PENS
7/27/07
4:00 pm

The U.S. Strategic Petroleum Reserve and Cartel Deterrence

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Version: July 1, 2007

This paper presents a novel purpose for the US Strategic Petroleum Reserve (SPR) for national energy security. In a repeated game framework, this paper demonstrates how a reserve of sufficient size can potentially deter OPEC from any noncompetitive quantity-setting behavior indefinitely, thus achieving indirect energy independence. The paper derives the minimal levels of reserves necessary to maintain a steady-fill state in dynamic equilibrium. A calibration of the model returns feasible target levels for the SPR.

Key Words: Strategic Petroleum Reserve, Energy Security, Cartel Deterrence

1. INTRODUCTION

In 1975, in the aftermath of the OPEC oil embargo, President Ford signed the Energy Policy and Conservation Act (EPCA), authorizing the creation and fill of a national Strategic Petroleum Reserve (SPR). Fill began in July of 1977. Today, with roughly 700 million barrels in storage, the SPR is the world's largest government-owned reserve of crude oil, and is regarded by both academics and policymakers as an important tool of the nation's energy policy. However, fierce debate continues over the purpose and ultimate worth of the SPR. (E.g. Taylor and Van Doren (2005).)

Recently, the debate has gained sharpened urgency in the face of the high and volatile energy prices since 2001. In his 2006 State of the Union Address, President George W. Bush announced his intention to double the capacity of the reserve to over 1 billion barrels[2] Furthermore, China, India, and other newly industrializing nations are either in the process of constructing or planning SPRs of their own.

In this paper, I present a novel purpose for the Strategic Petroleum Reserve. Previous researchers and policymakers have viewed the SPR variously as an emergency reserve for wartime use, as a price-smoothing buffer stock, or as a deterrent against political blackmail by OPEC embargoes. In this paper, I demonstrate how

[1]The author would like to thank Graham Allison, Avinash Dixit, Bill Hogan, Greg Mankiw, and the seminar participants at Harvard University and NBER for comments and encouragement. The author thanks Deanna Harvey of the Office of the Strategic Petroleum Reserve for support in gathering data. The author is especially grateful to John Deutch and Marty Feldstein for patient supervision, insightful discussions, and thoughtful guidance. The author acknowledges the financial support of Harvard University and NBER's Starr and Economics of National Security Fellowship. All errors are my own. Department of Economics, Harvard University, Littauer Center, Cambridge, MA, 02138, pahn@fas.harvard.edu and National Bureau for Economic Research, 1050 Massachusetts Ave., Cambridge, MA, 02138, pahn@nber.org.

[2]The CRS Issue Brief for Congress: IB87050 provides a detailed overview of the history and political issues surrounding the Strategic Petroleum Reserve.

a SPR of sufficient size can deter any noncompetitive quantity-setting behavior by OPEC indefinitely. Thus, the SPR can indirectly achieve US energy "independence" without actually physical substituting all imports from OPEC, which many economists consider to be impractical. A subsequent calibration returns realistically feasible target SPR levels, supporting the SPR as a potentially important and cost-effective tool to safeguard US energy security.

Most studies of the Strategic Petroleum Reserve, such as Teisberg (1981), Chao and Manne (1982), Oren and Wan (1986), Hubbard and Weiner (1986), and Yucel (1994), have focused on dynamic optimal fill/release policies in response to exogenous price movements. By contrast, this paper recognizes that prices are endogenously set by powerful oligopolists, whose behavior can be affected by the presence of a SPR. Building upon the game theoretic literature on repeated games, we model the dynamic game where OPEC and the US, through its SPR, can affect prices through quantity setting. We calibrate the model, and search for the levels of SPR necessary to deter any non-competitive behavior from OPEC.

Previous literature approaching the strategic issues surrounding the SPR include Nichols and Zeckhauser (1977), Balas (1981), Hogan (1982), and Murphy, Toman, and Weiss (1987). Nichols and Zeckhauser (1977) present a simple multi-period model where SPR fill/release decisions follow producer price-setting decisions. As the producers are forward-looking, they may change their behavior in response to the announced (and assumed credible) US SPR decisions. Hogan (1982) analyzes an international setting, where the US can be a Stackelberg follower or leader in SPR decisions, and studies the free-rider problem from other consumer nations. Murphy, Tomas, and Weiss (1987) also consider the international setting, analyzing the tariff and drawdown policies of multiple consuming nations in response to still exogenous embargo probabilities. The paper closest to the analysis below is Balas (1981). He also studied the pure deterrence effect of a SPR against embargoes, and derived the optimum size of the SPR. However, his model is essentially a purely static game with the US facing a hypothetical embargo to take place in 1985 by a cartel choosing among a finite number of strategies.[3]

With the benefit of the literature on infinite-horizon repeated games, in particular the repeated Cournot duopoly literature in Friedman (1971) and Abreu (1988), this paper analyzes the minimum SPR levels necessarily to deter embargoes indefinitely. Also, in contrast to the standard Cournot literature, this section also introduces a state-contingent element into the game; namely, the size of the SPR. The US can only release as much oil into the market as it has in its SPR, and OPEC understands this in making its decisions.

2. THE MODEL

2.1. World Oil Markets

We imagine four primary actors in the world oil market: the United States, the Organization of Petroleum Exporting Countries (OPEC), the non-US oil-consuming countries, and the non-OPEC oil producing countries. For simplicity, we assume the US is a pure consumer of oil, and the OPEC a pure producer of oil.

For simplicity, we imagine the non-OPEC world oil producers have the following

[3] In a slight abuse of words, I will use the term embargo loosely to mean any non-competitive quantity-setting behavior from OPEC.

linear supply curve:

$$S_t^{-OPEC}(P_t,t) = (1-\phi)\overline{S}e^{gt}[1+\epsilon_S(P_t-\overline{P})]$$

and the non-US world oil consumers have the linear demand curve:

$$D_t^{-US}(P_t,t) = (1-\chi)\overline{D}e^{gt}[1-\epsilon_D(P_t-\overline{P})]$$

The non-OPEC producers and non-US consumers form a competitive fringe around US and OPEC strategic behavior.

Here, g is the steady-state growth rate of the world economy, and hence, by homotheticity, of world oil supply and demand. Without loss of generality, we set $\overline{S} = \overline{D}$. We assume the non-OPEC oil producers and the non-US oil consumers are price takers.

Consider the benchmark steady state where neither OPEC nor US makes any strategic intervention into work markets. In the no-shock steady-state world oil market, we assume OPEC produces:

$$S_t^{OPEC,SS} = \phi\overline{S}e^{gt}$$

and the US consumes:

$$D_t^{US,SS} = \chi\overline{D}e^{gt}$$

Hence, in the long-run steady state with no shocks, the world oil supply and demand are:

$$\begin{aligned} S_t^{WORLD,SS} &= \overline{S}e^{gt} \\ D_t^{WORLD,SS} &= \overline{D}e^{gt} \end{aligned}$$

with the steady state oil price at:

$$P_t^{SS} = \overline{P}$$

Thus, in this no-shock steady state, OPEC produces a fraction ϕ of world oil production and the US consumes a fraction χ of world oil consumption.

2.2. Profit and Excess Expenditure

We define OPEC's net profit as:

$$\Pi_t^{OPEC} \equiv (P_t - c)S_t^{OPEC}$$

where c is OPEC's "cumulative" ex ante marginal cost of production.

In the same spirit, we define the negative of US "excess expenditure" on oil as the negative of its aggregate payments for oil over the marginal cost of oil production.:

$$\Pi_t^{US} \equiv -(P_t - c)D_t^{US}$$

For simplicity, we assume that the marginal cost of production is equal to the world steady state price $\overline{P}$. This would be true if we assume free-entry into the oil production sector and uniform costs of production across the world. This is empirically false, but putting in different costs of production for OPEC, fixed startup costs, etc., would needlessly complicate the analysis without changing the substance of our results.

