

An Alternative Pipeline Strategy in the Persian Gulf

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Executive Summary

This paper examines the idea of increasing the capacity of the trans-Saudi pipeline system by using second-generation drag reduction agent (DRA) technology, so that in the event of a Strait of Hormuz (SoH) closure¹, most of the oil², which currently flows through the Strait could be rerouted through the Red Sea. We find that it should be technologically feasible to upgrade the pipeline system to a capacity of 11 MBD for a cost of \$600 million. This capacity assumes the use of both the IPSA and Petrolina pipelines; we also present several lower capacity, lower cost options. The upgrades will take at least 18 months to install, so they cannot be implemented in response to a crisis. DRA technology thus represents an opportunity to buy strategic insurance at bargain rates.

The pipeline upgrade has several important strategic benefits. It can enhance the Saudi reputation as a stable, reliable oil producer, because it will allow Saudi oil to reach world markets even during a SoH crisis. It can reduce the economic damage to the world's oil importing nations in the event of a SoH crisis, allowing the world community to respond to a closure on a deliberate and risk-minimizing timeline. In particular, this may lessen the need for U. S. force to be based in the region. Finally, the existence of an alternate oil route can reduce the political leverage Iran can gain from threatening a SoH closure, as well as reduce their motivation to actually do so. It thereby increases regional security, and reduces the chance of a SoH crisis.

¹ Throughout this paper, when we refer to a SoH closure, we mean any event that interrupts the flow of oil through the SoH. The Strait need not be physically blocked with mines or naval forces if the perceived risk to shipping is high enough to cause a cessation of traffic.

² Our proposal only addresses rerouting Saudi oil. However, use of DRA technology should reduce the cost of any contingency pipeline, and we believe that other proposals such as trans-Omani pipeline for the export of UAE oil should be re-examined.

Background

The SoH is the most important chokepoint in the world oil transportation network, and much material has been written on its strategic importance. Here we give only a very brief summary. Approximately 14.8 MBD of oil (mostly crude, plus some refined products) flows through the SoH. This represents about 40 percent of the world's oil exports, and 20 percent of the world's total oil production. Thus, the SoH is by far the single most important chokepoint in the world oil transportation system.³ The importance of the SoH is enhanced because essentially all of the world's excess production capacity, the first line of defense against supply disruptions, is located in Saudi Arabia, UAE, and Kuwait, and would also be unavailable if the SoH were closed. Most of the oil exported through the SoH goes to Asia, with Japan, South Korea, India, and Singapore being the primary customers. The United States gets about 15 percent of its oil imports (7 percent of total consumption) from this source. However, the global nature of the oil market means that all oil-importing countries are exposed to economic damage of SoH closure via price increases.

One significant existing SoH bypass is the trans-Saudi Arabian Petroline, an oil pipeline that can move 5 million barrels per day (MBD) of crude oil from the Saudi oil fields to the port of Yanbu on the Red Sea. Petroline was originally built in 1981 with a capacity of 1.85 MBD in order to support the industrial development of Yanbu and other areas of western Saudi Arabia. During the "tanker war" in 1987, the Petroline was upgraded to a capacity of 3.2 MBD, presumably to serve as a SoH bypass in case the hostilities further restricted tanker traffic. The Petroline was upgraded a second time in 1993, to its current capacity of 5 MBD, coincident with a Saudi program to raise their total production capacity to 10 MBD.

Maintaining the free flow of oil through the SoH is of vital strategic interest to all of the world's oil-importing nations, including the United States, as well as to Saudi Arabia. The pipeline upgrade has several important strategic benefits. It would reduce the economic damage to the world economy in the event of a SoH crisis. The upgraded pipeline could allow the U.S. to respond to a closure on a deliberate and risk-minimizing timeline, and may lessen the need for U.S. forces to be forward based in the region. It can reduce Iranian motivation to close the SoH, and also reduce the political leverage they get from threatening to do so. It can assure the world oil markets that the Saudis can be relied on to produce and deliver oil even in the face of instability in the Gulf region, thus reducing the chance that other countries will develop production as a hedge, and thereby protect Saudi oil market share.

Of course, the preferred method of achieving energy security is a lessening of tensions between states in the Gulf region. The authors are aware of the recent improvement in relations between the Islamic Republic of Iran and the Kingdom of Saudi Arabia, and we wholeheartedly support this trend. However, Iran is indisputably increasing their capability to disrupt traffic through the SoH, with purchases of anti-ship cruise missiles, patrol boats, and mines, and by upgrading their forces on the islands near the Strait. It is a maxim of strategic planning that it is prudent to base contingency plans on capabilities rather than intentions. We therefore believe that a pipeline upgrade deserves serious attention.

³ The Strait of Malacca is second, with about half of this flow.

Pipeline cost and technical feasibility

This section addresses the cost and technical feasibility of upgrading Petroline and IPSA with DRAs. We start with a brief description of DRAs, including how they work, how much they cost, and how they are used in a pipeline. We then describe seven options for adding DRA technology to Petroline and IPSA. For each option, we estimate the total expected throughput of crude oil and the cost. We then briefly examine the portion of the oil distribution system that is further downstream, including the port capacity at Yanbu, and the impact of a SoH closure on the global oil tanker fleet.

We obtained most of the information in this section from unofficial sources in the oil industry. There may be some inaccuracies in our discussion, but we believe that our main conclusions, the approximate pipeline capacities and associated costs are substantially valid.

