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96th Congress
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THE FUTURE OF SAUDI ARABIAN OIL PRODUCTION

A STAFF REPORT

TO THE

SUBCOMMITTEE ON INTERNATIONAL ECONOMIC POLICY

OF THE

COMMITTEE ON FOREIGN RELATIONS UNITED STATES SENATE

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APRIL 1979

Printed for the use of the Committee on Foreign Relations

U.S. GOVERNMENT PRINTING OFFICE
41-565 O WASHINGTON : 1979

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PREFACE

An accurate understanding of the facts respecting the capabilities and the limitations on future oil production is essential to the formulation of a realistic energy policy by the United States. With this in mind, the staff of the International Economic Policy Subcommittee of the Committee on Foreign Relations has conducted over the past year an intensive study of the technical and financial considerations which are likely to play a formative role in determining the levels of production that can be expected from the Saudi Arabian oil fields in the remaining decades of this century. Saudi Arabia, as the holder of the world's largest reserves of oil, plays a pivotal role in world energy calculations.

The staff investigation and this report concentrate on essentially technical, conservationist, and financial considerations affecting Saudi Arabian production. These considerations have had a significant effect on the plans to reduce the levels of present and future production and capacity of the Saudi Arabian fields. Factors which are other than purely technical and financial have played, and are likely to continue to play, a significant role in the final decisions which determine the level of oil production in Saudi Arabia.

The facts uncovered by the staff investigation and set forth in this report demonstrate that there are significant technical and other considerations which indicate that the optimistic and highly expansive predictions respecting the levels of production from Saudi Arabia are problematic at best and cannot with any measure of prudence be relied upon as an element in the formulation of United States energy policy over the next two decades.

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INTRODUCTION AND SUMMARY

Oil production in Saudi Arabia[1] is recognized as a critical element in future oil supply. Historically, the world has depended upon Saudi Arabia to maintain a margin of spare capacity that can be utilized in time of surging demand and "shut in" when demand slackens. For the most part during the last five years, Saudi Arabia has been able to play this role. However, when Saudi Arabia has been at the outer limit of its production capacity—with demand pressures still strong—shortfalls in crude oil supplies and higher crude oil prices have resulted. For example, with no spare capacity available in December 1978, Saudi Arabia was unable substantially to moderate OPEC's 1979 price increases. For the first quarter of 1979 the country was producing at levels near its full capacity of approximately 9.8 million barrels a day (mmbd) to make up for the loss of Iranian oil. However, with a pre-Iranian crisis spare capacity of 2.0 mmbd to 2.5 mmbd, Saudi Arabia was not able to fill the gap in supply caused by the loss of 4.5 mmbd to 5.0 mmbd of Iranian exports, until Iran resumed significant exports.

Even though Saudi Arabia has the largest accumulation of known oil reserves in the world today, technical, conservationist and financial considerations will significantly affect future oil production decisions. These three considerations will in large part define the parameters for decision; they do not, however, predict whether any one production level would be the most desirable or the most likely. Failure to understand the parameters governing future Saudi Arabian production decisions would lead the United States to misinterpret these decisions or to rely unreasonably on open-ended volumes of Saudi Arabian crude oil to meet the United States' energy needs.

This report details the technical, conservationist and financial parameters which will affect Saudi Arabian oil production decisions. The effect of the Saudi Arabian concern about the erosion of its oil revenues by inflation, as well as about the optimum expansion of industrialization given economic and social realities on oil production decisions is beyond the scope of this report. The report also does not attempt to evaluate political, diplomatic and security factors which may have a bearing on decisions respecting future production levels.

Based upon information collected by the Committee staff over the last year, it seems evident that the United States should not base its energy plans on the premise that Saudi Arabia, as residual supplier, will produce enough oil to supply the needs of the United States or the world economy over the next two decades at anticipated rates of oil consumption. The current long-term production target for Saudi Arabia appears to be 12 mmbd. Three considerations bear upon this decision. First, higher production rates would require costly in-

[1] Production from the Neutral Zone, currently about 0.3 million barrels a day, has not been considered a part of Saudi Arabia throughout this analysis.

vestments and might not be maintained for a period of time acceptable to the government. Second, there are perceived or actual technical restraints on increased production from individual fields. Third, there are strong conservationist concerns in Saudi Arabia.

Saudi Arabia's decision to cut back its producing target to 12 mmbd was significantly influenced by the conclusion that higher production rates would require costly investments and might not be maintained for a period of time acceptable to Saudi Arabia. The oil production level that can be maintained until it begins to decline to lower levels is known as the "production plateau." The plateau that the Arabian American Oil Company (Aramco) [2] now uses as a basis for its planning indicates that a rate of 12 mmbd may last 15–20 years before irreversibly declining, a period Saudi Arabia now finds uncomfortably short. Higher rates, such as 16 mmbd, could only be maintained for a shorter period of time before decline. Moreover, the prospect of future discoveries in Saudi Arabia is highly uncertain. In addition, technical problems have complicated the management of the oil fields since the early 1970's. Taking into account all these factors, it would be imprudent for the United States to plan on a change in Saudi Arabian oil development plans to increase long-term production above 12 mmbd. The current plan of a target capacity of 12 mmbd achieved no earlier than 1987 is a considerable change from an earlier one which envisioned a capacity of 16 mmbd in 1983.

The Committee staff has obtained no evidence that Saudi Arabia has established its long-term production goal to express displeasure with, or to change, the Middle East policies of consuming nations, including the United States.

Future constraints on Saudi Arabia's production capacity add unprecedented urgency to efforts in the United States and other consuming nations to develop more effective energy policies. Rational planning now could ease the difficulties inherent in the transition to an economy less dependent on oil. The United States is fast approaching the period in the mid to late 1980's, when the world's capacity to produce oil is otherwise likely to be outpaced by increasing oil demand.

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[2] The Arabian American Oil Company (Aramco) is currently owned jointly by the Saudi Arabian Government and four American oil companies—Exxon Corporation, Texaco Inc., Standard Oil Company of California, and Mobil Corporation. The Saudi Arabian Government owns 60 percent; the companies, the remaining 40 percent.

SAUDI ARABIA'S OIL PRODUCING ABILITY

In the early 1970's, Aramco had intended to build capacity to levels as high as 20 million barrels a day (mmbd) by the early 1980's. As time passed and demand growth slowed, this target level was lowered to 16 mmbd, which was to be reached first in 1983. But in October of 1977, Saudi Arabia changed the target capacity and imposed financial constraints that deferred until post-1986 the time when even this lowered level would be reached. The target capacity level for the indefinite future has been lowered to 14 mmbd of *facility capacity* or only 12 mmbd of *maximum sustainable capacity*.[1] For planning purposes, maximum sustainable capacity is the most relevant concept, as it refers to the amount of oil that can be produced for a longer than temporary period of time.

At the heart of this cutback is the resolve of Saudi Arabia to maintain production of its oil fields at a sustained level for as long as possible. The decision to limit the long-term level of production to 12 mmbd was influenced by the declining estimates of the duration of sustainable production at chosen rates, before these rates decline, and the technical problems that had previously occurred in oil field management.

Length of Production Plateau

Saudi Arabia has frequently articulated its concern that its petroleum wealth remain available for future generations. In a speech on April 19, 1978, for example, Crown Prince Fahd reemphasized the importance that Saudi Arabia attaches to protecting this legacy:

> Saudi Arabia has worked and is working sincerely and earnestly to provide an appropriate level of oil and gas production as an expression of its feeling of shared responsibility in the international community, but our feelings of responsibility toward future generations in Saudi Arabia also claim careful consideration and the establishment of a calculated balance between the present and the future.

The Crown Prince's message to consuming nations was to reduce their consumption of oil and find alternative sources of energy.

The legacy for future generations would obviously be greater the longer a chosen rate can be sustained before declining. As an oil field

[1] *Facility capacity* refers to the total installed capacity of gas-oil separating plants, main trunk pipelines and oil loading terminals; the current facility capacity is approximately 12.8 mmbd. *Maximum sustainable capacity* represents the maximum production rate that can be physically sustained for several months, usually six or more; approximately 9.8 mmbd was the figure for the first quarter of 1979. Maximum sustainable capacity takes into account the operating experience of the total production system and is generally 90 to 95 percent of facility capacity. Production at the sustainable capacity does not necessarily mean that it is a prudent rate to prevent damage to the oil field. *Surge capacity* represents the level that can be produced for a short period of time, as much as a few weeks; the recent daily production peaks of 10.5 mmbd approximate the current level.

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operator, Saudi Arabia would choose a plateau rate of production that optimizes the value of revenues and field performance. The length of time the production plateau is sustained depends upon the amount of reserves, the level of production consistent with prudent oil field practice, and the level of capital invested.

Several years ago Saudi Arabia was operating under the premise that rates of 20 mmbd could be sustained through the end of this century. Now it appears to be basing its calculations on rates of 12 mmbd being sustained until that time. A key factor in the recent scaling down of its oil development plans may lie in the steadily diminishing lengths of time that each production plateau rate can be maintained.

In the case of Saudi Arabia the length and level of the production plateau for the whole country represents the combination of plateaus from many different fields. Because it is unlikely that any two fields will have a plateau that lasts for the same period of time, fields must be developed and oil produced at carefully planned intervals in order to maintain a constant production plateau for the whole country. Thus, as the most prolific fields reach the point of decline, more costly capacity additions in the smaller fields must be constructed and put into operation to compensate. At some point, the newer fields are unable to make up for declining production in older fields. At this time the production plateau of the entire country begins to decline.

In the period when oil production is in its early stages, an oil company, such as Aramco, will draw a production profile for the entire country using short-hand methods, to avoid the complex and uncertain process of estimating development plans far into the future. The short-hand method used is to select a target production level and compute the length of time it can be produced before reaching a preselected ratio of total oil reserves to yearly production—a ratio of 20:1 or 15:1 is usually chosen. When the reserves to production ratio declines to this point, world-wide experience has shown that a plateau rate for an entire country is unlikely to be maintained much longer without new discoveries or reserve additions. Any one field, however, may be able to sustain a plateau rate until a ratio of 10:1 is reached. Aramco has used this short-hand method in its early efforts to construct production profiles.

For computing the point of eventual production decline, the short-hand method is less accurate than the predictions from a reservoir model. The short-hand method begins with a reserve estimate and mechanically computes the time of decline. However, the reservoir model—using reservoir properties and historical oil field performance—predicts both the time of decline and the amount of oil ultimately recovered. At present, the most sophisticated reservoir models are for the Ghawar, Abqaiq, Berri and Safaniya fields.[2] As a result, the margin of error in predicting the time of decline is much less for these four fields, which have 61 percent of Aramco's probable reserves, than it is for determining the point of decline for the whole country.