Hence, in no-shock steady state, OPEC's net profit and US' excess oil expenditures are zero:

$$\Pi_t^{OPEC,SS} = \Pi_t^{US,SS} = 0$$

2.3. Intervention in World Oil Markets

As said above, the non-OPEC oil producers and the non-US oil consumers are price takers. However, OPEC, through the use of its embargo, and the US, through the use of its SPR, are quantity setters.

Suppose OPEC makes a v_t fractional reduction from its steady-state output, thus reducing its production from $\phi\overline{S}e^{gt}$ to $\phi\overline{S}e^{gt}(1-v_t)$. Similarly, we imagine the US taps its SPR to satisfy a fraction u_t of its steady-state consumption (assuming sufficiently large R_t), reducing its demand from $\chi\overline{D}e^{gt}$ to $\chi\overline{D}e^{gt}(1-u_t)$.

Their joint behavior $\{u_t, v_t\}$ causes world equilibrium prices to move to a new level, $\widehat{P}_t$. (We assume world oil markets are fungible, hence precluding any attempt by OPEC to "target" its embargo solely on the United States.)

OPEC's embargo causes world oil supply to shift to:

$$S_t^{WORLD} = (1-\phi)\overline{S}e^{gt}[1+\epsilon_S(\widehat{P}_t - \overline{P})] + \phi\overline{S}e^{gt}(1-v_t)$$

and the US' SPR release causes world demand to shift to:

$$D_t^{WORLD} = (1-\chi)\overline{D}e^{gt}[1-\epsilon_D(\widehat{P}_t - \overline{P})] + \chi\overline{D}e^{gt}(1-u_t)$$

The new equilibrium price $\widehat{P}_t$ is determined by the world oil market clearing condition:

$$\begin{aligned}(1-\phi)[1+\epsilon_S(\widehat{P}_t-\overline{P})]+\phi(1-v_t) &= (1-\chi)[1-\epsilon_D(P_t-\overline{P})]+\chi(1-u_t)\\ \widehat{P}_t &= \overline{P}+\frac{\phi v_t - \chi u_t}{\epsilon_S(1-\phi)+\epsilon_D(1-\chi)}\end{aligned}$$

For cosmetic purposes, let us define:

$$\xi \equiv \frac{1/\overline{P}}{\epsilon_S(1-\phi)+\epsilon_D(1-\chi)} > 0$$

Then the equilibrium price expression becomes:

$$\widehat{P}_t = \overline{P}[1+\xi(\phi v_t - \chi u_t)]$$

As expected, $v_t > 0$, i.e. an embargo, puts upward pressure on world oil prices, and $u_t > 0$, i.e. a SPR release, puts downward pressure on world oil prices.

2.4. Payoff Functions

In this section, we derive the ultimate objective functions of the US and OPEC. Given joint intervention, OPEC's net profits now become:

$$\begin{aligned}\Pi_t^{OPEC} &= (\widehat{P}_t - \overline{P})\phi\overline{S}e^{gt}(1-v_t)\\ &= X_t^{OPEC,SS}\xi(\phi v_t - \chi u_t)(1-v_t)\end{aligned}$$

where

$$X_t^{OPEC,SS} \equiv \phi\overline{PS}e^{gt}$$

is OPEC's revenue from oil production in steady state.

Let x be the fraction of oil production in OPEC's total income in steady state.

$$x \equiv \frac{X_t^{OPEC,SS}}{Y_t^{OPEC,SS}}$$

Then we can now compute OPEC's new profits not in dollar terms but as a share of its steady-state output:

$$\frac{\Pi_t^{OPEC}}{Y_t^{OPEC,SS}} = x\xi(\phi v_t - \chi u_t)(1 - v_t)$$

Similarly, we can derive the US' negative excess expenditure on oil as a fraction of its steady state income as:

$$\frac{\Pi_t^{US}}{Y_t^{US,SS}} = -m\xi(\phi v_t - \chi u_t)(1 - u_t)$$

where:

$$M_t^{US,SS} \equiv \chi \overline{PD} e^{gt}$$

is US's total expenditure on oil in steady state, and m is the fraction of US's total steady state income expended on oil.

$$m \equiv \frac{M_t^{US,SS}}{Y_t^{US,SS}}$$

Lastly, we impose adjustment costs on the US SPR for fills/releases. For simplicity, we assume it takes the simple quadratic form:

$$c^{US}(u_t) = c^{US} Y_t^{US,SS} u_t^2$$

Hence, c^{US} is the cost of filling/releasing u_t as a fraction of US steady-state GDP. In practice, this c^{US} will be very small. Similarly, we impose quadratic embargo costs on OPEC:

$$c^{OPEC}(v_t) = c^{OPEC} Y_t^{OPEC,SS} v_t^2$$

c^{OPEC} is the cost of embargoing/flooding v_t as a fraction of OPEC steady-state GDP. This may be interpreted as the costs to OPEC to maintain unity internally, geopolitical costs from the rest of the world, or costs from the threat of military intervention. These costs may be more significant than the US adjustment costs.[4]

Finally, we assume that OPEC and US make embargoes/SPR releases to maximize their net profit/minimize their excess expenditure respectively as a fraction of their total steady-state income, taking into account their adjustment costs.

Thus, we can write our payoff functions for the US and OPEC for our deterrence analysis:

$$\begin{aligned}
\pi_t^{OPEC} &\equiv \frac{\Pi_t^{OPEC} - c_t^{OPEC}}{Y_t^{OPEC,SS}} = x\xi(\phi v_t - \chi u_t)(1 - v_t) - c^{OPEC} v_t^2 \\
\pi_t^{US} &\equiv \frac{\Pi_t^{US} - c_t^{US}}{Y_t^{US,SS}} = -m\xi(\phi v_t - \chi u_t)(1 - u_t) - c^{US} u_t^2
\end{aligned}$$

Note that, given prices higher than the long-run mean (i.e. $\phi v_t - \chi u_t > 0$), OPEC payoffs are increasing in x, the fraction of OPEC income earned from oil

[4] While adding to the complexity of the model, these costs are necessary, because they will bias the US and OPEC socially toward inaction, though they would still be tempted to deviate given inaction by the other party. Without these costs, the desired steady-fill state will not be supportable even dynamically.

exports. In essence, the more the OPEC is dependent on oil revenues for its income, the more wealth as a fraction of its total income it gains from higher oil prices, and thus the higher the temptation to embargo. Similarly, US payoffs are decreasing in m, the fraction of US spending on oil.

For analytic cleanliness later, it will be convenient to define:

$$\begin{aligned}\kappa_1 &= 1 + \frac{c^{OPEC}}{x\xi\phi} \\ \kappa_2 &= 1 + \frac{c^{US}}{m\xi\chi}\end{aligned}$$

In the rest of the analysis, we drop the terms $x\xi$ and $m\xi$ in front of the payoff functions, as they are common to all periods and thus make no difference to our analysis.

$$\begin{aligned}\pi_t^{OPEC} &= (\phi v_t - \chi u_t)(1 - v_t) - \phi(\kappa_1 - 1)v_t^2 \\ \pi_t^{US} &= -(\phi v_t - \chi u_t)(1 - u_t) - \chi(\kappa_2 - 1)u_t^2\end{aligned}$$

2.5. Exhaustible Reserve

We let R_t denote the amount of oil in the SPR as a fraction of total non-shock steady-state US consumption in the reserve at time t. Hence, if $\Re_t$ is the actual physical amount of oil in the reserve, then:

$$R_t = \frac{\Re_t}{D_t^{US,SS}} = \frac{\Re_t}{\chi\overline{D}e^{gt}}$$

Hence, the law of motion of the reserve size R_t is as follows. A fractional release u_t extracts an actual amount $u_t D_t^{US,SS}$ from the reserve, leaving:

$$\begin{aligned}R_{t+1} &= \frac{\Re_{t+1}}{D_{t+1}^{US,SS}} \\ &= \frac{\Re_t - u_t D_t^{US,SS}}{e^g D_t^{US,SS}} \\ &= e^{-g}(R_t - u_t)\end{aligned}$$

The US is constrained to keep $\Re_t \geq 0$, or equivalently, $R_t \geq 0$. This caps the maximum possible one-time release at the size of its reserves: $u_t \leq R_t$.