Drag reduction agents

The flow in most crude oil pipelines (including Petroline and IPSA) is turbulent; this means that most of the drag, or energy loss while pumping, is due to turbulent eddies in the oil rather than to the friction from the pipeline walls [13]. Drag reduction agents are chemicals that are injected into crude oil pipelines to reduce this energy loss. The process by which these agents work is not definitively established, but they are believed to inhibit the formation of microscopic eddies in the oil. By eliminating this loss of energy, the hydraulic gradient is made less steep and the oil flows faster for the same amount of energy lost [16]. Even if the physics of the process is not completely understood, DRAs are proven technology for increasing throughput in pipelines. DRAs are typically used off shore and in gathering pipelines to handle peak loads; however, they have also been used on the Alyeska 48-inch pipeline to increase the flow rate by about 600,000 barrels per day [3], and in the Colombian pipeline system to help counteract lost capacity due to guerilla attacks [23].

DRAs are injected into pipelines in concentrations between 30 parts per million (ppm) and 70 ppm. They are long chain polymers with molecular weights of approximately 20 million, and are soluble in crude oil. These molecules are fragile, and tend to break down when passing through a pump, so that DRA injectors need to be installed downstream of each pump station on a pipeline. The injectors are essentially self-contained units that inject a measured amount of DRA at a steady rate through a small opening in the pipeline wall. The DRAs leave essentially no residue on pipeline walls, and are easily removed in the standard refining process, where they remain in the bottom of the refinery stack with the “sludge,” the other heavy components of crude oil.

DRAs cost about \$30 per gallon. If used on the Petroline at a concentration of 70 ppm, and injected downstream of each of the 11 pump stations, the DRAs would cost just under \$1 per barrel of crude oil.

When using DRAs, two options will increase pipeline throughput [5]:

Add additional pumps and horsepower to maintain the hydraulic gradient, i.e., operate the pipeline at a higher flow rate but at its design pressure, or

Use only the existing pumps and horsepower, but change the pump impellers to be able to handle the higher flow rates, which will be achieved with the lower drag oil.

The first option costs more, but also gives higher total throughput.

Existing pipeline system

The Saudi Petroline consists of parallel (also referred to as “looped”) 56-inch and 48-inch pipes, extending 1,200 km from Abqaiq to the port of Yanbu on the Red Sea [1,2]. There are 11 pump stations along the pipeline, each powered by five gas turbines with a total of 1.2 million horsepower. The pipeline has a design capacity of 5.1 MBD, and has been tested to 5.0 MBD. There is a parallel natural gas liquids (NGL) pipeline with a capacity of 290,000 per day. Petroline is connected to the onshore production from al-Ghawar, Abqaiq, and Hawtah.

The Petroline is currently operated well below capacity, moving roughly 1.9 MBD. Most of this oil (1.1 MBD) is exported from Yanbu, and the remaining 0.8 MBD feeds refineries near Yanbu and Riyadh [3,4]. The oil flow through the Petroline is determined by market conditions. Saudi oil customers can take delivery at either Ras Tanura or Yanbu, paying a slight premium (currently 25 cents per barrel) at the latter port to cover the pipeline costs. It is more economical for most of these customers to use Ras Tanura [22].

There is an additional 48-inch pipeline, the Iraqi Pipeline in Saudi Arabia (IPSA), which runs parallel to the Petroline from Pump Station No. 3 to the port of al-Mu’ajjiz just south of Yanbu on the Red Sea [18]. IPSA has a 1.65 MBD capacity, and has been out of operation since Desert Storm. It was built during the Iran-Iraq war to give Iraq an export route not subject to Iranian interdiction, and is still owned by the Government of Iraq. Use of IPSA will require a difficult Saudi political decision, and possibly some (deferred?) means of compensating Iraq.

Description and cost of proposed configurations

We analyzed six options for installing DRA capability in the Saudi pipeline system. These options differ in whether additional horsepower is added or only new pump impellers are installed; and in whether the IPSA pipeline is upgraded, used during the crisis without prior upgrades, or not used at all. The following list briefly describes each of the six options along with the total pipeline capacity and approximate cost of each. All costs are rounded to the nearest \$50 million to avoid giving a false impression of precision. A breakdown of the cost estimates is given in the following section, and detailed capacity calculations are presented in appendix A. In all cases, the contingency offset capacity is 1.9 MBD less than the total system capacity because of the normal operating flow in the pipeline system. The amount of additional capacity being purchased with each option is 5.0 MBD less than the total system capacity, because the capacity of the unmodified Petroline is already available without any additional investment.

Install DRA injectors and extra pump horsepower on both the Petroline and IPSA. This option also requires the additional pipeline segment from Abqaiq to Pump Station No. 3. We calculate a combined pipeline capacity of 11.0 MBD at a cost of \$600 million.

Install DRA injectors and new pump impellers on both the Petroline and IPSA. This option also requires the additional pipeline segment from Abqaiq to Pump Station No. 3. We calculate a combined pipeline capacity of 9.0 MBD at a cost of \$300 million.

Install DRA injectors and extra pump horsepower only on Petroline. IPSA is not used at all in this option. We calculate that this would raise Petroline's capacity to 8.3 MBD at a cost of \$350 million.

Install DRA injectors and new pump impellers only on Petroline. IPSA is not used at all in this option. We calculate that this would raise Petroline's capacity to 6.8 MBD at a cost of \$100 million.

Install DRA injectors on and extra pump horsepower on Petroline. Build an additional 48-inch pipeline segment from Abqaiq to Pump Station No. 3. Use IPSA unmodified to move oil from Pump Station No.3 to Mu'ajjiz. This option would result in a 9.9 MBD capacity at a cost of \$500 million. It would involve the political cost of using IPSA; however, it would not be necessary to modify IPSA prior to the crisis.

Install DRA injectors on Petroline. Install extra pump horsepower on the segment of Petroline between Abqaiq and Pump Station No. 3. Install new pump impellers on Petroline from Pump Station No. 3 to Yanbu. Use IPSA unmodified to move oil from Pump Station No. 3 to Mu'ajjiz. This option would result in an 8.4 MBD capacity at a cost of \$150 million. Again, it would not be necessary to modify IPSA prior to the crisis.