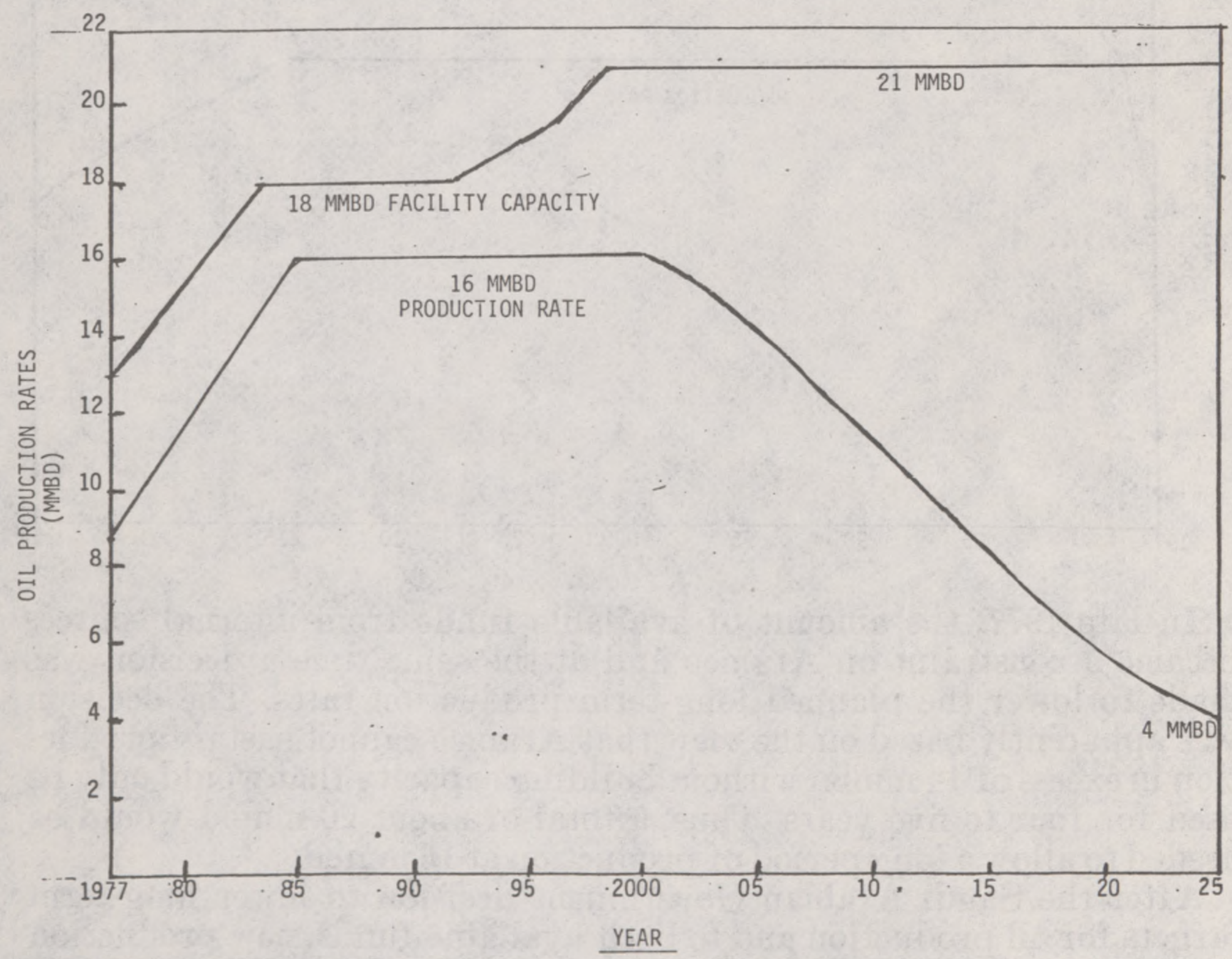
In mid-1973, the Saudi Arabian Government expressed concern to Aramco that oil production not decline for a long period of time. It indicated that to achieve a 20 mmbd rate without wasting a national asset and damaging reservoirs would require a greatly stepped-up

[2] These four fields combined accounted for approximately 87 percent of Saudi Arabia's sustainable capacity of 9.8 mmbd during the first quarter of 1979.

exploration program. It also expressed concern that the Abqaiq field was being overproduced, a charge Aramco officials denied.[3]

At the end of 1973, Aramco had profiled two plateau rates, 20 mmbd and 25 mmbd, and assumed no additional discoveries to the existing reserves of 245 billion barrels (the upper range of the possible reserve category). Production profiles with these assumptions would have shown that the plateau rates could have been sustained for 15 and 8 years, once the plateau rates of 20 mmbd and 25 mmbd, respectively, were reached in the early to mid 1980's.

The question of plateau rates and decline reappeared in early 1977. A plateau rate of 16 mmbd, sustained as long as possible and based upon reserves of 245 billion barrles, was analyzed. This analysis concluded that this rate could be sustained for 15 years—from 1985 to 2000—before it started to decline, a decrease of 5 mmbd from the plateau of 20 mmbd that had been projected to last for 15 years.



An important new factor appeared in the calculations: the ever increasing amount of facilities required merely to maintain high levels of sustainable capacity. Within seven years after a plateau rate of 16 mmbd would be reached, significant additions to facility capacity at increasing costs would be required merely to maintain that rate. (The cost factors are further discussed in Appendix C.) After 13 years, a facility capacity of 21 mmbd would have to be in place to sustain a plateau production rate of 16 mmbd.

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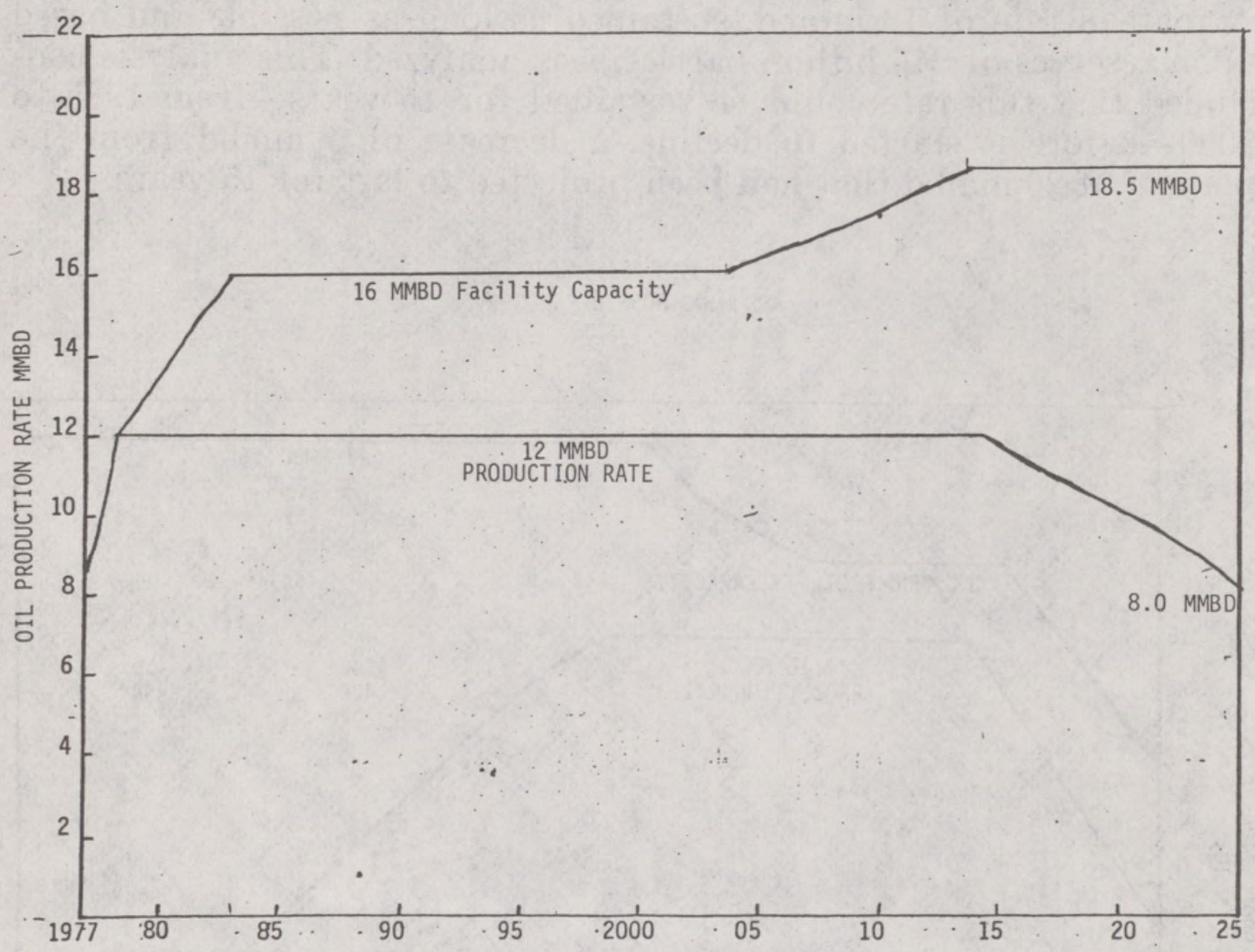
[3] See Multinational Corporations and United States Foreign Policy. Hearings before the Subcommittee on Multinational Corporations of the Committee on Foreign Relations, United States Senate, 93rd Congress, 2nd Session, Aug. 7, 1974, Part 7, at pp. 538 and 560.

A short time later in 1977, an estimate of the length of a 12 mmbd production plateau was also modeled. Based on "possible" reserves of 225 to 245 billion barrels, this lower rate was sustainable for 36 years until the year 2014, if a facility capacity of 16 mmbd were constructed and eventually increased in the latter years to 18.5 mmbd. In the year 2025, production under the 12 mmbd case would be 8.0 mmbd, compared to the 4.0 mmbd rate of the 16 mmbd case.



In late 1977, the amount of available funds from internal sources became a constraint on Aramco and at the same time a decision was made to lower the planned long-term production rates. The decision was apparently based on the view that Aramco cannot sustain production in excess of 14 mmbd without building capacity that would only be used for four to five years. Thus, a total of about 20 mmbd would be needed to allow a long period of production at 16 mmbd.

After the Saudi Arabian Government decision to lower long-term targets for oil production and to limit available funds, new production profiles were computed by Aramco in the spring of 1978. These profiles projected lower expectations as to how long a plateau production rate could be maintained. These new profiles resulted in part from a lowering of the expected oil recovery for planning purposes from "possible" to "probable" reserves.

Aramco has three categories of oil reserves, defined by degrees of certainty concerning expected recovery from the ground.[4] Aramco

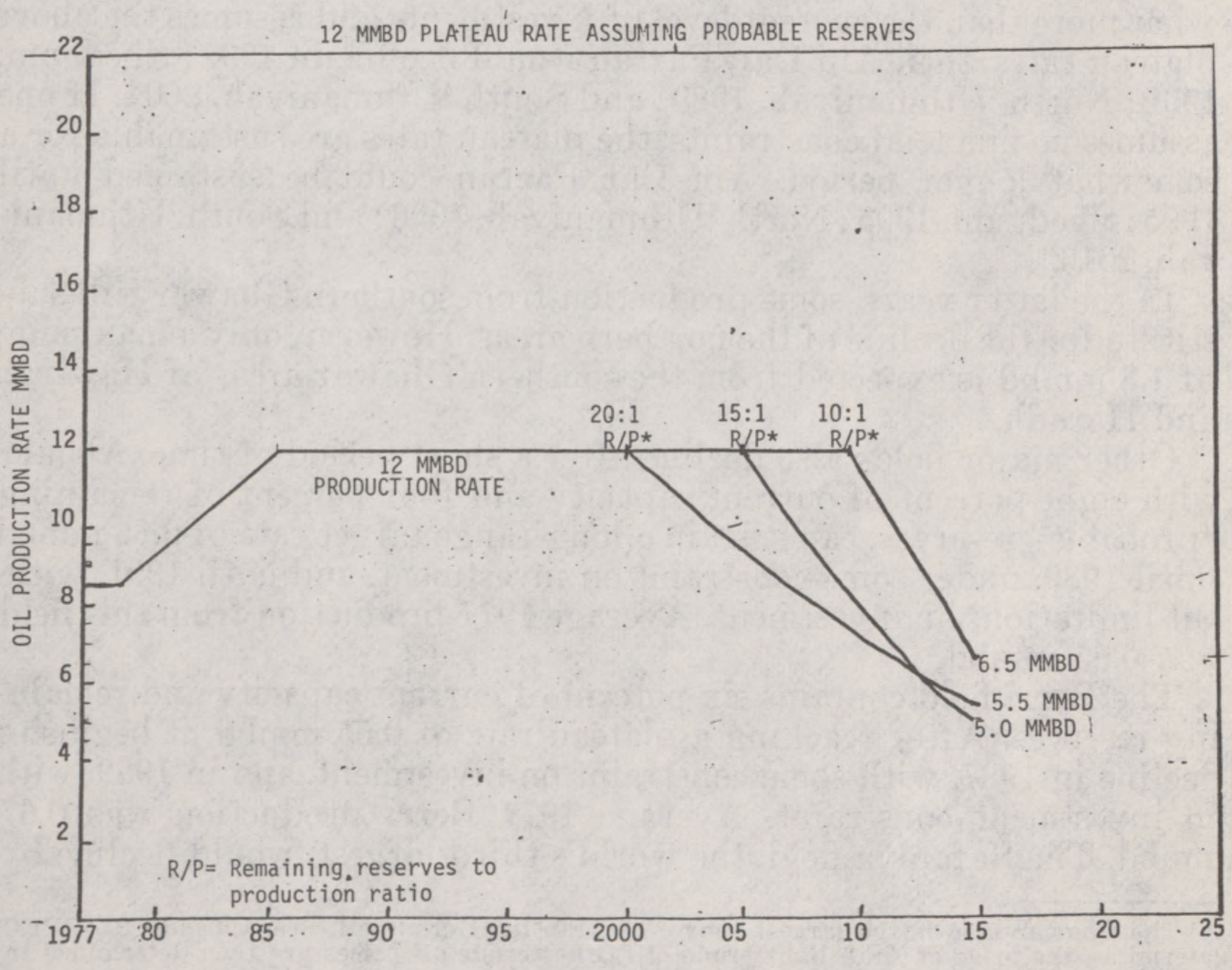
[4] The categories are: (1) proven; (2) probable; (3) possible. The terms reflect the varying expectations of the ultimate quantity of oil recoverable from a particular oil field, with proven being the most certain, and possible the least certain. The categories refer only to known oil fields; they carry no implication about the amount of oil that remains undiscovered. It is standard practice in the industry to employ several categories of reserve estimates for planning purposes.

