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MANAGING THE STRATEGIC PETROLEUM RESERVE: ENERGY POLICY IN A MARKET SETTING

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INTRODUCTION

Ten years ago the US Congress authorized the creation of the Strategic Petroleum Reserve (SPR) with the intent of bolstering energy security. Today the Reserve stands at over 450 million barrels of oil—a large and potentially powerful policy instrument.

The questions surrounding the Reserve, however, are many, complex, and largely unresolved. This paper examines these questions, in the process reviewing the analytical approaches to resolving them.

The Problems of Oil Supply Disruptions

Supply shocks are a recurrent feature of the modern, petroleum-fueled economy. Six times since World War II the world has witnessed disruptions in the flow of crude oil from the Middle East. In 1953, 1957, and 1967, taking advantage of excess production capacity, governments and oil companies cooperated to patch the system together (1, 2).

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By the 1970s, this excess capacity had all but vanished, save in the areas most subject to disruption. The 1973–1974 and 1978–1979 shocks caused oil prices to skyrocket, and were followed by recession in the industrialized countries. The damage in terms of lost economic growth in the OECD and oil-importing developing countries was staggering. The close historical relation between oil price increases and recession in the United States is documented in (3).

The development of buffer stocks can be seen as an attempt to restore the capability to deliver additional supplies rapidly to the oil market in periods of disruption. Such is the view adopted here. We shall have nothing to say about the military uses of strategic supplies; rather our paradigm is that of political economy. We approach the problem from the standpoint of the United States, but bear firmly in mind the international nature of the oil trade.

The implications of treating the SPR as an instrument of economic policy are several. First, a framework for analyzing how the oil market works is required in order to estimate the Reserve's potential impact on oil prices. Second, we need to understand the relationship between oil price shocks and macroeconomic performance. Finally, we must recognize the SPR's role as but one player in the market arena. The actions of others—oil-exporting countries, the domestic petroleum industry, other importers that hold buffer stocks—can make the difference between a potent SPR and an impotent one.

The Role of Policy

What can be done to alleviate the problems caused by oil supply disruptions? What should be done? These questions are meaningless in the abstract; no policy makes sense in the absence of a clearly articulated goal.

We assume that the goal of policymakers is to advance the economic welfare of the citizenry to the maximum extent possible. Here this implies protecting the economy from oil supply disruptions. Whether this goal stems from altruism or from the desire to remain in office is unimportant for our purposes.

According to the well-known "invisible hand" proposition first put forth by Adam Smith, national economic welfare is maximized when governments allow markets to operate freely. Only when some sort of market failure is present is there justification for public intervention. The case for any energy security policy, be it a Strategic Petroleum Reserve, energy conservation, or anything else, requires a demonstration of market failure.

The justifications for government intervention in the oil market on the grounds that the interests of private agents and the nation are not identical are four:

1. MACROECONOMIC LOSSES These have been substantial in the past (4–6). A large, unanticipated increase in the price of oil generates economic losses for oil-importing nations through cyclical losses in aggregate demand, deteriorating terms of trade, and reduced potential output. The first effect is transitory, and is traceable primarily to downward inflexibility of nominal wages and nonoil prices, and to demand management problems. Related demand-side costs may stem from the redistribution of income among sectors, possibly affecting aggregate demand because of differences in propensities to spend.

The last two effects are more long-term. As oil is a major input to the economy's production process, an oil price increase will reduce potential output, i.e. the output attainable with all resources fully and efficiently employed. Conservation of energy and substitution for energy of other factors of production (e.g. capital and labor) in a free market will reflect adjustments to higher energy costs, but the reduction in energy consumption may lower capital and labor productivity (7).

2. MONOPSONY POWER The United States is a "large player" in the world petroleum market; its actions affect market outcomes. An example is the price-control and entitlements program, which subsidized oil imports in the 1970s, thereby putting upward pressure on world oil prices. Imported oil thus has an additional cost associated with it (sometimes called the "monopsony premium"), inasmuch as increased US imports result in higher prices, and greater wealth transferred abroad.

3. VULNERABILITY The level of national preparedness could affect the likelihood of a disruption (8, 9). This argument clearly applies only to the case of deliberate action taken by foreign powers against the United States.

4. NATIONAL SECURITY The nation's security objectives may cause it to incur foreign-policy and military costs, regardless of whether a disruption is deliberately directed against the United States. An example of such a cost is the maintenance of the Rapid Deployment Force.

Two additional arguments for public intervention are based on imperfections in other markets. Information is the basis for the first; the government could have confidential access to intelligence regarding future supply conditions, and thus be in a position to make better decisions than private agents (10). The second is based on insurance; private agents may fear to act in their own best interests because they cannot insure against a possible public outcry for additional government regulation or taxation (e.g. windfall profits tax) during the disruption, and because of past behavior, the government cannot credibly commit itself to avoiding such actions (11).

The importance of each of these arguments is an empirical question, and will vary according to circumstance. Those who believe that the best energy security policy is to leave everything to the market, however, are obliged to reject them all.

Few analysts favor a public policy of pure laissez-faire. Support for a strategic reserve, possibly in conjunction with other government actions, is based on a mixture of theoretical and practical considerations. The alternatives to augmenting supply in order to lower price necessarily entail discouraging demand or price regulation. The unpalatability of these alternatives is an important factor in favor of maintaining a buffer stock.

Price controls are direct and highly visible, and thus politically attractive. The US experience in the 1970s resulted in unhappiness with price controls (12). Economists' arguments against price controls (apart from innate professional distaste) in a disruption divide into three. First, they discourage additional supply. This argument is weak unless supply is elastic in the short run, which seems unlikely. Second, they discourage conservation when it is most needed. Like the previous argument, this one depends on a short-run elasticity (in this case, of demand). There is an important additional consideration, however; the United States is not autarkic. Given imports as the marginal supply source, increased US demand exerts upward pressure on world prices, which in a disruption are very sensitive. No shortages need result, since only domestic prices are controlled, but demand pressure can raise world prices enough that even the controlled domestic price eventually exceeds the price that would prevail in a free market (13). Finally, price controls redistribute substantial income, creating beneficiary groups (in the past, US refiners and consumers) and making rescission difficult after the emergency has passed.

A short-term, or "disruption," tariff, tax, or quota is designed to exploit US monopsony power. By restricting domestic demand, downward pressure is exerted on world oil prices. In an economy free of macroeconomic rigidities (such as "sticky" wages), these are "first-best" policies for correcting market externalities, and thus improving social welfare. Although such policies are well suited to the objective of easing oil market conditions, they do so at the expense of raising domestic prices still further, thereby aggravating the macroeconomic harm associated with a disruption, and ought to be viewed with extreme skepticism. Nevertheless, they have been seriously proposed (14, 15). It should be noted that a buffer stock can also be a first-best policy response to the market-power externality.

Emergency mandatory conservation and fuel-switching combine the negative aspects of price regulation and demand restriction. That is, they are not only inefficient—since there is no reason that those who can most economically conserve will do so—but also have macroeconomic costs.

Finally, it is worth noting that the SPR is preferable to other forms of intervention on the grounds of political acceptability as well as economics. Past experience has demonstrated that measures that discourage consumption—long lines at gasoline stations, import tariffs, mandatory conservation—are tremendously unpopular as well as inefficient. Indeed, use of the Reserve is the only emergency policy endorsed by the current US administration (16).

Management Considerations

Acceptance of a government role in maintaining a buffer stock opens the door to a host of questions.

SIZE The most obvious consideration is the size of the Reserve. The more oil stored, the more potent the SPR can be in a disruption. The chief criticism leveled at the Reserve, however, is its cost—each barrel must be purchased and stored. If the SPR is seen as a national insurance policy, the question arises: How much insurance is needed?

As important as size is the means by which the size is determined. What factors need to be taken into account? US oil consumption? Oil imports? Oil imports from potentially unstable areas? The likelihood of a supply shock? The behavior of oil prices, should one occur? Prospective damage to the economy? Reactions of other stock managers at home and abroad? Changing circumstances call for a reconsideration of the optimal size.

FINANCE Like any large capital project, the SPR must be financed. To date, roughly $15 billion has been spent. Who should pay the cost? How should the financing be structured? Should those who pay have a say in its disposition?

INSTITUTIONS Maintaining a reserve entails a grab-bag of institutional issues. Although these have little economic significance, they may be important nonetheless. Among such issues are the location and nature of the storage facilities, the type of oil to be stored, the means of procurement, the maintenance of physical and personnel infrastructure, and bureaucratic jurisdiction over planning and implementation.

USE The drawdown decision is arguably the most important of all. A Reserve that is never expected to be used is no better than no Reserve at all.

How should the drawdown decision be made? By a policy rule or discretion? Should price serve as a trigger? Should the size of the shock? Should the Reserve be released immediately, or held back in case of catastrophe? Should releases be announced in advance? Should the size of the drawdown be a policy decision, or left to the market? Should it depend on the behavior of other importing countries?

How should sales of SPR oil be conducted? Who should be allowed to purchase? Should any groups be favored? If so, which, and how? By allocating a fraction of the Reserve? By giving them a subsidy?

HISTORICAL BACKGROUND ON STOCKPILING

Commodities have always been stored (17), both to facilitate smooth operation of distribution systems and in anticipation of future scarcity. Indeed it has become ritual to invoke the biblical tale of Joseph's storing grain against the seven lean years. The division of storage into "operational stocks" and "speculative stocks," although widely made in the literature (18), is not meaningful for analysis. Economists consider all inventory as held for the same purpose—profit maximization—with an associated "convenience yield" that is large for the initial units of inventory, and declines smoothly with size. This framework allows us to dispense with such nonsensical questions as "are stocks near minimum operating levels?"

Private Oil Stockpiling

Recalling that a public stockpile is justified only if market imperfections can be demonstrated, a review of past stockpiling behavior is in order. Table 1 presents data on the inventory-to-sales ratio (where both numerator and denominator have been seasonally adjusted) and the current-dollar and inflation-adjusted marginal cost of crude oil to US refiners[1] over the period 1960–1981. The data in the first column of Table 1 can be interpreted as "days of consumption." An examination of the table reveals a gradual decline in the inventory-to-sales ratio over the period 1960–1972, as stocks were not built as fast as demand increased. The almost flat nominal price indicates a declining real price over the period, and certainly a negative ex-post profit from holding speculative stocks when interest and physical carrying costs are taken into account.

Stocks were built up both absolutely and relative to sales during the period of the Arab oil embargo, and again during the second oil shock

[1] Various regulations have complicated the definition of P^{US} (defined briefly at the bottom of Table 1). A time series was constructed as follows. For the first quarter of 1960 (1960 : 1) to the third quarter of 1973, when the average refiner's acquisition cost of domestic crude oil (*PD*) exceeded the average refiner's acquisition cost for imported oil (*PM*), P^{US} was equal to *PD*. Beginning in the fourth quarter of 1973, *PM* exceeded *PD*, which was kept down by price controls. From the fourth quarter of 1973, through the third quarter of 1974, *PM* was the marginal price of oil. From the fourth quarter of 1974 through the third quarter of 1976, the marginal cost faced by American refineries was measured as *PM* less the value of crude oil entitlements to refineries (*N*), which effectively acted to reduce the marginal cost. Beginning in the fourth quarter of 1976, the price of domestically produced stripper oil was uncontrolled. Therefore, from the fourth quarter of 1976 to the present, we used the price of stripper oil to refineries net of *N* as the marginal cost of oil. For more details, see (12).