Note that even without any releases, i.e. $u_t = 0$, due to the continued growth in the US economy and proportionate growth in steady-state demand, the size of the reserve will be decreasing at a rate $-g$. To keep the reserve size steady at $R_t = \overline{R}$ $\forall t$ requires a steady fill $u_t = -\overline{R}(e^g - 1)$ $\forall t$. For cosmetic purposes, let $1 + \gamma = e^g$. Then the steady fill requires: $u_t = -\gamma\overline{R}$. Also note that even starting from zero reserves, if the US maintains this steady fill rate $u_t = -\gamma\overline{R}$, in the long-run, the reserve size will revert to $\overline{R}$.

3. STATIC ANALYSIS

We return to the optimization problems of OPEC and the US, to maximize π_t^{OPEC} and π_t^{US} respectively. We can derive the optimal response functions of OPEC to a US release, and vice versa:

π_t^{OPEC} is maximized when the following first-order condition (FOC) is satisfied: (Since payoff functions are quadratic, the SOC is immediately satisfied.)

$$\frac{d}{dv_t}\pi_t^{OPEC} = \phi + \chi u_t - 2\phi\kappa_1 v_t = 0$$

Hence, the optimal response of OPEC is:

$$R^{OPEC}(u_t) = \frac{1}{\kappa_1}(\frac{1}{2} + \frac{\chi}{2\phi}u_t)$$

Similarly, the optimal release response of the US can be derived from its FOC:

$$\begin{aligned}
\frac{d}{dv_t}\pi_t^{OPEC} &= \chi + \phi v_t - 2\chi\kappa_2 u_t = 0 \\
R^{US}(v_t) &= \frac{1}{\kappa_2}(\frac{1}{2} + \frac{\phi}{2\chi}v_t)
\end{aligned}$$

And we can also rewrite the payoff functions as:

$$\begin{aligned}
\pi_t^{OPEC} &= \frac{\phi}{4\kappa_1} - (1 - \frac{1}{2\kappa_1})\chi u_t + \frac{\chi^2}{4\phi\kappa_1}u_t^2 - \phi\kappa_1[v_t - \frac{1}{\kappa_1}(\frac{1}{2} + \frac{\chi}{2\phi}u_t)]^2 \\
\pi_t^{US} &= \frac{\chi}{4\kappa_2} - (1 - \frac{1}{2\kappa_2})\phi v_t + \frac{\phi^2}{4\chi\kappa_2}v_t^2 - \chi\kappa_2[u_t - \frac{1}{\kappa_2}(\frac{1}{2} + \frac{\phi}{2\chi}v_t)]^2
\end{aligned}$$

3.1. Static Nash Equilibrium

The static Cournot-style Nash Equilibrium is achieved when:

$$v_t^C = R^{OPEC}(R^{US}(v_t^C))$$

The static NE can be shown to be:

$$\begin{aligned}
v_t^C &= \frac{1}{4\kappa_1\kappa_2 - 1}(\frac{1}{2}\kappa_2 + \frac{\chi}{\phi}) \\
u_t^C &= \frac{1}{4\kappa_1\kappa_2 - 1}(\frac{1}{2}\kappa_1 + \frac{\phi}{\chi})
\end{aligned}$$

3.2. Exhausted Reserve

However, the Cournot equilibrium is achievable only when the US has sufficient reserves to make a release u_t^C. This is where the analysis of embargo deterrence can differ from standard Cournot analysis, due to the nonnegative SPR reserve constraint $R_t \geq 0$.

Suppose instead now that the US has exhausted its SPR ($R_t = 0$) and must set $u_t^E = 0$. Then the optimal response of OPEC would be to embargo:

$$v_t^E = R^{OPEC}(0) = \frac{1}{2\kappa_1}$$

This results in embargo payoffs:

$$\begin{aligned}
\pi_t^{OPEC,E} &= \frac{\phi}{4\kappa_1} \\
\pi_t^{US,E} &= -\frac{\phi}{2\kappa_1}
\end{aligned}$$

3.3. Steady SPR Fill

As shown above, to maintain the SPR at a stationary level $\overline{R}$, the US is required to fill at a level: $u_t^F = -\gamma\overline{R}$. Suppose OPEC makes no intervention: $v_t^F = 0$. The payoffs when the US fills at this rate and OPEC makes no intervention is:

$$\begin{aligned}\pi_t^{OPEC,F} &= \chi\gamma\overline{R}\\ \pi_t^{US,F} &= -\chi\gamma\overline{R}(1+\gamma\kappa_2\overline{R})\end{aligned}$$

As we will see, this steady-fill state is the equilibrium we would like to support in the dynamic setting.

3.4. OPEC Temptation to Embargo

Given a steady fill by the US, $u_t^F = -\gamma\overline{R}$, OPEC would be tempted to deviate to:

$$v_t^{TO} = R^{OPEC}(-\gamma\overline{R}) = \frac{1}{\kappa_1}(\frac{1}{2} - \frac{\chi}{2\phi}\gamma\overline{R})$$

This results in payoffs:

$$\begin{aligned}\pi_t^{OPEC,TO} &= \frac{\phi}{4\kappa_1} + (1-\frac{1}{2\kappa_1})\chi\gamma\overline{R} + \frac{\chi^2}{4\phi\kappa_1}\gamma^2\overline{R}^2\\ \pi_t^{US,TO} &= -[\frac{\phi}{\kappa_1}(\frac{1}{2} - \frac{\chi}{2\phi}\gamma\overline{R}) - \gamma\chi\overline{R}](1+\gamma\overline{R}) - \chi(\kappa_2-1)\gamma^2\overline{R}^2\end{aligned}$$

3.5. US Temptation to Release

Now let us analyze the optimal behavior of US SPR releases given no embargo from OPEC, assuming it has sufficient reserves to do so.

Since there is no embargo, $v_t^T = 0$, and the optimal response of the US would be to release:

$$u_t^{TU} = R^{US}(0) = \frac{1}{2\kappa_2}$$

This results in payoffs:

$$\begin{aligned}\pi_t^{OPEC,TU} &= -\frac{\chi}{2\kappa_2}\\ \pi_t^{US,TU} &= \frac{\chi}{4\kappa_2}\end{aligned}$$

3.6. No-Intervention State

The no-intervention state with $u_t^e = v_t^e = 0$ replicates the perfectly competitive general equilibrium, where both the US and OPEC are price-takers. By the First Welfare Theorem, this competitive equilibrium achieves the Pareto efficient optimum for the world's welfare. In this case, the US and OPEC payoffs are zero.

$$\pi_t^{OPEC,e} = \pi_t^{US,e} = 0$$

Note, this would also be the optimum of a social planner who weights the US and OPEC equally:

$$\begin{aligned}\pi_t^{OPEC} + \pi_t^{US} &= (\chi + \phi)u_t v_t - \phi v_t^2 - \chi u_t^2 \\ &\quad -\phi(\kappa_1 - 1)v_t^2 - \chi(\kappa_2 - 1)u_t^2\end{aligned}$$

One can show this is always ≤ 0, with equality only when $u_t^e = v_t^e = 0$. However, as seen above, this no-intervention state is not supportable in the static setting. Given $u_t = 0$, OPEC would be tempted to deviate to $v_t = v_t^E$. Also, given $v_t = 0$ and given sufficient reserves, the US would be tempted to deviate to $u_t = u_t^T$.