was told to employ for planning purposes the category of "probable" reserves, which totals 177.6 billion barrels, rather than continue to use "possible" reserves 248.1 billion barrels. Aramco believed that the "probable" category more accurately reflected the amount of oil ultimately recoverable than did the "possible" category. If these reduced reserve estimates were later found to be conservative, then any given production plateau would be sustainable for a longer time than indicated in the text.

Even if these new production profiles had not been known in late 1977 when a decision was made to limit target capacity, the change in plateau life may have reinforced the decision to slow capacity growth. If it assumed Aramco's profiles were correct, Saudi Arabia could now rely on a production rate of 12 mmbd for 15 to 20 years, from 1985 to the period 2000–2005. A rate of 16 mmbd, reached in 1990, may be sustainable for only two to seven years before declining in the period 1992–1997.

COUNTRYWIDE PRODUCTION PLATEAU LENGTHS, ASSUMING PROBABLE RESERVES

	Year plateau rate achieved	Plateau duration at selected reserves-to-production ratios (years)		Year decline begins at selected reserves-to-production ratios	
		20:1	15:1	20:1	15:1
Millions of barrels per day:					
12	1985	15	20	2000	2005
16	1990	2	7	1992	1997



The time at which Ghawar,[1] the world's largest field with 10 percent of the world's remaining reserves, begins to decline is the single most important factor in computing a production profile for the whole of Saudi Arabia. Ghawar currently accounts for more than 50 percent of Saudi Arabia's capacity and 37 percent of its reserves. Under any set of assumptions about the level of capital expenditures and the level of production, Ghawar begins to decline in a relatively short period of time.

If one assumes (1) a combined production plateau of 6 mmbd for Abqaiq (0.7 mmbd) and Ghawar (5.3 mmbd), which is the approximate current production level for these fields, (2) a somewhat higher level of investment than currently planned, (3) an expected recovery rate that approaches the figure for "probable" reserves (Aramco's best estimate), and (4) no significant new discoveries or advances in the technologies of oil recovery, then the aggregate production of these two fields begins declining by 1993. Abqaiq and Ghawar account for roughly 60 percent of Aramco's current sustainable capacity.

Saudi Arabia would not extend the Ghawar plateau for more than a few years by removing the limit on the amount of money available for investments. Actions that could extend the Ghawar plateau include additional drilling, installation of artificial lift, and expanded facilities to handle corrosive salt water. At a 5.3 mmbd rate, Ghawar's production would include significant amounts from the areas of Ain Dar (1.0 mmbd), Shedgum (1.255 mmbd), North 'Uthmaniyah (1.9 mmbd) and South 'Uthmaniyah (0.4 mmbd).[2] If one assumes somewhat more than the current level of investments and assumes the above plateau rates, then Ain Dar/Fazran would decline in 1992; Shedgum, 1992; North 'Uthmaniyah, 1989; and South 'Uthmaniyah, 2004. If one assumes no financial constraints, the plateau rates are sustainable for a somewhat longer period. Ain Dar/Fazran could be sustained until 1995; Shedgum, 1995; North 'Uthmaniyah, 1996; and South 'Uthmaniyah, 2016.

In the latter years, some production from southern Ghawar will substitute for the decline of the northern areas. However, only a maximum of 1.3 mmbd is expected from the southern Ghawar areas of Hawiyah and Haradh.

Other major fields also decline after a short period of time. Abqaiq, with eight percent of current capacity and four percent of remaining "probable" reserves, can sustain a long-range target rate of 0.65 mmbd until 1989, under some constraint on investment, and until 1991, without limitations on investment. Average 1977 production from this field was 0.85 mmbd.

The Berri field contains six percent of current capacity and remaining reserves. After reaching a plateau rate of 0.65 mmbd, it begins to decline in 1987, with some constraint on investment, and in 1989, with no investment constraint. Average 1977 Berri production was 0.67 mmbd. The Safaniya field, the world's third largest, would decline by

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[1] The Ghawar field is the largest source of Arab light crude oil. See Appendix D. OPEC determines the price of Arab light crude oil. Other crude oil prices are then determined in relationship to this benchmark price.

[2] Average 1977 production from these areas of Ghawar was as follows: Ain Dar, 1.3 mmbd; Shedgum, 1.25 mmbd; North 'Uthmaniyah, 1.65 mmbd, and South 'Uthmaniyah, 0.4 mmbd.

1994 at target rates for its principal reservoir of 1.575 mmbd, after a plateau life of only 11 years. It is unknown if the Safaniya plateau can be maintained by additional investments. Average 1977 Safaniya production was 1.05 mmbd.

The above four fields account for 61 percent of Aramco's remaining probable reserves and 87 percent of its first quarter 1979 sustainable capacity of approximately 9.8 mmbd. Even under optimistic assumptions on the level of investments, these fields will all be in decline before the end of the century at production rates which approximate current production. Thus, if Saudi Arabia wished to raise capacity, or even wished to sustain current capacity beyond 1990, it would need to develop other fields in addition to these four. One alternative to developing additional fields would be to raise the North 'Uthmaniyah productive capacity from 1.9 mmbd to 2.6 mmbd. But this increase could cause North 'Uthmaniyah to decline in 1987 rather than decline at the lower production level in 1992–1996.

Reserves

As Aramco has gathered additional information about the oil fields and analyzed these fields' historical performance, it has been able to make more precise estimates of the amount of oil that will be ultimately recovered. This continuing assessment has led to decreasing reserve estimates.

The amount of oil that is physically present underground sets the theoretical limit on how much oil can be produced. But in practice, only a certain percentage of the oil underground, or as it is known the "oil in place," can be recovered and brought to the surface. Reservoir characteristics and production techniques have a substantial impact on the relative amount of oil ultimately recovered.

The amount of oil in place in the discovered fields of Saudi Arabia is subject to only minor dispute among Aramco geologists; their estimate of the original oil in place is approximately 530 billion barrels. The amount of oil which will be recovered from these reservoirs is much more in dispute.

Recoverable oil, not oil in place, is what is known as oil "reserves". Aramco currently is carrying "possible" reserves of 248.1 billion, "probable" amounts of 177.6 billion and "proven" amounts of 110.4 billion. None of these reserve categories includes expectations about future discoveries. The most conservative estimate of recovery is proven reserves, a recovery rate for the whole country of 31 percent of the oil in place on average, although recovery rates for individual fields vary. The most speculative estimate is "possible" reserves, a recovery rate on average of 52 percent of the oil in place. "Probable" reserves represent a recovery rate of 38 percent of the oil in place.

The use of "possible" reserve assessments to describe likely levels of ultimate recovery dates back at least to mid 1973, when the sensitive subject of reserves and depletion rates was discussed in the context of an analysis of reservoir performance and oil depletion rates of country's oil fields. Aramco emphasized the "conservative" nature of the reserve figures and the length of time production could be sustained at "relatively high levels" (i.e., 20 mmbd). It suggested that explora-

tion would most likely increase reserves significantly. Saudi Arabia's fears that its oil resource would be depleted in a short time contributed to the sensitivity of the subject.

The companies' approach at this time combined the four different types of Arabian crude oil—usually treated separately—because production of the preferred Arabian light crude would have reached a plateau rate in 1978 at the anticipated production rates of that time. This would have meant Ghawar—the largest field in the world—would have already reached a plateau rate by 1978. The companies decided that rather than use figures of individual fields, some of which could reach a plateau earlier than others, such as Ghawar and Abqaiq, they would approach the reserve study by using countrywide aggregate figures. This approach stressed the growth of reserves over time, including optimistic predictions of future discovery from exploration, rather than the plateau production rate. Moreover, the decision was made to use the category of "possible" reserves (the most optimistic estimate, with a range of 195 to 245 billion barrels).

In November 1973, Aramco put forward production profiles of 20 and 25 mmbd, employing a reserve basis of 245 billion barrels. The use for planning purposes of the "possible" reserves of approximately 245 billion barrels lasted until the early months of 1978, when a reassessment of the country's reserve figures took place. By March of 1978, a contention was advanced by reservoir engineers that the reserve planning base should be changed from "possible" to "probable." While higher management had maintained that the "possible" reserves were conservative, technical considerations suggested that "probable" reserves were more realistic estimates for known fields. The evidence of a lower expected oil recovery than "possible" reserves was to be found in the production history of Ghawar, the major Arabian light field: wells were becoming contaminated with salt water earlier than the reservoir models had predicted and pressures were more difficult to reestablish than anticipated.

On the basis of latest Aramco studies, top management of the shareholder companies concluded that gas-gathering facilities in northern Ghawar would operate only five to nine years at peak capacity before the oil and gas production began to decline in that area; this information was reported to the Saudi Arabian Government in April 1977. Only a short time before, the companies had presented studies which had shown adequate gas volumes through the year 2000. The change in gas availability was due in part to lowered reserve estimates. Shortly thereafter, an official decision was made to use "probable" reserves as the planning basis for all crude oil development projects.

The final reserve figures, especially for the less developed Arab medium and Arab heavy crude oil fields, may well be revised, upward or downward, from Aramco's "probable" figures when more data on specific fields is available. However, all planning is now proceeding as if "probable" reserves are the expected recovery level. While the companies' reservoir models for Ghawar project an ultimate recovery level between "possible" and "probable" reserves, Aramco has concluded on present evidence that the "probable" reserve of 177.6 billion barrels are the more realistic estimate of the amount of oil that will be ultimately recovered. The evidence to support the change to "prob-

able" reserves comes principally from the most developed parts of northern Ghawar, where the most accurate estimates of reserves can be made.

The change over five years from "possible" to "probable" reserves as the basis for planning is a significant reduction—71 billion barrels of oil. This amount is more than all the remaining "proven" and "probable" reserves of any one of the next largest producing countries, such as Iran (60 billion barrels), the Soviet Union (40 billion barrels), the United States (39 billion barrels), Mexico (30 billion barrels), or China (20 billion barrels). To the extent this shift in calculations is associated in the minds of Saudi Arabian officials with decreasing reserves, it will serve to reinforce tendencies to deplete the oil resource slowly. In Ghawar, the difference between "probable" and "possible" reserves—17 billion barrels—is more than either Venezuela or Canada has as "proven" and "probable" reserves.