Table 1 Quarterly crude oil inventory-to-sales ratio and prices

Year:quarter	I/S	1960–1981 P^{US}	P^{US}/P	Year:quarter	I/S	1960–1981 P^{US}	P^{US}/P
1960: 1	81	3.07	4.49	1971: 1	69	3.58	3.79
2	81	3.07	4.48	2	68	3.64	3.80
3	82	3.07	4.46	3	70	3.67	3.80
4	79	3.07	4.45	4	68	3.67	3.77
1961: 1	85	3.07	4.46	1972: 1	65	3.60	3.65
2	83	3.08	4.45	2	63	3.61	3.63
3	82	3.08	4.43	3	63	3.67	3.66
4	83	3.09	4.44	4	57	3.80	3.74
1962: 1	79	3.09	4.40	1973: 1	56	3.72	3.61
2	80	3.09	4.38	2	58	3.84	3.67
3	82	3.09	4.38	3	56	4.25	3.99
4	80	3.09	4.35	4	60	5.87	5.40
1963: 1	77	3.08	4.31	1974: 1	66	11.59	10.47
2	81	3.08	4.31	2	65	12.93	11.40
3	78	3.08	4.30	3	64	12.65	10.87
4	78	3.07	4.28	4	65	11.25	9.39
1964: 1	81	3.07	4.24	1975: 1	72	10.62	8.64
2	78	3.07	4.23	2	68	10.73	8.62
3	76	3.06	4.19	3	69	11.10	8.83
4	76	3.06	4.18	4	71	11.76	9.12
1965: 1	75	3.06	4.15	1976: 1	69	10.72	8.24
2	75	3.06	4.13	2	66	10.83	8.25
3	73	3.06	4.10	3	67	11.16	8.40
4	72	3.06	4.08	4	62	11.60	8.60
1966: 1	73	3.07	4.06	1977: 1	64	11.48	8.39
2	71	3.07	4.01	2	68	11.36	8.17
3	72	3.08	4.00	3	69	12.02	8.52
4	72	3.10	3.99	4	73	12.45	8.69
1967: 1	75	3.11	3.97	1978: 1	65	12.47	8.59
2	73	3.12	3.97	2	63	12.84	8.62
3	75	3.14	3.96	3	62	13.04	8.58
4	74	3.15	3.93	4	68	13.18	8.48
1968: 1	72	3.15	3.88	1979: 1	59	13.65	8.61
2	75	3.16	3.85	2	64	15.90	9.82
3	75	3.19	3.85	3	66	21.48	13.01
4	74	3.22	3.83	4	70	26.03	15.49
1969: 1	72	3.26	3.84	1980: 1	79	28.90	16.77
2	72	3.29	3.82	2	80	29.14	16.50
3	68	3.33	3.81	3	81	29.01	16.13
4	68	3.36	3.80	4	78	29.87	16.13
1970: 1	67	3.37	3.75	1981: 1	88	38.72	20.38
2	68	3.40	3.73	2	84	37.76	19.55
3	67	3.44	3.75	3	78	35.95	18.22
4	70	3.50	3.76	4	84	35.86	17.79

Notes: I/S = inventory-to-sales ratio (of seasonally adjusted quantities); P^{US} = marginal cost of crude oil to US refiners in dollars per barrel (construction described in footnote 1); P = GNP deflator (1972 = 1.000).

(Figures 1 and 2). The data for 1979–1981 point up difficulties in trying to isolate a speculative motive in oil inventory demand. It has frequently been stated that oil inventory levels were low prior to the interruption of oil supplies in Iran. Table 1 shows, however, that in the third quarter of 1978, the quarter before supplies were disrupted, inventory levels were not abnormal. The inventory-to-sales ratio did not fall to historically low levels until the end of the first quarter of 1979. This drawdown indicates not necessarily that oil companies were unprepared for a disruption, but rather that inventories may have been used to offset the supply reduction during the initial months. The recent downturn in oil prices, in combination with high interest rates, has encouraged oil companies to reduce their inventories.

This drawdown has occurred, but more slowly than many observers had expected—a likely consequence of a number of factors. First, oil demand has fallen short of what oil companies had predicted, leaving them with large quantities of unsold oil in inventory. Working through a standard oil demand function, companies may have underestimated the responsiveness of demand to higher prices (price elasticity) and the severity of the current recession. Second, if demand is weak, inventory reduction requires a reduction in oil purchases by oil companies. Such reductions may be limited in the short run by contracts or, in the case of the Aramco partners, by a special relationship with the producing country.

Public Oil Stockpiling in the United States

A brief review of the institutional history of the SPR will prove useful for subsequent analysis; a detailed discussion can be found in (19). The US government took its first step toward decreasing the growing dependence on foreign oil during the Eisenhower administration. After implementation of an unsuccessful voluntary program designed to decrease dependence, President Eisenhower acted under authority of the Trade Agreements Extension Act of 1955, establishing a quota system that remained in place until 1973.

In July 1973, the National Petroleum Council issued a report recommending that a stockpile of 540 million barrels of oil be secured in salt domes by 1978, enough to protect the United States from a supply disruption of the magnitude and length of 3.0 million barrels per day (bbl/d) for a six-month period (20). Also in 1973, Senator Henry Jackson introduced the Petroleum Reserves and Import Policy Act, calling for a strategic petroleum reserve of government-owned stocks held in salt domes.

During the debate over the Jackson proposal, events in the Middle East made apparent US vulnerability to foreign oil supply fluctuations. Soon after followed the Arab oil embargo. In 1974, President Nixon announced

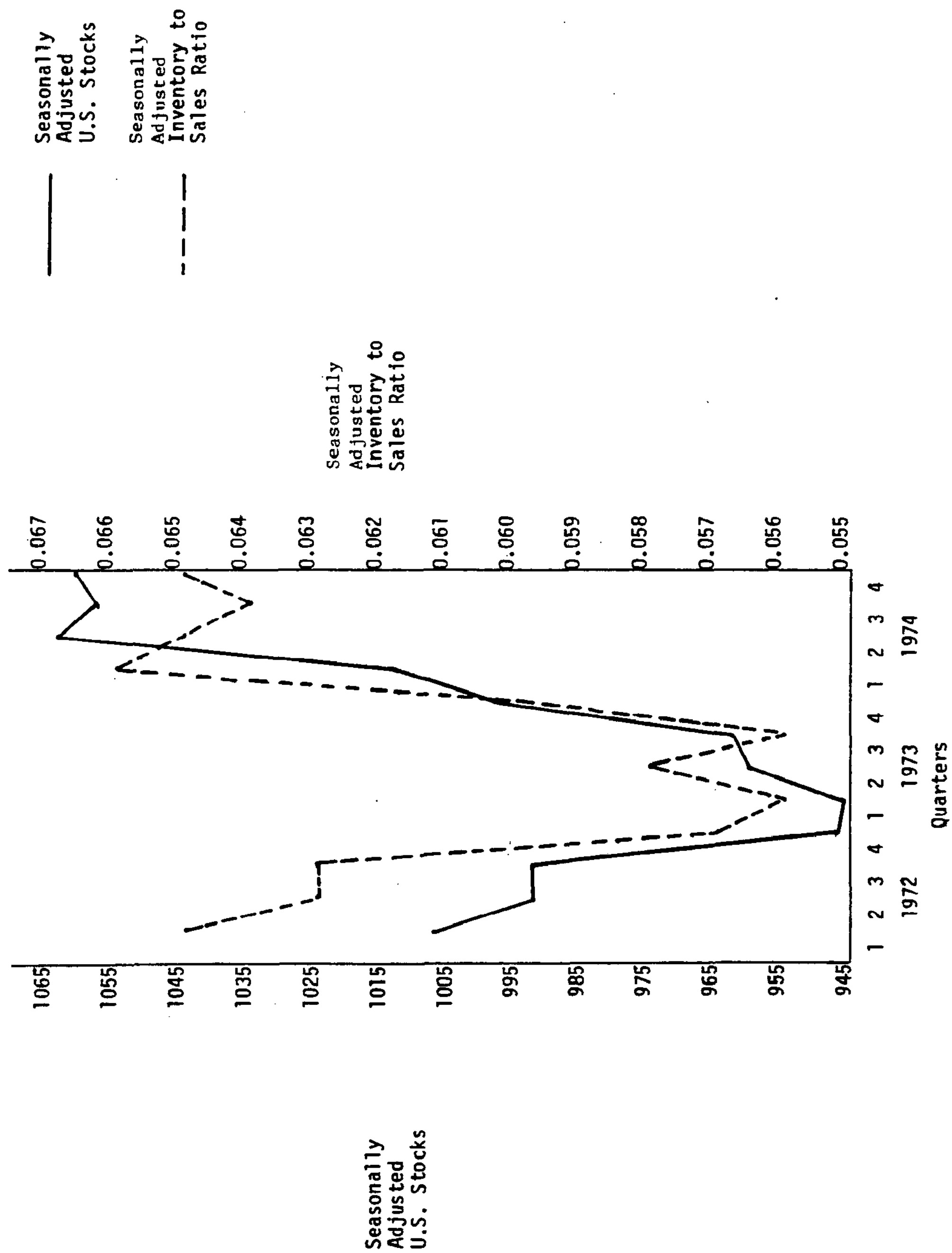
Project Independence, which required the United States to be energy self-sufficient by 1980. The Project Independence report mentioned several fundamental concerns. First, the report listed the key considerations in designing a storage system: the type and location of the system and the size of the stockpile, in relation to the probability, magnitude, and duration of cutoffs. The report also included the two major costs, i.e. the economic costs of supply disruption and the costs of a stockpile necessary to buffer a disruption.

Finally, on December 22, 1975, President Ford signed into law the Energy Policy and Conservation Act (PL 94-163). The EPCA required that the Federal Energy Administration (FEA) submit a plan for implementation of the Early Storage Reserve within 90 days. Further, the FEA had to submit a comprehensive plan of the Strategic Petroleum Reserve by December 15, 1976. In April 1977, actual implementation of the SPR began. In addition, the Carter administration announced its plans to accelerate and expand the SPR program.

Difficulties in implementation came soon enough, however (20). Appeals to reduce SPR funding came from the Office of Management and Budget in 1978. In fact, not only was SPR oil not released following the Iranian revolution, but filling continued through August 1979. For a full year thereafter, there were no additions to the Reserve.

One of the reasons for this outcome was international political pressure. Though the SPR had little political opposition at home, it raised political problems at the international level. In the spring of 1979, US Government sources began leaking to the press that Saudi Arabia was threatening to cut its oil production by 1 million bbl/d if oil for the SPR were purchased. The Saudis claimed that US stockpiling purchases added to world oil demand and price pressure, undercutting their attempts to control OPEC's pricing policy. The US Department of Energy (DOE) was thus placed in the uncomfortable position of explaining away SPR purchases. It wanted neither to increase world demand or prices nor to aggravate the Saudis (whose 1 million bbl/d increase in production was helping to soften the shortfall caused by the collapse in Iranian production). Thus, the purchasing of reserve oil was halted or "delayed," as government sources claimed, until the world oil situation settled down.

The moratorium on filling the Reserve lasted from spring of 1979 through September 1980. Congress finally took steps to resume oil purchases through the Energy Security Act of 1980 (PL 96-294, 94 Stat. 932), urging the adoption of a fill rate of at least 100,000 bbl/d. By the end of 1980, the reserve contained only 107.8 million bbl of crude oil, well short of even revised schedules. Consequently, in 1981 Congress requested that the President "seek" to fill the reserve at an increased rate of 300,000 bbl/d. The