Note that none of these options can be implemented in response to a crisis. All require the purchase and installation of major capital equipment. The lead times for pumps, impellers, and turbines is typically on year to 18 months [20], and the items must be installed once acquired. Additionally, the IPSA pipeline is not presently in usable condition: two to three months of deferred maintenance would need to be done before it could operate at capacity [21].

Cost breakdown

Table 1 gives a breakdown of our cost estimates. Each component of the cost estimate is discussed in turn below. The estimates include both the cost of upgrading the pipelines, the costs associated with typing extra Saudi production into the start of the pipeline at Abqaiq, and the costs to upgrade the capacity of the Red Sea ports.

Table 1. Cost estimate details for upgrade options

Cost of augmenting pipeline (millions of dollars)						
	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Horsepower (Petroline)	276	0	276	0	276	50
Horsepower (IPSA)	69	0	0	0	0	0
Impellers/pumps (Petroline)	0	60	0	60	0	49
Impellers/pumps (IPSA)	0	9	0	0	0	0
Abqaiq to Pump Station 3 pipeline	158	158	0	0	158	0
Tankage at Abqaiq	23	23	23	23	23	23
Ras Tanura to Abqaiq pumps	12	12	12	12	12	12
DRA injectors	2	2	1	1	1	1
Port upgrades	60	40	40	20	40	20
Total	598	302	351	115	510	154

Horsepower

Petroline is a looped 48-inch/56-inch pipeline. The looped system is capable of moving 5 MBD. According to [5], the efficient allocation between the two pipelines is 2 MBD to the 48-inch line and 3 MBD to the 56-inch line and 52,000 hp per pump station on the 56-inch line. There are 11 pump stations, so the Petroline would use approximately 1,000,000 hp (of its 1,200,000 installed horsepower) when operated at 5 MBD.

When DRA is added to the Petroline, holding the hydraulic gradient constant requires additional horsepower in direct proportion to the increased throughput. At 8.3 MBD, the required horsepower is $(8.3/5.0) \times 1,000,000 \text{ hp} = 1,660,000 \text{ hp}$, so 460,000 extra horsepower needs to be installed. At a cost of \$600 per installed horsepower [20], this would cost \$276 million.

Operating IPSA at a constant hydraulic gradient with DRA also requires adding horsepower. IPSA has a capacity of 1.65 MBD, so it must have about 20,000 hp per pump station or 180,000 hp from Pump Station No. 3 to the Red Sea. Increasing the flow from 1.65 MBD to 2.7 MBD would require 115,000 extra horsepower, at a cost of \$69 million.

Pump impellers

The effect of DRAs is to require less horsepower for a given throughput. However, the pumps need to be configured to handle the increased flow. A pump characteristic curve describes the relationship between the throughput in a pipeline, and the amount of horsepower necessary to achieve a specific level of throughput. Initially, the relationship between horsepower and

throughput is close to linear; successive increments of horsepower produce proportionate increase in throughput. But at some point, decreasing returns are reached and the amount of power must increase faster than throughput. Pumps on pipelines are typically operated in the decreasing returns portion of the pump curve. The reason is stability. If pumps are operated in the flat portion of the curve (i.e., where the relationship between horsepower and throughput is still linear), the pipeline control system is unstable because the sensor system is not sensitive enough to detect small changes in flow.

The Petroline pumps were manufactured by Byron-Jackson (BW/IP International Pump). They estimate the cost of changing the impellers to be \$50/hp. Using the horsepower figures from the previous section, this gives a cost of \$60 million for Petroline, \$49 million for the segment of Petroline from Pump Station No. 3 to Yanbu, and \$9 million for IPSA.

Pipeline segment from Abqaiq to Pump Station No. 3

If IPSA is to be used to move Saudi oil, there is a bottleneck between Abqaiq and Pump Station No. 3, where IPSA intersects the Petroline system. To free this bottleneck will require a 48-inch pipeline from Abqaiq to Pump Station No. 3. This is a distance of 140 miles. Rules of thumb for pipeline costs vary between \$20,000 and \$40,000 per mile diameter inch. The right of way and infrastructure for Petroline already exist along this route, so we will use the lower value, which gives an estimate of \$134 million. In addition, two pump stations would normally be required for a pipeline of this length. We will assume that existing pumps at Abqaiq and a higher concentration of DRA can be used on this segment so that only one pump station would be required. The cost would be \$24 million for four 17,250 HP turbines and the associated pumps. The total cost of this segment is thus approximately \$158 million.

Storage tanks at Abqaiq

While there is already significant oil infrastructure at Abqaiq, operation Petroline at the much higher capacities discussed here is likely to require extra storage tanks to both buffer the reverse flow from Ras Tanura, and to help segregate the crude oil into batches by type. (Under our proposals, Arabian Super Light, Arabian Light, Arabian Medium, and possibly Arabian Heavy would all have to move through the pipeline.) We have allowed for these operational considerations by adding one million extra barrels of tankage at Abqaiq, at a cost of \$23 million.

Pumps at Ras Tanura

There is a 55-mile pipeline system from Abqaiq to Ras Tanura that can handle approximately 6 MBD. There are seven 48-inch pipelines that were built with a taper so that the pressure limit is lower at the Ras Tanura end. In normal operation, the flow through these pipes is from Abqaiq to Ras Tanura, which is the main Saudi oil export terminal. All six of our proposed configurations move more oil through Petroline than the total Saudi production connected to Abqaiq. The extra oil would have to come from the Saudi northern and offshore fields which are currently connected to Ras Tanura. Pumps would need to be installed to run the Abqaiq to Ras Tanura pipelines in reverse. It will require approximately 20,000 hp to move 3 MBD on this route if the throughput is allocated to three 48-inch lines. At the above quoted \$600/hp this would cost \$12 million.

