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Parametric Analysis of In Situ Retorting Options for NOSR 1

Naval Oil Shale Reserves
Management Support and
Systems Engineering Project

Performed under Contract No. DE-AC01-78RA32012
for the U.S. Department of Energy

September 1980

TRW ENERGY SYSTEMS PLANNING DIVISION
8301 GREENSBORO DRIVE, McLEAN, VIRGINIA 22102 • (703) 734-6500

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1. INTRODUCTION AND OVERVIEW

The Parametric Analysis of In Situ Retorting Options report has been prepared by TRW as part of its work under DOE Contract DE-AC01-78RA 32012, Management Support and Systems Engineering for the Naval Oil Shale Reserves (NOSR) Predevelopment Project. The Parametric Analysis is being conducted as part of an overall assessment of technologies for the development of NOSRs 1 and 3. Technology assessment, resource assessment, baseline environmental analysis, EIA/EIS, and community requirements analysis constitute the key elements of a Master Development Plan for NOSR development.

The parametric analysis of in situ retorting options study was triggered by earlier analyses* which showed that the cost of producing upgraded (hydrotreated) shale oil by vertical MIS techniques on NOSR 1 was 55 to 90% more expensive than comparable shale oil produced by surface retorting. Some of this difference may be attributed to the oil yield values assumed in that study for the recovery of oil from MIS retorts.

Because vertical MIS technology is still in a developmental stage, technical parameters that will define commercial operations - oil yield, optimal retort configuration, spacing between retorts within a cluster and spacing between clusters, rubble size distribution and control for uniform flow and oil recovery, the ability to clean retort waste water for reuse in steam generation, optimization of operating conditions, etc. - are still being evaluated in field operations.

So as not to bias the results against the use of an MIS concept on NOSR 1, due to lack of field data and poor assumptions, a parametric analysis was undertaken which would evaluate this technology for the following variables: oil yield, retort configuration, cost, and compatibility with the

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* Conceptual Design of Shale Oil Production Systems for NOSR 1, September 1979, and a Supplemental Report, August 1980. Prepared by TRW under DOE Contract DE-AC01-78RA 32012.

NOSR 1 resource. The analysis assumes yield and retort sizes and calculates the selling price of oil. The objective of the analysis is to define that range of shale grades, and/or product yields, and/or retort configurations, that will make the MIS technology competitive with surface retorting. Within this competitive range, the MIS requirements (yield, grade, retort configuration) will be matched against the resource to determine whether or not the NOSR 1 resource can support a MIS technology producing at least 50,000 BPD of oil over a 20-year period.

The MIS retorts have been designed to match existing information in the public domain. The Oxy MIS Concept is considered with an average void volume of 20%, a retort height-to-base width ratio ranging between 2 and 6, a burn rate of 1 ft/day, and a retort gas mixture of 30% steam and 70% air. Two retorting scenarios were considered: MIS retorting only and MIS/surface retorting combinations.

Gulf Research & Development Company performed the bulk of this work. TRW had the overall responsibility for this study and provided study guidelines and technical direction.

2. SUMMARY AND CONCLUSIONS

A parametric analysis has been performed in evaluating the vertical MIS technologies as a function of retort configuration, shale grade, oil yield, costs and resource compatibility. Two basic retorting scenarios were evaluated: MIS retorting alone, and MIS/surface retorting combination. In all cases the raw shale oil was upgraded to produce refinery feedstock grade shale oil. The following is a summary of the major results of this study and conclusions relative to the compatibility of vertical MIS technologies with the NOSR 1 resource.

MIS Retorting Only

Figure 2-1 shows that when MIS retorts are operated alone, the product selling price decreases as the in situ rubblized shale grade increases and/or as the yield of oil from the retorts increases. For a 24 gpt in situ shale grade, oil yields greater than 80% are required to make the MIS process competitive with surface retorting at $25/B. An average selling price of $25/B (at 15% DCF-ROR) reflects the most expensive surface retorting option evaluated. The economical and financial bases for comparing MIS retorting with surface retorting are the same.

Figure 2-1 further shows that the in situ shale grade has to be 30 gpt and richer with a minimum of 60% oil yield from the retorts to be competitive. High yields (93-95%) or high in situ grades of shale (greater than 38 gpt) will reduce the selling price of oil to about $18/B.

An assessment of the NOSR 1 resource* has demonstrated that the Northwest quadrant of the reserve has the greatest potential for vertical MIS retorting because of its higher grade shale and the fact that this shale is thicker than in any other part of the reserve. Based on this resource

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* Resource Assessment Naval Oil Shale Reserve No. 1, September 1979. Prepared by TRW under DOE Contract DE-AC01-78RA 32012.

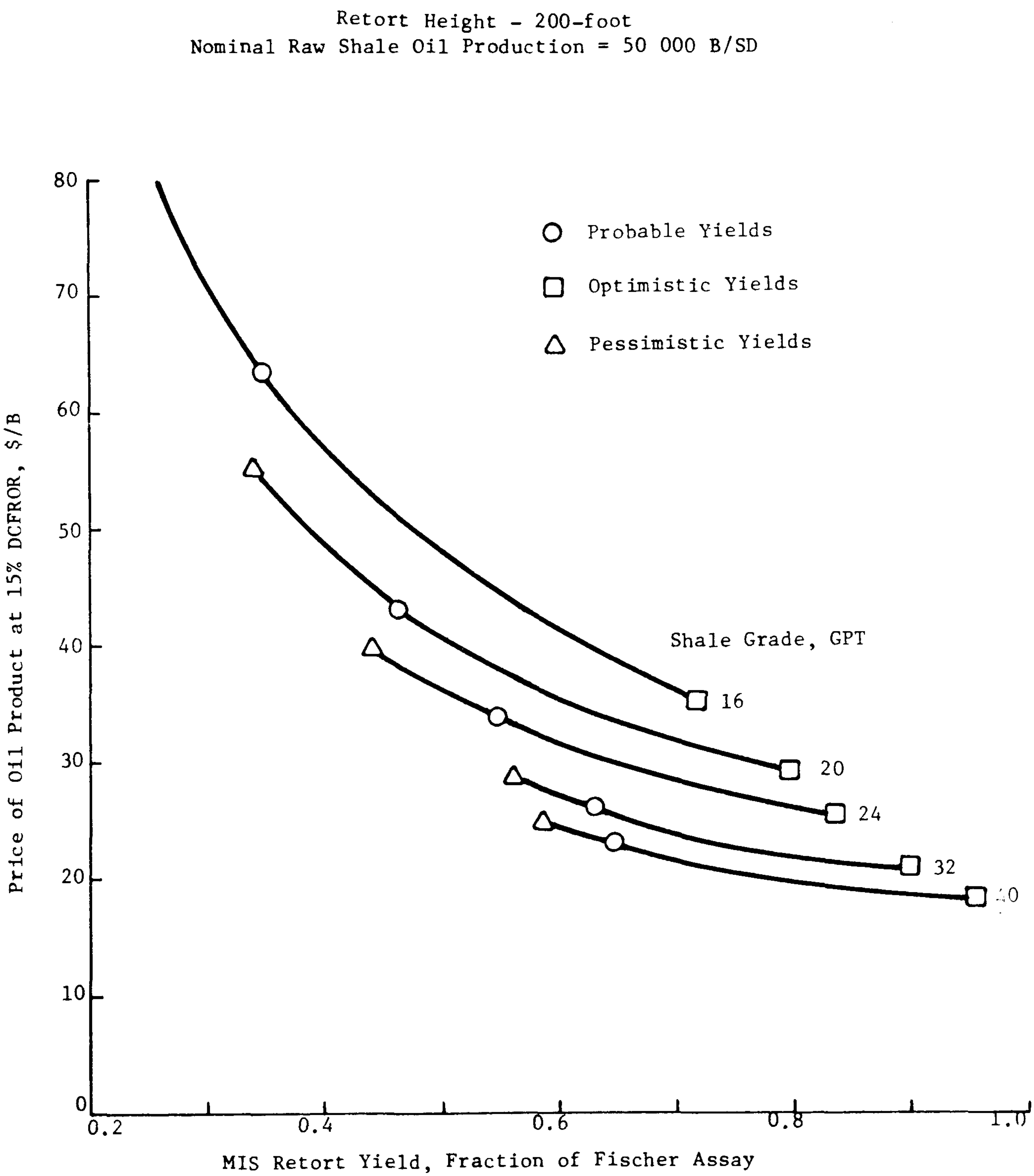

Figure 2-1. MIS Retorting Only: Effect of Shale Grade and Yield on Product Price

assessment, it has been shown that the reserve can sustain a 50,000 BPD plant for at least 20 years when retorting 24 gpt shale in 200 ft high retorts, or when retorting 20 gpt shale in 300 ft high retorts. However, the NOSR 1 resource is not rich enough to support MIS retorts with in situ shale grades much over 25 gpt. Furthermore, based on the current level of development of MIS technology, it is believed that 80% in situ retort oil yields are not possible for 24 gpt grade shales to make them economically competitive with surface retorting.