Seasonally Adjusted U.S. Stocks
Seasonally Adjusted Inventory to Sales Ratio
Seasonally Adjusted Inventory to Sales Ratio
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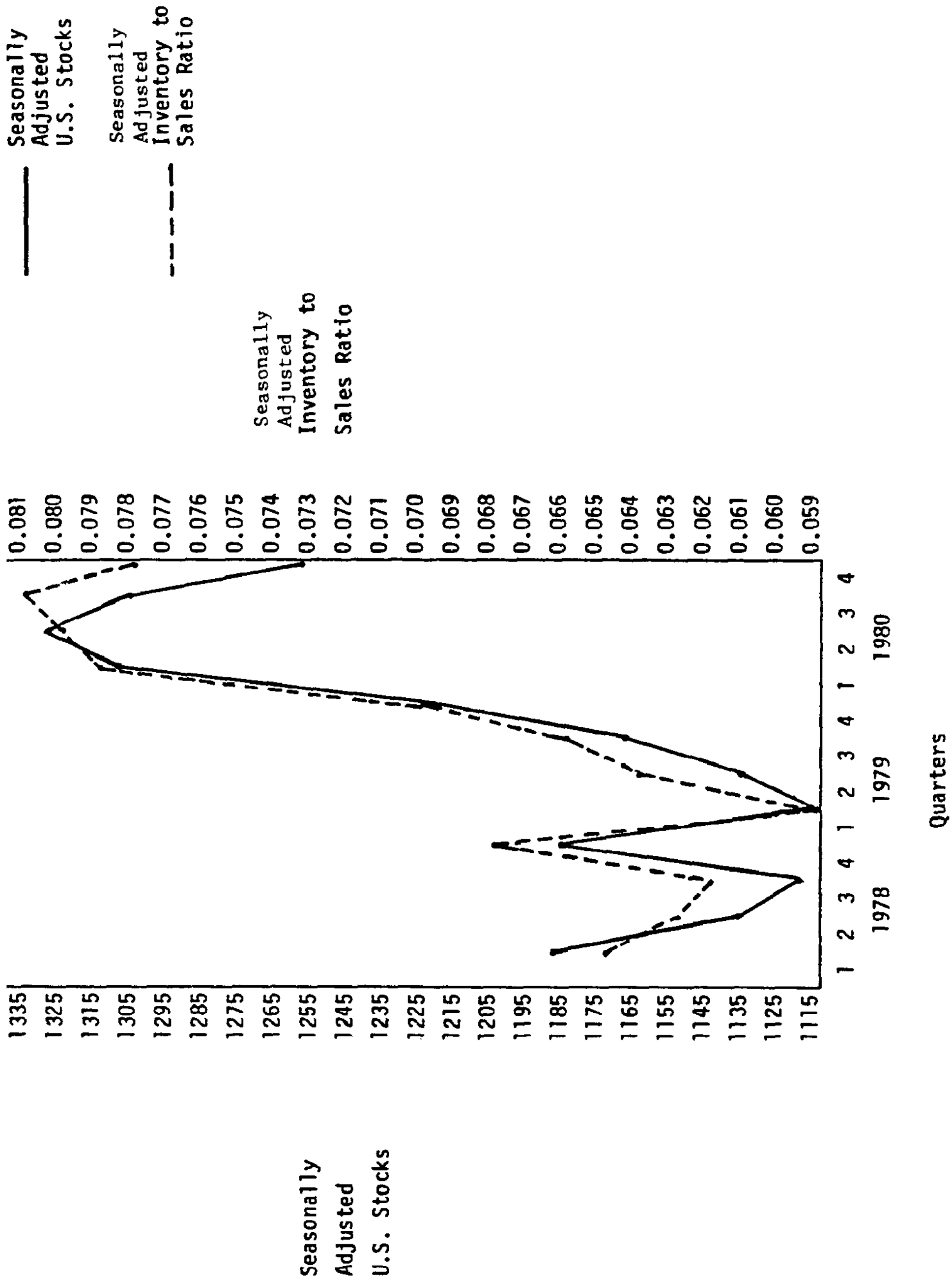
1065
1055
1045
1035
1025
1015
1005
995
985
975
965
955
945
1 2 3 4 1 2 3 4 1 2 3 4
1972
1973
1974
Quarters
Seasonally Adjusted U.S. Stocks

Figure 1


Seasonally Adjusted U.S. Stocks
Seasonally Adjusted Inventory to Sales Ratio
Seasonally Adjusted Inventory to Sales Ratio
0.081
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Seasonally Adjusted U.S. Stocks
1335
1325
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1295
1285
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1225
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1205
1195
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1165
1155
1145
1135
1125
1115
1 2 3 4 1 2 3 4 1 2 3 4
1978 1979 1980
Quarters

Figure 2

Reagan administration initially provided strong executive support for the SPR and oil was put into the reserve at an unprecedented rate. Oil in storage by the end of 1981 reached 230.3 million bbl. In addition, funding for the SPR was transferred to an "off-budget" Treasury account.

In 1982, to reduce federal expenditures, the administration proposed to slow down the fill rate from over 300,000 bbl/d to just over 200,000 bbl/d, moving the final completion date from 1989 to 1990. In addition, oil fill had rapidly caught up with available storage space. By the end of 1982, 300 million bbl were in the SPR. (By the end of 1983, 379 million bbl of oil had been accumulated.)

In 1985, with 450 million barrels in place, the SPR has become the principal tool with which the administration can deal directly with an oil disruption. In fact, it represents President Reagan's only activist energy policy, reflecting the administration's view that the energy market functions best with as little government intervention as possible [see the discussion in (21)]. Table 2 records the growth of the SPR from the beginning of 1978 through the end of 1983.

The SPR's current level and facilities permit a maximum drawdown rate of 2.1 million bbl/d for approximately 90 days, or 1.7 million bbl/d for around 150 days, after which the rate would progressively decline. Assuming a 6 million bbl/d import rate in the entire year of 1984, the drawdown would be equivalent to 35% of the imports for 90 days, or 28% for the 150-day period.

Public Oil Stockpiling Abroad

Primary OECD inventories, which stood at just over 3 billion barrels at the beginning of 1984, play a role in balancing short-run supply and demand fluctuations. As in the United States, strategic stocks are set aside (usually under government control) in Japan and Western Europe for potential use during a crisis. Government intervention has followed three approaches: (*a*) the US-style approach with the establishment and control of reserves by the government, (*b*) the establishment of minimum required stock levels to be held by private companies, and (*c*) creation of public corporations to finance and manage emergency stockpiling programs. A summary of the stockpiling programs employed in major consuming countries that are members of the European Economic Community (EEC) and the International Energy Agency (IEA) appears below in Table 3. A summary of the size of stocks in the OECD Big 7 (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) is given in Table 4 below.

Only Canada and New Zealand have no official program; some others are implementing more than one of the three approaches. With the

Table 2 Size of the US strategic petroleum reserve

(millions of barrels)
1978–1984

Year : month	Stock level	Year : month	Stock level	Year : month	Stock level	Year : month	Stock level
1978 : 1	11.1	1980 : 1	91.2	1982 : 1	235.0	1984 : 1	384.0
2	14.3	2	91.2	2	241.0	2	387.0
3	17.1	3	91.2	3	249.0	3	392.0
4	21.8	4	91.2	4	256.0	4	397.0
5	25.6	5	91.2	5	261.0	5	404.0
6	30.1	6	91.2	6	264.0	6	414.0
7	35.2	7	91.2	7	267.0	7	424.0
8	41.0	8	91.2	8	274.0	8	429.0
9	47.1	9	92.8	9	278.0	9	431.0
10	53.1	10	96.6	10	285.0	10	438.0
11	59.3	11	102.3	11	290.0	11	443.0
12	66.9	12	107.8	12	294.0	12	451.0
1979 : 1	73.1	1981 : 1	112.5	1983 : 1	301.0		
2	78.2	2	116.1	2	306.0		
3	82.5	3	120.9	3	312.0		
4	83.9	4	134.2	4	318.0		
5	86.9	5	150.1	5	327.0		
6	88.6	6	163.1	6	332.0		
7	90.1	7	173.1	7	341.0		
8	91.2	8	184.7	8	352.0		
9	91.2	9	199.2	9	361.0		
10	91.2	10	214.8	10	367.0		
11	91.2	11	222.5	11	371.0		
12	91.2	12	230.3	12	379.0		

Source: US Dept. Energy, *Monthly Energy Rev*. (various issues).

Table 3 Government emergency reserve programs of EEC and IEA member nations

	Industry compulsory	Government owned	Public corporation	No program
Australia	×	—	—	—
Austria	×	—	—	—
Belgium	×	—	—	—
Canada	—	—	—	×
Denmark	×	—	×	—
France	×	—	—	—
Germany	×	×	×	—
Greece	×	—	—	—
Ireland	×	—	—	—
Italy	×	—	—	—
Japan	×	×	—	—
Luxembourg	×	—	—	—
Netherlands	×	—	×	—
New Zealand	—	—	—	×
Norway	×	—	—	—
Portugal	×	—	—	—
Spain	×	—	—	—
Sweden	×	×	—	—
Switzerland	×	—	×	—
Turkey	×	—	—	—
United Kingdom	×	—	—	—
United States	—	×	—	—

Source: (22).

exception of the United States, all have used the compulsory program for industry, mandating the amount of stocks that companies must maintain for use during emergencies. The public stockpiling policies of some of the major oil-importing countries are discussed in more detail in Appendix A.

Institutions for International Stockpile Coordination

A broad consensus holds that international cooperation in meeting oil shocks is at the same time essential and damnably difficult. Among the OECD countries, cooperation is under the aegis of the International Energy Agency (IEA).

It is not our task here to provide a detailed critique of past IEA actions; suffice it to say that consumer cooperation has not always been a resounding success. Indeed it has sometimes proved difficult to detect. The relevant regulations are codified in the International Energy Program,

Table 4 Stock-consumption ratios for the OECD (Big 7)

(days of consumption)
1973–1983

Year: quarter	Canada	France	Germany	Italy	Japan	United Kingdom	United States
1973	93	91	NA	NA	61	80	58
1974	101	115	89	111	76	104	64
1975	104	124	82	97	82	100	69
1976	95	111	85	94	82	103	64
1977	101	121	91	109	82	89	71
1978	85	97	92	99	81	93	68
1979	85	107	102	101	89	100	72
1980: 1	85	100	118	89	79	98	73
2	103	119	126	108	104	122	85
3	108	176	131	123	123	144	90
4	96	120	144	109	104	117	82
1981: 1	96	110	139	83	90	117	81
2	110	143	163	109	126	131	91
3	111	172	145	119	118	127	94
4	103	116	140	103	104	104	93
1982: 1	98	115	129	90	96	90	87
2	104	122	151	101	128	111	88
3	93	146	144	115	121	110	94
4	93	120	140	109	109	95	95
1983: 1	97	104	132	95	97	89	95
2	89	102	132	106	115	95	94
3	85	131	140	111	110	99	96
4	80	93	127	85	103	95	95

Source: Calculated from *Monthly Energy Rev.*, various issues.

signed by the United States in 1974. The details are too involved to present here [see (23)], but the salient points are three. First, countries are required to hold buffer stocks in proportion to their imports. Second, the agreement is dormant until a determination of emergency is made. (The emergency is signaled by a shock large enough to reduce supply by 7% compared to its preshock value. In practice the time unit is the quarter, and the preshock value is a moving average of the previous four quarters.) Third, the agreement calls for countries to "restrain demand" by 7% (through taxes, tariffs, regulation, exhortation, etc.) and substitute buffer stock releases in making up any remaining loss in supply (e.g. a 10% reduction in quantity supplied calls for 3% to be made up by stockpile releases in addition to the 7% demand restraint). The scheme's monopsonistic intent is clear.

Various technical problems with such a program have been pointed out in the literature; here, we take note of two broader difficulties. First, the 7% threshold corresponds to a severe disruption. Assuming oil consumption of roughly 50 million bbl/d in the noncommunist world, and taking the IEA share of consumption as constant,[2] a loss of 3.5 million bbl/d (net of increased exports by other producers) is necessary to trigger the emergency mechanism. The Iranian crisis, during which oil prices more than doubled, was of considerably lesser magnitude. Second, demand restraint proved easier said than done; the March 1979 agreement to cut consumption by 5% was honored more in the breach than in the observance.

Among the lessons to come out of the 1979 and 1980 supply shocks was that while high stockpile levels are a sine qua non for the functioning of international sharing agreements, it is the drawdown (or buildup) behavior that is likely to spell the difference between containment and disaster. Another is that actions taken in a so-called sub-trigger disruption (one falling beneath the threshold) may serve to avert a 1979-style catastrophic price run-up. Demand restraint's having failed, the economic damage attending a sub-trigger disruption has called forth proposals for coordinated drawdown programs.

In evaluating SPR drawdown strategies, international coordination considerations must be kept in mind. How effective would SPR draw be in relieving pressure in the world oil market if other IEA members do not do likewise? Or, even worse, what if some countries fill while others draw?

ANALYSIS OF STOCKPILE POLICY

The Strategic Petroleum Reserve represents a source of supply (or demand, depending on whether it is being released or filled) in the oil market. To evaluate its role, it is essential to have a framework for describing the behavior of the other participants—and hence of prices—in the market. This is not the place for a treatise on oil market modeling, but a quick review will be helpful in understanding the discussion of stockpile policy that follows.

Modeling the World Oil Market

Models of the world oil market fall into two categories. Long-run models are based on dynamic optimization; producers maximize the present value of income subject to demand conditions. While well-suited to examining depletion and long-term price evolution, these models perform systematically poorly in accounting for short-term price perturbations (24).

[2] This will be strictly true only if the elasticities of demand in the IEA and the noncommunist world as a whole are equal.

The question of "what causes oil price shocks?"—that is, how does the market behave in the very short term?—has not been resolved satisfactorily (25). Modelers are confronted with a world wherein inventory fluctuations can play a critical role, spot prices and official government selling (i.e. contract) prices may diverge widely, and information disseminates slowly compared to the speed of market events.

The "facts" to be explained are the enormous price increases of 1973–1974 and 1978–1979, and the absence of one in 1980, despite the fact that the three shocks [OAPEC (Organization of Arab Petroleum Exporting Countries) embargo, Iranian revolution, Iran-Iraq war] were of the same order of magnitude. It should be clear that the causes of an oil price shock must be addressed in order to evaluate the SPR's efficiency in alleviating it.