New Discoveries in Saudi Arabia

For the eight-year period 1970 to 1977, the amount of new oil discoveries which eventually will be classified "proven" reserves is not expected to equal the cumulative production for that period. In other words, Aramco apparently produced more oil than it found in new fields. In only three of the eight years did Aramco discover new fields whose "proven" reserves exceeded the total production during that year. Most of the yearly revisions in Aramco's reserve figures result from additions to known fields, rather than from new discoveries. Revisions are often made in the size of an oil field or in the rate of expected recovery when more certain information becomes available.

In 1977, Aramco added probable reserves of 3.4 billion barrels, while producing 3.3 billion barrels. The discovery of new fields contributed only 136 million barrels to these reserve additions. However, revisions to the size of existing oil fields accounted for 1.0 billion barrels. Changes in the rate of expected recovery from existing fields contributed another 2.2 billion barrels.

Several additional examples serve to show the discrepancy in equating increases in published reserve estimates with new discoveries. In 1970 no new oil fields were discovered, yet Aramco reported a large net gain in proven reserves solely through revisions and extensions in the amount of oil in existing fields. In 1975, Aramco discovered three large new fields and increased its reserves by nearly 7 billion barrels, far above the 2.5 billion barrels it produced. However, "proven" reserves from the three new discoveries were only 500 million barrels; the other 6.5 billion barrels were extensions and revisions of older fields.

The prognosis for future discoveries in Saudi Arabia is uncertain. Shareholder companies do not believe vast amounts of oil remain to be discovered in Saudi Arabia. One company believes that there is an undiscovered reserve potential of 33 billion barrels in the whole of Saudi Arabia. For the five-year period ending in 1980, the shareholder companies believe they will be fortunate to obtain an additional 5 billion barrels of "proven" reserves from discoveries of new oil fields.

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Technical Concerns

Low reservoir pressures in the largest Saudi Arabian field, Ghawar, that have finally been corrected after six years of effort, and concerns about production levels in two other fields, Abqaiq and Berri, appear to have reinforced conservationist objectives of the government of Saudi Arabia. If one uses as a yardstick in assessing past production the practice often accepted in the industry as prudent (that is, that reservoir pressures remain above the pressure level known as critical gas saturation point [5]), it appears that the Ghawar field has been produced at too low a pressure in some areas. If one judges producing practices by the more conservative standards set by the government in 1973 (that is, pressures remain above the bubble point), and to which the companies consented, producing practices in Ghawar have fallen short of those mandated. Most of the North 'Uthmaniyah and Shedgum areas of Ghawar had reservoir pressures below the bubble point for significant periods of time. The companies have denied that they have overproduced the fields or that technical limitations will preclude Saudi Arabia from reaching capacity levels above 12 mmbd.

The reservoir pressure standards, the production limitations on individual fields and areas of fields, and even the 65 percent limitation on the relative volume of Arab light crude oil to total crude oil are rules which are fundamentally based on technical grounds. The Saudi Arabian conclusion that Ghawar in the past has been overproduced has led to the imposition or the reaffirmation of production rules to prevent reservoir damage.

Technical concerns are relevant to Saudi Arabian production levels. First, unsolved technical problems, such as low reservoir pressure, have the potential to limit the present ability to produce oil. Second, an undesirably low pressure could result in the permanent loss of reserves. Third, a reservoir manager may limit production rates from individual oil fields to preselected maximum levels in order to ensure the highest ultimate recovery. Saudi Arabia has already imposed such long-term limits on the Berri and Abqaiq fields. Fourth, technical problems, if they persist, may impede future expansion of capacity until corrected. (Appendix A contains more detailed background for understanding technical issues. Appendix B details the technical concerns of the Saudi Arabian Government from pre-1973 to December 1976.)

Currently, past problems with reservoir pressures are being contained. With minor exceptions, existing reservoir rules are designed to prevent a recurrence of past problems. They do not reflect current technical problems.

Recent Technical Developments and Concerns

December 1, 1976 to October 1, 1977

On December 15, 1976, the OPEC ministers in Doha, Qatar failed to reach an agreement on a new price level for the benchmark OPEC crude oil, Arab light. All OPEC producers except Saudi Arabia and the United Arab Emirates agreed to raise prices 10 percent on Janu-

[5] For definition of "bubble point" and "critical gas saturation point," see Appendix A.

ary 1, 1977, and another 5 percent on July 1, for a full year average increase of 12.7 percent. Saudi Arabia and the U.A.E. decided to raise prices by only 5 percent for the entire year.

It was predicted that the higher prices proposed by other OPEC members would fail to hold in the market place as Saudi Arabia opened up its "11.8 mmbd" production capacity to dampen the price. Saudi Arabia would produce to the limits of its capacity if the market could absorb it. However, it became evident that Aramco's peak capacity was actually about 9.3 mmbd in January 1977, nowhere near 11.8 mmbd, largely because of pressure problems, an inadequate number of wells, equipment delays, and limitations on tanker loading capacity.

For the most part, Aramco's actual production for the first four months of 1977 was at its sustainable capacity. In January, for example, sustainable capacity was 9.3 mmbd while actual production was 8.4 mmbd; in February sustainable capacity was 9.6 mmbd and actual production was 9.5 mmbd; in March sustainable capacity was 9.7 mmbd, as was actual production; and in April sustainable capacity was 9.8 mmbd while production was 10.0 mmbd. Finally, with production reaching a high of 10.0 mmbd for only one month, Saudi Arabia compromised, raising its prices 5 percent to match the higher tiered OPEC price of January. Other OPEC producers, as a concession, agreed to forego the scheduled July increase.

The lack of sizeable spare capacity hampered the government in its efforts to moderate prices. Prior to the price split Aramco had been producing an average of 8.3 mmbd, with December production at 8.8 mmbd. This left at most only 1.0 mmbd to 1.5 mmbd of spare capacity for the first three months of 1977. As late as November 1976, Saudi Arabia apparently believed that Aramco capacity was 11.2 mmbd on a sustained basis. This, however, represented the facility capacity level. Inadequate reservoir pressures in Ghawar played an important role in this capacity shortfall.

The chronology of events was as follows:

After the meeting in Qatar, a Saudi Arabian decision was made to do everything possible to narrow the gap between sustainable capacity and the facility limit, by concentrating first on Arab heavy, Arab medium and then on total crude oil, in that order. All limits the Ministry of Petroleum and Mineral Wealth had previously imposed for technical reasons on the rates of production from Abqaiq, Berri and Ghawar were temporarily suspended. Aramco was to make all efforts to maximize production. Aramco believed that its sustainable capacity, for 1977, would be 9.8 mmbd at the end of the first quarter; 10.6 mmbd at the end of the second quarter; 11.5 mmbd at the end of the third quarter; and 11.9 mmbd at the end of the fourth quarter.

In the first month of all-out production, the producing rate fell to 8.4 mmbd because of tanker scheduling difficulties and problems in the Juaymah port which were accentuated by the weather. Production jumped to 9.5 mmbd in February, and peaked at 10 mmbd in April 1977. In May the first of two fires in the Abqaiq area, attributable to pipeline corrosion, caused a marked decrease in production to an average 8.3 mmbd for the month. In June projected sustainable capacity for 1977 was revised downward to 10.8 mmbd at the end of the third

quarter, 11.1 mmbd at the end of the fourth quarter and 11.2 mmbd for calendar 1978.

By the time production returned to 9.6 mmbd in July, the OPEC price dispute was resolved.

The high production levels in the early months of 1977 did not help reservoir pressures in Ghawar. After learning during the first half of 1977 that at the beginning of 1977 most of 'Uthmaniyah was below the bubble point, with some areas as much as 300 psi below this level, Saudi Arabia stopped production from wells in the areas where pressures were more than 200 psi below bubble point, as these wells were "shut in" at Saudi Arabia's direction.

Saudi Arabia also mandated that pressures not be allowed to decline further in areas 100 psi or more below bubble point. These restrictions on production were further tightened by an Aramco agreement with the Ministry to maintain reservoir pressures in the main Arab light producing fields, i.e., Ghawar and Abqaiq, at the levels prevailing at the beginning of 1977. This constraint, coupled with slippage in the seawater injection program needed to substitute for the declining availability of salty aquifer water, led the companies to revise significantly downward their earlier expectations concerning Arab light capacity for 1978. In addition, Arab light production would be further restricted by the lack of facilities to separate corrosive salt water from crude oil until their installation beginning in 1979.

In July of 1977, the government concluded that overproduction in some Arab light fields had caused irreparable damage and reduced ultimate recovery. Shortly thereafter, allowable production levels were sharply reduced for north Ghawar, Abqaiq and Berri. The sustainable capacity of North 'Uthmaniyah, the most prolific area in Arabia, was trimmed from 2.14 mmbd to 1.755 mmbd, due to declining water available to maintain pressures and to a desire to return pressures in all areas of the field to bubble point or higher as soon as possible. The government trimmed Shedgum sustainable capacity by 60,000 barrels a day to 1.32 mmbd, Berri by 100,000 barrels a day to 0.75 mmbd, and Abqaiq by 150,000 barrels a day to 0.9 mmbd, in order to maintain current pressures. Future production levels were dependent upon the condition of reservoir pressure. This lowered Aramco's sustainable capacity to 10.4 mmbd for the third quarter of 1977.

October 1977 to Present

Over the next year, a Saudi Arabian official publicly elaborated upon the government's 12 mmbd target for future sustainable capacity, which had been imposed in late 1977. He indicated the 16 mmbd rate could not be met for technical reasons—the rate of depletion would be too high. He went on to say that Saudi Arabia had no technical capacity to produce over 12 mmbd unless more reserves were discovered. One of the Aramco owners noted that this official seemed to sincerely believe that 12 mmbd is a real technical limitation, apparently based on studies he had seen (not done by Aramco).

Aramco conceded in January 1978 that rates of 15 mmbd or higher were impossible unless Saudi Arabia allowed Aramco to change the way in which salt water was injected for pressure support. Currently, it is injected at the periphery of the field as opposed to in a pattern

throughout the field. The government believes that pattern injection would harm the level of ultimate recovery and has refused to allow it.

In late 1977, oil field pressure problems continued to affect adversely Aramco's sustainable capacity and forced the Ministry to impose production limits below capacity for some areas of Ghawar. Cutbacks in South Ghawar were required because of a persistent low pressure area which was not responding as quickly as desired to increased levels of water injection. Shedgum production was reduced because pressures were declining even with record high levels of water injection in the fourth quarter. Because of inadequate water injection, expected production from Berri fell below 0.65 mmbd in order to rebuild reservoir pressures in the center of the field. Aramco estimated in the spring of 1978 that pressures would finally exceed the bubble point in all areas of Shedgum and 'Uthmaniyah sometime after the end of 1978. Pressures had fallen below the bubble point of Shedgum in 1972 and in 'Uthmaniyah in 1973.

As part of its revision of long-run production plans, the government imposed stringent rules on reservoir management that will affect Aramco's future producing practices. The relative amount of Arab light production was to be controlled. In February 1978, it was decreed that light crude oil can only be 65 percent of total exports of crude oil. The government had made clear that its long-run policy was to bring relative production of Arab light crude oil into line with the Arab light percentage of total reserves.

In April 1978, a rule was imposed controlling the absolute amount of Arab light production. Production from the three Arab light fields accounting for 95 percent of current sustainable capacity for Arab light—Ghawar, Abqaiq, and Harmaliyah—was limited to no more than 6 mmbd, unless an even lower level was mandated by sound reservoir practice. The desired reservoir practice was specified. All projects to maintain or expand capacity must be designed to maximize ultimate recovery under conditions of first class oil field practice. Only peripheral water injection should be used. Pressures must be maintained above the bubble point.