MIS/Surface Retorting

Results of the combined MIS/surface retorting case show that there is an advantage (in product selling price) in retorting higher grade shale aboveground, especially when the rubblized shale grade is low. This advantage disappears as the rubblized shale grade increases; both product oil prices tend to converge to $20/B at an in situ grade of 40 gpt.

As in the MIS retorting case, the selling price of oil decreases as the grade of rubblized shale increases and/or the in situ oil yield increases for the MIS/surface retorting case. Because of the large number of variables involved - retort height, oil yields, surface retort shale grades, and rubblized in situ shale grades - it is not possible to represent the results in a simple diagram like Figure 2-1. However, limiting cases have been identified and are discussed below:

- For a 20 gpt rubblized shale grade, and 37.5 gpt shale grade to the surface retorts, in situ oil yields of about 80% must be realized for this combination system to be competitive with surface retorting alone at $25/B.

- For the case when 25 gpt of shale is retorted on the surface, an average in situ shale grade of 27 gpt (with a probable oil yield of 59%) is needed for the combination system to be competitive at $25/B. If optimistic yields are assumed, a 20 gpt in situ shale grade with 80% oil yield is required to be competitive. It is believed that surface retorting of shales below 25 gpt is not currently considered to be economically feasible.

- Under the most optimistic case, 19 gpt rubblized shale grade and 37.5 gpt surface retorting shale grade are required to give a product selling price of $25/B. The oil yield from the in situ retorts, under these circumstances, has to be 78-79%.

Based on an assessment of the NOSR 1 resource, it is determined that in situ grades of 20 gpt with surface retorting grades of 37.5 gpt can be supported by the resource for the production of 50,000 BPD of shale oil over at least 20-25 years plant life. However, based on the current level of development of MIS technology, it is believed 80% in situ retort yields are not possible.

The NOSR 1 resource is not rich enough to support a combination system with a 25 gpt surface retorting shale grade and 27 gpt in situ shale grade. It can support production for a 20 gpt in situ shale grade combined with 25 gpt surface retort shale grade; however, 80% in situ oil yields are not believed to be currently possible.

The NOSR 1 resource can also support production from a 19 gpt in situ shale grade/27.5 gpt surface retorting shale grade combination. However, 78-79% in situ oil yields are not believed to be possible at the current level of technology development.

Based on the discussion above, it is concluded that the NOSR resource is not configured for current MIS retorting technologies to be a viable alternative to surface retorting technologies.

3. MODIFIED IN SITU OIL SHALE RETORTING

In the Modified In Situ (MIS) oil shale retorting process, retorts are created in the shale bed by mining out some shale (say 20 to 40%) from a given retort volume to allow for voidage. The remaining shale in the volume is rubblized with explosives, oil is retorted by injecting a combustion-supporting gas into the retort volume, and retort products, oil, gas, and water, are withdrawn to the surface. Current practice is to inject the combustion-supporting gas into the top of the retort (vertical MIS) and collect the products at the bottom. The combustion gas is air or oxygen plus steam, recycled product gas, or inert gases. Development to date has involved only air/steam mixtures.

The reaction zone occurs in a rather narrow band perpendicular to the flow of gas. As the combustion-supporting gas flows into the reaction zone, residual carbon is burned. The hot combustion gas heats the raw unretorted shale which decomposes the organic matter in the shale, called kerogen, into oil vapor and other gases. Water vapor is also produced. Residual carbon, subsequently consumed in the combustion reaction, is left behind. The reaction products are swept out of the reaction zone by the combustion gases, but the oil and water are condensed by heat exchange with the relatively cool shale past the reaction zone. Gases other than oxygen in the combustion-supporting gas act as diluents to the oxygen, to control the temperature. If steam is used, it also reacts with the residual carbon to produce carbon monoxide and hydrogen. The reaction products are withdrawn to the surface.

At the surface, the oil, water and gases are separated. The oil is processed for pipelining, refinery feedstock, etc. The water is treated and discharged, or purified further and used internally. The gas can amount to 50,000 to 80,000 SCF per barrel of raw oil produced or 40 to 50% of the total heating value of the products. If air is used as the source of oxygen in the retorting gas, nitrogen dilutes the off-gas, causing it to have a very low heating value in the range of 50 to 100 Btu/SCF. Although combusting this gas may be a problem, most MIS retorting schemes assume that it can be utilized as fuel for the process.

Mining strategy for creating the voidage for the MIS retorts can be designed to either mine from lean shale strata, in which case the mined shale is disposed, or mine from rich strata, in which case the rich shale can be retorted in surface retorts to produce additional oil. The choice of the surface retort can be from several currently being developed: Tosco, Lurgi, Paraho, Union or Superior.

The Occidental Oil Shale Company concept for vertical MIS retorting is assumed for this study. An air/steam mixture is used as the retorting gas. The raw shale oil is upgraded by hydrotreating to make it compatible with petroleum refinery feedstocks.

4. BASE CASES

4.1 MIS Retorting

4.1.1 Mining and Retorting

Mining development includes main entry advance, swell room excavation to allow for voidage, construction of retort bulkheads and exhaust drift advance. Mine development also includes construction of necessary mine facilities such as underground shops, mine electrical systems, ore passes, water pumps and ancillary surface shops, buildings, and waste disposal sites.

Mining takes place in at least two levels: an upper level at the top of the retorts and a lower level at the bottom. Intermediate levels may also be mined, depending on the height of the retorts. The mining levels are in very lean oil shale strata and the mined shale is disposed on-surface.

The mining plan is shown in Figures 4-1 and 4-2 for the upper and lower levels, respectively. Double entries on the upper level provide access for upper retort development and exhaust air. Triple entry mains and double entry exhaust mains are used on the lower level for development access, conveyor haulage, exhaust air and combustion product exhaust air. At right angles to the mains, clusters of eight retorts are developed and fired together.

The swell rooms in the upper level are of sufficient height to allow for easy access for the blasthole drilling equipment. The lower level swell rooms are higher to take advantage of gravity as much as possible. A high extraction ratio of 70% within the swell zones is assumed because of the load-carrying capacity of the exterior retort cluster pillars.

Pillars between retorts are spaced approximately one retort width apart along a line parallel to the main entries and one-half retort width apart perpendicular to the entries. This spacing, which should provide adequate support to the retorts while they are in the fired mode, results in an areal recovery factor of approximately 40%.