DRA injectors

CONOCO representatives indicated that they could deliver self-contained DRA injectors, on air transportable pallets, for approximately \$100,000 each [23]. One DRA injector per pump station is required, so eleven Petroline pump stations can be outfitted for about \$1 million, and the nine IPSA pump stations outfitted for an additional \$1 million. Obviously, and somewhat

surprisingly, the cost of the DRA injectors is an insignificant component of the total upgrade cost.

Port facilities

Yanbu has the capacity to export 4.2 MBD of crude oil [4]. This capacity is provided by four Very Large Crude Carrier (VLCC) berths, each of slightly different design.

Port facilities are normally designed to minimize tanker waiting times (or “demurrage charges”); however, during a severe oil supply disruption, it is economically feasible to have tankers queue up while waiting to load rather than storing oil on shore to await the arrival of a tanker.⁴ Such a change in operations actually somewhat increases port capacity, because the loading berths are occupied a higher percentage of the time. Even with this change, some addition to the Yanbu port facilities is necessary to handle the 8.3 MBD Petrolina flow envisioned here.

We estimate that adding two more VLCC berths would be sufficient to allow the export of 7.5 MBD (recall that 0.8 MBD is diverted to Saudi refineries). Each of these berths would consist of a floatable dolphin fed by a single flexible hose. We received an industry estimate of \$20 million per berth, including a minimal amount of onshore support piping [22]. Only one additional berth would be required if Petrolina was upgraded to only 6.8 MBD. Yanbu has 11 million barrels of tank storage, which should be sufficient for the operations envisioned.

Similarly, the port of al-Mu’ajjiz, the export terminus for the IPSA line, could be upgraded to handle the increased flow with a single additional dolphin and flexible hose at a cost of \$20 million. Al-Mu’ajjiz will also not require any additional tanks; it already has a 10-million-barrel storage capacity.

DRA inventory

Several thousand barrels per day of DRA will be necessary to operate Petrolina and possibly IPSA at higher upgraded flow rates; the exact amount is different for each options. This exceeds CONOCO’s production capacity [23], so some provision must be made for DRA stockpiling.

Stockpiling should not be technically difficult. The DRA is a non-hazardous material, which can be stored in 55-gallon drums. Extreme heat and low humidity can damage the product, so some modest climate control would be required for warehouses in Saudi Arabia. Shelf life is in excess of five years [19].

To run the Petrolina and IPSA at the highest flow rate under consideration, 11 MBD (option 1), requires 300,000 gallons per day of DRA. At \$30 per gallon, a 60-day stockpile would cost about \$500 million. This apparently large cost is not a showstopper for two reasons. First, this cost is incurred only if the SoH bypass capability is used, and we have already shown that the cost is less than \$1 per barrel of oil, and is economically feasible in the event of a closure. Second, it is highly likely that a significantly lower price could be negotiated for such a large bulk purchase. Presumably, the Saudis would pay CONOCO the holding cost of the material (including capital costs and warehousing costs), and take delivery only if needed: a very rough estimate would be \$50 million per year for the highest capacity options.

⁴ A 250,000 DWT tanker “rents” for \$20,000 -- \$35,000 per day, which is about 2 cents per barrel of crude per day of waiting.

Another possibility would be for Saudi Aramco to build a DRA production facility with sufficient capacity. The cost of such a facility, and the issues of technology transfer or coproduction agreements are beyond the scope of this paper.

Tanker issues

To be complete, an analysis of technical feasibility must consider the entire oil transportation system, from oil well to market. We have already shown that oil can be moved from production sites to export terminals on the Red Sea. We also investigated the effect a SoH closure would have on the world oil tanker fleet. We present here only a summary of this analysis.

There are two effects of concern. First, if the Strait is closed, especially without warning, some fraction of the world's tanker fleet will be trapped inside the Arabian Gulf, and thus be unavailable to move oil from the Red Sea export terminals. We estimate that about seven percent of the world's VLCCs would be trapped inside the Gulf in the event of a no-notice closure.

The second effect is increased travel time to the new loading ports. Most of the oil that flows through the SoH is bound for Asia. Loading this oil at Yanbu instead of Ras Tanura adds an extra 790 n.mi. one-way transit distance. Loading at al-Mu'ajjiz adds an extra 760 n.mi. At typical tanker speeds, this results in a five-day increase to each round trip, and thereby reduces the total oil delivery capability of the tanker fleet.

Both of these effects result in less than a 10-percent loss of tanker delivery capability. We believe that this deficit can be made up by operation tankers at higher speeds. Each one-knot speed increase by the VLCC fleet increases its delivery capability by 8 percent. Operating tankers to these higher speeds is more costly, but the difference amounts to only a few cents per barrel of oil, and so is clearly possible during a crisis.

Bottom line

We conclude that the throughput of the existing pipeline system can be significantly increased with the use of drag reduction technology. As many as 11 MBD could be moved through the combined Petrolina-IPSA system for an investment of \$600 million. Alternately, a noticeable increase in Petrolina throughput can be obtained for as little as \$100 million. All options require an additional annual cost of roughly \$50 million to hold DRA inventory, or additional investment to build DRA production capacity in Saudi Arabia.

The additional cost of moving oil during a crisis by this route is less than \$1 per barrel. This is clearly economically feasible in the event of a SoH closure; the price of oil will rise more than \$1 per barrel in this case, covering the additional costs. It is just as clearly not economically viable as a routine peacetime alternative: Yanbu exports are already economically unattractive (compared to Ras Tanura) for most Saudi customers, and adding DRAs would increase costs of oil at Yanbu even further.