As a result of the changes in investment patterns caused by financing limitations (see next section), sustainable capacity at the end of 1978 was estimated at approximately 10.1 mmbd, even though production on a surge basis advanced to as high as 10.5 mmbd on some days. However, at these levels pressures began to fall in Abqaiq. In fact, 10.1 mmbd was apparently above the sustainable capacity for the fields. Aramco's sustainable capacity for the first three months of 1979 was somewhere on the order of 9.8 mmbd.

In January of this year, the government limited Aramco to an average monthly production of 9.5 mmbd for the first three months of 1979. The evidence indicates that this level represented the government's desire to conserve its oil resources. A rate of 9.5 mmbd may have represented the maximum Aramco production consistent with the 65 percent limitation on production from Arab light fields. Sustainable capacity in fields other than Arab light fields was approximately 3.3 mmbd, which, under the 65 percent rule, allowed a maximum Arab light production of 6.2 mmbd. In addition, because sustainable capacity for Aramco production appeared to be less than 10.0 mmbd for the first three months of 1979, the limit may even have represented the govern-

ment's perception of its sustainable capacity, even if it would have imposed no ceiling on production.

Whatever the precise capacity level today, at the time of the December 1978 OPEC meeting in Abu Dhabi, Aramco was producing at the limits of its sustainable capacity. This fact was known to other OPEC countries. Under these circumstances the ability of Saudi Arabia to moderate OPEC's prices was severely limited. OPEC, as a result, was able to raise the base crude oil price by 14.5 percent over the course of 1979.

Self-Financing Constraint

Saudi Arabia has required that all investment to maintain or expand crude oil producing capacity be derived from internally generated funds. Prior to the January 1, 1979 OPEC price hike, Aramco estimated that this ruling would allow only $0.50 per barrel for reinvestment, an estimated $1.7 billion per year. These calculations may be affected by the subsequent price hikes.

Because of rising costs associated both with projects to maintain capacity, such as those for oil field pressure support or the separation of corrosive salt water from crude oil, and with projects to expand capacity, especially in smaller and more remote fields, the self-financing constraint will seriously delay Aramco's attainment of the lowered production target of 12 mmbd. The current Aramco estimate, made before the recent Iranian crisis, is that the maximum sustainable production capacity will reach only 10.8 mmbd by 1983,[6] with an important variable being the average level of Aramco production in the next several years. The following table was constructed by the staff to show the approximate capacity of the current plan.

TABLE 1.—OCTOBER 1978 PLAN: TOTAL CRUDE OIL

[million barrels per day, mid-year levels]

Year	Production	Maximum sustained capacity (limited by the number of wells)	Snapback maximum sustained capacity [1]	Facility capacity
1978	7.4	10.1	10.1	12.5
1979	7.4	10.5	10.8	12.8
1980	7.4	10.2	11.0	12.8
1981	7.4	10.5	11.4	12.9
1982	8.0	10.6	11.5	13.0
1983	8.5	10.8	11.9	13.2

[1] The amount of capacity that would be sustainable 1 year after a decision were made to increase the rate of well drilling. See discussion on p. 19.

Aramco's prediction of a 1983 capacity of 10.8 mmbd reflects a significant decrease in expected capacity growth. Formerly, Aramco's target capacity had been essentially open-ended. In November 1973, Aramco estimated production profiles that had plateau rates of 20 mmbd and 25 mmbd. In March 1974, Aramco planned to reach a sustainable capacity of over 16 mmbd by 1979, of which Arabian light sustainable capacity would have totaled at least 10.0 mmbd, most

[6] Sustainable capacity was approximately 9.8 mmbd for the first quarter of 1979.

of it located in Ghawar. Under consideration by the shareholders was a plan to raise facility capacity as high as 19.4 mmbd by the end of 1980, although this program was shelved as too ambitious.

From the end of 1973, demand slackened because of the OPEC price increases and the recession that developed in the consuming nations. By October 1976, the projected target facility capacity had decreased to 16.0 mmbd to be reached in the 1981–1982 period. Projected sustainable capacity was slightly lower, at 15.2 mmbd in 1982. Of this total, over 8.3 mmbd of facility capacity (7.8 mmbd of sustainable capacity) was planned for the Arab light fields. The difference between sustainable and facility capacity was primarily due to Saudi Arabian technical restrictions on Abqaiq and Shedgum. But in November 1976, only some of the proposed projects to reach this projected level were approved. As a result, a commitment had not yet been made to the 16.0 mmbd target.

In February 1977, a proposal to reach a facility capacity of 16.1 mmbd by the end of 1982 was presented. Although a tentative agreement was reached on the program as presented and indications given that it could be budgeted accordingly, a final decision was deferred pending further discussions with the government.

As October 1977 approached, the companies could see that the current system of funding projects solely from Aramco's cash flow would soon become inadequate. The massive gas-collection project, designed to gather for productive use the natural gas that was produced in association with the crude oil, had risen in cost from $4 billion to $14 billion, and had been significantly cut back in scope to prevent even further cost increases. Moreover, the costs of maintaining crude oil producing capacity and of adding additional capacity were increasing significantly. By April 1977, the companies became aware that Saudi Arabia would have to provide supplemental funding.

By October 1977, Aramco planned to reach a facility capacity of 16.1 mmbd by 1983 (a sustainable capacity of 15.5 mmbd). A breakdown of capacity by crude oil type indicated that 9.2 mmbd of facility capacity (9.0 mmbd of sustainable capacity) would have been built in the Arab light fields. The Ghawar field alone would have accounted for 7.5 mmbd of this light crude oil capacity. Arab heavy crude oil would have accounted for a facility capacity of 3.2 mmbd (3.1 mmbd of sustainable capacity), with the Safaniya field alone responsible for over two-thirds of the Arab heavy capacity total.

By the end of 1977, the decision was clear: Aramco would finance all crude oil development from self-generated funds. It was further stipulated that, even if the funds available would allow construction of a higher level of capacity, the capacity target for the indefinite future was to be 14 mmbd. Several months later this target was clarified to mean a maximum of 12 mmbd of sustainable capacity. While the gas gathering project would be financed separately by the government, expenditures for the crude oil programs would have to be derived from approximately five percent of Aramco's gross revenues; the remaining portion of gross revenues pays for the 85 percent Saudi Arabian tax on gross earnings and for operating expenses.

The companies felt the 16.1 mmbd plan should not be put aside. They had several reasons for this view: that the plan would provide

a significant return on investment and represents the business the government knows best; that reduced capacity would limit the government's options and its flexibility to respond to unexpected changes in demand; that a worldwide crude oil shortfall of 2 mmbd would develop in the 1980's, even if output from Saudi Arabia were 16 mmbd; that the financial limit would increase Aramco's vulnerability to various problems associated with delaying projects to separate corrosive salt water from crude oil and with delaying a project to substitute sea water for aquifer water: and that six to seven percent of gross revenue, not four to five percent, would be required to achieve a sustainable capacity of 14 mmbd.

In January 1978, Aramco prepared seven alternate crude oil development programs which attempted to maximize sustainable capacity by deferring some projects and by obtaining outside financing for others. Only one plan met the twin concerns: namely, that the plan be entirely self-financing and that major projects, such as the sea water injection system for Ain Dar and Shedgum, not be deferred. This plan would have achieved 11.4 mmbd of sustainable capacity in 1982, and 11.6 mmbd for the period 1985 through 1987. The following table constructed by the staff estimates the approximate capacity of this plan.

TABLE II.—JANUARY 1978 PLAN: TOTAL CRUDE OIL

[Million barrels per day, mid-year levels]

Year	Production	Maximum sustained capacity	Facility capacity
1978	8.5	10.1	12.5
1979	8.5	10.7	12.8
1980	8.5	10.7	12.9
1981	8.5	11.2	13.1
1982	8.5	11.4	13.1
1983	8.5	11.4	13.1

The exact meaning of the 14 mmbd target was clarified in the spring of 1978. In March, Aramco was to use 12 mmbd as a round number for sustainable capacity. In May this view was publicly reiterated. While the 14 mmbd target level referred to facility capacity, in reality this limit represented a sustainable capacity ceiling of only 12 mmbd.

Aramco's next planning effort in June 1978 resulted in a proposal to achieve a sustainable capacity of 10.7 mmbd in 1983. Arab light sustainable capacity was reduced to 60 percent of total sustainable capacity in 1983, down from a 65 percent share in the January plan, although this was still well above the approximately 49 percent ratio of Arab light reserves to total reserves.

The plan was rejected in July on the basis that a development plan with severely limited funds should be based on the most conservative financial assumptions. The June plan's assumed production rate, and thus the expected capital availablity, was considered too optimistic for planning purposes. In the short term through 1981, Aramco would base its plan on a production level of 7.4 mmbd to provide a margin of financial safety.

In October 1978, this more conservative financial assumption resulted in a new development plan (with projected revenues based on the more conservative production forecast). This plan, which in essential re-

spects remains in effect today, profiled a sustainable capacity of 10.8 mmbd in 1983 and 11.2 mmbd in 1987. Sustainable capacity for Arab light crude oil, which accounts for approximately 49 percent of remaining probable reserves, is limited to 63 percent of total sustainable capacity in 1983 and 57 percent in 1987. Sustainable capacity for Arab medium crude oil, 22 percent of remaining reserves, rises from 11 percent of total sustainable capacity in 1978 to 19 percent in 1987. The relative amount of sustainable capacity for Arab extra light and Arab heavy crude oil remains essentially constant at 6 percent and 18 percent, respectively.

Financial constraints aside, under the current plan some capacity could become physically available within any one year merely by drilling more wells, principally in northern Ghawar. This is known as "snapback capacity" in the table on page 16. In any year from 1980 to 1983 a one-time-only increase in sustainable capacity of 0.8 mmbd to 1.0 mmbd would be available in this way. However, any additional capacity above this amount would require the construction and installation of additional equipment—primarily salt water separators and water injection facilities—that would require two to four years to install after a decision had been made. Under the current plan, Aramco's flexibility to expand capacity on short notice is severely limited.

A more detailed explanation of the costs of maintaining and expanding production facilities is found in Appendix C.

Demand for Crude Oil From Saudi Arabia

Saudi Arabia is universally recognized as the country with the largest petroleum reserves, containing proven and probable reserves of 177.6 billion barrels. It alone accounts for approximately one-fourth of the world's proven and probable reserves. During recent years, Saudi Arabia has attempted to act as residual supplier, balancing increases in demand with larger production while cutting back production in the face of slack demand. Its huge reserves, large capacity, and relatively smaller revenue needs have allowed Saudi Arabia to assume this role.

Experts have viewed Saudi Arabia as the primary source for the incremental increase in oil supply necessary to meet future demands. As more and more OPEC nations reach their long-term production plateaus, it becomes increasingly clear that Saudi Arabia is virtually the only producer who might be able to increase capacity significantly. Because of its perceived position as incremental supplier, analysts have often estimated the likely future demand for oil from Saudi Arabia by determining the difference between projected world oil demand and oil supplies that will be available from sources other than Saudi Arabia. This difference then becomes the demand for Saudi Arabian oil. Because the demand for oil is subject to numerous variables, the demand for Saudi Arabian oil computed by this method is essentially derivative and cannot be assessed with a high degree of certainty.

Many experts who have analyzed Saudi Arabian demand have concluded that more than 12 mmbd will be required from Saudi Arabia by

1990, unless policies in consuming nations, or sharply higher prices, ration a smaller Saudi Arabian supply. The following table summarizes some of these estimates of demand for Saudi Arabian oil.

Estimator	Date of assessment	Demand for OPEC oil	Demand for Saudi oil: Amount (million barrels per day)	Demand for Saudi oil: Year
CIA	April 1977	47–51	19–23	1985
Petroleum Industry Research Foundation	May 1978	[1] 51.7	23	1990
		[2] 43.1	17	1990
		[3] 35.8	[4] 13	1990
Standard of Indiana	August 1978	38.0	12.5	1985
		41.0	15.0	2000
Exxon	August 18, 1978		17.1	1990
Texaco	December 1977		18.0	1990
Aramco	June 1978		14.0	1985
Workshop on Alternative Strategies at the Massachusetts Institute of Technology	1977		20.0	1990
CRS	November 1977		16.6	1985
			20.0	1990

[1] High.
[2] Medium.
[3] Low.
[4] Less than.