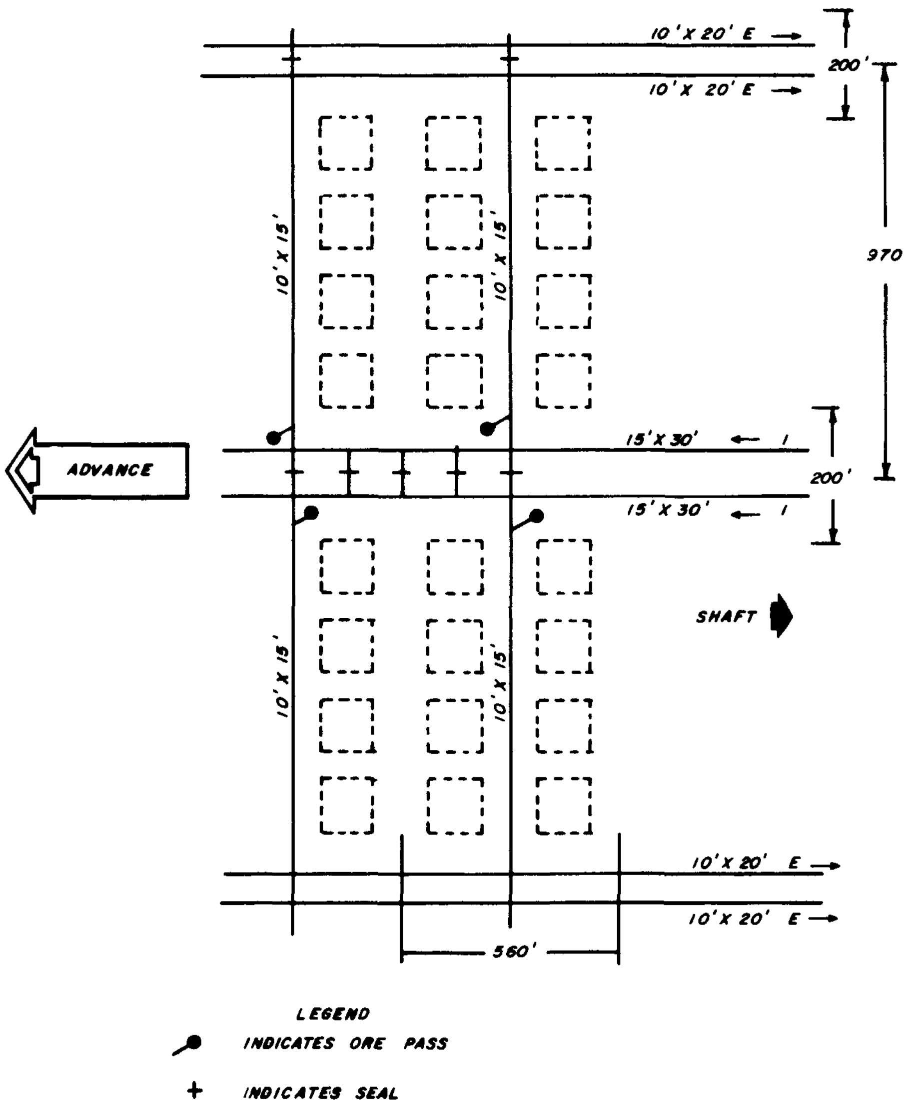

Figure 4-1. MIS Retort--Upper Level Development

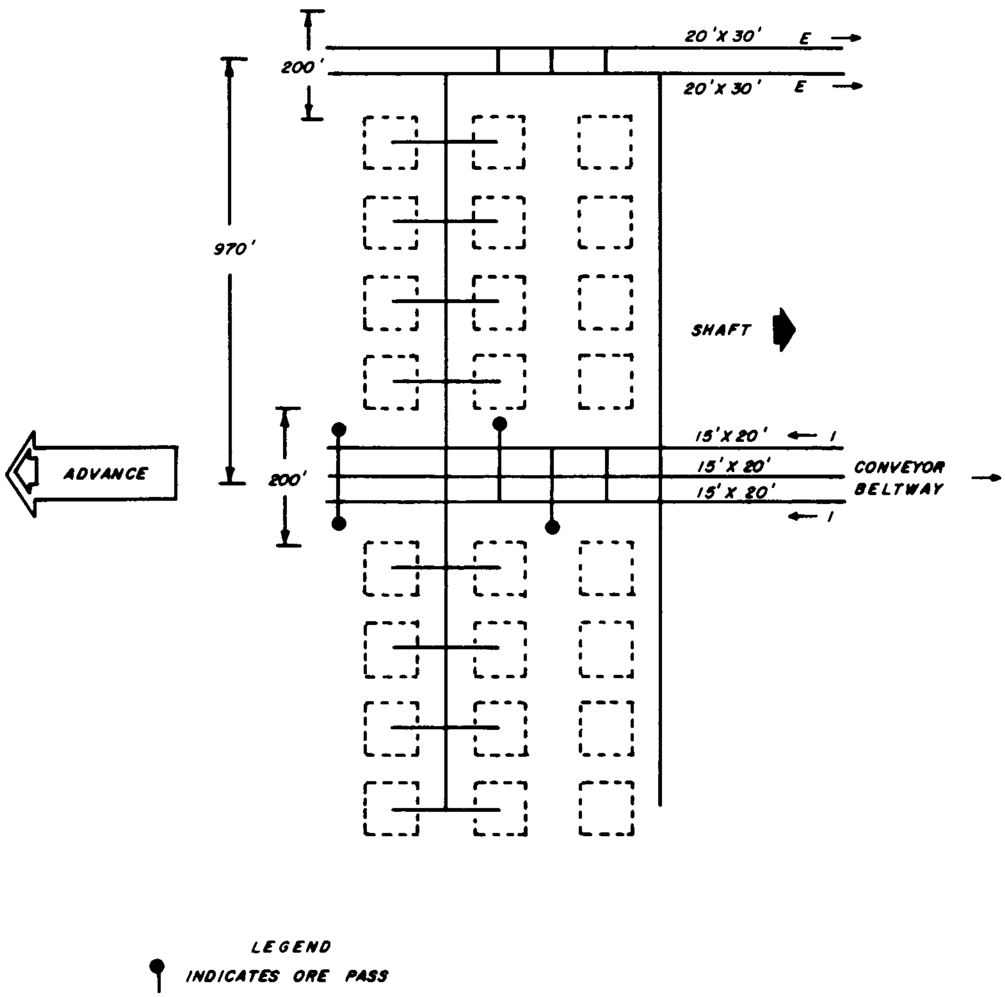

Figure 4-2. MIS Retort--Lower Level Development

All development rock is drilled and blasted conventionally using two-boom hydraulic jumbos and ANFO explosives. Broken rock is hauled, using load-haul-dump machines, to ore passes or feeder-breakers, crushed to -12 inch and conveyed to the surface disposal site. Retort rubblization is done by blasthole drilling rigs and ANFO explosives. Once a cluster is rubblized, protective ventilation bulkheads are installed and the retorts are ignited one by one. At full production, from 170 to 350 retorts (depending on retort dimensions) are ignited simultaneously.

Crushed waste rock is disposed on the surface in specially prepared areas having drainage and stability controls. Disposal areas are in adjacent canyons and extend to the ridge lines to minimize water diversion and control measures.

4.1.2 MIS-5, Process Description

The base cases for the parametric study were taken from the initial screening study.[1] Two involve MIS-retorting only. A block flow diagram for the first of these, MIS-5, is shown in Figure 4-3. The system is sized to produce 50,000 B/SD of raw shale oil and is designed to manufacture an oil suitable for charging directly to a petroleum refinery.

The MIS retorts measure 98 x 98 x 187 ft. Voidage to allow for swelling during rubblization is created by mining a 25 ft zone at the top of the retort volumes and a 30 ft zone at the bottom of the retorts. Extraction from the swell zones is 70% so that voidage is 20% within the retort volume.

The rubblized shale in the in situ retort has a grade of 24 gal per ton, Fischer assay (gpt). Yield of raw shale oil is 55% of Fischer assay (Figure 5-1) or 13.2 gal per ton. Therefore, for a production rate of 50,000 B/SD of raw shale oil, 175,000 tons/SD* of shale must be rubblized and 52,400 tons/SD must be mined to create the retorts.

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* Assuming that 10% more rock must be rubblized than actually retorted to allow for problems.