Strategic assessment

There are several strategic benefits to establishing a SoH bypass. From the Saudi perspective, upgrading the pipeline enhances their position as the world's stable, reliable oil producer, and hedges against loss of market share. From the perspective of the world's oil importing countries, the most important effect is a reduction of economic damage in the event of SoH closure. There are also strategic benefits in the security sphere, including a possible deterrent effect on Iran, a lessening of Iranian political leverage in the region, and a possibility to reduce the U.S. military

presence in the region. All of these effects are in both the Saudi and U.S. interest. At the end of this section, we briefly discuss three second-order issues, all of which make the pipeline upgrade seem somewhat less attractive.

The upgraded pipeline system will not relieve the U.S. of the need to maintain the capability to reopen the SoH, for two reasons:

The upgraded pipeline system is only a temporary offset. The Petroline upgrade can be operated only for as long as the DRA stocks hold out, and is not an economical long-term alternative to the SoH.

The U.S. cannot acquiesce to an Iran closure of the SoH because of its long held commitment to ensuring free navigation of international straits.

A trans-Saudi pipeline, whether or not upgraded with DRAs, has limited strategic value if it can easily be put out of operation by Iranian action. We briefly examined the vulnerability of the pipeline system to truck bomb attack, SCUD attack, attack on the Yanbu port facilities, and mining of the Bab el Mandeb, and concluded that if prudent defensive measures were taken, the pipeline system could serve as a viable SoH bypass. A detailed analysis of vulnerabilities, and of measures necessary to defend them, is beyond the scope of this paper.

Saudi economic considerations

Saudi Arabia has a declared strategic goal of being the world's "stable, reliable" oil producer. [17] Obviously, any additional steps the Saudis could take to ensure world markets that oil deliveries could continue during a SoH crisis with Iran enhances their reputation for stability, and reduces the chance that other contingency source (e.g. the Caspian fields) will be developed by other nations as a hedge against Arabian Gulf instability.

For internal planning purposes, the Saudi oil producer, Aramco, reportedly uses a standard assumption that the price elasticity of crude oil demand is very inelastic. That is, oil demand is not price sensitive, especially in the short run. Specifically, it is assumed that the elasticity of quantity demanded with respect to price is -0.1 . A one-percent increase in market price leads to one-tenth of one-percent decreases in demand, starting from equilibrium. The inverse holds; the price elasticity of oil demand with respect to quantity supplied is therefore $1/(0.1)$, or -10 . A one-percent decrease in oil supplied to world markets drives up world oil market prices by 10 percent.

We can therefore estimate the Saudi oil sales revenue results in the event of a SoH closure, using Saudi planning factors. We evaluate three scenarios:

Baseline. Typical daily oil revenues at normal world prices and normal Saudi delivery rates.

Crisis "as is." Daily Saudi oil revenues in the event of Hormuz blockage, assuming world prices applied to Saudi deliveries via Petroline, not enhanced by DRA. We also assume that the U.S. is delivering oil from the SPR at 4 MBD.

Crisis with DRA. Daily Saudi oil revenues and world prices, assuming that Petroline deliveries are enhanced by DRA, again also including use of the SPR.

First we determine how much oil is supplied to or held off the world market in each case, and hence what the world market price is likely to be. Then, we apply that prevailing market price to Saudi deliveries, estimating Saudi revenues. As the marginal cost of additional oil deliveries is very low for Aramco, and in particular most delivery costs are sunk capital costs, the revenue effect dominates. The results of these calculations are presented below in table 2.

Table 2. Aramco oil revenues in the event of a SoH closure.^a

<u>Scenario</u>	-----World Markets-----		-----Saudi Arabia-----	
	<u>Oil Prices</u> <u>US \$/Barrel</u>	<u>Quantity</u> <u>MBD</u>	<u>Deliveries</u> <u>MBD</u>	<u>Revenues</u> <u>\$M per day</u>
SoH closes, SPR + Petrolina	\$33	54	5	\$165
SoH closes, SPR + DRA	\$19	60	11	\$198 ^b
Upgrade Baseline	\$14.25	62	10	\$142.5

As a purely financial project, DRA enhancement is not a particularly attractive investment for the Saudis. We see in table 2 that Saudi Arabia can earn perhaps \$30 million per day more in the event of a closure for Hormuz if DRA is used to augment the pipeline system capacity. If we suppose that a SoH closure would last 90 days, and that it has a 10 percent chance of occurring (both assumptions are high-end estimates), then the expected pay-off for the DRA enhancement is about \$270 million.⁵ If the closure was through to be likely to last 60 days, and has a 5 percent chance of occurring, then the expected pay-off is about \$90 million. It is clear that these payoffs cannot alone justify the cost of upgrading the pipeline.

However, the Saudis have a strong reason to prefer the DRA enhanced case in the event of a SoH crisis. The critical difference between the no DRA and DRA cases (rows 1 and 2 in table 2) is deliveries. Without DRAs the Saudis deliver only 5 MBD, a significant loss of market share that may not be easily regained after the SoH reopens. With DRAs the Saudis deliver 11 MBD, which is actually a slight gain over their current production.

^a Assumes the elasticity of crude oil demand $(dq/Q)/(dP/P) = -0.1$

^b Net of DRA cost of \$1 per barrel.

⁵ We are ignoring the time value of money, or discount factor, which would reduce the net present value of this expected pay-off.

Economic Impact on oil importing countries

All oil importing countries will suffer economic damage during a SoH closure, via higher oil prices, even if they do not normally get their oil from the Gulf region. In this section, we calculate the economic damage to the U.S. We expect that the effects of a SoH closure on the other major industrialized countries in Europe and Japan will be similar.

Estimating the economic impacts on the U.S.

We estimate the economic effects on the U.S. with the “Disruption Impact Simulator” (DIS) model created and maintained by the Energy Information Agency of U.S. Department of Energy (DoE). The DIS model is specifically designed to evaluate major disruptions in world oil market supply and demand. The measures of impact we monitor here are:

- The price of crude oil per barrel
- The price of gasoline (most noticeable to consumers/voters)
- The drop in the growth of U.S. Gross National Product from trend
- The increase in the rate of U.S. unemployment
- The increase in the U.S. inflation rate (increase over trend of the consumer Price Index).