Saudi Arabia, within the last year, has urged the United States and other consuming nations to conserve oil. It has indicated its view that the crude oil market will be extremely tight in the 1980's at targeted Saudi Arabian production of 12 mmbd unless demand is constrained. On August 29, 1978, Shaykh Ahmad Zaki Yamani, the Saudi Arabian Minister of Petroleum and Mineral Wealth, warned that, "if the United States and the other industrial states fail to reduce their consumption and if the rate of oil consumption continues to increase, we believe that we will soon see a shortage of oil compared to demand. The shortage will be great." Because of the numerous variables in predicting precise volumes of supply and demand, he refused to specify a date when the shortage would begin, but stated, "every expert in the energy field knows that the quantity of oil that we have in the world today is insufficient to meet the world demand for energy at the rate of today's consumption, and the rate this consumption will be in the future."

Supplies From Other Countries

Middle East producing capacity outside of Saudi Arabia is not expected to increase significantly over the next decade. A critical factor in this conclusion is the fact that by 1990 all Middle East producing countries, except Abu Dhabi, Kuwait and Saudi Arabia, are expected by many analysts to have reached a reserve-to-production ratio of 15 to 1 for known reserves, close to the maximum practical production rate for a given quantity of reserves in a country. This ratio is a guideline for estimating when plateau production capability will decline, but is not to be confused with the concept of production plateau. A country can sustain a production plateau only as long as a reserve-to-production ratio *above* 15 to 1 is maintained. When the ratio of 15 to 1 is reached, production generally goes into decline. Thus, by

1990, the production of all Middle East countries, except the three mentioned, will probably be in decline. At levels of production anticipated prior to the recent Iranian difficulties, peak production from known reserves would have declined in Iran by 1985 and Iraq by 1988.

The Department of Energy's latest projections are as follows:

	Saudi Arabia production	OPEC production including Saudi Arabia	Total free world production	Free world demand
1985	10–12	37–39	61–65	58.3–65.5
1990	12–17	37–43	62–71	61.0–82.1

An infusion of increased production from the two most promising new producing areas, Mexico and the North Sea, will be helpful but probably insufficient to forestall the probable supply shortfall. Significant production from yet-to-be discovered oil is extremely unlikely until after 1985 because of the time required for development of the discovered reserves. For example, Mexico, with initial discoveries in 1972, is expected to produce 2.2 mmbd in 1980, only 1.7 mmbd above Mexico's 1971 production level of 0.5 mmbd.

North Sea production, currently at approximately 1.7 mmbd, should peak in 1986 at an optimistic level of 4.0 mmbd and decline to 3.7 mmbd by 1990. Mexican production, currently at 1.5 mmbd, could grow to as much as 4.5 mmbd by 1985, although a maximum of 3.5 mmbd is more likely in that year.

Unless demand growth is slowed in the interim, by 1990 the physical capacity for oil production could result in supplies insufficient to meet oil demand at current prices. Higher prices or stringent new policies by consuming governments would then be required to ration the limited supplies. The consuming nations could begin a fierce political and economic struggle for scarce supplies, straining relations between Western allies and between richer and poorer nations. The international economy could undergo yet another setback, with adverse implications for the lives of people everywhere.

Appendix A

TECHNICAL BACKGROUND

The focus on the technical concerns has been fundamentally with reservoir pressures and with the proper level of production. To understand the important elements of the technical debate, a general understanding of oil field production is required. Although all oil fields are not the same, the principles applicable to the Ghawar field can be generalized to other Saudi Arabian fields in most important respects.

In Ghawar, oil and gas were originally mixed in solution under immense pressures of 3,200 pounds per square inch (psi). As production proceeded, reservoir pressures were reduced in acceptable fashion until they began to approach the "bubble point," the pressure level at which the gas and oil begin to separate. Until the bubble point is reached, decreasing reservoir pressures are the primary mechanism driving the oil and gas to the surface. At some lower reservoir pressure level, further pressure declines would result in the loss of some oil; this oil, otherwise producible, would remain in the reservoir and as a practical matter could not be recovered economically.

To prevent pressure from declining below the desired pressure levels, salt water or fresh water is artificially injected as a replacement for the produced oil. Reservoir engineers attempt to match the voidage caused by depleting oil with sufficient injections of water; in Ghawar it is desirable to inject at least 1.5 barrels of water for every additional barrel of oil produced. If the voidage is not replaced, the pressures will decline. The natural influx of water is inadequate by itself to match the reservoir voidage at higher production levels.

The proper pressure level that should be maintained is subject to some dispute. Some experts maintain that a field should be produced at or above the bubble point, the pressure at which the gas separates from the oil but does not yet move within the reservoir. Saudi Arabia has, since 1973, established the bubble point as its target minimum pressure for production, a level with which the companies agreed. However, other engineers contend that reservoir pressures can properly fall even lower, until just above the "critical gas saturation" level, the pressure at which the gas, already separated from the oil at the bubble point, now begins to migrate away from the oil from which it came. The companies have used this theory when discussing the fact that they have not in practice maintained pressures in all areas of Ghawar above the bubble point level. For Ghawar, this critical gas saturation pressure is approximately 115 to 165 psi on average lower than the bubble point, although individual areas of the field could have critical gas saturation pressures substantially above this average. Most experts believe that in a field such as Ghawar, prudent reservoir

management dictates that pressure levels be maintained above the critical gas saturation point at a minimum. However, because of the wide distances in Ghawar from where water is injected to where pressures are maintained,[1] others have contended that any plan to produce this field near the critical gas saturation point is too risky because pressures throughout such a large field cannot be maintained this precisely in practice.

Salt water encroachment is an expected phenomenon in a maturing oil field. The salty formation water found primarily at the edges of the oil field, together with the salt water artificially added for pressure maintenance, advances toward the producing wells as the oil is produced. Eventually, this extremely salty water mixes with the oil and is produced in combination with it. Because refineries and other equipment would be damaged by crude oil with a salt content above 10 parts per million of solids, these wells, "contaminated" by the salt water, are shut in, in some cases until they can be repaired, or in other cases until desalting equipment is added. In the short term, shut-in wells will limit capacity until the necessary work is completed or equipment added.

The controversy over the salt water encroachment relates not to the fact of encroachment but to its timing. Because salt water has been encroaching on some wells sooner than predicted by the companies' models, this premature encroachment in some instances has been seen as evidence of overproduction. Premature encroachment has also been cited by one company's reservoir engineer as evidence that "possible" reserve estimates for Ghawar are optimistic.

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[1] The distance between water injection wells and the center of the field is over 6 miles in some parts of Ghawar.

Appendix B

HISTORICAL BASIS OF TECHNICAL CONCERNS

Pre-October 1973 Embargo

Saudi Arabian technical concerns with the condition of its fields date back to the time prior to the October 1973 Arab oil embargo. During that time period Aramco fell behind schedule for injecting water to maintain pressure. This insufficient water injection created pressure drops in Ghawar which in the government's view eventually lessened to some extent the expected recovery of oil from Ghawar. In its concern to protect its fields, the government, at least since 1973, has imposed rules on the level and methods of production.

In the early 1970's, Aramco production skyrocketed, increasing from 3.2 mmbd in January 1970 to 8.3 mmbd in September of 1973. In no other country was production expanded so rapidly. Initially, Aramco accomplished this with minimal cost and effort. However, as 1973 approached, Aramco was under intense pressure to accelerate capacity and production, but had difficulty matching capacity increases with the increased demands for crude oil. Between August and December of 1972 the companies increased their forecast of expected demand in 1973 for Aramco crude oil by over 10 percent, from 7.145 mmbd to 7.878 mmbd.

At the same time in 1972-73 that Aramco was rapidly expanding capacity, the largest field, Ghawar, was reaching the pressure level at which Aramco planned to initiate pressure support—the bubble point. The effective operation of water injection projects, necessary to stabilize pressures above the bubble point at increased production levels, fell behind schedule, with completion delays, start-up problems and difficulties finding an adequate water source adversely affecting early performance.

Despite these difficulties with water injection, Ghawar production continued to increase at rapid rates, achieved in part by drilling additional wells. These extra wells substituted for the decrease in flows of existing wells that resulted from the diminishing reservoir pressure. By March 1973, 0.8 mmbd of well capacity had already been lost until pressures could be restored. By July 1973, new increments of capacity in 'Uthmaniyah were coming on stream and were failing to produce at anticipated levels because of low reservoir pressures. The increased production, unsupported by adequate water injection necessary to maintain reservoir pressure, resulted in rapidly falling reservoir pressures.

Aramco's plan at the beginning of 1972 was to increase gradually the level of water injection in northern Ghawar from 1.8 mmbd to

8.1 mmbd by year-end 1974, an amount adequate to support corresponding oil production increases to approximately 5.4 mmbd. However, in the third quarter of 1973, Aramco was producing 4.2 mmbd of oil from the area, while injecting only 2.6 mmbd of water.

The failure of the pressure maintenance efforts in northern Ghawar stemmed from several causes. Salt water from aquifers, the fluid of choice for pressure maintenance in Saudi Arabia, was in short supply. The drilling of wells for water injection experienced problems. Sand and corrosion prevented operation at planned levels. Prototype pumping equipment for water injection failed to operate as planned.

This large increase in Aramco's production from 5.4 mmbd in May 1972 to 8.3 mmbd in September 1973 occurred primarily in two major Saudi Arabian fields, Berri and Ghawar. But in both fields Aramco's plans for water injection fell behind schedule. Oil production in Berri, in the summer of 1972, jumped from 300 to 600 thousand barrels a day, although water injection did not become significant in Berri until the summer of 1973. Even with increased water injection, Berri reservoir pressures on average decreased until early 1974. In the Shedgum area of Ghawar, oil production rose in late 1972 from 1.1 mmbd to a plateau of 1.3 mmbd, while adequate water injection levels were not achieved before early 1974, at which time pressures began to stabilize. Ain Dar oil production increased from 0.75 to 1.0 mmbd in the last quarter of 1972, while adequate water injection was not achieved before the last quarter of 1973. North 'Uthmaniyah production rose most dramatically, from 0.5 to 1.9 mmbd in the first six months of 1973. Water injection rates did not outpace production until the second quarter of 1974, when pressures began to stabilize. Berri and Ghawar accounted for over 5.2 of the 8.3 mmbd produced by Aramco during September 1973.

Many experts believe that production below the critical gas saturation point causes some damage to ultimate recovery. According to this theory the production rates of September 1973 in the Shedgum and North 'Uthmaniyah areas of Ghawar, which averaged 3.2 mmbd in the third quarter of 1973, were close to damaging the reservoirs. Despite Aramco's plan to produce all fields at or above the bubble point, large areas of northern Ghawar had fallen below this level by October 1, 1973. Pressures were falling in some areas at rates as high as 10 psi per month. Areas of Shedgum and 'Uthmaniyah were below or approaching the critical gas saturation point.

*The government was concerned about the increase in production. In April of 1973, it warned Aramco that sentiment was building among the Saudi ministers to limit production, "some because they felt it was a wasting of the national asset, and others because they felt it merely enabled the United States to continue its present policy of support to an unfriendly state." Aramco was urged that, if it wished to reach an eventual production level of 20 mmbd, "in order to avoid criticism of wasting a national asset and damaging reservoirs, it would be absolutely essential to have a greatly stepped-up exploration program." The Ministry staff charged that Abqaiq was being overproduced, a charge Aramco vigorously disputed.

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*For source of entire paragraph, see Multinational Petroleum Companies and Foreign Policy, Hearings before the Senate Subcommittee on Multinational Corporations of the Committee on Foreign Relations, United States Senate, Ninety-Third Congress, Second Session, August 7, 1974, at pp. 560 ff.