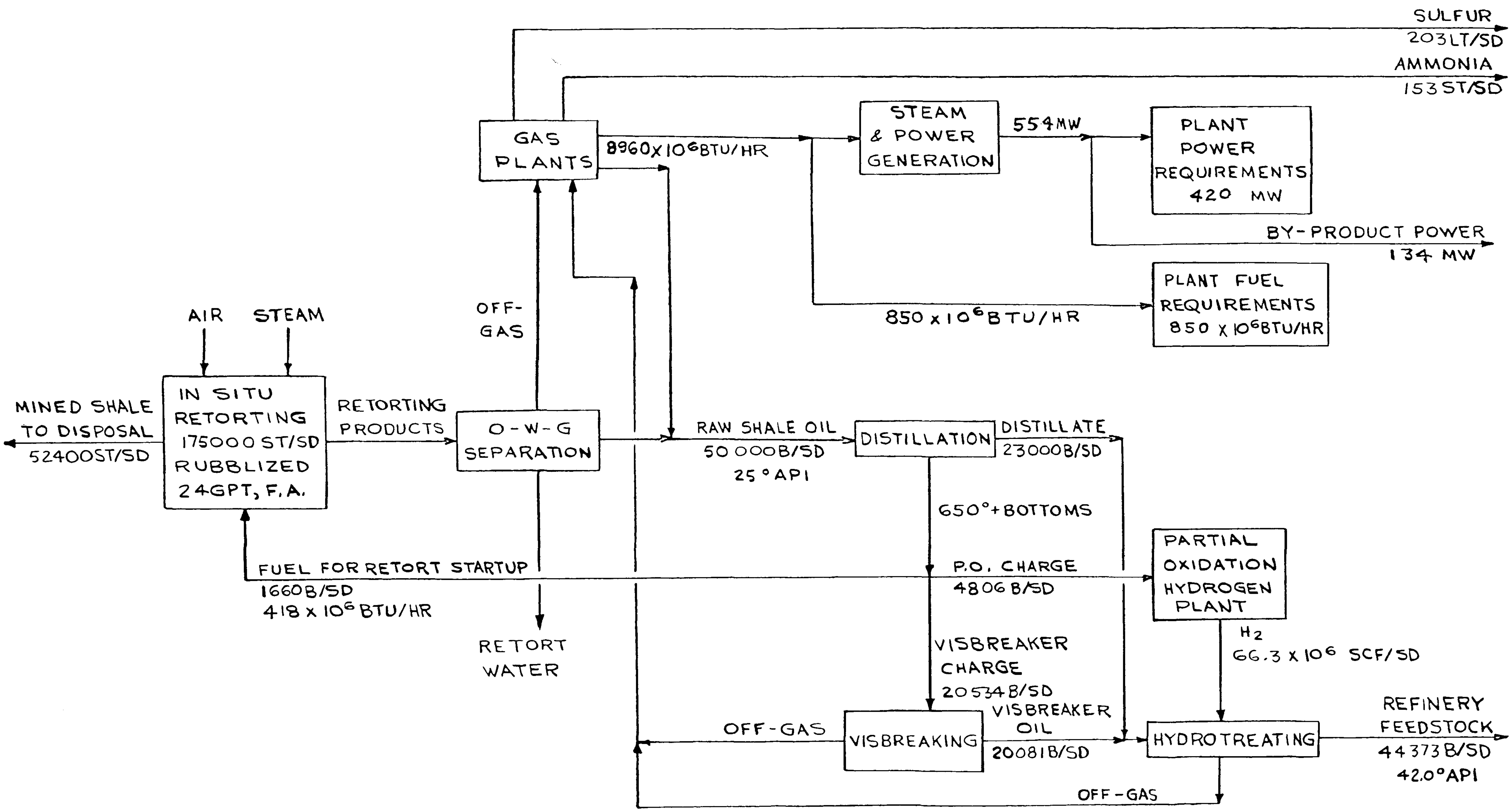

Figure 4-3. Flow Diagram for MIS-5 Base Case

The oil is retorted with a mixture of 70% air and 30% steam and the front advance rate in the retort is assumed to be 1 ft per day. At this front advance rate and with this injection gas mixture, it can be shown, based on experimental data,[2] that the gas injection flux will be about 0.65 SCF/min/ft^2.

The raw shale oil is fractionated at 650°F in an atmospheric unit to produce 23,000 B/SD of distillate and 27,000 B/SD of residue. Six percent of the residue is recycled to the retorts as startup fuel, 18% is charged to partial oxidation to make hydrogen for hydrotreating, and the rest is visbroken. The visbroken oil and the fractionator distillate are charged to the hydrotreater, which produces 44,373 B/SD of refinery feedstock for sale.

Approximately 53,000 SCF (dry) of off-gas is produced by the retorts for each barrel of raw shale oil or about 40% of the total heating value of the products. The gas is purified by removing oil mist, particulates, ammonia, and sulfur compounds to produce fuel gas with a heating value of 8.96×10^9 Btu/hr. About 9% of the fuel gas is used to satisfy the process fuel requirements and the rest is used to generate 1,799,000 lb/hr of low pressure steam for the process and 554 MW of electricity (the utility balance is shown in Table 4-1). The electricity is more than required to satisfy the process requirements so that 134 MW of electricity is sold to a power grid as a by-product.

The water balance is shown in Figure 4-4. Raw water, at a rate of 7,866 gpm (6.1 B/B product), is treated for cooling tower makeup, process water, potable water and boiler feed water. About 15% of the raw water is assumed for blowdown from the water treatment units. Wastewater from the various blowdown streams and the foul water from the retorts are combined and treated sufficiently for discharge. Not shown in Figure 4-4 is the water requirement for the steam power plant which, for a power plant generating 554 MW of electricity, amounts to 9,340 gpm (7.2 B/B product); the total water requirement is 17,206 gpm or 13.3 B/B product.

Table 4-1. Summary of Utilities for MIS Base Case

Case	MIS-5	MIS-6
Fuel Gas Balance, 10^6 Btu/hr (HHV)		
Steam and Power Generation	8110	11160
Process Fuel Requirements	850	990
Fuel Produced from Off-Gas	8960	12150
Electrical Power Balance, MW		
Power Generated	554	764
Power Required	420	567
Power Sold	134	197
Steam Balance, 10^3 lb/hr		
Retort Steam	1679	2309
Other Steam Requirements	351	376
Total Steam Requirements	2030	2685
Steam Plant	1799	2454
Process Waste Heat Boilers	231	231
Total Steam Generated	2030	2685

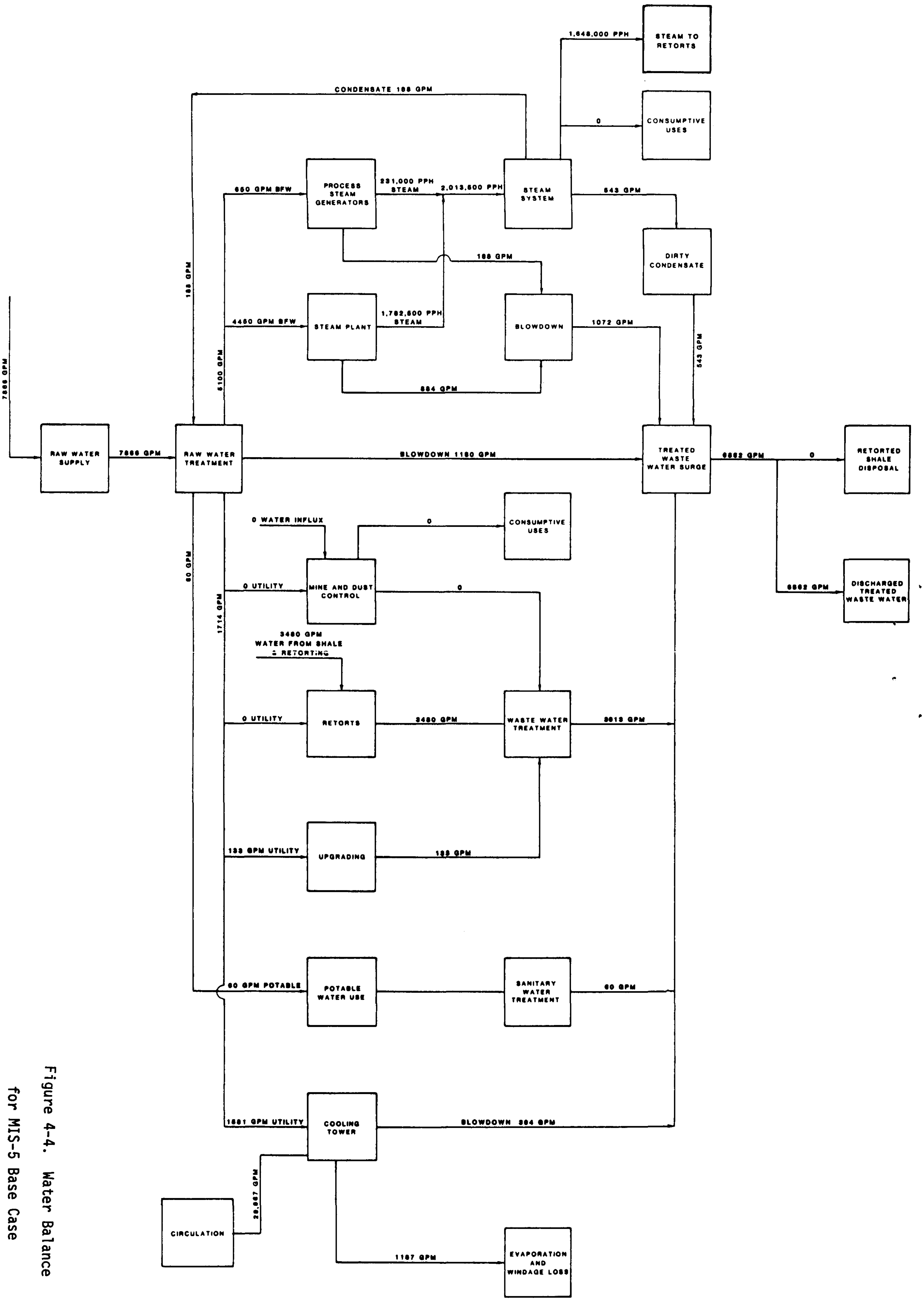

Figure 4-4. Water Balance for MIS-5 Base Case

4.1.3 MIS-6, Process Description

A block flow diagram for the second MIS base case, MIS-6, is shown in Figure 4-5. The MIS retorts are sized at 164 x 164 x 305 ft and the rubblized shale grade is 20 gpt. Yield is 46% of Fischer assay (Figure 5-1) or 9.2 gal per ton. For a production rate of approximately 50,000 B/SD of raw shale, 250,700 ST/SD of shale must be rubblized and 74,770 ST/SD must be mined to create the retorts.

Voidage to allow for swelling during rubblization is created by mining a 25 ft zone at the top of the retort volumes, a 25 ft intermediate zone and a 31 ft zone at the bottom. Extraction from the swell zones is 70% so that voidage is 19% within the retort volume. The other design bases for MIS retorting are the same as given for MIS-5.

Raw shale oil is produced at 50,146 B/SD and fractionated at 650°F to yield 23,067 B/SD of distillate and 27,079 B/SD of residue. Four percent of the residue is recycled to the retorts as startup fuel, 10% is charged to partial oxidation to make hydrogen for hydrotreating and the rest is visbroken. The visbreaker oil and fractionator distillate are charged to the hydrotreater which produces 44,944 B/SD of refinery feedstock for sale.