Countermeasures: SPR, Petroline, and DRA

Two countermeasures for a Hormuz cut-off scenario are already in place: the U.S. Strategic Petroleum Reserve (SPR) and the trans-Saudi Arabia pipeline system. We are evaluating the additional benefits contributed by yet a third countermeasure, or “insurance policy,” upgrading the pipeline system with DRA technology.

Strategic Petroleum Reserve

The SPR is managed by the U.S. Department of the Energy (DoE) and has a storage capacity of some 600 million barrels of oil. Presently about 560 million barrels are stored in the SPR. The SPR can deliver about 4.5 MBD to the domestic U.S. market for the first 30 days, and about 3.9 MBD thereafter [8]. This is an average delivery rate of 4.1 MBD for the duration of a three-month closure. The delivery rate capacity between days 30 and 90 is scheduled to increase to 4.1 MBD by late 1999, which would raise the average delivery rate to 4.2 MBD.

The SPR has never had a full workout, in the sense that even during the Gulf War only 20 million barrels total were sold. However, there is reason to believe that deliveries would in fact be made as planned if so ordered. While the oil would be delivered to U.S. markets, oil is fungible and trades on a unified world market. The SPR deliveries would mitigate the impact on world markets, not just U.S. markets. As the SPR does not normally deliver oil to market, the entire delivery rate is an increment to world supply.

Petroline throughput and current capacity

At present, 1.9 MBD flows through the Petroline across Saudi Arabia to the Red Sea. Most of this oil (1.1 MBD) is exported from Yanbu, and the remaining 0.8 MBD feeds refineries near Yanbu and Riyadh [3,4]. With the current capacity to deliver 5.0 MBD of crude oil to Yanbu, Petroline could provide 3.1 MBD of incremental supply that could be delivered to world markets in a contingency, rerouted to avoid the blockage of the Strait of Hormuz.

Petroline with DRA

As our capacity calculations about show, the combined Petroline plus IPSA system, upgraded using our highest-throughput DRA option, could deliver 11 MBD to Red Sea ports, 6 MBD more than the existing pipeline. This is a net incremental supply of 9.1 MBD to world markets, again after deducting the current pipeline flow.

Simulation results

The time horizon simulated is short term: the impact is computed for a one-quarter closure. The economic impact of the closure, with the various offsets, is shown in table 3.

Table 3. Impact on prices and the U.S. economy of world oil supply reductions caused by a 3-month blockage of the Strait of Hormuz.⁶

	Current	No offset	Petroline “As is”	Petroline +SPR	Petroline w/DRA	Petroline w/DRA + SPR
Crude oil (barrel)	\$14.25	\$96	\$72	\$47	\$37	\$20
Gasoline (gallon)	\$1.18	\$3.12	\$2.56	\$1.95	\$1.72	\$1.30
GNP growth	- 0 -	-4.7%	-4.0%	-2.9%	-2.4%	-0.8%
Unemployment	- 0 -	+1.9%-	+1.6%	+1.2%	+0.9%	+0.3%
Inflation	- 0 -	+7.0%	+6.0%	+4.4%	+3.5%	+1.2%

⁶ Scenario results are from the DoE DIS model.

Assumed Elasticities

Standard economic theory holds that demand for most commodities is usually inelastic when supply is low and prices are high, and elastic when prices are low and supply is plentiful. The DoE DIS model departs from this standard pattern, and has “sliding elasticities,” featuring inelastic demand in equilibrium but elastic demand if supply shocks result in high prices. The argument is that consumers are indifferent to price fluctuations in normal ranges, but change their behavior when prices shoot up. Around the usual equilibrium values for supply and demand, the DIS model uses an elasticity of -0.1 . This is a standard assumption both among econometricians and in the industry [14,15]. However one feels about the assumed shape of the demand curve for crude oil, these features of the DoE DIS model do not impact the analysis here, for two reasons. One, it turns out that the countermeasures can largely offset the closure supply shock by temporarily returning the world oil demand and supply balance close to the initial equilibrium, where the DIS model approximates the standard model. Two, the DIS model is “conservative,” in the sense that it understates the impact of closure for big “un-muffled” closure shocks.

No offset case

The first case we show results for is a total loss of all oil that currently flows through the SoH. This case should not occur in practice, because the Petroline and SPR are already in place to mitigate these effects. Nonetheless, it is instructive to see the full possible impact of a closure. Gasoline could triple in price at the pump in the U.S., as crude soars near \$100 per barrel. The impact on the U.S. economy would be a drop of 4.7 percent in the annualized GNP growth rate,⁷ 1.9 percent added to the unemployment rate, and 7 percent added to the inflation rate. When we recall that this is a conservative estimate of impact, it’s clear that this is a contingency worth insuring against, if possible.

Closure offset by the current Petroline

Exporting oil through the Petroline and Yanbu noticeably reduces the economic impact of the crisis. Gas at the pump goes to \$2.56, not to over \$3.00 per gallon. The unemployment rate uptick is cut by seven-tenths of a percentage point, which translates into nearly two million jobs safeguarded. Inflation still increases by 6 percent. This case is less serious than an un-offset closure, but it is still very bad.

Closure offset by the SPR and the Petroline

Combining the two existing “insurance policies” helps even more. U.S. gasoline goes to \$1.95 per gallon, and the unemployment uptick is only 1.2 percent. However, the two together do not offset the shortages completely. The shock still knocks almost 3 percent off of U.S. GNP, and about one million jobs are lost.