* In July 1973, the government repeated its concern about the production rates of the Abqaiq field. It urged Aramco to produce more of the Arab heavy and medium crude oils and less light crude oil. To achieve this, Aramco was asked to install capacity in fields not then being produced in order to bring relative production of the various crude oil streams more in line with reserves. This was a harbinger of the current rule limiting Arab light crude oil production to a maximum of 65 percent of total crude oil exports. A Saudi official also expressed concern that the current production level of 8.5 mmbd would rekindle conservationist tendencies in the Saudi hierarchy.

A combination of commercial incentives dictated that the Arab light fields be preferentially developed and produced, with other fields developed at a later date. First, the companies could increase capacity in the Arab light fields at low costs. Second, because their refineries were designed primarily to process Arab light crude oil, costly adjustments would be required to optimize the ability of these refineries to process Arab medium and heavy crude oils.

In the summer of 1973, a study questioned the advisability of increasing production in the Abqaiq field above the then current 800,000 barrels a day. As a result, the companies believed that there was a serious question concerning approval for a project to double Abqaiq capacity to 1.6 mmbd by the end of 1976. One shareholder company indicated that Saudi Arabia's concern at Abqaiq was probably only the first indication of government limitations on individual field producing rates. The question of possible field limitations was believed particularly sensitive due to the conditions developing at Shedgum and 'Uthmaniyah. Soon thereafter, approval was refused for the first increment in this Abqaiq expansion plan.

Even before the 1973 embargo a strong conservationist strain was evident in the Saudi Arabian government. On several occasions, in August 1973 for example, Aramco was warned of government concerns about production levels. This conservationist sentiment continued to appear even as production was restored after the embargo. It was not limited to concern with technical oil field performance but also included apprehension with the pace of Saudi Arabian development.

Aramco took seriously the possibility that production would be cut back and in early September prepared an estimate of the effects that curtailment of production would have on its overall financial picture.[1] Aramco's analysis was based on three cases: 7.2 mmbd (Aramco's April 1973 projections for the year 1973), 9.4 mmbd (the approximate capacity to export crude oil), and 7.8 mmbd (an intermediate case that paralleled expected average production levels for 1973).

On August 28, 1973, a disagreement arose with increasing production in Abqaiq above its current level until studies on the field could be completed. The grounds for concern were that any increase in production rates above the reservoir's capacity must affect the quantities of oil that can be recovered.

Sometime in October 1973, production in Berri was limited to 0.64 mmbd, a limit reimposed several times over the next several years and in effect today.

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*For source of entire paragraph, see Multinational Petroleum Companies and Foreign Policy. Hearings before the Senate Subcommittee on Multinational Corporations of the Committee on Foreign Relations, United States Senate, Ninety-Third Congress, Second Session, August 7, 1974, at pp. 538 ff.

[1] Ibid., p. 543.

October 17, 1973 to March 1, 1974

On October 17, 1973, the first day of the "oil embargo", Aramco began to cut back production from a September average of 8.3 mmbd to a November low of 6.1 mmbd. The government ordered the cutback in conjunction with an effort by the Organization of Arab Petroleum Exporting Countries (OAPEC) to force an Israeli withdrawal from occupied territories. The cutback took place one day after OPEC had raised prices by 70 percent, from a benchmark price for Arab light of $3.011 to $5.119. Effective January 1, 1974, the benchmark price shot up again, to $11.651.

Aside from the obvious political dimension explaining Aramco's October cutback, insight into other possible factors which may have carried weight in the Saudi decision was provided during Senate hearings in 1974.

On June 20, 1974, W. W. Messick, Executive Staff, Production, of Standard Oil Company of California, testified before the Subcommittee on Multinational Corporations of the Senate Committee on Foreign Relations. In response to questioning by the Subcommittee's Counsel concerning the Arab oil embargo in October 1973, Messick noted:

> Mr. Levinson. When we met with you in San Francisco you did tell us in your judgment you had been "taken off the hook" on the decline of pressure rate by the embargo? . . . Without the embargo you would have had to confront the dilemma of cutting back production at the time when the offtakers were screaming for as much crude as possible. . . .
>
> Mr. Messick. Yes; and I think that is substantially correct. There was a good deal of pressure on Aramco to maximize production substantially and had this embargo not occurred and our schedule on getting the water injection rate up to its target rate, we would have had some wells I believe that would have crossed this threshold performance level and we would have had to shut them in.

Aramco's expected production for October, November and December 1973 was 8.8 mmbd, 9.1 mmbd, and 9.2 mmbd, respectively. On September 10, 1973 Aramco "sharply reduced" its expectations of oil availability for October and November from planned amounts.[2] The reduction was caused in part by "unexpected losses in well potentials" in the Ain Dar and 'Uthmaniyah areas of Ghawar and in Berri because of inadequate water injection. It appears that Aramco had reached the limits of its sustainable capacity at a level below the demand on it for oil, even before an oil embargo was planned.

Many contend that production below the critical gas saturation point is harmful to oil recovery. At the time of the embargo, areas of Ghawar had pressures approaching or below this level. These pressure drops were observed even at production rates lower than those originally intended for the last quarter of 1973. If Aramco had been able to attain its original planned production schedule for the fourth quarter rather than the lower embargo levels, pressures would have been even lower by the first of January 1974, than actually were the case.

In the Shedgum area, the October decrease in production rates was insufficient to stabilize reservoir pressures. Pressures which had been declining before the embargo at a rate of 10 psi per month in this area

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[2] See Multinational Petroleum Companies and U.S. Foreign Policy. Hearings before the Senate Subcommittee on Multinational Corporations of the Committee on Foreign Relations. United States Senate, Ninety-Third Congress, Second Session, August 7, 1974, at p. 485.

continued to decline at a rate of 5 psi per month even after the embargo cutback, because insufficient quantities of water were being injected to replace the produced oil. Even in 'Uthmaniyah where water injection increased dramatically at the same time production was cut back, pressures continued to fall in some areas of the field for several months until water injection became effective. By January 1, 1974, most of Shedgum and North 'Uthmaniyah had reservoir pressures below the bubble point.

In the first quarter of 1974, as overall Aramco production was returning to levels of September 1973,[3] production levels on individual fields were closely monitored. In February 1974, the companies' concentration of development drilling efforts for 1974 on two main areas, North Ghawar and Berri, was questioned and the conclusion reached that if oil reservoirs in Shedgum deteriorated further, curtailment of production could not be ruled out to conserve the petroleum resources.

In March 1974, production in Abqaiq was cut back from 0.95 mmbd to 0.8 mmbd in order to conserve this reservoir and to maintain its productivity at a high rate of efficiency for as long as possible. Aramco was obliged to proceed forthwith with the implementation of this action in order to prevent any further damages that may occur in this reservoir in the future.

In these circumstances, Aramco drew up a significantly revised crude oil development program. The plan emphasized development of fields containing Arab medium and heavy crudes and reduced the growth rate of the Arab light fields. High priority was placed on increasing capacity in new fields. The rationale was that with all fields developed, less possibility existed that any one field, such as Ghawar, would be depleted at too high a rate.

March 1974 to December 1, 1976

By April of 1974, the view was held that certain fields, from a technical standpoint, could not support continuing increases in their producing capacity. Thus, it was perceived that there was a pressing necessity to observe these fields closely in order to avoid any grave damage that may adversely affect the producing life of the reservoirs and the quantities of oil extracted.

This conclusion was based on evidence from certain important field reservoirs. It was felt that the studies and actual observations of reservoir behavior showed that these reservoirs could not continue at the producing capacity planned for them. The noticeable pressure decline in a large number of these reservoirs was cited as an example. In addition, there were other problems which had resulted from increased production, such as an increase in the ratio of water produced with oil as a result of the rapid advance of displacement water which had begun to invade certain producing wells, as well as an increase in the ratio of gas produced with oil.

On the basis of these results and implications, it was felt that plans should be revised to include the development of the greatest number of

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[3] September 1973 production was 8.3 mmbd. The "September 1973" standard evolved into the 8.5 mmbd Aramco production ceiling that is now the general Saudi Arabian limit on production. In view of the current Iranian oil situation, the Government raised temporarily this production limit to 9.5 mmbd for the first three months of 1979.

oil-bearing strata in the various fields. At the same time, reservoirs which had not yet been produced, and reservoirs which had recently been discovered, were to be developed within a specific timetable. In this connection, the interval between the discovery of oil in commercial quantities in an oil-bearing stratum and the commencement of producing it was not to exceed a period of 24 to 30 months, except in exceptional cases.

It was felt necessary to begin the preparation of such programs and the preparation of a comprehensive production plan to include the greatest number of oil-bearing strata to insure the integrity and optimum exploitation of all reservoirs.

In June 1974, Aramco analyzed the reservoir performance of Abqaiq, Berri and north Ghawar, concluding that the technical problems were being brought under control. The analysis concluded that pressures in northern Ghawar had fallen below planned levels, and would continue to fall for another six months to a year, with Shedgum pressures turning around in early 1975, and with 'Uthmaniyah pressures not until mid 1975. Noting that it has been preferentially restricting production in these two areas, Aramco indicated in its analysis that all of its practices were consistent to maximize ultimate oil recovery.

Significant producing restrictions remained. The Abqaiq limit for its principal reservoir of 0.8 mmbd has remained in force to the present, except for a brief period in early 1977 during the OPEC price split.

The performance of the Berri field has been closely watched. The ceiling of 0.65 mmbd was made permanent on August 1, 1976, for the protection of the reservoir, although the ceiling was temporarily relaxed during the 1977 price split. The pressure rules and the production limits reflected technical concerns. It was felt that higher production rates could harm Berri's ultimate recovery.

Production limits on individual areas of Ghawar were imposed during 1975 and 1976 to hasten pressure restoration in the north portion of the field and to prevent pressure declines in the southern portion. Shedgum remained a dominant focus with production restricted to 1.2 mmbd. Aramco sought to have the limit raised to the facility capacity level of 1.435 mmbd, and in June 1976 Aramco temporarily increased production levels to facility capacity. In July 1976 the production limit was raised to an intermediate 1.32 mmbd level through the end of the year.

In other areas of Ghawar, production limitations were imposed as a result of water injection problems. During 1975, areas in south Ghawar were restricted to less than full facility capacity until the performance of the aquifer used for water injection could be evaluated. In December 1975, Aramco was unsure when this restricted capacity of 0.4 mmbd would become available because of problems with the water injection system.

'Uthmaniyah water injection continued to cause serious problems because of water supply difficulties. To conserve fresh water for agricultural use, the government had restricted the type of water available for pressure maintenance to that more saline than 4000 parts per million of solids. As the supply of this salt water diminished, Aramco fell further behind its injection targets. As a result, in January of 1976 the shareholders were advised that the amount of Arab light

crude oil that could be expected for 1976 was 6.5 mmbd, down from a previously forecasted 7.0+ mmbd, because of the 'Uthmaniyah water problems. Aramco believed that it would average only 6.5 mmbd of Arab light until the seawater injection system became operational in mid 1978. The 6.5 mmbd producing capacity for Arab light is the approximate Arab light capacity even today.

On at least three occasions during 1975, 1976 and 1977, the Saudi Arabian Government's objective to have as many fields developed as possible was reemphasized. Accordingly, Aramco was to take into consideration that production be reduced, if there was a need, from highly developed and old fields (Abqaiq, Ain Dar, Shedgum, 'Uthmaniyah, Berri) and that the company continue and expand its plans for producing oil from remote fields and unused reservoirs.

In early 1976, the government stressed its desire to proceed with the development of remote areas and undeveloped reservoirs, so that all undeveloped fields would be connected by 1980–1981. Aramco was urged to move in the direction of better balance between production rates and remaining reserves of the various crude oil grades. In February 1977, the 16.1 mmbd plan for crude oil development was found not to have been sufficiently evaluated from the technical aspects concerning oil and gas reservoirs and optimum producing rates so as to insure maximum recovery of reserves. The policy of developing and producing remote fields by the end of 1982 and of assuring a balance between the producing rates of various crude oil streams and the ratio of each crude stream to total reserves was reemphasized in April 1977.