4. DYNAMIC ANALYSIS

Hence, we turn to the analysis of the dynamic repeated game context, where the Folk Theorem can potentially support otherwise statically unsupportable equilibria. We suppose the US and OPEC maximize the infinite discounted stream of payoffs, with a common discount factor δ.

$$\begin{aligned}V^{OPEC} &= \sum_{t=0}^{\infty} \delta^t \pi_t^{OPEC} \\ V^{US} &= \sum_{t=0}^{\infty} \delta^t \pi_t^{US}\end{aligned}$$

We analyze a period where US currently has a reserve of size $\overline{R}$. Unfortunately, neither the Cournot NE (u_t^C, v_t^C) nor the no-intervention efficient state (u_t^e, v_t^e) are supportable even in the dynamic setting. Given positive growth in US consumption, the SPR size would steadily shrink to the point where OPEC could safely embargo with no threat of retaliation. So instead we look for strategies able to support the steady-fill state (u_t^F, v_t^F).

4.1. Punishments

Akin to Abreu (1988), we look for credible two-phase subgame-perfect punishment strategies.[5] In particular, we consider the following "carrot-and-stick" deterrence strategies: Produce the steady-fill state (u_t^F, v_t^F) while there is no deviation. If either the US or OPEC detects a deviation, then produce the punishment level, which are (p^{US}, p^{OPEC}) respectively. If correct punishment level is jointly set in the previous period (p^{US}, p^{OPEC}), then return to the original path (u_t^F, v_t^F).

First, for simplicity, we consider punishments that the US can inflict an integer number of periods: $p^{US} = \frac{\gamma}{(1+\gamma)^N - 1}\overline{R}$. One can show, given initial reserve size $\overline{R}$, the law of evolution, and the non-negativity constraint on the SPR, the US would be able to inflict this punishment for exactly N periods only. In the appendix, I extend the analysis to consider non-integer releases.

We also restrict attention to $p^{OPEC} = p$ sufficiently high that the optimal response $R^{US}(p) > \overline{R}$. This is only for simplicity; as we are interested not in OPEC threat to deter US SPR releases, but US policies to deter OPEC embargoes.

[5] In his analysis of the repeated Cournot duopolists, Friedman (1971) considered strategies where the two firms would produce monopoly output q^m while no firm deviates. But if there is a deviation, then the two would produce q^C henceforth. But the set of discount factors in which Friedman (1971)'s strategies can support the efficient outcome is more restrictive than that of Abreu (1986).

This restriction is analytically the following:

$$R^{US}(p) = \frac{1}{\kappa_2}(\frac{1}{2} + \frac{\phi}{2\chi}p) > \overline{R}$$

or that:

$$p > \frac{2\chi}{\phi}(\kappa_2\overline{R} - \frac{1}{2})$$

4.2. Punishment and Deviations from Punishment Payoffs

If both the US and OPEC establish punishment strategies $(p^{US}, p^{OPEC}) = (\frac{\gamma}{(1+\gamma)^N-1}\overline{R}, p)$, then the one-period payoffs will be:

$$\begin{aligned}
\pi_t^{OPEC,P} &= (\phi p - \chi\frac{\gamma}{(1+\gamma)^N-1}\overline{R})(1-p) - \phi(\kappa_1 - 1)p^2 \\
\pi_t^{US,P} &= -(\phi p - \chi\frac{\gamma}{(1+\gamma)^N-1}\overline{R})(1 - \frac{\gamma}{(1+\gamma)^N-1}\overline{R}) \\
&\quad -\chi(\kappa_2 - 1)\frac{\gamma^2}{[(1+\gamma)^N-1]^2}\overline{R}^2
\end{aligned}$$

However, given the punishment by the opposing party, OPEC and the US might be tempted to deviate to:

$$\begin{aligned}
v_t^{dp} &= R^{OPEC}(\frac{\gamma}{(1+\gamma)^N-1}\overline{R}) = \frac{1}{\kappa_1}[\frac{1}{2} + \frac{\chi}{2\phi}\frac{\gamma}{(1+\gamma)^N-1}\overline{R}] \\
R^{US}(p) &= \frac{1}{\kappa_2}(\frac{1}{2} + \frac{\phi}{2\chi}p)
\end{aligned}$$

Recall our assumption that $p > \frac{2\chi}{\phi}(\kappa_2\overline{R} - \frac{1}{2})$. Therefore, even though ideally the US would like to set $R^{US}(p) = \frac{1}{\kappa_2}(\frac{1}{2} + \frac{\phi}{2\chi}p)$, the best it can do is set $u_t^{dp} = \overline{R}$. This results in devation-from-punishment payoffs:

$$\begin{aligned}
\pi_t^{OPEC,dp} &= \frac{\phi}{4\kappa_1} - (1 - \frac{1}{2\kappa_1})\chi\frac{\gamma}{(1+\gamma)^N-1}\overline{R} + \frac{\chi^2}{4\phi\kappa_1}\frac{\gamma^2}{[(1+\gamma)^N-1]^2}\overline{R}^2 \\
\pi_t^{US,dp} &= -(\phi p - \chi\overline{R})(1-\overline{R}) - \chi(\kappa_2 - 1)\overline{R}^2
\end{aligned}$$

4.3. Subgame Perfection at the Steady-Fill State

First, we must establish that both parties would prefer to maintain the steady-fill state rather than deviate once, receive the punishment, then return to the steady-fill state:

$$\begin{aligned}
\frac{1}{1-\delta}\pi_t^{OPEC,F} &\geq \pi_t^{OPEC,TO} + \delta[\pi_t^{OPEC,P} + \delta\frac{1}{1-\delta}\pi_t^{OPEC,F}] \\
\frac{1}{1-\delta}\pi_t^{US,F} &\geq \pi_t^{US,TU} + \delta[\pi_t^{US,P} + \delta\frac{1}{1-\delta}\pi_t^{US,F}]
\end{aligned}$$

Rearranging the condition for OPEC, we have:

$$\begin{aligned}
\pi_t^{OPEC,F} &\geq (1-\delta)\pi_t^{OPEC,TO} + \delta(1-\delta)\pi_t^{OPEC,P} + \delta^2\pi_t^{OPEC,F} \\
(1+\delta)\pi_t^{OPEC,F} &\geq \pi_t^{OPEC,TO} + \delta\pi_t^{OPEC,P}
\end{aligned}$$

We also have the condition for the US:

$$(1+\delta)\pi_t^{US,F} \geq \pi_t^{US,TU} + \delta\pi_t^{US,P}$$

4.4. Subgame Perfection at the Punishment Stage

Next, we must establish that both parties would rather punish correctly, rather than deviate from that correct punishment. For the US, the condition is simply that the payoff from punishing correctly and reestablishing the steady-fill state forever is superior to a one-shot deviation to the punishment, followed by a correct punishment, then finally reestablishing the steady-fill state:

$$\begin{aligned}
\pi_t^{US,P} + \delta\frac{1}{1-\delta}\pi_t^{US,F} &\geq \pi_t^{US,dp} + \delta[\pi_t^{US,P} + \delta\frac{1}{1-\delta}\pi_t^{US,F}] \\
(1-\delta)\pi_t^{US,P} + \delta\pi_t^{US,F} &\geq \pi_t^{US,dp}
\end{aligned}$$