The explanations offered for the price shocks are several. First, the oil market was cartelized by the Organization of Petroleum Exporting Countries (OPEC) in the early 1970s (26–29). Second, the decline in new discoveries, pessimistic perceptions regarding alternatives, and ever-increasing demand forced prices higher; OPEC merely validated the new scarcity (30, 31; 32 agrees for 1973–1974, but cites monopoly power for 1978–1979). Third, the market is competitive, but the supply curve is backward-bending; the higher the price received, the less oil will be produced (33–35). Fourth, the market is competitive, but the replacement of the multinational companies by nationals with lower discount rates resulted in a decline in production (because oil in the ground would now be worth more), and hence, higher prices (36, 37). Although each of these theories contains elements of plausibility, and each has its vocal adherents and detractors, none provides a completely convincing characterization of the market, and none can explain price behavior over the last 10 years.

Some assumption about market structure is needed if the SPR is to be evaluated. The exercise is usually undertaken through the use of a "stockpile premium"—the value to society of a barrel added to the Reserve, above and beyond the purchase price of this additional barrel.

While the idea of such a premium is legitimate (although not necessarily important for policy), the methodology employed to calculate it is not. The premium—along with its similarly questionable companion, the "import premium" (the cost to society of the marginal barrel of imported oil above and beyond its purchase price)—is typically arrived at by assuming that the oil market is competitive (38, 39). As noted above, the competitiveness of the oil market is far from manifest. In such cases, it is necessary to establish the robustness of the calculations under various market structures. That this is not done presumably owes to the fact that the problem must be set up differently under the different market regimes.

The second oil shock could not be predicted or explained by these theories, spawning further attempts to characterize oil market behavior in the short run. A prototype model had been built by Gately, Kyle & Fischer (40), in which unused production capacity resulted in exporters' lowering prices; prices were raised as producers approached their capacity constraints. Although the pricing rules offered were ad hoc, this approach succeeded in formalizing the notion of a "tight" market. It did not, however, address the critical role of inventories.

Attempts were also made to capture the dynamics of spot and long-term contract pricing, and their interaction. The "ratchet theory" (41, 42) described the process this way: In the absence of supply shocks, spot and contract prices are flat. A supply shock raises spot prices, whereupon oil-exporting countries respond by increasing their official contract prices. When the shock eases, the exporters cut production to maintain the higher prices. Thus prices evolve by remaining constant most of the time, but "ratcheting upward" periodically. The implications for SPR policy are clear: quashing the initial ratchet lowers oil prices permanently.

This model has two serious problems. The first is suggested by this "free lunch" aspect of SPR release: The ratchet theory is lacking in economic rationale, since the behavior ascribed to exporters is internally inconsistent. The second objection is even more basic: Under the ratchet, oil prices can never fall. That the theory appears foolish today could easily have been anticipated, since all commodity prices have risen and fallen periodically since time immemorial. Nevertheless, the ratchet appears to have been taken seriously for a while.

A related, somewhat more sophisticated approach to spot and contract pricing was first suggested in the copper market (43), and later adapted to the oil market (14). Under this analysis supply shocks register first in the spot market, and are reflected in contract prices only with a lag. No motivation is offered for this behavior, however; thus the recommendation for SPR policy—release as much as possible as soon as possible in order to damp the initial spot price run-up—stands on shaky ground. The model is at least internally consistent; OPEC does not exert market power, but rather acts competitively. Although the model is unsatisfactory as an explanation of pricing behavior in the oil market (25), it can be made to fit the data well, and has been used in a number of empirical studies (44–46).

The faults in our models of the oil market run deeper, however. Once we admit the possible divergence of spot and contract prices, no longer can we assert the traditional economist's view that "the world oil market, like the world ocean, is one big pool" (47). Would that it were, for then arbitrage would immediately eliminate spot-contract price differentials, making the modeler's job easier.

The other extreme assumption—that embargoes against particular countries, and "access" to oil supplies, make sense—is simply unbelievable in a market as large and liquid as world oil. The 1973–1974 shock was spread roughly evenly across importing countries (48). Warnings of dire consequences due to increasing "rigidities" since then (49) have a curious Chicken Little aspect to them; since an analytical framework is lacking, it is unclear even what would constitute supporting evidence. Unfortunately, although the effects of buffer stock policy are sensitive to assumptions about the ease of reshuffling trade patterns, we are just beginning to model the case intermediate between the "no transaction cost" and "infinite transaction cost" poles (50).

Inventory behavior presents additional difficulties for oil-market modeling. The importance of oil inventory demand, which fell during the last shock but climbed sharply during the previous two, is widely acknowledged. A satisfactory explanation for inventory behavior remains elusive, yet is critical in assessing the private sector's response to public stockpile policy. For example, the SPR will be rendered impotent if its releases are hoarded by private stockholders. Without a model of their behavior, however, it is impossible to predict how these agents would react to an SPR release.

Inventories always smooth shocks in a well-functioning market (51), by reallocating supplies to periods when they are valued most. Claims that stock accumulation ("hoarding") by private agents exacerbated the 1979 shock (14, 41, 52) depend on these agents' acting irrationally—i.e. "buying dear and selling cheap" (not a very promising explanation)—or on some unspecified market imperfection that allows inventory accumulation in the anticipation of higher prices, yet prevents arbitrage from eliminating these speculative profits immediately.

Size

How large should the Reserve be? Answering this question entails solving three related problems: First, how will the Reserve be used? Drawdown policy is discussed below; size studies typically assume the SPR will be used optimally. Although the assumption itself is questionable, it is useful methodologically, and serves to calculate an upper bound on the optimal size of the stockpile. Inferior drawdown strategies will reap fewer benefits, which implies a smaller Reserve, assuming decreasing marginal returns to size.

Second, how will releasing the SPR benefit the economy? Answering this question requires a model of the oil market, as discussed above, as well as a model of energy-economy interaction. Simply treating gross national product as a function of oil prices (53) is inadequate; a production-function (microeconomic) or income-expenditure (macroeconomic) approach, or both, is required.

The final, and hereunto most difficult, problem with which to grapple is the characterization of uncertainty. The correct approach is stochastic dynamic programming, which entails calculation of the best fill-cum-draw strategy at each point in time, given expectations of the entire future path of oil prices. Such a calculation is prohibitively difficult, and has been solved only by reducing the oil market to a very small number of states—typically two (54) or three (55, 56) that correspond to a disruption's being "on" or "off" (or "small" or "large" in the latter case)—and introducing a Markov transition matrix describing the probabilities of moving between states.

Unfortunately, while Markov matrixes are appropriate for discrete systems, the oil market is not characterized by being "disrupted" or "normal"; supply and demand are continuous, and thus so are prices. Envisioning it this way is apt to be misleading, and misses entirely the dynamic issues discussed above. Nevertheless, in the absence of more realistic models, this approach is useful in generating estimates of optimal stockpile size.

The benefits stemming from a Reserve must be compared with its costs in order to determine the optimal size. These costs comprise the purchases of oil to be stored, the increase in world oil prices resulting from these purchases, the interest paid on capital borrowed to make the purchases, the purchase or development costs of storage capacity, and the operation and maintenance costs of the storage program.

Given the diverse assumptions and methodologies used to attack the three problems listed above, it is encouraging, as well as surprising, that the recommendations regarding SPR size fall in a relatively narrow band. A survey by the National Petroleum Council (57) found that of 20 studies conducted in the 1970s, all but two suggested figures between 500 million and 1000 million barrels, with the more recent recommendations in the upper half of this range. Analyses conducted in the early 1980s, when the climate appeared most menacing, recommended sizes of 750–2000 million barrels (55, 56, 58, 59).

These analyses assume a perfectly competitive oil market. That the dynamic programming models returned verdicts similar to those of the most "naive" models, which employ a fixed supply (e.g. 58), suggests that future research should adopt a simplified characterization of uncertainty, and instead focus on alternative models of oil market structure. Indeed, even stockpile models with no uncertainty (8, 9, 60) afford considerable insight into the roles played by market power and strategic behavior. One approach is to have the shocks follow a low-order autoregressive process, thereby capturing much of the complicated transition matrix apparatus in one or two parameters (50).

Finance

Demonstration of the public good aspects of public strategic stockpiling of oil points up the need to consider ownership of SPR oil in the context of the economy's portfolio of assets. Modern theories of the valuation of capital assets (61, 62) emphasize the importance of not only the mean return on an asset, but also the covariance of that return with that on the market portfolio as a whole. Given that oil price increases have been associated with losses in real income and declines in aggregate wealth, the return on SPR oil is likely to be negatively correlated with the return on financial assets. That is, claims to SPR oil have a high payoff in states of nature in which other sources of income are low. Ownership of SPR oil may thus be advantageous for purposes of portfolio diversification.

Apart from the issue of the optimal size of a public oil stockpile, the question of how the stockpile is to be financed arises. That is, given that the economy as a whole gains from the existence of an SPR, but that individual risk preferences may be different, are taxpayers better off with compulsory or voluntary participation in an SPR investment program? Certainly to the extent that public oil stockpiling shifts ownership of stocks from private interests demanding a positive risk premium to taxpayers who because of macroeconomic costs of oil supply disruptions demand a negative risk premium, the overall allocation of risk is improved. [See (63) for further discussion.]

Complete financing of SPR acquisitions by the government may be unnecessary. In addition to taxpayer financing of public benefits, private benefits can also be financed through oil-denominated equity or bonds. By allowing a market allocation, these types of private ownership would act to equalize the risk premium across agents in the economy.

Under the former, or public capitalization, approach, the government would sell to the public certificates entitling the bearer to a set quantity of oil (in the SPR). These certificates would be bought, sold, and traded in secondary markets, much as common stocks are traded today. Investment returns would be determined exclusively by changes in the market price of oil.[3] Under the latter (debt financing) option, the federal government would

[3] Institutionally, the public capitalization proposal allows for maximum government control, since the SPR administration is left with sole charge of drawdown management. Possible pressure to draw down the SPR when certificate holders wish to "cash in" at (what they consider) peak value should be compensated for in an active secondary market. Certificate holders would be free to sell at any time, and as long as investors remain confident in the SPR's ultimate survival, prospective buyers should be plentiful.

issue a new series of bonds whose sole purpose would be to raise funds to finance the SPR. Various suggestions have been made as to the potential yield of such bonds, including return tied to the rate of oil price appreciation, and return connected with the prevailing market interest rate.[4]

In addition to the options outlined above, two dirigiste alternatives are possible—development of an Industrial Petroleum Reserve (IPR)[5] or mandatory private contributions to the SPR.[6] Regardless of the alternative, the proper way to view the financing issue is through an economic analysis of the benefits (public and private) of ownership of SPR oil as an asset. Discussions of whether the SPR should be financed "on budget" or "off budget" merely reflect the fact that "current account" and "capital account" components are not distinguished in the federal government budget.[7]

Drawdown: The SPR and the Oil Market

The issues surrounding drawdown are perhaps the most difficult analytical facet of a study of the Strategic Petroleum Reserve. Before considering some specific options for stock release, we examine three related areas of inquiry that will determine the effectiveness of the SPR as an economic policy instrument—(*a*) market structure, (*b*) expectations (about the likelihood of future

[4] New bond issues may or may not provide a steady flow of income for the SPR. If the bond return is linked to some fixed long-term interest rate, the inflow of capital should be stable. However, a return based on oil price appreciation would make budget planning more difficult (as oil price forecasts would be necessary). Should the sale of bonds collect less than the expected revenue, direct federal outlays would be required to meet the shortage. Furthermore, upon drawdown of the SPR oil, oil prices would have to have increased by more than the rate of interest paid, or the sale of reserves would not cover the cost of establishing and administering the SPR. The difference would be absorbed in the government budget deficit.

[5] Numerous proposals have been put forth to outline how the government could elicit industry participation in an IPR.

(*a*) The President could require all importers and refiners of foreign oil to store up to 3% of their annual consumption in an "emergency inventory" ("decree" option).

(*b*) The government could provide financial incentives (in such forms as tax credits and direct subsidies) to firms if they would increase their inventories of stock crude oil ("incentives" option).

(*c*) The government could require that each firm be responsible for storing a set amount of oil. Firms could store the oil themselves or see to it that somebody else stores it for them. So long as a firm could account for its required share, the government would not distinguish between the two (the "sufficient evidence" option).

[6] This agenda calls for firms that import, refine, or domestically produce oil to be directed by the government to make specified amounts of oil available for use by the SPR. The government could either allow the firms to bear this cost (to the degree that they would be unable to pass the costs on to the oil-consuming public), or it could subsidize them.