Appendix C

COST OF MAINTAINING AND EXPANDING PRODUCTION FACILITIES

A secondary concern evidenced in the decision to plan for an ultimate production level of 12 mmbd is the impact of the rising costs of sustaining the level of existing capacity and constructing new capacity. Costs have risen dramatically from the days of the early 1970's when additional capacity required no more than a new well with connecting pipelines. As the government has assumed the role of ownership of the producing properties, it has also become responsible for the investment of capital to maintain and expand the capacity of these properties.

The increased costs are not large when judged by petroleum industry standards. For example, in 1977 the anticipated cost of expanding facility capacity from 11 mmbd to 16 mmbd was projected to be approximately $11.4 billion in current dollars, or $2,280 per barrel of daily capacity. In the North Sea, new capacity will cost on the order of $7,000 to $10,000 per barrel of capacity. However, the absolute cost of maintaining and expanding capacity must be evaluated in relation to the alternative uses of these capital funds to the Saudi Government. In this context, petroleum revenues today must be used and invested for the day when the oil revenues decline. The alternative investment to new capacity is investment in other productive assets which would maintain the Saudi Arabian Government revenues after the oil has been depleted.

The absolute cost of maintaining and expanding capacity must also be evaluated in relation to the expected productive life of these facilities. As capacity is increased to higher levels, the time span over which capacity is usable declines significantly. At 16 mmbd, existing equipment may have to be scrapped after five years, as individual areas reach depletion, and be rebuilt elsewhere at significant cost just to maintain the 16 mmbd capacity. Saudi Arabia stressed on several occasions that the government does not wish to build capacity that would be prematurely idled after only five years. This was a principal reason suggested for the decision to impose the self-financing constraint.

Costs of Maintaining Crude Oil Capacity

As the producing operations reach mature levels of development, their complexity and costs increase dramatically. Initially, when the Aramco fields were first developed, oil production increases were uncomplicated and inexpensive. But as pressure in individual fields

has declined and approached the bubble point, pressure maintenance equipment has been required.

There are two aspects associated with the increasing costs of pressure maintenance: first, as more fields reach mature stages, an ever growing amount of pressure maintenance equipment is required just to maintain capacity; second, because of declining volumes of salt water available from aquifers, Aramco has been obliged to substitute seawater for aquifer water as a pressure maintenance device. Both factors raise significantly the cost associated with pressure maintenance operations.

The seawater project for water injection is a complex and costly undertaking. Aquifer water could be pumped directly into the oil reservoir without treatment. Seawater, on the other hand, must be filtered before injection to remove harmful particles. The expensive construction of necessary equipment and the higher operating costs associated with seawater filtration and injection have raised the cost of pressure maintenance activities. The cost of water injection facilities required to support existing capacity is approximately $1.5 billion. or $280 per b/d of oil capacity, making the cost per barrel of capacity of the seawater injection project alone roughly equivalent to what it cost to install the entire original crude oil producing capacity.

As the fields mature, oil production begins to include increasing amounts of salt water. This corrosive salt water must be removed to prevent damage to refineries and other facilities. In Saudi Arabia, the underground water which is produced in conjunction with the oil at mature stages of production is extremely saline. Thus, minute amounts of salt water render the crude oil too saline for export. In some cases, the corrosive salt water can be eliminated by reworking the well bore. In Saudi Arabian fields such as Ghawar, however, most salt encroachment today is caused by the advancing waterfront. Only the installation of desalting equipment, a normal procedure at some stage of the field's development, can enable the "shut-in" wells to resume production. The cost of the desalting equipment required to maintain a facility capacity of 9.2 mmbd is $1.5 billion, or $165 per b/d of oil capacity.

Costs of Expanding Production Capacity

As of 1977, the Aramco facility capacity of 11.1 mmbd had been built and maintained at an investment cost of $5.0 billion, or $455 per b/d of oil capacity. If Aramco were to increase facility capacity to 16 mmbd, an additional investment of $11.4 billion or $2,280 per barrel of capacity would be necessary, a substantial increase in the average cost of new capacity. This figure is just an average; the development costs of a few fields run as high as $3,000 per barrel of capacity.

In the 1950's and 1960's, the owner companies constructed refineries that were designed to use Arabian light crude oil. If crude oil other than Arab light were to be used in these refineries without expensive modification, the refineries would be forced to operate at lower levels of output and would produce a less valuable mix of refined products. Arab light crude oil is predominantly found in two large fields—Abqaiq and Ghawar. Historically, these fields, with their desirable reservoir properties and their central location—could be expanded

cheaply with a minimal initial investment. In the past, the owner companies of Aramco sought to produce the Arab light and Arab extra light fields at as high a rate as possible because of these commercial incentives.

Additional capacity increases for the most part will be found in the Arab medium and Arab heavy fields. Because these fields are smaller than the huge Arab light fields, and are also located in more remote locations, the cost of development will be substantially higher.

Appendix D

SAUDI ARABIAN CRUDE OIL TYPES

Saudi Arabian oil fields produce four types, or "streams," of crude oil. These streams represent various ranges in the crude oil's gravity, essentially a measure of the oil's viscosity. Generally, the higher the gravity of crude oil, the more valuable it is to refiners, because it yields a greater percentage of the more valuable petroleum products, such as gasoline, without the need for expensive additional refining equipment.

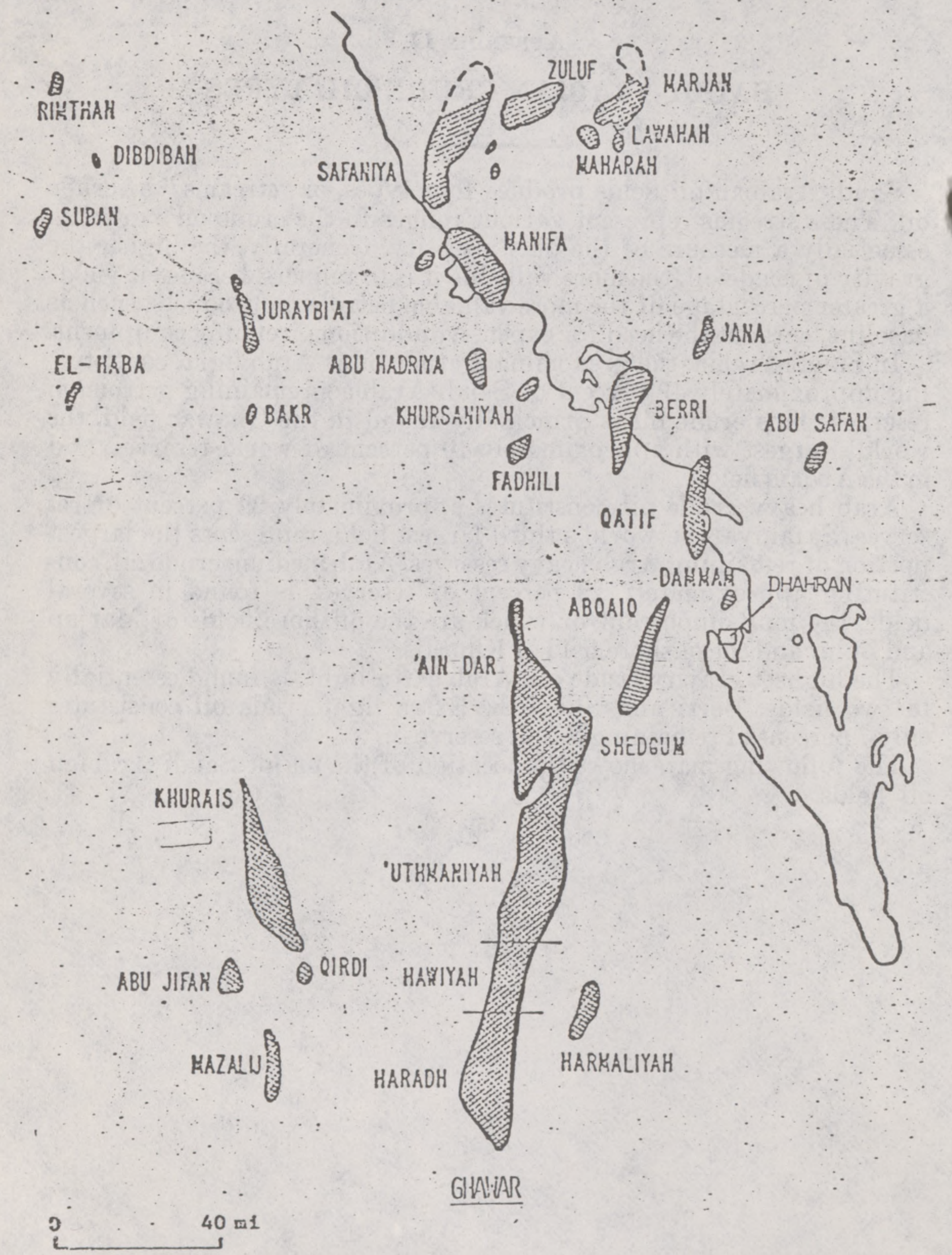
In Saudi Arabia, the predominant crude oil is Arab light, constituting approximately 49 percent of Saudi Arabia's remaining petroleum reserves. This crude oil is principally found in the Ghawar field, the world's largest with approximately 10 percent of world reserves, and in the Abqaiq field.

Arab heavy crude oil constitutes approximately 22 percent of reserves. Safaniya, the world's third largest field, represents the largest portion of remaining Arab heavy reserves. Arab medium crude oil, constituting approximately 22 percent of reserves, is found in several fields, the most important of which are the offshore fields of Marjan and Zuluf and the onshore field of Khurais.

The highest gravity crude oil, Arab extra light, is found essentially in two fields, Berri and Shaybah. Extra light crude oil constitutes only 7 percent of remaining Saudi reserves.

The following map shows the location of the major Saudi Arabian oil fields.

SAUDI ARABIAN OIL FIELDS



APPENDIX E

ARAMCO CRUDE PRODUCTION

[Thousand barrels per day]

	1971	1972	1973	1974	1975	1976	1977	1978
January	3,997.4	5,336.5	6,574.7	7,263.6	7,631.4	7,270.9	8,369.0	7,603.2
February	4,134.1	5,283.3	6,967.8	7,535.0	6,523.2	7,739.3	9,450.0	8,200.0
March	4,326.2	5,390.6	7,228.3	7,860.2	6,297.7	8,160.8	9,682.0	7,470.0
April	4,643.1	5,731.0	7,100.9	8,382.1	5,653.0	8,072.7	10,000.0	7,800.0
May	4,540.7	5,385.2	8,024.3	8,737.0	6,759.8	8,250.1	8,275.0	[1] 7,100.0
June	4,453.5	5,349.5	7,260.8	8,599.8	6,547.2	8,324.1	9,370.6	[1] 7,300.0
July	4,861.4	5,200.2	8,441.6	8,481.8	6,716.2	8,749.7	9,612.9	[1] 7,200.0
August	4,449.0	5,984.7	8,173.1	7,995.0	7,953.7	8,528.1	8,445.2	[1] 6,900.0
September	4,475.7	6,104.0	8,290.8	8,536.8	8,099.7	8,071.2	8,496.6	[1] 8,100.0
October	4,651.3	6,257.1	7,557.6	8,805.7	5,631.2	8,968.2	8,467.7	[1] 9,000.0
November	4,593.9	6,381.9	6,054.4	8,541.0	6,694.6	9,103.3	8,743.3	[1] 9,950.0
December	4,815.2	6,388.1	6,396.6	7,775.9	7,376.0	8,855.6	9,351.6	[1] 10,100.0
Year average	4,497.6	5,733.4	7,344.0	8,209.0	6,826.9	8,343.9	9,016.7	[1] 8,070.0

[1] Estimated.