The condition required to deter OPEC from deviating from its correct punishment is very different from that of the US, because of the non-negativity constraint on the US SPR. OPEC recognizes that the US can at most punish N times before it exhausts its reserves. Once the US exhausts its reserves, OPEC can enjoy embargo profits forever.

$$\pi_t^{OPEC,P} + \delta\frac{1}{1-\delta}\pi_t^{OPEC,F} \geq \frac{1-\delta^N}{1-\delta}\pi_t^{OPEC,dp} + \delta^N\frac{1}{1-\delta}\pi_t^{OPEC,E}$$

5. CALIBRATION

To summarize, we have the following parameter values for the model:

$$\begin{aligned}
\delta &= \text{the discount factor common to the US and OPEC} \\
\gamma &= \text{the steady-state economic growth rate} \\
\phi &= \text{the share of OPEC in world steady-state oil supply} \\
\chi &= \text{the share of the US in world steady-state oil demand} \\
\epsilon_S &= \text{the price elasticity of non-OPEC oil supply} \\
\epsilon_D &= \text{the price elasticity of non-US oil demand} \\
x &= \text{the share of oil revenue in OPEC income} \\
m &= \text{the share of US income spent on oil} \\
c^{OPEC} &= \text{the cost of embargoes/floods as a fraction of OPEC income} \\
c^{US} &= \text{the cost of SPR releases/fills as a fraction of US income} \\
\overline{P} &= \text{the steady-state price of oil}
\end{aligned}$$

We would like to look for $\overline{R}$ – the size of the SPR as a fraction of total steady consumption, p – the deviation punishment from OPEC, and N – the number of times the US can punish OPEC by releasing from the SPR, that satisfy the following inequality conditions to prevent the US and OPEC from deviating from the steady-fill state:

$$\begin{aligned}
(1+\delta)\pi_t^{OPEC,F} &\geq \pi_t^{OPEC,TO} + \delta\pi_t^{OPEC,P} \\
(1+\delta)\pi_t^{US,F} &\geq \pi_t^{US,TU} + \delta\pi_t^{US,P} \\
(1-\delta)\pi_t^{US,P} + \delta\pi_t^{US,F} &\geq \pi_t^{US,dp} \\
\pi_t^{OPEC,P} + \delta\frac{1}{1-\delta}\pi_t^{OPEC,F} &\geq \frac{1-\delta^N}{1-\delta}\pi_t^{OPEC,dp} + \delta^N\frac{1}{1-\delta}\pi_t^{OPEC,E} \\
p &> \frac{2\chi}{\phi}(\kappa_2\overline{R} - \frac{1}{2})
\end{aligned}$$

First, we need to calibrate the parameter values:

For our benchmark analysis, we set the discount factor $\delta \approx 0.95$. We set the worldwide steady growth rate as $\gamma \approx 0.025$. In 2005, the total world oil demand was about 84.028 million barrels of oil daily. Of this, the OPEC produced about 34.272 million barrels of oil daily. Hence, the share of OPEC in world oil production was $\phi \approx 0.408$. In 2005, the US consumed 20.802 million barrels of oil daily, or 24.8% of total world oil demand: $\chi \approx 0.248$.

For elasticities, in line with Hogan (1989) and Dahl and Duggan (1996), we calibrate $\epsilon_S \approx 0.5$ as a rough estimate of the price elasticity of non-OPEC oil supply. Brown and Phillips (1989) estimates the long-term (over a year) price elasticities of demand for crude oil at 0.56. Cooper (2003) estimates it at 0.453. In our numerical analysis, we use $\epsilon_D \approx 0.5$ for the long-run elasticity of demand.

Historically, the US spent about 3-4% of its income on oil, which is the value we shall set for $m = 0.04$. In 2006, the US spent about 3.1% of its income on oil. As we shall see, however, changing this parameter makes little to no difference to desired SPR levels.

We set the share of oil revenue in total OPEC GDP to be 43%, which is the value-added of the petroleum sector in the total GDP of all OPEC countries excluding Indonesia in 2005. We exclude Indonesia from our calculations, as it is now a net oil importer. [6]

Lastly, we move to the estimates of the adjustment cost parameters: Remember that the US cost function captures only the costs of filling/tapping the SPR, not of acquiring the oil. The SPR's oil is stored in highly cost-effective and conveniently accessible sites, linkable to the national pipeline infrastructure with the push of a button. Thus, we assume away any SPR adjustment costs.

The estimates for the international coordination and geopolitical costs of OPEC embargoes must be vaguer. OPEC's adjustment cost function can capture many things: the internal coordination costs of mounting a unified embargo, the diplomatic backlash from the rest of the world, engineering costs of shutting off an oil field, and even the threat of military intervention in response to an embargo. For lack of more precise numbers, we conservatively set $c^{OPEC} = 0.1$. This would mean an embargo of half its total output from OPEC, i.e. setting $v_t = 0.5$, would cause a 2.5% cost of steady-state GDP. By comparison, during the 1973 embargo, OPEC removed roughly 10% of its output from world markets. A 10% reduction, $v_t = 0.1$, would correspond to a 0.1% cost of steady-state GDP.

5.1. Numerical Results

We look for a solution numerically. Figure 1 shows a typical plot from the simulation. The OPEC punishment level p is on the x-axis and the SPR size $\overline{R}$ is on the y-axis. The shaded region denotes the phase space where the bundle $\{p, N, \overline{R}\}$ satisfies the inequalities above, and thus support the steady-fill equilibrium. Note that, as expected, increasing reserve sizes widens the range of feasible deterrence strategies. A value of $\overline{R} = 1$ corresponds to one year of oil consumption cover.[7]

[6] OPEC currently consists of the following nations: Algeria, Angola, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela. Angola has recently joined in January 1, 2007, and was not a member of OPEC in 2005. The data comes from OPEC Annual Statistical Bulletin for 2005.

[7] In our analysis, we assumed the US is a pure importer. However, in 2005, the US also produced about 8.322 million barrels of oil daily, or about 9.9% of world oil demand, satisfying about 40% of its own demand. SPR releases deter OPEC by dumping the required amount of

Table 1 show the minimum SPR levels computed for various combinations of parameter values. The benchmark analysis on the top row provides a minimum SPR level of 1.384, or 505.2 days of cover. This is far larger than the 30-odd days of cover that the SPR currently provides. Figures 2 and 3 show the past and current size of the SPR, in absolute terms and in days of cover. Clearly, the SPR as it is now provides nowhere near the amount of cover necessary to deter OPEC embargoes. But further analysis with different parameter values will not only shed light on the model but also potentially bring down the minimum SPR level.

In the benchmark, we set ϕ assuming that the US is facing a monolithic OPEC with control of 40.8% of world oil supply. However, the situation may not be as dire. OPEC has been historically plagued by divisions among its members, with many producers consistently exceeding their quotas. Suppose that instead of a unified OPEC, the US faces embargo threats from only an aggressive price-setting "core" with control of only half of the original number, or 20.4%, of world oil supply. This is roughly the amount produced by Saudi Arabia, Iran, and Venezuela. As expected, this significantly reduces the amount of import cover necessary, to 394.3 days.