[7] This is not to deny the political importance of the issue.

shocks or the duration of present ones), and (*c*) the reaction of domestically held private stocks and foreign public stockpiles to announced and unannounced SPR policy. We consider below these three areas together in a simple theoretical model emphasizing the joint determination of oil prices and private and public inventory decisions. While the framework is simple (and described in more detail in Appendix B), it yields predictions for the response of private stocks to public stock changes and for the chances of success of international stockpiling agreements. We then take an example of the model and combine it with an econometric model of the US economy to test some of the predictions in simulation exercises.

I. PRIVATE STOCKS AND OIL PRICES To study the interaction of public and private stocks, we begin with a stylized model of the short run. Detailed description of the model is presented in the Appendix; only a summary is given here. Throughout, we suppose that oil production and consumption are responsive to the current period price, and are subject to transitory supply and demand shocks.

Of course, total demand is the sum of consumption and inventory demand. Speculators trade in inventories on the spot market in anticipation of changes in price and are assumed to maximize expected profit from speculation.[8] Holding stocks is assumed to be costly—in fact, increasingly costly—in the size of the stock due to payments to factors fixed in the short run, such as storage facilities, tankers, and pipelines. Thus changes in price expectations cannot be fully acted upon instantaneously. The optimization problem described here yields speculative holdings as a function of the expected increase in price, taking into account the cost of adjusting stock levels.

Since quantities demanded and supplied in the market must be equal in equilibrium, the assumptions about the behavior of consumption, speculative stockpiling, and production can be used to determine the market (spot) price. Under simplifying assumptions of linear supply and demand functions, the rational expectations solution for the price P can be written as

$$P_t = \psi P_{t-1} + \beta(\varepsilon_{Dt} - \varepsilon_{St}), \qquad 1.$$

where ε_D and ε_S represent the transitory demand and supply shocks, respectively.[9] ψ and β are functions of the parameters of the system—the

[8] That is, they are assumed to be risk-neutral. The assumption of risk neutrality is not necessary for the results that follow; it merely simplifies the exposition.

[9] That is, ε_D and ε_S are independently and identically distributed with mean zero and variance σ_D^2 and σ_S^2, respectively.

price responsiveness of production and consumption and the cost of adjusting stock levels.

Explaining the persistence effect of oil shocks is important for understanding the impact of energy policy interventions. Here even transitory shocks exhibit persistence effects on the price because of the behavior of inventories. It can be shown (see Appendix B) that the more price-responsive is consumption, the smaller is the initial increase in price from a supply shock and the lower is the persistence. Hence, policies such as oil import tariffs or certain types of buffer stock stabilization policies (which effectively raise this price responsiveness) can mitigate both the impact and the long-run effects of transitory shocks on prices.

Equation 1 can be used to motivate empirical work and simulation exercises, as we demonstrate below. As a qualification, while this discussion illustrates the importance of private speculative stockpiling for analyzing the behavior of oil prices during supply disruptions, consideration of the SPR and of realistic disruption scenarios requires an examination of serially correlated quantity shocks. Suppose that demand and supply shocks follow first-order autoregressive processes, so that

$$\varepsilon_{Dt} = \rho_D \varepsilon_{Dt-1} + v_{Dt}, \quad \text{and} \qquad 2.$$

$$\varepsilon_{St} = \rho_S \varepsilon_{St-1} + v_{St}, \qquad 3.$$

where v_{Dt} and v_{St} are white noise and $\sigma_{v_D v_S} = 0$.

Given this structure of shocks, we can rewrite the solution for price as

$$P_t = \psi P_{t-1} + \gamma(1-\gamma\rho_D)v_{Dt} + \gamma(1-\gamma\rho_S)v_{St}. \qquad 4.$$

Note that in this situation persistence effects come also from the serial correlation parameters ρ_D and ρ_S.

As long as supply shocks are purely transitory, inventories will be drawn down in response to a negative supply shock. Speculative accumulation requires either serially correlated shocks or the expectation that the disruption will get worse. Given a negative supply shock ($\varepsilon_{St} < 0$), the likelihood of stock accumulation in response to a supply disruption is greater the higher the serial correlation of the shocks (ρ_S) and/or the higher is the intertemporal correlation of price changes (ψ).

Quantifying the impact of SPR releases on oil prices requires a set of assumptions about the behavior of private stocks. The discussion above indicates that the consideration of market structure, the characteristics of the shocks (e.g. "transitory" versus "permanent"), and expectations of future shocks must be central elements in any attempt to model that linkage.

II. PUBLIC STOCKS In addition to understanding the role of domestic private stocks, consideration of the precise way in which (domestic and foreign) stocks are to be used is important for modeling efforts. For example, the simplest sort of intervention is an exogenous injection of supplies at the onset of a shock, a move tantamount to reducing the magnitude of a supply shock ε_{St}. Such a move will dampen private stock drawdown if the shock is perceived to be transitory, or blunt speculative accumulation if the shock is perceived as likely to get worse in the future.

A second type of public stock response is to substitute a rule for discretion. For example, one countercyclical rule would be to determine stockpile releases S as a function of deviations of prices from trend, i.e.

$$S_t = \omega P_t, \qquad \omega > 0. \tag{5}$$

A rule of the form of Equation 5 is analytically equivalent to an *ad valorem* tariff. The price responsiveness of demand is effectively heightened, reducing the price, as well as the persistence effects of the shocks.[10]

These examples of stockpile intervention, however, beg the question of optimal public stockpile behavior. Focusing on the optimizing process of the public authority facilitates consideration of the government's objectives, specific sources of market failure, and the potential benefits from international stockpile coordination (e.g. the IEA agreements).

To illustrate the formulation of such an optimizing process, suppose that the public stockpile is used in accordance with an assumed economic policy of maximizing real income (output less payments for imported intermediate goods). More specifically, suppose that the stockpile authority is risk-neutral, and that its objective is to maximize real income (by minimizing oil price increases) less the cost of carrying out the stockpile program and of adjusting stockpile levels, subject to the constraint that stockpile releases not exceed the amount of oil held in the reserve.

There is a clear distinction between the optimization problem for the public stockpile authority and the problem for the private firm discussed earlier. The public authority pays attention to aggregate output. Private firms do not consider the macroeconomic effects of their stockpiling behavior; that is, they do not consider the impact of their transactions on the world oil price.[11]

[10] See (64) for a discussion of stockpiling rules.

[11] Hence the division of stocks between the private and public sectors is important. In addition, in the argument in the text, we have implicitly assumed that there is a single stockpiling authority in consuming countries. In reality, there are strategic stocks in each country. Because the stockpiling decisions of other countries affect the price of oil, they can affect the optimal release strategy of the domestic authority.

Ceteris paribus, the larger the oil consumption, the greater will be the stockpile release because of the benefits of lowering the price paid on inframarginal imports. As with the case of private stocks, the expected persistence of shocks is an important factor in determining the optimal public stockpile policy. The greater the persistence of the shocks, *ceteris paribus*, the smaller the release at the onset of the shock. We pursue this issue in more detail in the next section, in the context of international cooperation in drawing down strategic stocks.

III. INTERNATIONAL COORDINATION OF PUBLIC STOCKPILES Since the oil market is internationally integrated, the use of a buffer stock by one country has spillover effects on others. The possibility of international policy coordination thus becomes important in attempting to reduce the impacts of oil shocks. While our example below finds merits (in terms of lower prices) of international stockpile coordination, issues of whether such an outcome would occur in the absence of an agreement and of what types of institutional mechanisms might facilitate cooperation have been largely ignored.

That cooperation can reap benefits begs the question of how it might be achieved. Regulation at the international level is difficult to enforce; since there is no regulator with the power to require compliance, the incentive question naturally arises. While import restriction is clearly in the interest of the group as a whole, the effectiveness of the regulatory rule in attaining the cooperative outcome is not evident.

As with the case of private-public interaction, the characteristics of shocks and of expectations play an important role in modeling international policy coordination. Those characteristics in turn may depend on elements of market structure—e.g. the use of long-term contracts in the oil market in addition to spot transactions. More specifically, in a related paper (50), we show that, following a negative supply shock, the anticipation of higher oil prices in the future (i.e. serial correlation of the effects of the shock) leads to a higher rate of public inventory accumulation (lower optimal stockpile release) in the current period.

During a crisis in which the (now higher) oil price is expected to decline, countries are willing to draw down their stockpiles at the onset of a shock, even in the absence of a coordinating agreement. If the oil price is expected to increase further, however, a drawdown in the current period mandated by a stockpile coordination agreement is not in the interests of the individual members.

Given a specification of the optimizing behavior of the public stockpiles of consuming countries, we can estimate the benefits of stockpile coordination using "game-theory" methods in economics. In our analysis of public stockpile behavior as an international game (50), we found that whether member countries to an agreement drew down more stocks at the onset of a shock than if there had been no agreement depended on (*a*) the expected persistence of the shocks and (*b*) the heightened monopsony power made possible by coordinated buyer behavior.

Our discussion of persistence in the previous sections assumes new importance here because given monopsony power, the greater the persistence effect of shocks on oil prices, the greater the cooperative optimal drawdown relative to noncooperative optimal drawdown. That is, the benefits (in terms of lower world oil prices and recouped GNP loss) of participating in an international agreement are greatest when the impact of oil shocks on oil prices exhibits substantial persistence.

The simple example of the previous section used inventory-smoothing behavior as a motivation for persistence. Perhaps more important in the oil market are long-term contracts. Given that only a fraction of oil trade occurs on spot markets, oil prices adjust only gradually to even transitory shocks. This institutional complication influences the benefits from agreements. By examining the structure of contracts in the oil market, we found (50) that persistence depended on, among other things, the fraction of trades carried out through contracts and on the price responsiveness of demand in consuming countries. Because these factors changed the persistence effects of oil shocks, the relationship between the best stockpile responses of the SPR alone and those of an international agreement also changed.

Those results have clear implications for the operation of the IEA agreement. The use of current quantity loss as a regulatory signal is misdirected, since it ignores the critical influence on national optimizing behavior of market dynamics. Loosely speaking, whether the shock is anticipated to "improve" or "worsen" determines the relationship between the cooperative and noncooperative solutions.

Of course, any policy not in effect at all times requires a "trigger" to activate it. A natural candidate, used in buffer stock schemes for some commodities, is price. In a market characterized by short-run contract rigidities, however, a supply shock leads to at least two prices' prevailing at any given time. However, treating the spot price as the marginal cost of acquiring oil is in general unwarranted; the usefulness of this price as a signal depends on the fraction of trades carried out in the spot market. It is the marginal acquisition cost that is relevant.

Finally, scattered evidence suggests that the market is becoming more flexible (i.e. the share of contract trade is declining), implying that noncooperative behavior will be less costly in the future than in the "high persistence" regime of the past. If such is the case, we should concentrate on developing guidelines for using the Strategic Petroleum Reserve and not be preoccupied with other nations' incentives to cooperate.

IV. SPR RELEASES AND OIL PRICES: AN EXAMPLE We use a short-run "price reaction" function, based on capacity, following (13, 38, 44, 45), in order to formalize the notion of market "tightness." We employ two prices as proxies for the many prevailing in the market at any given time. Crude oil is sold under term contracts at the contract price. The spot price (labeled P^s below) is paid for oil purchased on a single-cargo basis. The contract price is set by OPEC in accord with its production decisions and demand estimates. Given the difficulty in forecasting demand and the numerous minor shocks inherent in any market, the contract price will not in general equate supply and demand. The spot market serves to satisfy the excess, and thus acts as a signal of market disequilibrium to OPEC, which adjusts the contract price. The process is then repeated.

The spot price increases when the market tightens. Two forms of tightening are possible—demand can increase due to changes in consumption or stock buildup, and supply can decrease in response to disruption in a producing country or deliberate production cuts.

When a disruption occurs, capacity is removed from the market, and the output-to-capacity ratio of the nondisrupted producers rises. At higher prices, these producers are willing to accelerate output, thereby bumping up against their own capacity constraints. When excess capacity no longer exists (output/capacity = 1), even large increases in the spot price can elicit little further supply response; hence the nonlinearity of the curve. In equation form,

$$P_t^s = \psi P_{t-1}^s + \mathrm{f}(X_t/X_t^*), \qquad 6.$$

where t indexes the time period, f is a function (f$' > 0$), ψ indicates the persistence effects of shocks on the spot price, and X and X^* are OPEC output and capacity output, respectively.