The incremental impact of DRA

Enhancing the counter-measure effectiveness with DRA helps a lot. When exports through the upgraded Petroline are combined with sales from the SPR, the disruption in oil supplies is small. The price of gas at the pump increases to only \$1.30, a level which has been caused by non-crisis market conditions in the recent past. Only a few hundred thousand jobs are affected, which is within the normal range of quarter-to-quarter fluctuations in employment. The loss of U.S. GDP is also minimal. And, Saudi Arabia can export all its normal production and more, safeguarding her economic equilibrium.

⁷ For example, if the economy was growing a 3 percent per year before the crisis, it would enter a recession, shrinking at a rate of 1.7 per year.

Discussion

The existing counter-measures are valuable, and should mitigate the impact of a SoH closure on the world economy. But the SPR and Petroline cannot fully offset a SoH closure, and economic consequence would still be severe. Enhancing the throughput of the pipeline system with DRAs, combined with sales from the SPR, can offset a SoH closure, thus significantly reducing the severity of the crisis.

Time to respond

In the last section we showed how the upgraded pipeline system can essentially offset the loss of oil to world markets due to a SoH closure, and thereby prevent economic damage to all oil importing nations. A closely related strategic consideration is that this lack of economic damage, and consequent lack of political pressure for quick action, will allow the world community to respond to the SoH closure on a militarily prudent timeline. This leads to strategic benefits to both the U.S. and Saudi Arabia. From the U.S. perspective, the U.S. military should have sufficient time to move all required forces to the region, and to conduct all necessary preparations, so that when they act to reopen the Strait, it can be done quickly and with minimum risk. From the Saudi perspective, a reduced requirement for quick action should permit the U.S. forces assigned to respond to such a crisis to be based outside of the region – a development with clear political benefits.⁸

Deterrent effect

One reason the Iranians have been increasing their capability to control the SoH is to place the oil flow through the Strait under their influence. Thus, providing an alternate route for that oil beyond Iran's reach should make them less likely to decide to precipitate a SoH crisis. Closing the SoH is a very serious step for Iran. In addition to involving Iran in a military confrontation with the United States, it also closes the route that Iran uses for almost all of its exports (including all of its oil exports), as well as almost all of its imports; therefore, Iran will suffer serious economic damage as a result of this action.⁹ We are not claiming that this deterrent effect on Iran is very important, but we do claim that the effect of an upgraded Petroline on Iranian behavior is likely to be a small net reduction in the chance that they will decide to precipitate a SoH crisis.

At a minimum, the upgraded pipeline system gives the Iranians a more difficult diplomatic and operational problem. If they still wish to affect the oil flow, they need to interdict both routes. The operational problem is that they need to attack both routes nearly simultaneously, because their chance for success either in closing the Straits or in severing the Petroline is significantly reduced if there is warning of their intentions. The U.S. Navy could act to prevent mining in the SoH, for example, or the Saudis could increase security around their key pipeline facilities. The diplomatic difficulty is that any attempt to attack the Petroline would involve an escalation beyond actions which can be portrayed as self-defense. The Iranians either would need to conduct a direct attack on Saudi soil, or would need to mine the Bab el Mandeb, an international waterway far from their shores through which a large amount of neutral merchant shipping must pass. These actions are obviously unpalatable to Iran, even in a period of rising tensions.

⁸ This benefit will become evident only when the Iraq situation is resolved to the point where it does not determine the requirement for U.S. forces in the region.

⁹ If Iran tried to selectively close the SoH only to non-Iranian shipping, U.S. military action is very likely to deny the SoH to Iranian traffic.

Relations between Saudi Arabia and Iran are currently improving, but we believe that it is in the Saudi interest to hedge against a return by Iran to the confrontational policies of the 1980s. Even if Iran never acts to close the SoH, they could use their capability to do so as leverage on Saudi Arabia. A threat, explicit or implied, to disrupt the oil flow could be used to pressure Saudi Arabia to accede to Iranian demands on a large range of regional issues. The upgraded pipeline system gives the Saudis a ready countermeasure to a SoH closure, and hence would completely negate the Iranian leverage.

Other strategic considerations

We find three second-order strategic considerations, all of which make the Petroline upgrade seem somewhat less attractive.

Loss of natural gas and refined products

Some natural gas and refined products production inside the Gulf will be lost to world markets, even if all of the crude oil disruption is offset.

Qatar and the UAE both export liquefied natural gas (LNG) to Japan, through the SoH [7]. These exports will be blocked by a SoH closure, and no alternate transport route is available. Japan uses the LNG to generate electricity, so the loss of the LNG will compound the disruptions in oil supplies, which are partly used for the same purpose.

Saudi Arabia is a significant source of several refined products, especially methanol and MTBE.¹⁰ These products are exported through the SoH, and will be lost to the world market regardless of any Petroline upgrade [7].

Upgrades cannot match projected increases in oil flow

The oil flow through the SoH is projected to increase over the next twenty years. The actual amount of the increase is very uncertain, because it depends on the difference between two uncertain projections, the rise in world oil demand, and the increase in oil production outside the Gulf. (Some new production in the Caspian region may flow through the SoH if a pipeline to carry it is built across Iran, further adding to the uncertainty.)

The pipeline system cannot be easily upgraded beyond the 11 MBD discussed here. Further increases in trans-Saudi capacity will require the laying of additional pipes at much higher costs (billions of dollars). Essentially, there is a limit to the amount of cheap insurance that can be purchased with DRAs, and the adequacy of this insurance will decrease as the SoH oil flow increases. The strategic benefits of the upgrade will thus erode over the next 10-20 years.

Not a hedge against a major regional conflict

We have shown about that the upgraded pipeline system is not unduly vulnerable to Iranian attack, and that the Saudis have sufficient production to deliver 11 MBD into it. This second assumption does not hold in the event of a serious war between Iran and Saudi Arabia. At least 3.5 MBD of Saudi production comes from the offshore and northern fields, and these production facilities are very vulnerable to Iranian action. The major Saudi production facilities at Abqaiq and Ghawar could also be at least somewhat disrupted by a prolonged and determined Iranian

¹⁰ Methyl tertiary butyl ether, an oxygenated gasoline additive used primarily in the United States.

attack. So even if the pipeline system remains in operation, in the event of a major Iranian-Saudi war, it is unlikely that the Saudis will retain enough production to take full advantage of it. Upgrading the pipeline system does not offer a hedge against this particular possibility.