Approximately 73,000 SCF(dry) of off-gas is produced by the MIS retorts for each barrel of raw shale oil or about 50% of the total heating value of the products. The gas is purified by removing oil mist, particulates, ammonia and sulfur compounds to produce fuel gas with a heating value of 12.2×10^9 Btu/hr. About 8% of the fuel gas is used for process fuel requirements and the rest is used to generate 2,454,000 lb/hr of steam and 764 MW of electrical power. Power requirements for the facility are 567 MW so that 197 MW of excess electricity is available for sale as a by-product.

The water balance is shown in Figure 4-6. Raw water at a rate of 10,396 gpm (7.9 B/B product) is treated for cooling tower makeup, process water, potable water and boiler feed water. As in Case MIS-5, blowdown for the water treatment facilities is assumed to be 15% and blowdown from the

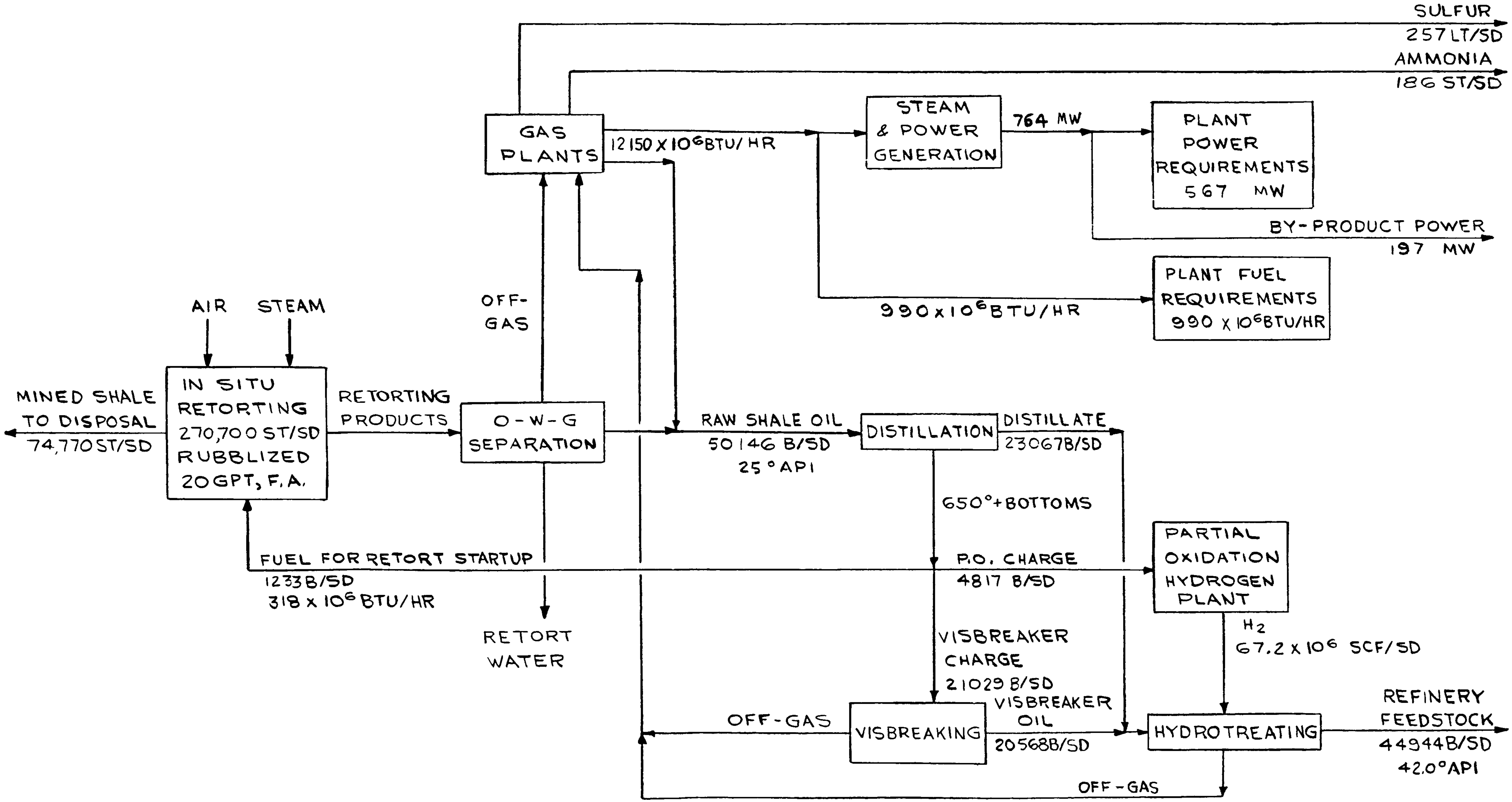

Figure 4-5. Flow Diagram for MIS-6 Base Case

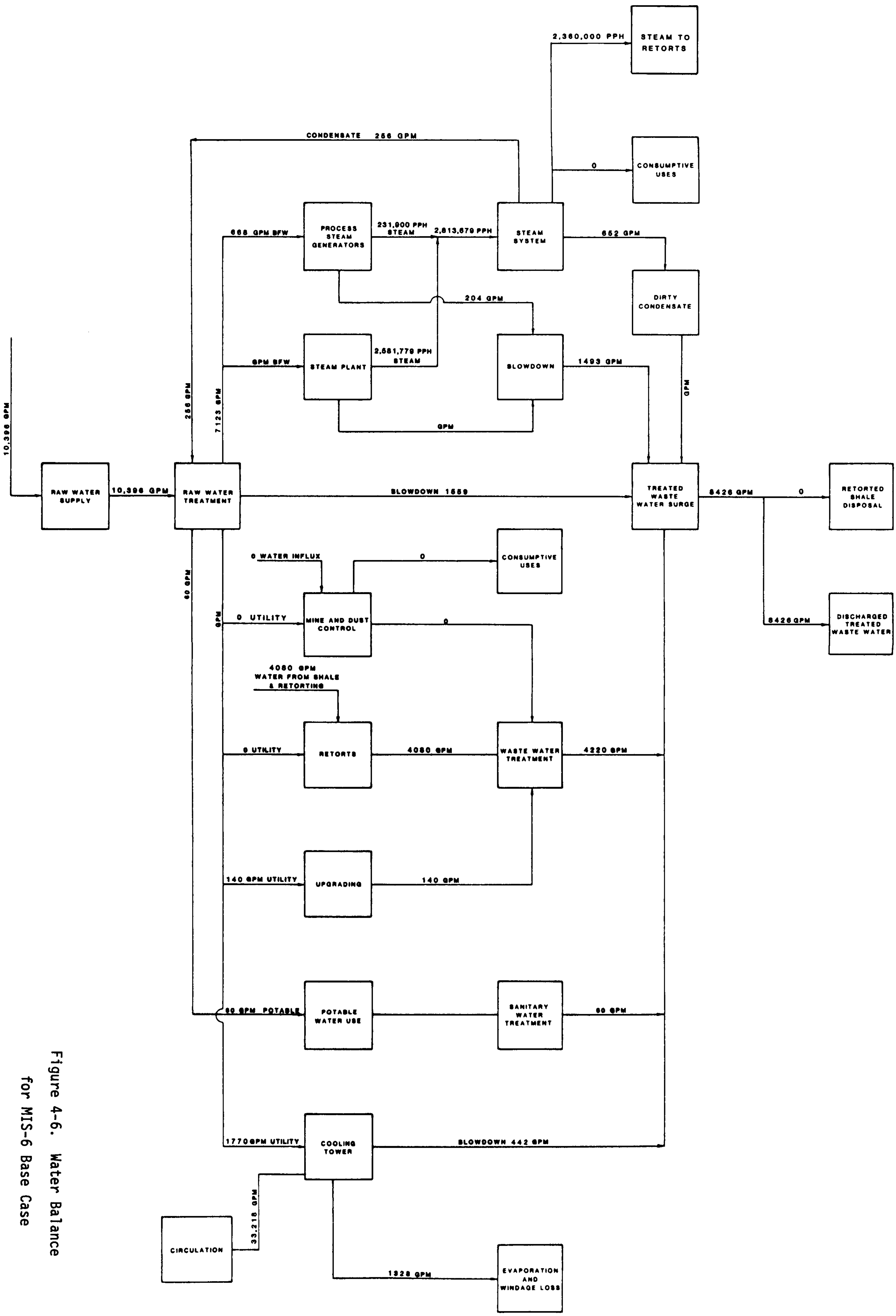

Figure 4-6. Water Balance for MIS-6 Base Case

various blowdown streams and the foul water from retorting are treated sufficiently for discharge. If the water requirements for the 764 MW power plant are included, the raw water usage is increased by 12,870 gpm (9.8 B/B product); the total water requirement is 23,266 gpm or 17.7 B/B product.

