alpha I}).$$

v_{1p} is a concave continuous function of x . Let \bar{x}_p denote the value of x at which v_{1p} is maximized. Then \bar{x}_p is found by setting the first derivative of v_{1p} to zero.

I.e.,

$$v'_{1p}(x) = \alpha K_1 e^{-\alpha x} - p = 0$$

I.e.,

$$\bar{x}_p = \begin{cases} \frac{1}{\alpha} \ln(\alpha K_1/p) & \text{if } \frac{1}{\alpha} \ln(\alpha K_1/p) \leq I \\ I & \text{if } \frac{1}{\alpha} \ln(\alpha K_1/p) > I . \end{cases}$$

The payoff to OPIC at this strategy \bar{x}_p is

$$v_{1p}(\bar{x}_p) = \begin{cases} -\frac{p}{\alpha} [1 + \ln(\alpha K_1/p)] - K_2 & \text{if } \frac{1}{\alpha} \ln(\alpha K_1/p) \leq I \\ -pI & \text{if } \frac{1}{\alpha} \ln(\alpha K_1/p) > I \end{cases}$$

The value of p_m is given by

$$\begin{aligned} p_m &= \max_{0 < x < 1} \frac{f(0) - f(x)}{x} \\ &= f'(0) \\ &= \alpha K_1 \end{aligned}$$

We can now describe the negotiation set of the game as

$$N = \{(v_{1p}(\bar{x}_p), p) : c \leq p < p_m\}.$$

The cooperative 2-person theory of von Neumann and Morgenstern singles out the negotiation set as the "cooperative solution" of the game. In words, the players act jointly to discard all the dominated payoff pairs and all undominated