Interestingly, our model can also provide guidance on an alliance of consumer nations against an OPEC embargo. Suppose the OECD, which consumes 59% of world oil demand, jointly creates an International Strategic Petroleum Reserve to mount a unified deterrence strategy against a unified OPEC. In the model, one can simply raise the parameter χ to 0.59. Much like the effect of reducing OPEC's unity, a unified SPR reduces the amount of reserve cover that each member of the consortium must store from the benchmark 505.2 to 409.2 days. This suggests international cooperation as a major direction to reduce the burden of a deterrent reserve. Even a coalition by the US, Europe, and Japan would give $\chi = 0.49$. Adding China and India to that would raise χ to 0.61.

Next, we test the implications of raising the OPEC's adjustment cost function parameter to $c^{OPEC} = 0.7$. Hence, OPEC must suffer a 70% loss of its steady-state GDP in imposing a full embargo. As expected, this reduces the minimum SPR level, to 338.4 days.

Next, we change the discount factor from $\delta = 0.95$ to $\delta = 0.75$. As the repeated Cournot literature might suggest, increasing OPEC's impatience might lessen the reserve size required to deter embargoes. Indeed, the simulation shows a slightly reduced SPR level of 498.6 days.

Now we see what happens if we assume away all growth in the world economy. Interestingly, I find there is no reserve size large enough such that a punishment strategy with $N = 1$ is feasible. And surprisingly, the minimum SPR level is 753.0 days, which is worse than in the positive growth case. One might find this counterintuitive, as the corrosive effect of economic growth on SPR levels might be seen as a liability. But intuitively, the growth rate of the US forces the US to make steady fill rates to maintain the size of their reserve constant. This in effect provides a "subsidy" to OPEC, who can benefit from higher prices due to US SPR fill. If the growth rate is zero and the US tries to deter OPEC from a situation

oil on world markets, reducing world prices and OPEC oil revenues. If we imagine that the US domestic oil production can be used as an additional source of dumpable supply, then $\overline{R}$ would correspond to the minimum period of *import* cover the SPR must provide. This ignores the domestic producer loss by preventing embargoes, but would be valid if we assume free-entry and price-taking competition in the US domestic oil industry, which would bring their ex ante profits to zero.

where the US makes no fill at all, it becomes that much more difficult to prevent OPEC from deviating.

Now, as a robustness check, we put in lower elasticities of supply and demand. (The analysis above shows that the two parameters enter into the model only through their sum.) Economically, this means oil consumers are less flexible in finding oil substitutes, and price-taking oil producers sluggish to increase output. All of this stickiness should strengthen the hand of OPEC. And as expected, we see the minimum SPR level rise to 687.7 days.

Next, we see what happens if we reduce the share of oil revenue in OPEC GDP from 43% to 10%. As said above, the more of OPEC's GDP portfolio is generated from the oil sector, the higher the temptation to embargo and see that much more wealth as a proportion of their total income generated. Hence, this experiment can be thought of as the effect of diversifying OPEC's economies away from oil and into other industries. This reduces the SPR shield necessary to 365.2 days.

As a final robustness check, we change the amount of US GDP spent on oil. If all of the action is happening on OPEC's end of the decision-making, then we should expect little change except perhaps in the punishment OPEC needs to deter any US deviation. And indeed, the minimum SPR levels remains unchanged at 505.2 days, with the OPEC punishment rising slightly, to 0.81.

6. POLICY RECOMMENDATIONS

From the simulations above, a conservative estimate for the minimum SPR level required to deter OPEC embargoes would be 400 days of cover, or at least an year's worth of total consumption. In 2007, that would translate into about 7.9 billion barrels. Even if we rely on US domestic production and only consider 400 days of import cover, this would still mean 4.8 billion barrels. This may seem like a daunting goal, compared to the less than 700 million barrels in the present SPR. Even the capacity-doubling target set by President Bush in his January 2006 State of the Union Address would raise the import cover to 122 days. Furthermore, even 400 days may underestimate the minimum target. The large budget surpluses by oil-exporting nations due to high recent energy prices mean they have built up substantial hard currency reserves which they can use to withstand a price war with the US.

However, it may be insightful to note that in the original legislation that created the SPR in 1977, the target SPR size was 1 billion barrels. Had they reached their target within the seven years stipulated, or by 1985, that would have translated into an import cover of 312.5 days. A target of 1.5 billion barrels would have meant a 468.8 day cover in 1985. And the recommended minimum size of the SPR is in line with the suggestions of other literature: E.g. Hogan (1982), recommended a stockpile between 1.5 and 2.5 billion barrels, or a 300-500 day import cover.

Also, the US SPR is shouldering the burden of deterring OPEC embargoes itself, while the rest of the world free-rides from its presence. As explained above, cooperation with other consuming nations can lessen the SPR cover considerably. But even going it alone, suppose the US spends \$60 on acquiring each barrel of oil, which is more than twice the historic mean. This translates into about \$288 billion on acquiring the oil itself. Then suppose there is another \$100 billion in construction and maintenance costs. Then there is the constant fill necessary to maintain the SPR size. At a growth rate of $\gamma = 2.5\%$, this becomes an additional \$144 billion, for a grand total of \$532 billion, discounting at a rate $\delta = 0.95$. Ahn

(2007) conservatively estimates the welfare gains from eliminating even half of the "disaster" component of oil price shocks would be 1.46% of GDP annually. This would aggregate to \$3.791 trillion.

And as the model suggests, a variety of other energy policy tools can help bring down the minimum size of the SPR even further. Diplomatic efforts to break OPEC's unity, warnings against revenue targeting, pressure to open their resources to market forces and competition, development aid to wean the OPEC nations off its overreliance on oil revenue, increases in domestic production, improvements in the economy's flexibility in using oil substitutes, and the creation of an International Strategic Petroleum Reserve by a consortium of major oil-consuming nations– all of these methods ideally should be followed in conjunction with a buildup of the SPR.

If \$500 billion dollars (which is roughly the total amount the US has spent on the Iraqi War thus far) nevertheless feels excessive, I suggest a method that may ease the sting. The US has at least 21 billion barrels of proven oil reserves within its own borders. Instead of acquiring the oil on world markets and facing a potential preemptive OPEC price war, the US can simply set aside 7.9 billion or whatever desired quantity of oil within its territory as its SPR. Much like the US nuclear missile second-strike capability, this reserve is a deterrent and theoretically should never be used. However, in the interests of credibility, the US must prepare all the infrastructure necessary to dump the quantity onto world markets within the required time period. Only then will OPEC be deterred from non-competitive behavior. As this reserve will never be used, in the end the unused oil is lost value to the United States. Nevertheless, this may be a small price to pay to achieve competitive world oil prices and the end of energy dependence.

7. CONCLUSION

This paper presents a novel use for the SPR in national energy security. It demonstrates how a reserve of sufficient size can potentially deter a cartel of oil producers, such as OPEC, from any noncompetitive behavior indefinitely, thus achieving indirect energy independence. A subsequent calibration returns large but nevertheless feasible target levels, supporting its use as a potentially important and cost-effective tool to achieve indirect US energy "independence."

APPENDIX A: NON-INTEGER RELEASES

In the paper, we made the simplifying restriction of considering only integer punishment releases from the US. But the simulation program can be extended to consider non-integer N. However, this does not have an accurate meaning in the discrete-period model. Hence, I discuss below the non-integer extension of the model.