4.2 Combined MIS/Tosco Retorting, COMB-3

4.2.1 Mining and MIS Retorting

Mine development for a facility in which the MIS retorting process is combined with surface retorting is essentially the same as the MIS retorting only cases discussed previously except that mining for the upper swell zone takes place in a rich oil shale stratum; the rich shale is crushed further and conveyed to surface retorts where it is retorted for additional shale oil. Tosco surface retorts were chosen for this study. The choice of the Tosco II retorts is arbitrary and any one of the other retorts could have been used. The shale grade from the upper swell zone is sufficiently high to maximize grade and output for surface processing. The lower swell zones are mined from lean strata and the shale is disposed as before. The facility is sized to produce a total of 50,000 B/SD from both retorting methods.

The MIS retorts measure 123 x 123 x 245 ft. Three levels of swell zones are mined: a 36 ft upper level in a rich oil shale stratum and two 25 ft lower levels in lean shale strata. With extraction at 70%, voidage is about 24%. The other design bases for MIS retorting are the same as discussed in Section 4.1.

The rubblized shale in the MIS retort has a grade of 19.5 gpt and the oil shale mined from the rich zone and charged to the Tosco retort has a grade of 37.4 gpt. Yield from the MIS retorts is 45% of Fischer assay (Figure 5-1) or 9.0 gal per ton. For a total production rate of 50,000 B/SD, 156,400 ST/SD of shale is rubblized, 36,300 ST/SD of shale is mined from lean strata and conveyed to the disposal pile and 19,800 ST/SD of shale is crushed and charged to the Tosco retorts.

4.2.2 Tosco Retorting

A flow diagram for the Tosco oil shale retorting process is shown in Figure 4-7.[3] Retorting in the Tosco II process is achieved by direct contact between hot ceramic balls and preheated oil shale. Raw shale that has been crushed to less than 1/2-inch is preheated by hot flue gas from a ball heater in a dilute-phase lift pipe system. The lift pipe system serves as a thermally efficient heat transfer device capable of handling a wide range of particle sizes with a low pressure drop.

The preheated shale is fed to a pyrolysis drum. Retorting of the oil shale is achieved by solid-to-solid heat transfer between the shale and hot ceramic balls, flowing cocurrently through the rotating pyrolysis drum. The pyrolysis drum is an efficient mixing device and complete retorting of shale is achieved at about 900°F during a short residence time. The shale oil vapors, the spent shale and the ceramic balls exit together and are separated in an accumulator. The balls are lifted by an elevator and reheated in a ball heater, which is a direct contact heat exchanger designed to heat the balls to about 1270°F. Waste heat in the ball heater flue gases is transferred to the shale in the lift pipe preheat system.

Spent shale exits from the accumulator vessel close to the retorting temperature of 900°F and goes through a special heat exchanger designed to cool the spent shale and also generate steam for plant use. The spent shale is then cooled further by direct contact with water and moisturized to a level of about 15%. The shale oil vapor is quenched and then fractionated using conventional hydrocarbon processing equipment. An oil mist is not formed so that no special separation equipment is needed.

4.2.3 Process Description

A block flow diagram for the combined MIS/Tosco retorting base case is shown in Figure 4-8. As shown, 32,617 B/SD of raw shale oil is produced by the MIS retorting process and 17,383 B/SD is produced by the Tosco process for