In this simple example, capacity decisions are assumed to be determined by longer-term considerations outside the scope of the model and are taken as exogenous. X is obtained from the conditions that supply and demand be equal:

$$Q^{\mathrm{US}} + Q^{\mathrm{F}} + S^{\mathrm{SPR}} + S^{\mathrm{US}} + S^{\mathrm{F}} = X + X^{\mathrm{D}} + X^{\mathrm{NO}}, \qquad 7.$$

where US stands for United States, F for foreign, Q for consumption, S for stock change, S^{SPR} for Strategic Petroleum Reserve fill or draw, X for the production of nondisrupted OPEC producers, X^{D} for the (reduced) output of disrupted producers, and X^{NO} for non-OPEC production.

US consumption is assumed to depend on the domestic refiners' acquisition cost (P^{US}), income (Y^{US}), and a vector of structural variables, including past prices (Z^{US}). Foreign consumption is defined similarly:

$$Q^{US} = j^{US}(P^{US}, Y^{US}(P^{US}), Z^{US}) \quad 8.$$

$$Q^{F} = j^{F}(P^{F}, Y^{F}(P^{F}), Z^{F}). \quad 9.$$

The US refiners' acquisition cost is taken to be an average of spot and contract prices (plus transport costs), and is assumed to adjust to the spot price. The domestic price abroad is defined similarly:

$$P_t^{US} = a_0 + a_1 P_{t-1}^{US} + a_2(P_t^s - P_{t-1}^{US}) \quad 10.$$

$$P_t^{F} = b_0 + b_1 P_{t-1}^{F} + b_2(P_t^s - P_{t-1}^{F}). \quad 11.$$

In general, the a's and b's will differ for institutional as well as tax reasons.

To obtain X in terms of consumption, stock change, and production by other countries, rearrange Equation 7 to obtain

$$X = (Q^{US} + Q^{F}) + (S^{SPR} + S^{US} + S^{F}) - (X^{D} + X^{NO}). \quad 12.$$

In this framework, the objective of stocks policy is clear—to lower the second of the three terms in order to reduce demand for OPEC output, thus moderating increases in the output-to-capacity ratio and reducing pressure on the spot price. Stock policy yields more "bang for the buck" as a disruption worsens, because of the nonlinearity of the price-reaction function.

In this framework, SPR releases have three effects on the spot price. The direct effect is to ease pressure as the SPR release reduces demand for OPEC output. A feedback effect occurs because holding down the spot price serves to hold down domestic prices at home and abroad as well, thus reducing the cutbacks in US and foreign consumption. The feedback effect clearly works against the direct effect. The interaction effect depends on the reaction of domestically held private stocks and foreign stocks to SPR releases. In equation form,

$$\frac{dP^s}{dS^{SPR}} = \underbrace{\frac{f'}{X^*}}_{\text{direct effect}} \underbrace{\left[1 - \frac{f'}{X^*}\left(a_2 \frac{dQ^{US}}{dP^{US}} + b_2 \frac{dQ^{F}}{dP^{F}}\right)\right]^{-1}}_{\text{feedback effect}} \underbrace{\left(1 + \frac{dS^{US}}{dS^{SPR}} + \frac{dS^{F}}{dS^{SPR}}\right)}_{\text{interaction effect}}. \quad 13.$$

The sign of the direct effect is positive. The term in brackets is larger than one; the feedback effect partly offsets the direct effect. The effect of international interaction depends on the sign of the interaction effect. Cooperation (on the part of private stocks or foreign stockpile authorities) serves to magnify the benefits of the SPR release, while competition serves to mitigate them. The magnification (or mitigation) effect is more than proportional, due to the nonlinearity of the price-reaction function. Thus for a given SPR drawdown, a higher value of $dS^{US}/dS^{SPR} + dS^{F}/dS^{SPR}$ not only hits the spot price proportionally through the interaction effect, but also works through the direct effect (by lowering the argument of f') to exert additional downward pressure. Hence cooperation provides more than proportional benefits.

Finally, we should note that the benefits of stock draw are likely to be underestimated by the above analysis, which covers only the "within-drawdown-period" effects. Insofar as future spot prices are determined by an autoregressive process such as Equation 6, an SPR drawdown will be felt in future periods as well.

In related papers (45, 65), we used a simulation model of the world oil market similar to that outlined above in conjunction with a quarterly econometric model of the US economy to examine the ability of stockpile policy to mitigate the economic costs of oil supply disruptions. In one case, we simulated a reduction in OPEC capacity of 7 million bbl/d for one year, starting in the first quarter of 1983.

Our analysis revealed that given a US laissez-faire policy (no SPR draw or fill) during the disruption, it made a noticeable difference whether the rest of the OECD followed a "cooperative" (draw) or "noncooperative" (build) path. Even under the moderate assumptions employed, the difference in the spot prices was substantial. The loss in US GNP was of the order of 30–40% greater in the "noncooperative" case in the first two quarters, and 15–20% greater in the next two quarters.

The effects of using the SPR were two. First, the decreased demand for OPEC output exerted downward pressure on spot prices. Second, SPR draw substituted for imported oil almost entirely; this import reduction improved the trade balance and hence the US GNP. In the case of unilateral drawdown by the United States, use of the SPR recouped about one-third of the loss in GNP traceable to the shock, yielding a value of the SPR oil of about $45/bbl. This figure measured economic benefits over and above the revenues accrued from SPR sales. In an intertemporal optimization calculation, these revenues must be compared with the costs of buying and storing oil for the reserve.

In addition, we found the claim that government stock drawdown is impotent due to countervailing actions taken in the private sector to be without foundation. Government releases damped spot price increases, serving to reduce private inventory accumulation, not increase it. The response of domestically held private stocks to the SPR release (as well as the response of foreign stockpile authorities) was an important factor in determining the effectiveness of the stock policy in reducing prices.

Releasing SPR oil on the spot market is not the only way in which stockpile intervention might occur. Devarajan & Hubbard (66) consider the case of selling SPR oil through futures contracts. Their simulation results, based on the model discussed above, indicate that futures sales (*a*) achieved much of the price-reducing benefits in the early stages of a disruption and (*b*) led to a lower price trajectory overall when compared with spot market sales. They also discuss some institutional benefits of using futures markets.

CONCLUSION

The economic losses accompanying the oil supply shocks of the 1970s provided the impetus for the search for beneficial energy security policies. In one development, the US Congress created the Strategic Petroleum Reserve. Currently storing over 450 million barrels of oil, the reserve is a potentially powerful policy instrument. Our discussion addresses economic issues in managing the SPR.

Taking as the goal of national economic policy the maximization of economic welfare, policy intervention is beneficial only in the presence of some sort of market failure. The case for any energy security policy requires a demonstration of market failure. Potential sources of market failure in the oil market include macroeconomic externalities, monopsony power, vulnerability to disruptions, and national security. The SPR is a politically acceptable and economically efficient—in some cases, first-best—option to address those imperfections.

Considered as an economic policy instrument, the SPR represents a source of supply (or demand, depending on whether it is being released or filled) in the oil market. Hence, evaluating its role requires a framework for describing the behavior of other players—and thus of prices—in the market. We review several modeling strategies, stressing the importance of market structure and the behavior of private stocks. By way of illustration, we discuss a simple simulation model of the SPR and the world oil market. In that exercise, use of the SPR during a simulated oil shock obtained substantial benefits in terms of reduced oil prices and increased GNP. The results obtained are particular to our input assumptions and are by no means definitive.

It is customary to conclude with recommendations for policy. Since this is a review article, our recommendations address SPR research policy, rather than SPR policy itself. It is clear that we have raised more questions than we have been able to answer.

Specifically, it should prove fruitful to assess oil supply disruptions in a general equilibrium framework, and dispense with the partial equilibrium premia that are characteristic of the present literature. There must be two-way interaction between the oil market and the rest of the economy.

The sensitivity of the wisdom of SPR policy to the structure of the oil market has been virtually ignored. This consideration is particularly important for analyzing drawdown decisions, where the responses of other players are crucial. For example, without a model of expectations formation, the desirability of announced versus unannounced releases, and of futures versus spot sales, cannot be addressed.

Much has been learned in a short time about the subject of managing the Strategic Petroleum Reserve, yet much work remains to be done. We close with this challenge to economists and energy policy analysts.

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APPENDIX A

Stockpiling Programs Outside the United States

GERMANY Until recent years, the German government refrained from regulating its domestic oil market closely. In 1965, however, the government imposed a storage requirement on refiners and dependent importers. The independents were excluded. In 1975, the requirement was raised to the present level of 90 days for refiners—i.e. the refiner must keep the equivalent of 90 days of his average production of finished products from imported crude during the previous year. Dependent importers were required to keep a 70-day supply of their average product imports, and independent importers a 25-day supply (but increasing to a 40-day supply by 1980), of their average imports during the previous year.

After 1975, that program was superseded by a joint proposal from the majors and independents to create a quasi-public corporation to manage oil stockpiles. All the companies refining and importing oil in Germany would be obliged to become members of this corporation. The corporation would hold the obligatory stocks for the companies, and by being able to take advantage of economies of scale otherwise not available to small firms, the corporation would reduce the costs of stockpiling to the industry as a whole and therefore to consumers. The corporation's debt would be financed by the capital market, and the running costs would be paid by the members—i.e. the oil companies. This would remove the grounds for the fears of the independents that the financial burden of holding stocks would be too high.

After a year of negotiations, the various segments of the oil industry and the government reached an agreement on the structure of this corporation and in the fall of 1978, the Erdolbevorratungsverband (EBV) was established. The most important feature of the EBV program is that it removes obligatory stocks from the balance sheets of the oil companies. It also causes emergency reserve to be segregated administratively, and to some extent physically, from commercial inventories.

As a parallel effort, the German government decided in 1970 to create a Federal Reserve of 8 million tons (about 70 million barrels, equivalent to approximately a 25-day supply of current net imports). This government stockpile was scheduled to be completed by 1980, but the 1979 Iranian crisis has caused a delay. The Federal Reserve is stored in underground cavities near Etzel in northern Germany.

The development of the Federal Reserve and the EBV indicates that the German government is willing to intervene in the oil industry for energy security purposes. Its policies for the use of these stocks, however, are very conservative. The government is reluctant to use its emergency stock as a first line of defense to disruptions (for example, as buffers to stabilize prices). The Germans support the view that subcrisis management can be handled by the market.

The Germans feel that the price of oil could climb above $40/bbl before they would attempt to draw down stockpiles to restrain price increases. Moreover, German law states that the German government has widespread control over the oil industry only in the case of a "real" (IEA designated) emergency; thus, it is not clear that the West German government could easily manage the drawdown of stocks in a less than severe crisis. On the other hand, the Germans feel that when a real crisis arrives, their government is better prepared to use their crisis instruments than the United States or any other country (67).

JAPAN The government agency responsible for energy regulations in Japan is the Ministry of International Trade and Industry (MITI). MITI's authority over oil affairs derives from the Basic Petroleum Law of 1962, which gave MITI the right to grant licenses for the construction of new refineries, recommend modifications in refinery production plans, and establish a "standard price" for oil products during the crises. MITI does not rely strictly on specific laws for its authority, however, but depends more generally on the traditional understanding that exists between government and industry.

In terms of oil stockpiling policy, MITI first "guided" Japanese oil companies toward holding a 60-day supply of oil in reserve in 1972. At that time the average stock level held by the companies for commercial operating requirements was about a 45-day supply. MITI hoped to meet the 60-day target by 1975, but the oil crisis of 1973–1974 upset this schedule. Japan's decision to join the IEA in 1974 established a new storage target; a 90-day supply of net oil imports by 1980. This much higher target would have a far greater impact on the oil industry, persuading MITI to seek formal, legislative approval and authority to require the oil companies to increase their stock levels in a schedule designed to meet the 90-day supply target. The Petroleum Stockpiling Law of 1975 was the result.

This law empowers MITI to "set an objective in terms of the stockpiling of oil for the following four fiscal years." MITI must detail its objectives for each year in ordinances that define the stockpiling obligations of oil refiners, marketers, and importers. Later in 1975, a MITI ordinance stated that the national storage target for 1976 would be a 70-day supply. This national obligation was parceled out of the various kinds of companies as follows: refining companies were obliged to store a 55-day supply based on their average product output in the preceding year; marketing companies, a 15-day supply calculated from their sales volume in the previous year; and product importing companies, a 45-day supply based on their import volume in the previous year. The plan was that MITI would adjust these company obligations yearly as it gradually increases the national stockpile target to a 90-day supply based on the previous year's oil sales by 1980, and perhaps a 120-day supply by 1985.