Conclusions and recommendations

We have shown that upgrading the Petroline with DRA technology is technically and economically feasible, and that this upgrade is in the strategic interest of Saudi Arabia and all of the world's oil importing nations, including the U.S.

For an investment of \$600 million, the combined Petroline-IPSA system could be modified to handle 11 MBD. This provides a 9.1 MBD capacity to offset a SoH closure; the other 1.9 MBD is already used in normal operations. There are several other lower-capacity upgrade options that are less expensive, and some avoid the complications of using the IPSA pipeline. Operation costs of the DRA enhanced pipeline during a crisis would add less than \$1 per barrel to the price of oil. The combination a 9.1 MBD offset from the pipeline system and the 4.1 MBD drawdown rate from the SPR can almost completely offset (for 90 days) the loss of oil to world markets due to SoH closure.

The pipeline upgrade has several important strategic benefits. It can assure the world oil markets that the Saudis can be relied on to produce and deliver oil even in the face of instability in the Gulf region, thus reducing the chance that other countries will develop production as a hedge, and thereby protect Saudi oil market share. It can reduce the economic damage to the U.S. in the event of a SoH crisis, allowing the U.S. to respond to a closure on a deliberate and risk-minimizing timeline, and may reduce the need for U.S. forces to be based in the region. It can reduce Iranian motivation to close the SoH, and also reduce the political leverage they get from threatening to do so.

Appendix A: Pipeline capacity calculations

At 30 ppm, second-generation DRA reduces drag by about 50 percent. At the concentration, first-generation DRA reduces drag by approximately 30 percent. The reduction in drag permits an increase in crude oil flow through the pipe. The amount of the flow increase depends on whether the pipeline is operated using only the existing pumping horsepower (i.e., only new pump impellers are installed), in which case

$$\text{Flow increase} = 1/((1 - DR))^{1/3},$$

Or if extra pumping horsepower is installed, in order to operate the pipe at its design pressure¹¹, then

$$\text{Flow increase} = 1/((1 - DR))^{1/2},$$

Where *DR* is the drag reduction.

Tables 4,5, and 6 give the increase in the throughput of Petrolene and IPSA for various concentrations of DRAs. Throughput for the case where horsepower is increased to maintain the hydraulic gradient was calculated by two methods: the Shell/MIT formula, which is a standard industry rule of thumb, and CONOCO's in-house computer program.¹² For all practical purposes, the results are the same, although the CONOCO computer program is more sophisticated and likely to be more accurate. DRA concentrations in the tables are not equally spaced because the CONOCO model takes desired pipeline capacity as an input, and calculates the required concentration of DRA.

Table 4. Capacity of Petrolene 56-inch pipe with DRA

DRA (ppm)	% Drag reduction	Extra pumps (horsepower increased)		New impellers
		Throughput (MBD) Shell/MIT formula	Throughput (MBD) CONOCO	Throughput (MMB/D) Shell/MIT formula
14	41	3.9	4.0	3.6
20	47	4.1	4.3	3.7
30	53	4.4	4.5	3.9
45	57	4.6	4.8	4.0
71	61	4.8	5.0	4.1
132	65	5.1	5.3	4.3

¹¹ Strictly, the design hydraulic gradient, as the pressure varies along the length of the pipe.

¹² CONOCO computer drag reduction for a 48-inch and 56-inch pipe for crude with a viscosity of 12 centistokes and a specific gravity of 33o API.

Table 5. Capacity of Petroline 48-inch pipe with DRA

DRA (ppm)	% Drag reduction	Extra pumps (horsepower increased)		New impellers
		Throughput (MBD) Shell/MIT formula	Throughput (MBD) CONOCO	Throughput (MMB/D) Shell/MIT formula
13	41	2.6	2.7	2.4
17	45	2.7	2.8	2.4
30	53	2.9	3.0	2.6
43	57	3.0	3.2	2.7
56	59	3.1	3.3	2.7
131	64	3.3	3.5	2.8

Table 6. Capacity of IPSA 48-inch pipe with DRA

DRA (ppm)	% Drag reduction	Extra pumps (horsepower increased)		New impellers
		Throughput (MBD) Shell/MIT formula	Throughput (MBD) CONOCO	Throughput (MMB/D) Shell/MIT formula
15	43	2.2	2.3	2.0
21	48	2.2	2.4	2.1
31	53	2.4	2.5	2.1
42	57	2.5	2.6	2.2
58	60	2.6	2.7	2.2
83	62	2.7	2.8	2.3

At a DRA concentration of 70 ppm, Petroline can be augmented to 8.3 MBD with extra pumps and horsepower, or to 6.7 MBD with new pump impellers. IPSA can be augmented to 2.7 MBD with extra pumps and horsepower, or to 2.2 MBD with new impellers. The results for the 48-inch pipe on Petroline and the 48-inch IPSA pipe are not identical, because the pipeline walls have different thickness and the pipelines operate at different pressures. The flow rates of our six options are various combinations of the individual pipe capabilities, as shown in table 7. The entries are flows in MBD with either extra pumps or new impellers—or, for IPSA without modification, as appropriate for each option.

Table 7. Upgrade option capacity details

Option	Petroline 56	Petroline 48	IPSA 48	Total
1	5.0	3.3	2.7	11.0
2	4.1	2.7	2.2	9.0
3	5.0	3.3	not used	8.3
4	4.1	2.7	not used	6.8
5	5.0	3.3	1.6	9.9
6	4.1	2.7	1.6	8.4

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