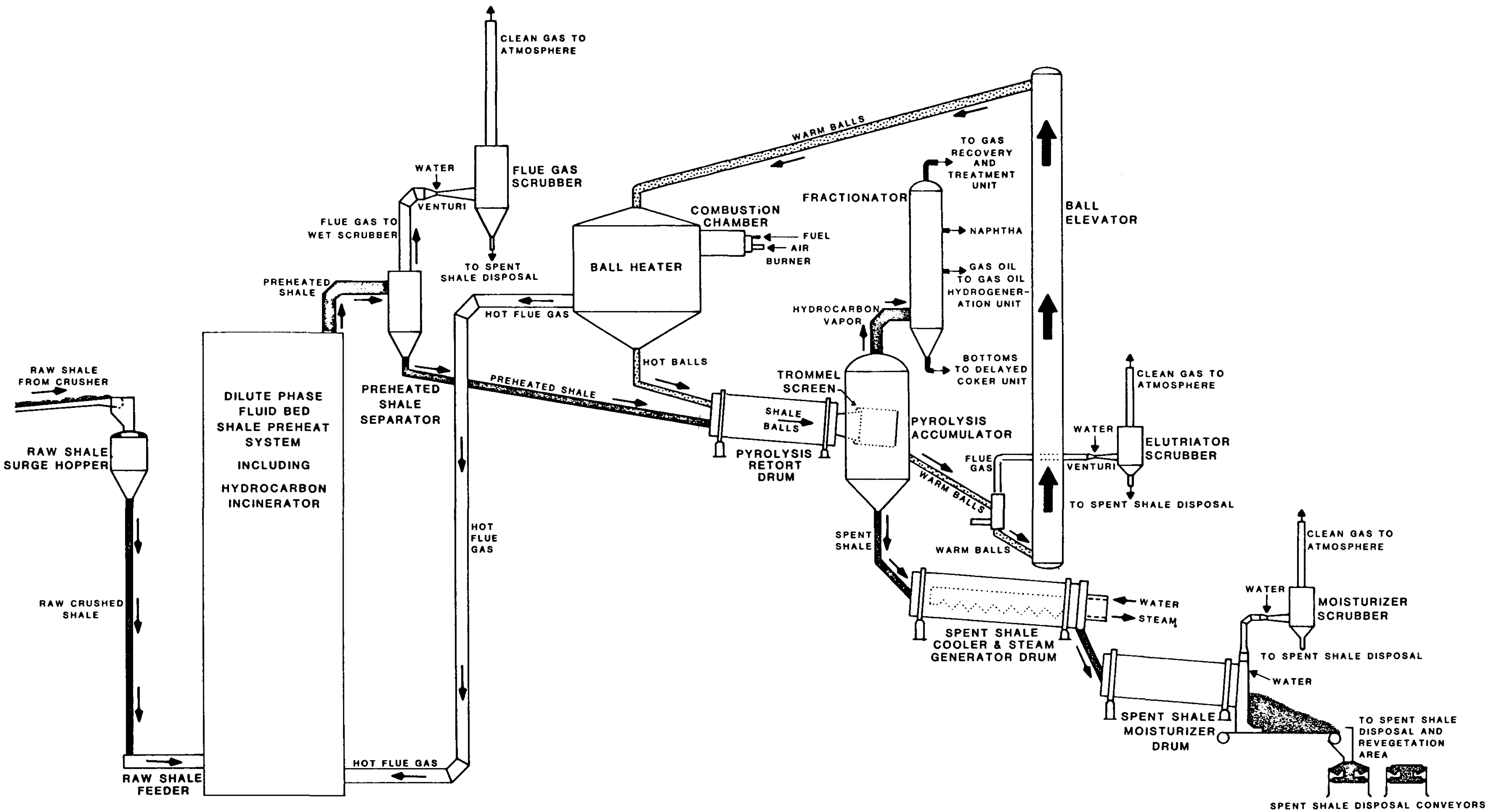

Figure 4-7. Tosco II Oil Shale Retorting Process

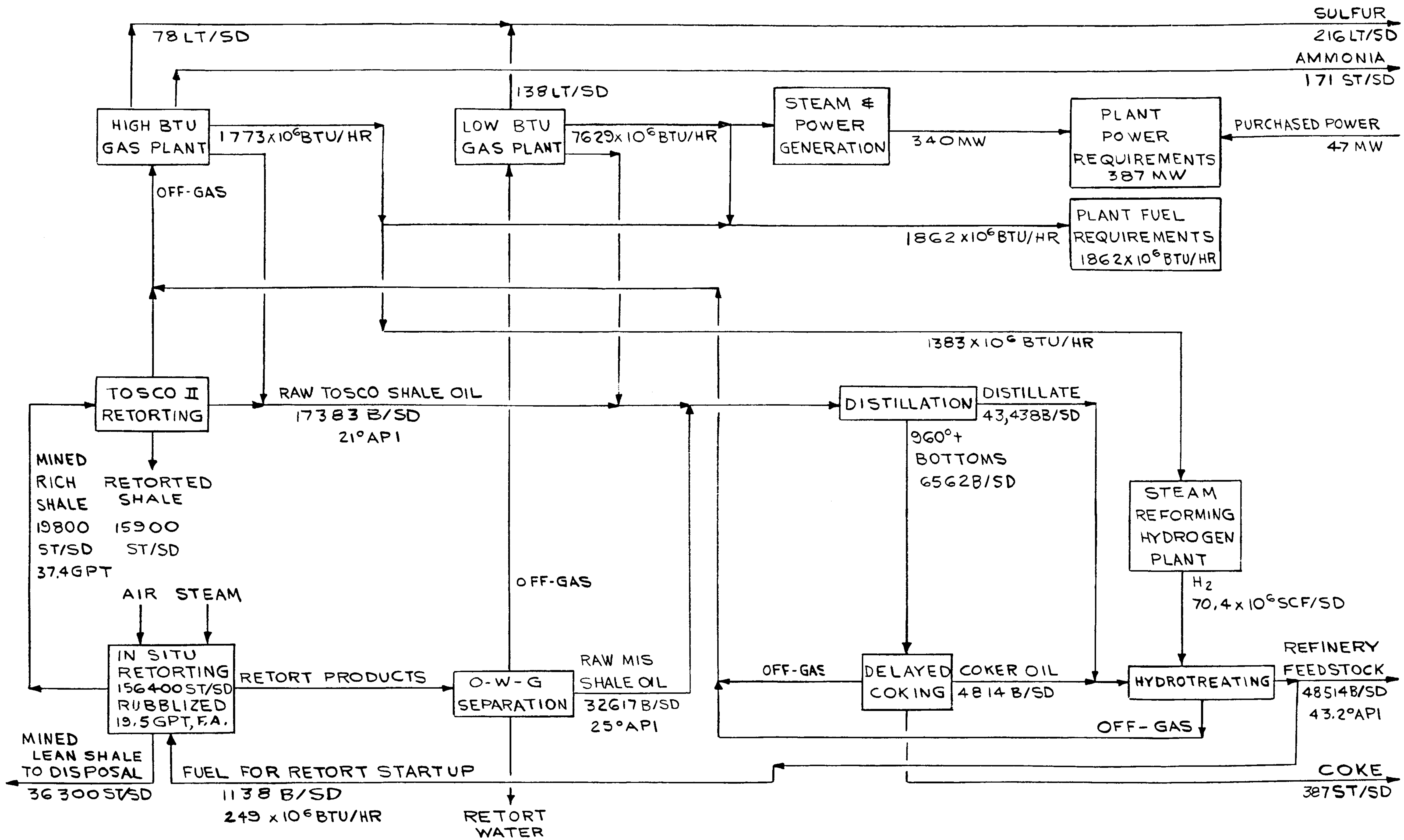

Figure 4-8. Flow Diagram for Combined MIS/Tosco Base Case

a total production rate of 50,000 B/SD. The raw shale oil is fractionated in an atmospheric-vacuum unit at 960°F to yield 43,438 B/SD of distillate and 6,562 B/SD of residue. The residue is charged to a delayed coker which yields 4,814 B/SD of coker oil and 387 ST/SD of green coke which is sold as a by-product. The coker oil and fractionator distillate are hydrotreated to yield 49,652 B/SD of refinery feedstock, but 1,138 B/SD of the product oil is recycled to the MIS retorts for startup fuel. Net yield of refinery feedstock for sales is 48,514 B/SD.

The MIS retorts produce 76,000 SCF(dry) of off-gas per barrel of raw shale oil or about 50% of the total heating value of the products. The gas is purified in the same fashion as described for the MIS retorting only cases to yield 7.63×10^9 Btu/hr of low heating value fuel gas. The off-gas from the Tosco retorts and upgrading processing units are purified to remove ammonia and sulfur compounds to yield 1.77×10^9 Btu/hr of high heating value fuel gas.

Part of the high heating value fuel gas, 842×10^6 Btu/hr, is compressed to 150 psig, purified in a Benfield unit to recover CO_2 by hot carbonate scrubbing, and charged to a steam reformer for making hydrogen for hydrotreating. The remaining high heating value fuel gas is combined with the low heating value fuel gas and used for the remaining fuel requirements of the plant. Electricity is generated at a rate of 340 MW; however, 387 MW are required for the process so that 47 MW of power must be purchased (the utility balance is shown in Table 4-2).

The water balance is shown in Figure 4-9. Raw water at a rate of 8,420 gpm (5.9 B/B of product) is treated for cooling water makeup, process water, potable water and boiler feedwater. As previously, blowdown for the water treatment facilities is assued to be 15%. The various blowdown streams and the four water from retorting are treated sufficiently for discharge. If the water requirements for the 340 MW power plant are included, the raw water requirement is increased by 5,602 gpm (4.0 B/B product) for a total of 14,022 gpm or 9.9 B/B of product.

Table 4-2. Summary of Utilities for MIS/Tosco Base Case

Fuel Balance, 10^6 Btu/hr (HHV)	
Tosco Retorts	821
Hydrogen Manufacture (including fuel)	1383
Steam and Power Generation	6157
Other Process Fuel Requirements	1041
Fuel Produced from Off-Gas	9402
Electric Power Balance, MW	
Power Generated	340.0
Power Required	387.0
Purchased Power	47.0
Steam Balance, 10^3 lb/hr	
MIS Retort Steam	1587.1
Other Steam Requirements	558.2
Total Steam Requirements	2145.3
Steam Plant	1941.2
Process Waste Heater Boilers	204.1
Total Steam Generated	2145.3

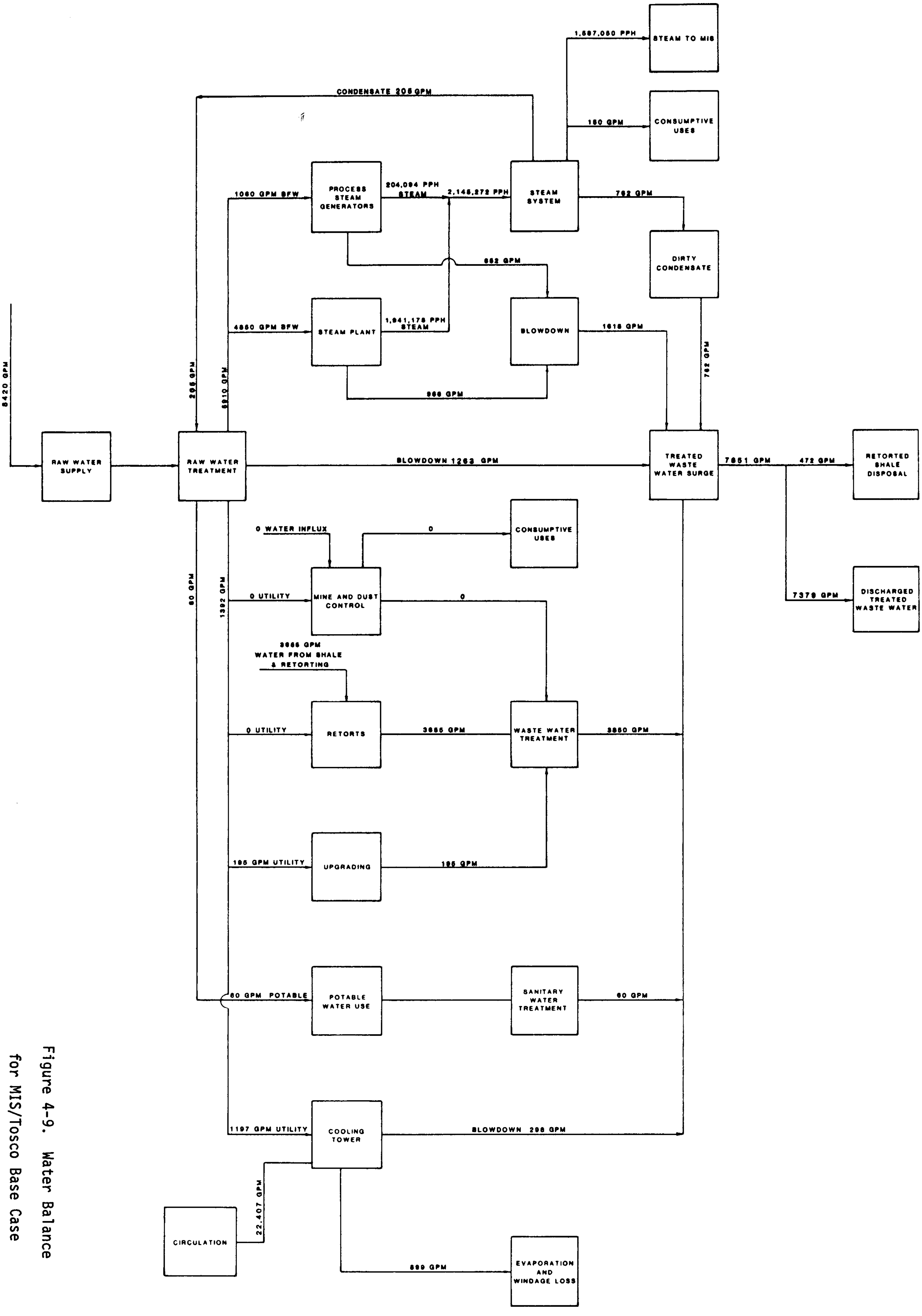

Figure 4-9. Water Balance for MIS/Tosco Base Case

4.3 Economics

The economics for the MIS-5, MIS-6 and combined MIS/Tosco, COMB-3, retorting processes are given in Tables 4-3, 4-4, and 4-5, respectively. Table 4-3 shows the operating expenses for the various sections of the process, a listing of the investments, a breakdown of the mining and material handling investments on a year-to-year basis, and the discounted cash flow calculation and product price for a 15% rate of return on investment. The economics calculations are based on the first quarter of 1979.