The storage target, being expressed in days, will contain a different amount of oil each year, in contrast to the American reserve, whose quantity will be fixed. The volume of oil in the stockpile will depend upon the level of Japan's oil consumption.

Most of the Japanese National Oil Company's (JNOC) stockpiling efforts interface with private Japanese companies. JNOC provides funds and low-interest loans to local governments to secure storage facilities and to private companies to subsidize the maintenance of higher inventory levels. JNOC has also created government-industry joint stockpiling companies. These companies have been designated to construct and operate additional storage facilities under leasing arrangements.

By law, MITI has established oil inventory levels to be maintained by each private oil company. During 1979, mandated targets for oil stocks were to reach 90 days of historical consumption levels. Certain companies were granted exemptions if their crude supplies were tight. By December 1979, Japan's total oil stocks were at record levels, and MITI instructed Japanese companies to draw down their inventories in stock levels to serve general economic objectives (68).

The analysis in (67) suggests that Japan will seriously consider a new oil emergency agreement to supplement its existing oil emergency policies and its participation in the IEA. Although the Japanese government is concentrating on improvements in economy and efficiency in energy use, it does have large oil stocks (as do the United States and West Germany) and realizes that, under the present IEA framework for stock management, no formal policies exist for their use.

FRANCE The French government has been an important factor in the operation of the petroleum industry at least since 1928, when the Loi Poincare gave the government powers to regulate the oil market. Although in 1978 the government announced it would liberalize the domestic petroleum market, it still remains under firm government controls.

Stockpiling policies have been imposed since 1928 also. In 1951, refineries were required to maintain the equivalent of 10 days of their average crude oil imports at all times. Another requirement instituted in 1958 and modified in January 1975 required all importers to maintain stockpiles equivalent to 25% of their inland sales during the preceding twelve months. This obligation is widely referred to as the "90-day" requirement.

Unlike the German storage program, the French program does not impose variable obligations on oil refiners and importers. The same obligation falls on any company licensed to import crude oil or finished products.

The French storage obligations today are less controversial than the storage regulations in Germany for a number of reasons. First there are not as many product importers. Second, the requirements have been in force since 1958; the companies built up their stocks when oil was cheap. Third, the French system of regulations gives the government control and also enables the companies to earn a "fair" return on their investment.

The French government has not agreed to remove the obligatory stock debt from the oil industry's balance sheets as the German government has done, but it does attempt to equalize the impact of the storage expenses on company cash flows.

Only insofar as the demand for French oil increases are there formal plans to increase the size of the national stockpile. There are no government requirements that stocks be located in centralized storage facilities; thus, stocks tend to be widely dispersed and refineries tend to shift their excess product stocks to downstream bulk terminals. This dispersal is explicitly encouraged by the technical specifications of the regulation (69).

ITALY The Italian government's intervention into oil affairs dates back to the 1920s, when the government created a number of state holding companies that evolved into Ente Nazionale Idrocarburi (ENI)—the fully integrated and international energy corporation in operation today.

Decrees in 1961 and 1976 established Italy's national storage target at stocks equivalent to 90 days of the previous calendar year's domestic sales. The burden of providing these stocks is divided between the owners of storage facilities (nonrefiners) and the refining industry. The owners of storage facilities are required to maintain as a minimum level of fill 20% of the capacities of their tanks. This 20% fill provision is a unique feature of the Italian program. It applies not only to oil businesses such as wholesalers, but also to any company or individual owning the requisite storage capacity. Thus, trucking firms, electrical utilities, petrochemical companies, and other large-scale oil users are subject to the storage regulations.

The practice of including part of the nonoil industry stocks in the national storage target, and hence of treating these stocks as a kind of emergency reserve, is the most extreme form of amalgamation of emergency reserves with commercial inventories. However, (69) argues that these reserves would exist even without regulation.

APPENDIX B

Private Stocks, Public Stocks, and Market Equilibrium

As in the text, to study the interaction of public and private stocks, we begin with the following stylized model of the short run. Let production Q^S and consumption demand Q^D be responsive to the current period price P. Production and consumption are subject to random additive disturbances ε_{St} and ε_{Dt}, respectively, which are assumed to be independently and identically distributed with mean zero and variances σ_S^2 and σ_D^2, respectively. Total demand is the sum of consumption and speculative inventory demand.

Speculators trade in inventories on the spot market in anticipation of changes in price, and are assumed to be risk-neutral, so that they maximize expected profit. Let the objective of the speculators over the period $(t, t+1)$ be

$$\max_{I_t} \mathrm{E}_t \left\{ \left(((1+\delta)^{-1} P_{t+1} - P_t) I_t - \frac{h}{2} I_t^2 \right) \right\}, \qquad \text{B1.}$$

where I represents the end-of-period stock level and δ is the discount rate. E_t denotes the expectation operator conditional on information available at time t. The first term represents speculative gains on the stock held, the second, holding costs. Holding stocks is assumed to be costly—in fact, increasingly costly—in the size of the stock due to payments to factors fixed in the short run, such as storage facilities, tankers, and pipelines. Thus changes in price expectations cannot be fully acted upon instantaneously. We follow the literature in modeling such costs as quadratic, the simplest specification of "diminishing returns"; these costs are indexed by the parameter h.

Maximizing the quantity B1 with respect to I_t yields the following demand function for stocks:

$$I_t = h^{-1}((1+\delta)^{-1}\mathrm{E}_t P_{t+1} - P_t). \quad \text{B2.}$$

As with most other specifications since the original development by Muth (1961), the holdings of risk-neutral speculators are a function of the expected increase in price, taking into account the cost of adjusting stock levels.[12] Inventory demand (stock change) is just

$$I_t - I_{t-1} = h^{-1}[(1+\delta)^{-1}(\mathrm{E}_t P_{t+1} - \mathrm{E}_{t-1}P_t) - (P_t - P_{t-1})]. \quad \text{B3.}$$

The spot price solves the following equation for market equilibrium:

$$Q^D(P_t) + h^{-1}(1+\delta)^{-1}(\mathrm{E}_t P_{t+1} - \mathrm{E}_{t-1}P_t) - h^{-1}(P_t - P_{t-1}) + \varepsilon_{Dt} = Q^S(P_t) + \varepsilon_{St}. \quad \text{B4.}$$

Under simplifying assumptions of linear responses of supply and demand to price, we have

$$Q^D(P_t) = A - aP_t, \quad \text{and} \quad \text{B5.}$$

$$Q^S(P_t) = B + bP_t. \quad \text{B6.}$$

Hence Equation B4 can be rewritten as

$$A - aP_t + \varepsilon_{Dt} + h^{-1}[(1+\delta)^{-1}\mathrm{E}_t P_{t+1} - P_t - (1+\delta)^{-1}\mathrm{E}_{t-1}P_t + P_{t-1}] = B + bP_t + \varepsilon_{St}, \quad \text{B7.}$$

or

$$[b + a + h^{-1}]P_t = A - B + \varepsilon_{Dt} - \varepsilon_{St} + h^{-1}[(1+\delta)^{-1}(\mathrm{E}_t P_{t+1} - \mathrm{E}_{t-1}P_t) + P_{t-1}]. \quad \text{B8.}$$

For simplicity, consider the case in which $\delta = 0$. If we define the long-run average price obtained when expectations are realized ($\mathrm{E}_t P_{t+1} = \mathrm{E}_{t-1}P_t = p_t$) by $\hat{P}$, then it follows that

$$\hat{P} = \frac{A - B}{a + b}. \quad \text{B9.}$$

Let lower-case variables be defined in deviation form (i.e. $P_t = P_t - \hat{P}$). Under the assumptions of rational expectations, we solve the second-order inhomogeneous difference Equation B8 by standard methods to yield

$$p_t = \alpha p_{t-1} + \frac{\varepsilon_{Dt} - \varepsilon_{St}}{a + b + 2h^{-1} - h^{-1}\alpha}, \quad \text{B10.}$$

[12] For a more general intertemporal optimizing model of oil inventory behavior under uncertainty, see (50).

where α is the root within the unit circle of the quadratic equation $h^{-1}\alpha^2 - (a+b+2h^{-1})\alpha + h^{-1} = 0$. Equation B10 corresponds to Equation 1 in the text, where $\beta = (a+b+2h^{-1} - h^{-1}\alpha)^{-1}$.

Hence even transitory shocks exhibit persistance effects on the spot price because of the behavior of inventories. Moreover, both the one-period and asymptotic variances of the spot price increase with α, since

$$\sigma_p^2(1) = \frac{\sigma_D^2 + \sigma_S^2}{(a+b+2h^{-1} - h^{-1}\alpha)^2}, \quad \text{and} \qquad \text{B11.}$$

$$\sigma_p^2(\infty) = \frac{\sigma_p^2(1)}{1-\alpha^2}. \qquad \text{B12.}$$

Note that since $d\alpha/da < 0$, the steeper is the demand curve for oil, the smaller is the initial increase in price and the lower is the persistence. Hence, policies such as oil import tariffs or certain types of buffer stock stabilization policies (which effectively raise a) can mitigate both the impact and the long-run effects of transitory shocks on prices.

We can easily extend the above analysis to the case of serially correlated quantity shocks. Suppose that demand and supply shocks follow first-order autoregressive processes (AR(1)):

$$\varepsilon_{Dt} = \rho_D \varepsilon_{Dt-1} + v_{Dt}, \quad \text{and} \qquad \text{B13.}$$

$$\varepsilon_{St} = \rho_S \varepsilon_{St-1} + v_{St}, \qquad \text{B14.}$$

where v_{Dt} and v_{St} are white noise and

$$\sigma_{v_D v_S} = 0.$$

Using Equations B13 and B14 for the demand and supply shocks, we can rewrite Equation B8 as

$$E_t\{P_{t+1}[h^{-1} - (a+b+2h^{-1})L + h^{-1}L^2]\} = -(\varepsilon_{Dt} - \varepsilon_{St}), \qquad \text{B15.}$$

where L denotes the lag operator. The solution to B15 given rational expectations is just

$$p_t = \alpha p_{t-1} + \gamma(1-\gamma\rho_D)v_{Dt} - \gamma(1-\gamma\rho_S)v_{St}, \qquad \text{B16.}$$

where α is the root within the unit circle of the quadratic equation contained within the brackets in B15 and γ is the root outside the unit circle.

Now persistence effects come also from the serial correlation parameters ρ_D and ρ_S. Equation B16 points up the need to consider the structural parameters determining α (and γ). As α and γ tend toward unity, the existence of serial correlation amplifies the price effects of shocks. The variance of the spot price is also higher when the shocks are serially correlated. Finally, if the shocks are serially correlated, then changes in α induced by policy changes have all the more impact.

It is clear from Equation B13 that as long as supply shocks are purely transitory, inventories will be drawn down in response to a negative supply shock, since

$$\frac{dI_t}{d(-\varepsilon_{St})} = \Omega(\alpha - 1) < 0, \quad \text{where} \quad \Omega = h^{-1}(dp_t/d(-\varepsilon_{St})) \qquad \text{B17.}$$

Speculative accumulation requires either serially correlated shocks or the expectation that the disruption will "get worse."[13]

Following this stylized model when shocks follow AR(1) processes, we note that the response of private stocks to a supply shock in the current period is

$$\frac{dI_t}{d(-v_{St})} = \gamma(\rho_S - (1-\alpha)). \qquad \text{B18.}$$

For negative supply shocks ($\varepsilon_{St} < 0$), Equation B18 implies that private shocks will increase if $\rho_S > 1 - \alpha$. That is, the likelihood of stock accumulation in response to a supply disruption is greater the higher the serial correlation of the shocks (ρ_S) and/or the higher the intertemporal correlation of price changes (α).

In the text, we considered the impact of optimal public stockpile behavior on private stockpiling and the world price. As in the text, suppose that the public stockpile is used in accordance with an assumed economic policy of maximizing real income (output less payments for imported intermediate goods). Output Y of a single final good is produced from oil Q^D and other factors $\bar{X}$ according to the production function

$$Y_t = F(Q_t^D, \bar{X}); \quad F_1, F_2 > 0, \quad \text{and} \quad F_{11}, F_{22} < 0. \qquad \text{B19.}$$

All oil is imported, and oil is the only imported intermediate input. Nonoil factor supplies are fixed.