Suppose the simulation returns a value $N' = N + x$, where N is the integer component of N' and x the residual. The amount of reserve $\overline{R}$ corresponding to N' allows a punishment release $p^{US} = \frac{\gamma}{(1+\gamma)^{N'}-1}\overline{R}$, N times. Next, we must solve for the residual amount y in the reserve necessary to match the punishment level of the remaining x-period fractional punishment. In other words, we must solve for

y such that the following inequalities are equivalent:

$$
\begin{aligned}
\pi_t^{OPEC,P} + \delta \frac{1}{1-\delta} \pi_t^{OPEC,F} &\geq \frac{1-\delta^{N+x}}{1-\delta} \pi_t^{OPEC,dp} + \delta^{N+x} \frac{1}{1-\delta} \pi_t^{OPEC,E} \\
\pi_t^{OPEC,P} + \delta \frac{1}{1-\delta} \pi_t^{OPEC,F} &\geq \frac{1-\delta^{N}}{1-\delta} \pi_t^{OPEC,dp} + \delta^{N} \pi_t^{OPEC,y} + \delta^{N+1} \frac{1}{1-\delta} \pi_t^{OPEC,E}
\end{aligned}
$$

Hence, we want to set:

$$
\frac{1-\delta^{N+x}}{1-\delta} \pi_t^{OPEC,dp} + \delta^{N+x} \frac{1}{1-\delta} \pi_t^{OPEC,E} = \frac{1-\delta^{N}}{1-\delta} \pi_t^{OPEC,dp} + \frac{\delta^{N}-\delta^{N+x}}{1-\delta} \pi_t^{OPEC,dp} + \frac{\delta^{N+x}-\delta^{N+1}}{1-\delta}
$$

This is equivalent to setting:

$$
\begin{aligned}
\frac{\delta^{N}-\delta^{N+x}}{1-\delta} \pi_t^{OPEC,dp} + \frac{\delta^{N+x}-\delta^{N+1}}{1-\delta} \pi_t^{OPEC,E} &= \delta^N \pi_t^{OPEC,x} \\
\frac{1-\delta^{x}}{1-\delta} \pi_t^{OPEC,dp} + \frac{\delta^{x}-\delta}{1-\delta} \pi_t^{OPEC,E} &= \pi_t^{OPEC,x}
\end{aligned}
$$

Here, the terms refer to the following expressions:

$$
\begin{aligned}
\pi_t^{OPEC,y} &= \frac{\phi}{4\kappa_1} - (1 - \frac{1}{2\kappa_1})\chi y + \frac{\chi^2}{4\phi\kappa_1} y^2 \\
\pi_t^{OPEC,dp} &= \frac{\phi}{4\kappa_1} - (1 - \frac{1}{2\kappa_1})\chi p^{US} + \frac{\chi^2}{4\phi\kappa_1} p^{US2} \\
\pi_t^{OPEC,E} &= \frac{\phi}{4\kappa_1}
\end{aligned}
$$

Entering the expressions, we have the following quadratic equation for y:

$$
\frac{1-\delta^{x}}{1-\delta} [-(1 - \frac{1}{2\kappa_1})\chi p^{US} + \frac{\chi^2}{4\phi\kappa_1} (p^{US})^2] = -(1 - \frac{1}{2\kappa_1})\chi y + \frac{\chi^2}{4\phi\kappa_1} y^2
$$

Hence, the true desired reserve level $\overline{R}^{TRUE}$ is:

$$
\overline{R}^{TRUE} = \frac{(1+\gamma)^N - 1}{\gamma} p^{US} + (1+\gamma)^N y
$$

This is the formula we use in Table 1.

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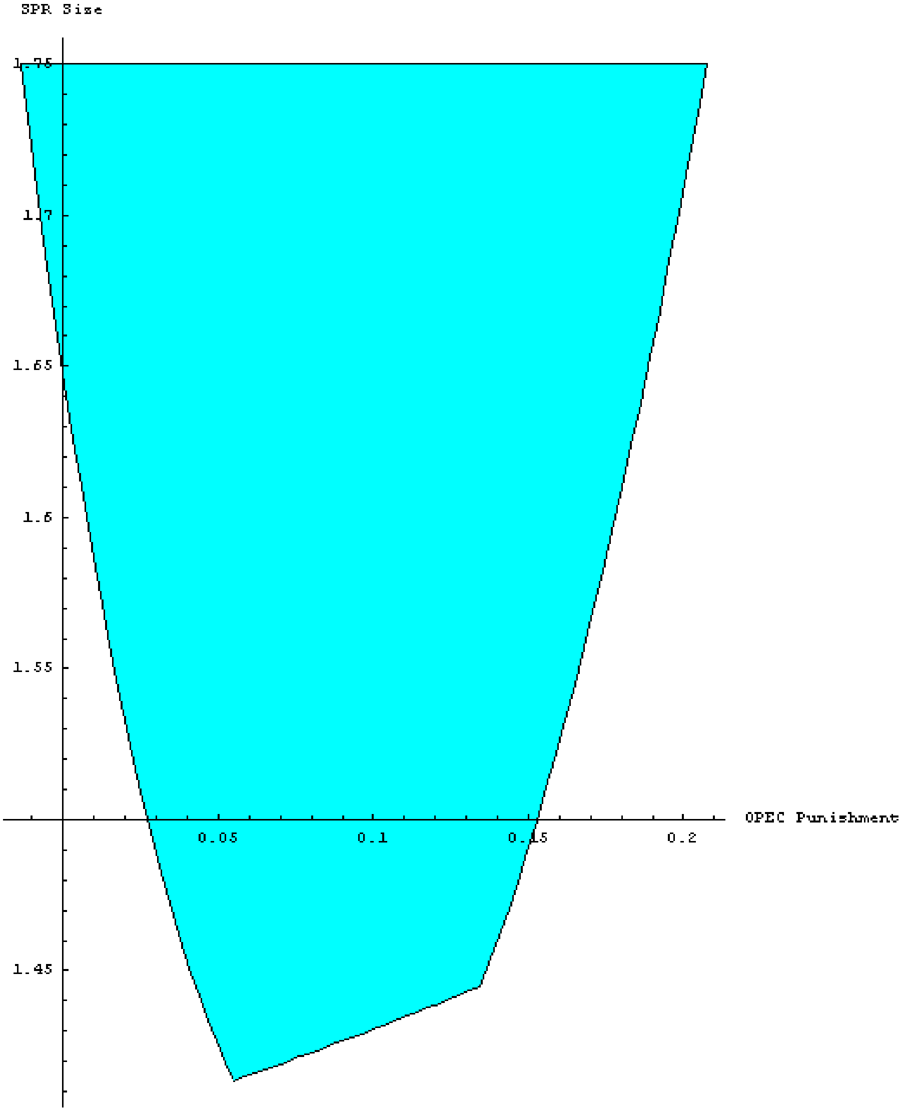

Typical simulation of feasible SPR levels, with $\delta = .95$, $\gamma = .025$, $\phi = .408$, $\chi = .248$, $\epsilon_S = \epsilon_D = .5$, $x = .43$, $= .04$, $c^{OPEC} = .1$, $c^{US} = 0$, $\overline{P} = 25$, and $N = 1.1$. The target SPR size $\overline{R}$ is on the y-axis, the necessary OPEC punishment level p is on the x-axis.