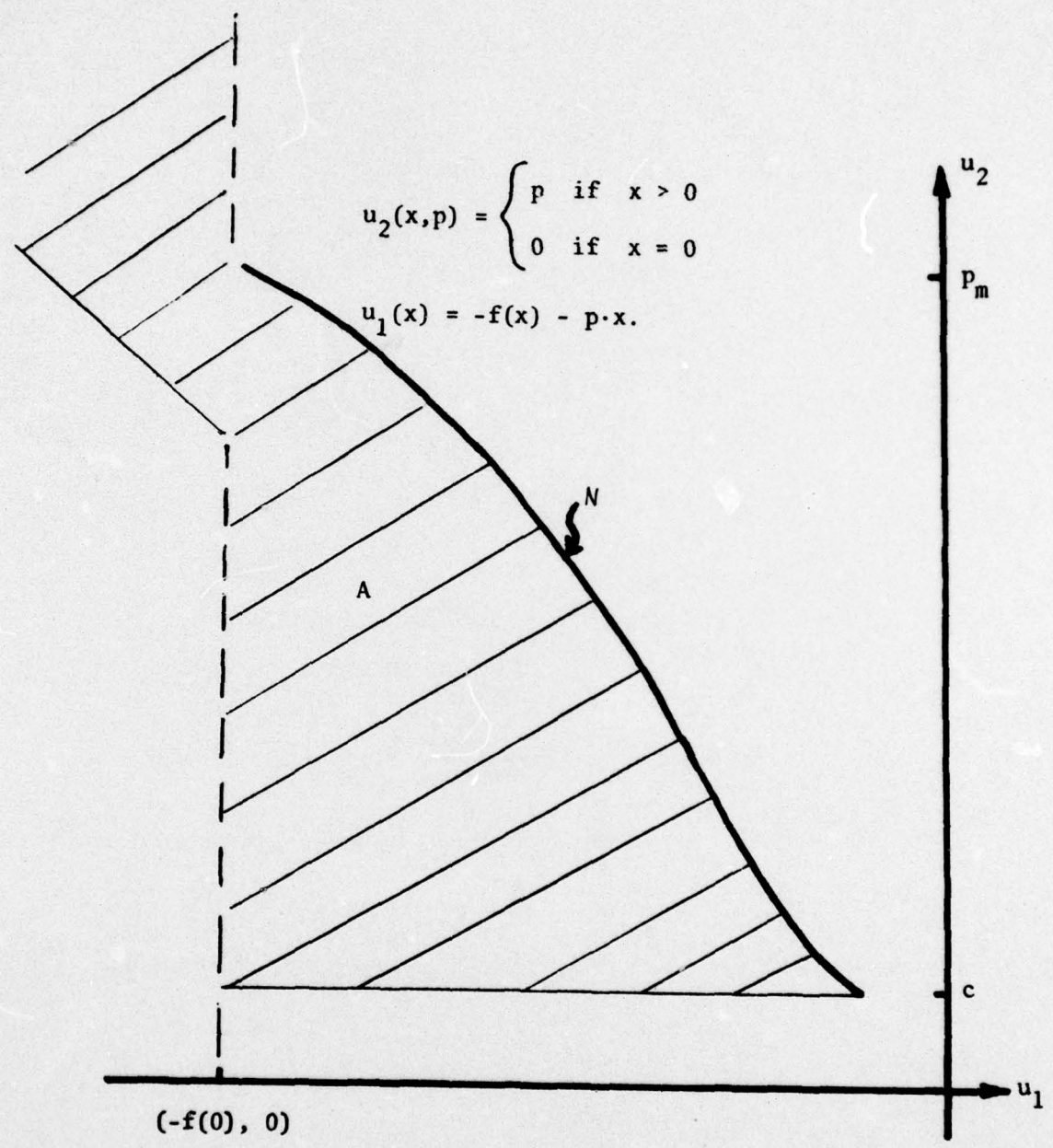


Figure 5. The negotiation set.

payoffs which fail to give each of them at least the amount he could be sure of getting without cooperating with the other player.

The actual selection of a payoff from the multiplicity of points in the negotiation set N depends on certain psychological aspects of the players which are relevant to the bargaining context. We shall consider one such outcome - Nash's solution - in the next section.

4.2. Nash's bargaining point solution.

The procedure for finding Nash's solution is as follows.

- (i) Change the origin of measurement of utility for each player so that the maximin point (v_1, v_2) is transformed into $(0,0)$ and let the resulting transformation of A be denoted by A' .
- (ii) In region A' , find the unique (if one exists) point $(u_1^{0'}, u_2^{0'})$ such that $u_1^{0'} \cdot u_2^{0'}$ is the maximum of all products $u_1' \cdot u_2'$ where $(u_1', u_2') \in A'$.
- (iii) The Nash's solution to the game (u_1^0, u_2^0) is obtained by inverting the utility transformation on $(u_1^{0'}, u_2^{0'})$.

Using the above procedure, we wish to find the value of p at which the

$$\max_{c \leq p < p_m} (f(0) + v_{1p}(\bar{x}_p)) \cdot (p)$$

is attained.

The value of p for which $\frac{1}{\alpha} \ln(K_1/p) = I$ is $p = \alpha K_1 e^{-\alpha I}$. So we need the value of p at which we attain

$$\max \left\{ \begin{array}{l} \max_{\alpha K_1 e^{-\alpha I} \leq p < p_m} pf(0) - \frac{p^2}{\alpha} [1 + \ln(\alpha K_1/p)], \\ \max_{c \leq p < \alpha K_1 e^{-\alpha I}} pf(0) - p^2 I \end{array} \right\}.$$

Let p_N be the value of p at which the above maximum is attained.

Case (i). $\alpha K_1 e^{-\alpha I} \leq p_N < p_m$.

In this case, the Nash's solution is given by

$$\left(-\frac{p_N}{\alpha} (1 + \ln(\alpha K_1/p_N)), p_N\right) \in P.$$

Case (ii). $c \leq p_N \leq \alpha K_1 e^{-\alpha I}$.

In this case, Nash's solution is given by

$$(-p_N \cdot I, p_N) \in P.$$

Nash's solution is based on the following bargaining model [3].

Consider a bargaining situation with the region A of possible payoffs and the status quo at the origin. Suppose that player 1 is holding out for a trade with utility payoffs (u_1', u_2') and 2 is demanding (u_1'', u_2'') where the two points are different and each is Pareto optimal. Who should make a concession? The argument is that player 1 should make a concession iff

$$\frac{u_1' - u_1''}{u_1'} \leq \frac{u_2'' - u_2'}{u_2'},$$

i.e.,

$$u_1' \cdot u_2' \leq u_1'' \cdot u_2''$$

and vice versa. Concession need not necessarily mean accepting the opponent's demand; rather the conceding player can suggest an alternative trade which will not require him to make a further concession in the next round of negotiations. But, for this to be so, he must propose some (u_1''', u_2''') having a component

product $u_1''' \cdot u_2'''$ at least as large as the component product of his opponent's demand and larger if possible. Clearly, this procedure raises the component product at each stage, and so it inexorably leads to the point for which the component product is a maximum - Nash's solution. The concession principle is based on the rationale that when the two demands are (u_1', u_2') and (u_1'', u_2'') , then very crudely $(u_1' - u_1'')/u_1'$ and $(u_2' - u_2'')/u_2'$ measure, respectively, the relative losses incurred when player 1 and 2 concede. The assumption, then, is that the player whose relative losses is the smaller will concede.