The stockpile authority is assumed to be risk-neutral, and its objective is to maximize real income (by minimizing oil price increases) less the cost of carrying out the stockpile program and adjusting stockpile levels, subject to the constraint that stockpile releases not exceed the amount of oil held in the reserve. The problem is to choose the stockpile level I^P in period t so that

$$\max_{I_t^P} E_t \left\{ Y_t - P_t Q_t^D + ((1+\delta)^{-1} P_{t+1} - P_t) I_t^P - \frac{h}{2} I_t^{P^2} \right\}, \qquad \text{B20.}$$

[13] One example might be an AR(2) process in which the first lagged coefficient is greater than unity and the second is negative.

subject to the constraint that

$$I_t^p = I_{t-1}^p + S_t, \qquad I_t^p \geqslant 0, \tag{B21.}$$

where δ is the discount rate. Again, the quadratic term is a proxy for the cost of adjusting stock levels. Assuming that the nonnegativity constraint does not bind, the solution to B20 can be written as

$$\begin{aligned} I_t^p &= h^{-1}((1+\delta)^{-1}\mathrm{E}_t P_{t+1} - P_t) - h^{-1}\omega Q_{t-1}^D \\ &= (h+(\alpha-1)\omega)^{-1}((1+\delta)^{-1}\mathrm{E}_t P_{t+1} - P_t - \omega Q_t^D), \end{aligned} \tag{B22.}$$

where $\omega = \mathrm{d}P/\mathrm{d}I^p$.

There is a clear distinction between the optimization problem for the public stockpile authority and the problem for the private firm stated earlier. The public authority pays attention to aggregate output. Private firms do not consider the macroeconomic effects of their stockpiling behavior; that is, they do not consider the impact of their transactions on the world oil price. The last term in Equation B22 captures this market power effect. *Ceteris paribus*, the larger the oil consumption, the greater will be the stockpile release because of the benefits of lowering the price paid on the inframarginal barrels. Equation B22 makes clear the role of persistence in determining the optimal public stockpile policy. That issue is pursued in more detail in the text in the context of international cooperation in stockpile drawdowns.

Literature Cited

1. Frankel, P. H. 1958. Oil supplies during the Suez crisis. *J. Industrial Econ.* 6:85–100
2. Kapstein, E. B. 1984. Alliance energy security: 1945–1983. *Fletcher Forum*
3. Hamilton, J. D. 1983. Oil and the macroeconomy since World War II. *J. Pol. Econ.* 91:228–48
4. Fried, C. R., Schultze, C. L., eds. 1975. *Higher Oil Prices and the World Economy*. Washington, DC: Brookings
5. Hickman, B. G., Huntington, H. G. 1984. *Macroeconomic Impacts of Energy Shocks: An Overview*. Mimeo, Energy Modeling Forum. Stanford
6. Mork, K. A., Hall, R. E. 1980. Energy prices and the U.S. economy in 1979–1981. *Energy J.* 1:41–54
7. Jorgenson, D. W. 1984. The role of energy in productivity growth. *Am. Econ. Rev. Pap. and Proc.* 74:26–30
8. Balas, E. 1980. Choosing the overall size of the strategic petroleum reserve. In *Energy Policy Modeling: U.S. and Canadian Experiences*, ed. W. Ziemba, S. Schwartz, E. Koenigsberg, pp. 144–58. The Hague: Martinus Nijhoff
9. Kinberg, Y., Shakun, M. F., Sudit, E. F. 1978. Energy buffer stock decisions in game situations. *TIMS Studies in the Management Sciences* 10:109–27
10. Marchand, M., Pestieau, P. 1979. Tarification et anticipations divergentes. *Annals Pub. Coop. Economy* 50:111–36 (In French)
11. Wright, B. D., Williams, J. 1982. The roles of public and private storage in managing oil import disruptions. *Bell J. Econ.* 13:341–53
12. Kalt, J. P. 1981. *The Economics and Politics of Oil Price Regulation*. Cambridge, MA: MIT Press
13. Hubbard, R. G., Fry, R. C. 1982. The macroeconomic impacts of oil supply

disruptions. *Energy and Env. Pol. Cent. Disc. Paper* E-81-07, Kennedy School of Govt., Cambridge, MA
14. Verleger, P. K. 1982. *Oil Markets in Turmoil*. Cambridge, MA: Ballinger
15. Hogan, W. W. 1982. Policies for oil importers. In *OPEC Behavior and World Oil Prices*, ed. J. M. Griffin, D. J. Teece, pp. 186–206. London: Allen & Unwin
16. US Dept. Energy. 1981. *Domestic and International Energy Preparedness*. DOE/EP-0027. Washington, DC
17. Devarajan, S. 1982. Commodity stockpiles: a summary of the literature and the experience. *Oil Stockpiling: An International Perspective*. Putnam, Hayes & Bartlett, report to the US Dept. of Energy
18. Colglazier, E. W., Deese, D. A. 1983. Energy and security in the 1980s. *Ann. Rev. Energy* 8:415–49
19. Weimer, D. L. 1982. *The Strategic Petroleum Reserve*. Westport, CT: Greenwood
20. Paris, D. L. 1982. *Energy Politics*. New York: St. Martin's
21. Hogan, W. W. 1984. Energy Policy in the Reagan Era. Cambridge, Mass: Energy and Environ. Policy Cent., Kennedy School of Government
22. Exxon Corp. 1981. *World Oil Inventories*. Background Series. New York
23. US Senate, Comm. Interior and Insular Affairs. 1974. *Int. Energy Program Hearing*. Washington, DC
24. Stanford Univ. Energy Modeling Forum. 1982. *World Oil*. Summary Report. Stanford, Calif.
25. Bohi, D. R. 1983. What causes oil price shocks? *Res. for the Future Disc. Paper* D-82S. Washington, DC
26. Adelman, M. A. 1982. OPEC as a cartel. In *OPEC Behavior and World Oil Prices*, ed. J. M. Griffin, D. J. Teece, pp. 37–63. London: Allen & Unwin
27. Singer, S. F. 1983. The price of world oil. *Ann. Rev. Energy* 8:451–508
28. Hope, C. W. 1984. *The Oil Price Without OPEC*. Presented at Ann. Int. Meet. Int. Assoc. En. Econ., 6th, Cambridge, UK
29. Adams, F. G., Marquez, J. 1984. Petroleum price elasticity, income effects, and OPEC's pricing policy. *Energy J.* 5: 115–28
30. MacAvoy, P. W. 1982. *Crude Oil Prices*. Cambridge, Mass: Ballinger
31. Roumasset, J., Isaak, D., Fesharaki, F. 1983. Oil prices without OPEC: a walk on the supply side. *Energy Econ.* 5:164–70
32. Chasseriaux, J.-M. 1982. Une interpretation des fluctuations du prix du petrole. *Revue d'Econ. Industrielle* 22:24–38 (In French)
33. Cremer, J., Salehi-Isfahani, D. 1980. Competitive pricing in the oil market: how important is OPEC? *University of Pennsylvania Working Paper*. Philadelphia
34. Teece, D. J. 1982. OPEC behavior: an alternate view. In *OPEC Behavior and World Oil Prices*, ed. J. M. Griffin, D. J. Teece, pp. 64–93. London: Allen & Unwin
35. Reza, A. M. 1981. An analysis of the supply of oil. *Energy J.* 2:77–94
36. Mead, W. J. 1979. An economic analysis of crude oil price behavior in the 1970s. *J. En. Dev.* 4:212–28
37. Johany, A. D. 1980. *The Myth of the OPEC Cartel*. Chichester, UK: Wiley
38. Plummer, J. L., ed. 1982. *Energy Vulnerability*. Cambridge, Mass: Ballinger
39. Bohi, D. R., Montgomery, W. D. 1982. *Oil Prices, Energy Security, and Import Policy*. Baltimore: Johns Hopkins Univ. Press
40. Gately, D., Kyle, J., Fischer, D. 1977. Strategies for OPEC pricing decisions. *Eur. Econ. Rev.* 10:209–30
41. Danielsen, A. L., Selby, E. B. 1980. World oil price increases: sources and solutions. *Energy J.* 1:59–74
42. Jacoby, H. D., Paddock, J. L. 1980. Supply instability and oil market behavior. *En. Systems and Policy* 3:401–23
43. Fisher, F. M., Cootner, P. H., Baily, M. N. 1972. An econometric model of the world copper industry. *Bell J. Econ. Manage. Sci.* 3:585–609
44. Nordhaus, W. D. 1980. Oil and economic performance in industrial countries. *Brookings Pap. Econ. Activity*, pp. 341–88
45. Hubbard, R. G., Weiner, R. J. 1983. The "sub-trigger" crisis: an economic analysis of flexible stock policies. *Energy Econ.* 5:178–89
46. US Gen. Account. Office. 1983. *Oil Supply Disruptions: Their Price and Economic Effects*. RCED-83-135, Washington, DC
47. Adelman, M. A. 1984. Sense and nonsense about world oil. *Energy J.* 5:169–71
48. Stobaugh, R. B. 1976. The oil companies in the crisis. In *The Oil Crisis*, ed. R. Vernon, pp. 179–202. New York: Norton
49. Neff, T. L. 1981. The changing world oil market. In *Energy and Security*, ed. D. A. Deese, J. S. Nye, pp. 23–46. Cambridge, Mass: Ballinger
50. Hubbard, R. G., Weiner, R. J. 1985. Oil

supply shocks and international policy coordination. *Eur. Econ. Rev.*
51. Muth, J. F. 1961. Rational expectations and the theory of price movements. *Econometrica* 29:315–35
52. Badger, D. B. 1984. The anatomy of a "minor disruption": missed opportunities. In *Oil Shock: Policy Response and Implementation*, ed. A. L. Alm, R. J. Weiner, pp. 33–53. Cambridge, Mass: Ballinger
53. ICF Incorporated. 1982. *Modeling the Effect of Strategic Petroleum Reserve Drawdown on the Oil Market and the Macroeconomy.* Report to the SPR Office, US Dept. of Energy. Washington, DC
54. Teisberg, T. J. 1981. A dynamic programming model of the U.S. strategic petroleum reserve. *Bell J. Econ.* 12:526–46
55. Chao, H.-P., Manne, A. S. 1982. An integrated analysis of U.S. oil stockpiling policies. In *Energy Vulnerability*, ed. J. L. Plummer, pp. 59–82. Cambridge, Mass: Ballinger
56. Hogan, W. W. 1983. Oil stockpiling: help thy neighbor. *Energy J.* 4:49–71
57. Natl. Pet. Council. 1981. *Emergency Preparedness for Interruption of Petroleum Imports into the United States.* Washington, DC
58. Rowen, H. S., Weyant, J.-P. 1982. Reducing the economic impacts of oil supply interruptions: an international perspective. *Energy J.* 3:1–34
59. US Dept. Energy. 1982. *Report to the President and the Congress on the Size of the Strategic Petroleum Reserve.* DOE/EP-0036. Washington, DC
60. Nichols, A. L., Zeckhauser, R. J. 1977. Stockpiling strategies and cartel prices. *Bell J. Econ.* 8:66–96
61. Sharpe, W. F. 1964. Capital asset prices: a theory of market equilibrium under conditions of risk. *J. Finance* 19:425–42
62. Lintner, J. V. 1965. The valuation of risky assets and the selection of risky investments in stock portfolios and capital budgets. *Rev. Econ. Stat.* 47:13–37
63. Bouhdili, C., Montgomery, W. D. 1983. Risk analysis of the strategic petroleum reserve: theory and preliminary evidence. *Res. for the Future Disc. Paper* D-82U. Washington, DC
64. Newbery, D. M. G., Stiglitz, J. E. 1981. *The Theory of Commodity Price Stabilization.* Oxford: Oxford Univ. Press
65. Hubbard, R. G., Weiner, R. J. 1984. Inventory optimization in the U.S. petroleum industry: empirical analysis and implications for energy emergency policy. Mimeo, Harvard University
66. Devarajan, S., Hubbard, R. G. 1983. Drawing down the strategic petroleum reserve: the case for selling futures contracts. In *Oil Shock: Report of the Harvard Energy Security Program*, ed. A. L. Alm, R. J. Weiner, pp. 187–96. Cambridge, Mass: Ballinger
67. Gibson, C. S. 1984. Cooperative oil stockpiling: evaluating a three-country agreement and designing a negotiation strategy. Mimeo, Kennedy School of Government, Harvard Univ.
68. US Dept. Energy. 1981. *Energy Industries Abroad.* DOE/IA-0012. Washington, DC
69. Krapels, E. N. 1980. *Oil Crisis Management.* Baltimore: Johns Hopkins Univ. Press

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