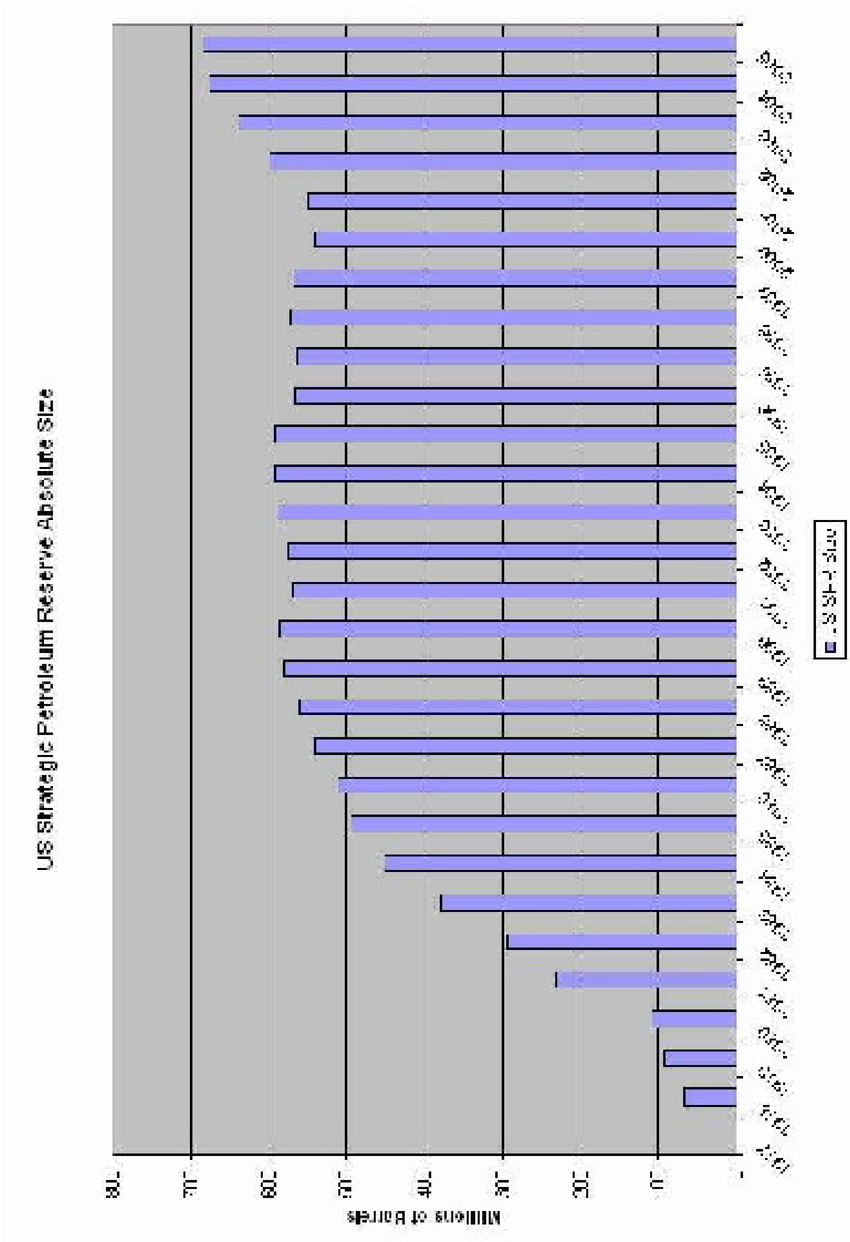

FIG. 1 History of the absolute size of the SPR, in millions of barrels.

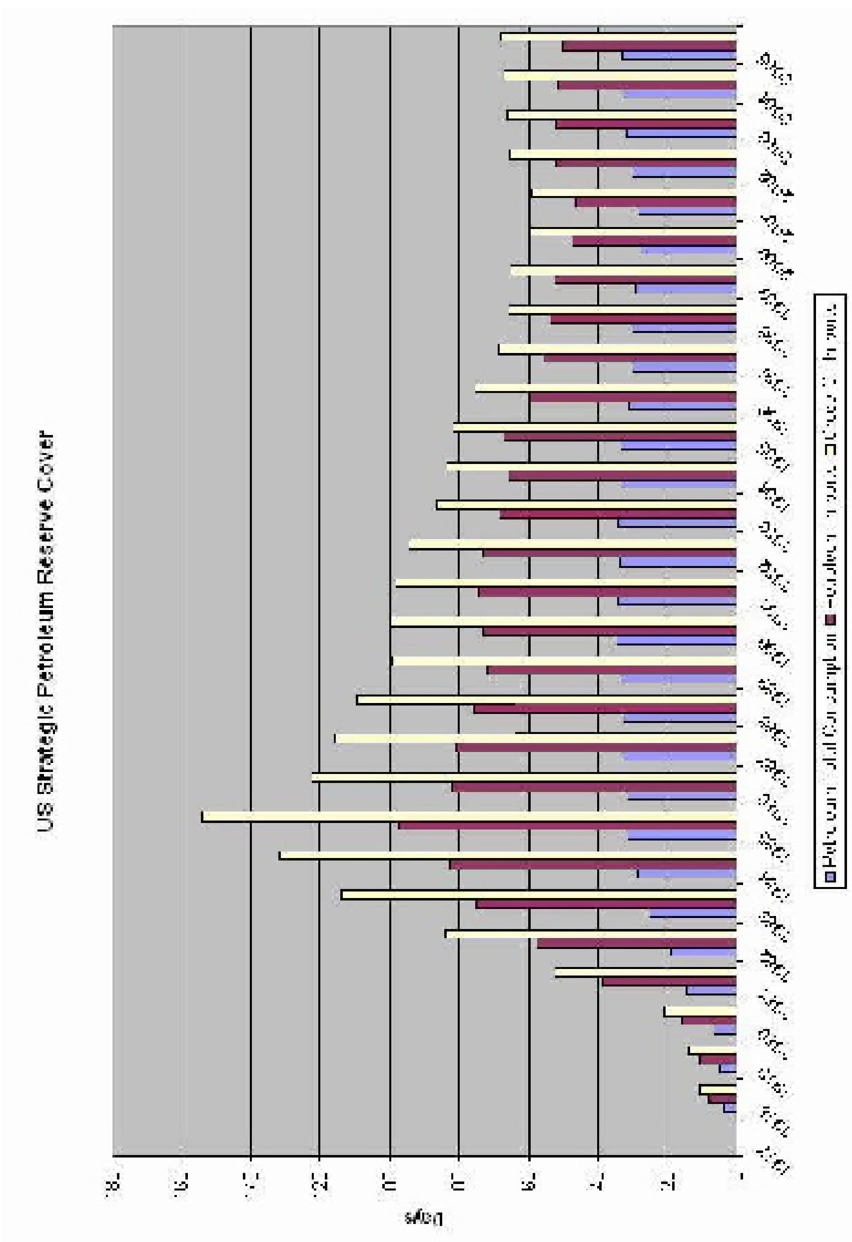

FIG. 2 History of the size of the SPR in days of cover over total consumption, petroleum imports, and crude oil imports.

	δ	γ	ϕ	χ	ϵ_S	ϵ_D	x	m	c^{OPEC}	c^{US}	$\overline{P}$	p	N	$\overline{R}$	$\overline{R}$ (days)
1	**.95**	**.025**	**.408**	**.248**	**.5**	**.5**	**.43**	**.04**	**.1**	**0**	**25**	**.075**	**1.071**	**1.384**	**505.2**
2	.95	.025	**.204**	.248	.5	.5	**.43**	.04	.1	0	25	.051	.761	.957	394.3
3	.95	.025	.408	**.590**	.5	.5	.43	.04	.1	0	25	.160	.882	1.121	409.2
4	.95	.025	.408	.248	.5	.5	.43	.04	.7	0	25	.011	.736	.927	338.4
5	**.75**	.025	.408	.248	.5	.5	.43	.04	.1	0	25	.084	1.013	1.366	498.6
6	.95	**0**	.408	.248	.5	.5	.43	.04	.1	0	25	.073	1.669	2.063	753.0
7	.95	.025	.408	.248	**.25**	**.25**	.43	.04	.1	0	25	.148	1.403	1.884	687.7
8	.95	.025	.408	.248	.5	.5	**.10**	.04	.1	0	25	.018	.774	.976	365.2
9	.95	.025	.408	.248	.5	.5	.43	**.5**	.1	0	25	.081	1.070	1.384	505.2

FIG. 3 Table 1: Numerical Results.