Acknowledgements.

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AppendixEstimation of the function $f(x)$ for the United States [1].

There are several stages of reactions which must be considered in assessing the ultimate economic impact of a shortfall in imports of oil. First, standby conservation measures would be invoked to reduce domestic consumption without significant economic consequences. The energy posture of the economy would be a major determinant of the extent to which such conservation measures would be effective. Thus, if the domestic policy heavily emphasized long-term conservation and austere demand restraint, then only minimal standby conservation reductions could be anticipated.

The second stage would likely involve an emergency allocation program to minimize the impact of a shortfall on vital industrial and commercial activities highly dependent on adequate supplies of energy.

The last stage of reaction would involve distribution of the shortfall among the various consuming and geographic sectors.

These stages reflect the aggregate effect of the shortfall on the economic (G.N.P.) growth of the country.

The National Petroleum Council developed a summary graphical representation of such effects during the 1973 embargo (Figure A.1).

The basic approximation made in deriving the impact of oil shortfalls in the United States by the Federal Energy Administration is represented by the linear curve indicated in Figure A.2. The linear approximation is based on two key parameters of real world significance: (1) K , the substitution/standby conservation level (in mmbd oil equivalents) that the economy can withstand without a perceptible loss in G.N.P.; and (2) M , the average multiplier

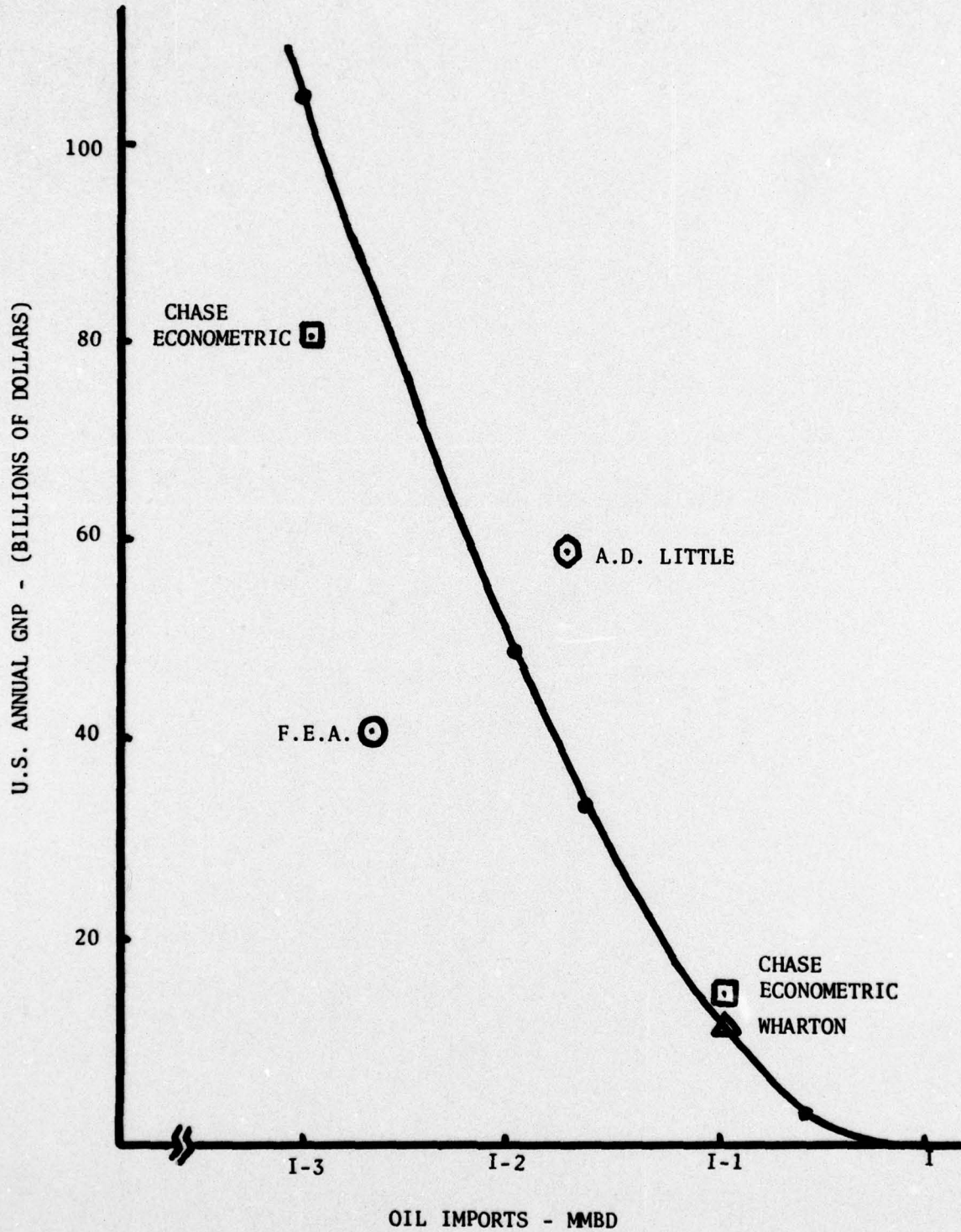
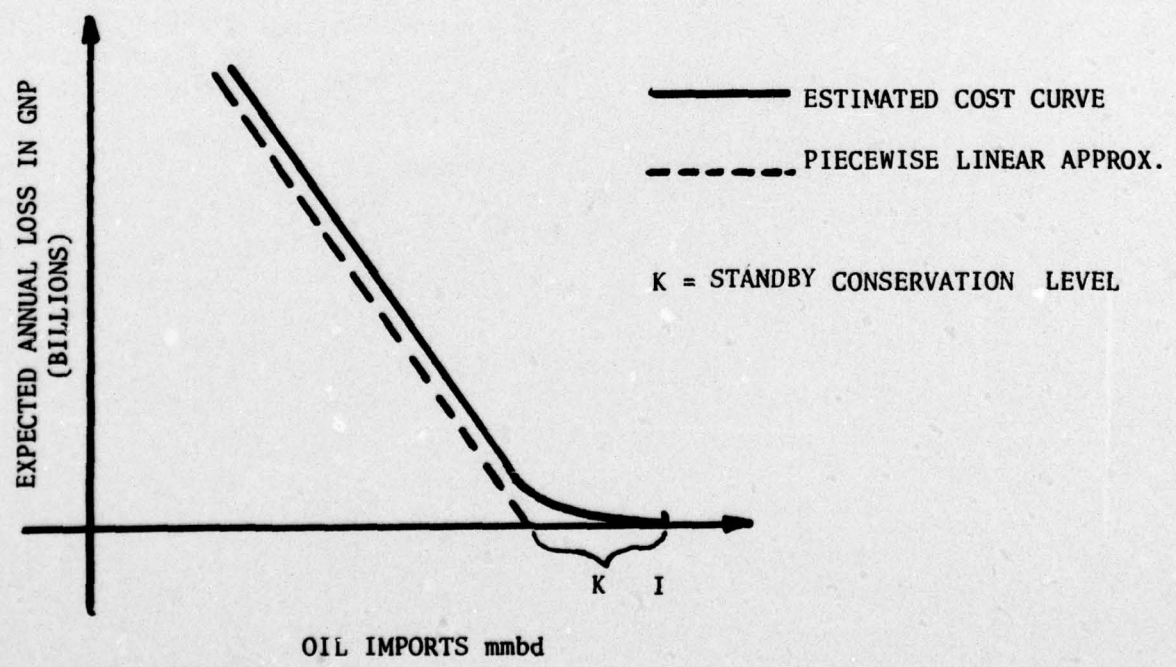


Figure A.1. N.P.C. SHORTFALL IMPACT ESTIMATE

effect used in estimating the value of G.N.P. cost of each unit of oil shortfalls beyond the level K.

The approximate values of K and M are not easily determined for any economy at any time. The value of K could be less than 1 mmbd. The value of M is highly uncertain, but is estimated at \$30 to \$40 billion per mmbd per year based on analysis of the impact of the '73-'74 embargo.



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