Mining investments are for mining equipment, mine access and support facilities, a water system, railroads, access roads, and site preparation. Material handling investments are for shale conveying, crushing, storage, waste rock disposal and spent shale disposal. Preoperational mine development is the operating expense for the mine which has been capitalized during the development years. Five years are required to develop the mine for the MIS cases.

The investment for the Tosco process was obtained from the literature.[4,5] The investment for manufacturing hydrogen via steam reforming of off-gases,[6] the investment for the hydrotreating unit[6] and the investment for the visbreaker[7] were also obtained from the literature.

The investments for the following units were obtained from Gulf data files:

Distillation
Delayed Coking
Wastewater Stripping and By-Product Recovery
Air (MIS) and Gas Compression
Oil-Water-Gas Separation (MIS)
Intermediate and Product Storage
Power Generation
Steam Generation
Cooling Tower
Hydrogen Production via Partial Oxidation

Table 4-3. MIS-5 Base Case

OPERATING EXPENSES:	$/BBL PRODUCT
MINING	8.845
MATERIALS HANDLING	0.0
SURFACE RETORTING	0.0
MIS RETORTING	1.890
OIL UPGRADING	1.477
UTILITIES AND OFF-SITES	2.651
PURCHASED ELECTRICITY	0.0
PURCHASED FUEL	0.0
GROSS OPERATING EXPENSE	14.863
BY-PRODUCT CREDITS - SULFUR	0.229
- AMMONIA	0.431
- COKE	0.0
- ELECT.	0.517
- TOTAL	1.177
NET OPERATING EXPENSE	13.686

Table 4-3. MIS-5 Base Case (Continued)

INVESTMENTS: MEGA $
YEAR: 1979
NRC : 732

	PRE-OPERATION INVESTMENT	DEFERRED INVESTMENT	TOTAL INVESTMENT
MINING AND MATERIAL HANDLING			
PRE-OP.MINE DEVELOPMENT	142.7	0.0	142.7
MINING	185.0	299.8	484.8
MATERIAL HANDLING	0.0	0.0	0.0
TOTAL MINING AND MAT'L HAND.	327.7	299.8	627.5
M-I-S RETORTING			
AIR COMPRESSION	18.0	0.0	18.0
OXYGEN PLANT	0.0	0.0	0.0
OTHER MIS RETORTING	0.0	0.0	0.0
OIL-WATER-GAS SEPARATION	75.0	0.0	75.0
GAS TREATMENT	176.0	0.0	176.0
TOTAL MIS RETORTING	269.0	0.0	269.0
SURFACE RETORTING			
RETORTS	0.0	0.0	0.0
GAS TREATMENT	0.0	0.0	0.0
TOTAL SURFACE RETORTING	0.0	0.0	0.0
OIL UPGRADING			
DISTILLATION	16.0	0.0	16.0
VISBREAKER	10.0	0.0	10.0
DELAYED COKER	0.0	0.0	0.0
HYDROTREATMENT	75.0	0.0	75.0
HYDROGEN PLANT	46.0	0.0	46.0
TOTAL OIL UPGRADING	147.0	0.0	147.0
UTILITIES AND MISC. OFF-SITES			
STEAM AND POWER GENERATION	256.0	0.0	256.0
OTHER UTILITIES AND OFF-SITES	265.0	0.0	265.0
TOTAL UTILITIES AND OFF-SITES	521.0	0.0	521.0
START-UP COSTS FOR SURFACE FACIL.	35.0	0.0	35.0
WORKING CAPITAL FOR MINE	20.0	0.0	20.0
WORKING CAPITAL FOR SURFACE FACIL.	12.4	0.0	12.4
LEASE BONUS/LAND PURCHASE	0.0	0.0	0.0
OTHER PRE-OP. INVESTMENTS	0.0	0.0	0.0
TOTAL INVESTMENT	1332.1	299.8	1631.9
SPECIFIC INVEST.($/BBL/SD)	30020.6	6756.3	36776.9

Table 4-3. MIS-5 Base Case (Continued)

MINING AND MATERIAL HANDLING INVESTMENTS

YEAR	MINING INVESTMENT	MATERIAL HANDLING INVESTMENT	MINING DEPRECIATION	MATERIAL HANDLING DEPRECIATION
1	29.70	0.0	0.0	0.0
2	50.70	0.0	0.0	0.0
3	58.40	0.0	0.0	0.0
4	26.90	0.0	0.0	0.0
5	19.30	0.0	0.0	0.0
6	37.60	0.0	61.24	0.0
7	13.80	0.0	49.68	0.0
8	13.80	0.0	44.72	0.0
9	13.80	0.0	39.77	0.0
10	13.80	0.0	34.81	0.0
11	13.80	0.0	29.86	0.0
12	13.80	0.0	24.90	0.0
13	13.80	0.0	19.94	0.0
14	13.80	0.0	14.99	0.0
15	13.80	0.0	14.99	0.0
16	13.80	0.0	14.99	0.0
17	13.80	0.0	14.99	0.0
18	13.80	0.0	14.99	0.0
19	13.80	0.0	14.99	0.0
20	13.80	0.0	14.99	0.0
21	13.80	0.0	14.99	0.0
22	13.80	0.0	14.99	0.0
23	13.80	0.0	14.99	0.0
24	13.80	0.0	14.99	0.0
25	13.80	0.0	14.99	0.0

Table 4-3. MIS-5 Base Case (Continued)

DISCOUNTED CASH FLOW CALCULATION AT 15% ROI - ANNUAL AMOUNTS IN MEGA $

YEAR	INVESTMENT	DEPRECIATION	TAXABLE INCOME	TAX	CASH FLOW	PRESENT VALUE
1	29.700	0.0	0.0	0.0	-29.700	-29.700
2	144.400	0.0	0.0	-2.227	-142.172	-123.628
3	292.650	0.0	0.0	-13.172	-279.477	-211.325
4	537.400	0.0	0.0	-27.805	-509.594	-335.067
5	295.550	0.0	0.0	-51.284	-244.266	-139.660
6	70.002	246.453	26.309	-15.187	244.257	121.439
7	13.800	202.967	48.053	22.104	263.168	113.775
8	13.800	183.645	57.714	26.548	258.724	97.264
9	13.800	164.321	67.375	30.993	254.279	83.125
10	13.800	145.000	79.288	36.472	248.800	70.725
11	13.800	125.678	98.609	45.360	239.912	59.303
12	13.800	106.356	117.931	54.248	231.024	49.657
13	13.800	87.034	137.254	63.137	222.135	41.519
14	13.800	67.712	156.575	72.025	213.247	34.659
15	13.800	57.167	167.120	76.875	208.397	29.453
16	13.800	46.623	177.664	81.725	203.547	25.015
17	13.800	36.079	188.208	86.576	198.696	21.234
18	13.800	25.534	198.753	91.426	193.846	18.013
19	13.800	14.990	209.297	96.277	188.995	15.272
20	13.800	14.990	209.297	96.277	188.995	13.280
21	13.800	14.990	209.297	96.277	188.995	11.548
22	13.800	14.990	209.297	96.277	188.995	10.042
23	13.800	14.990	209.297	96.277	188.995	8.732
24	13.800	14.990	209.297	96.277	188.995	7.593
25	-18.602	14.990	209.297	96.277	221.397	7.734
					SUM OF PRESENT VALUE	-0.001

DURING OPERATING PERIOD: REVENUE 498.566
OPERATING EXPENSE 199.494

PRODUCT PRICE FOR 15% ROI,$/BBL 34.203
COST OF CAPITAL,$/BBL 20.517

Table 4-4. MIS-6 Base Case

OPERATING EXPENSES:	$/BBL PRODUCT
MINING	11.265
MATERIALS HANDLING	0.0
SURFACE RETORTING	0.0
MIS RETORTING	2.576
OIL UPGRADING	1.470
UTILITIES AND OFF-SITES	3.200
PURCHASED ELECTRICITY	0.0
PURCHASED FUEL	0.0
GROSS OPERATING EXPENSE	18.511
BY-PRODUCT CREDITS - SULFUR	0.286
- AMMONIA	0.517
- COKE	0.0
- ELECT.	0.548
- TOTAL	1.351
NET OPERATING EXPENSE	17.159

Table 4-4. MIS-6 Base Case (Continued)

INVESTMENTS: MEGA $
YEAR: 1979
NRC : 732

	PRE-OPERATION INVESTMENT	DEFERRED INVESTMENT	TOTAL INVESTMENT
MINING AND MATERIAL HANDLING			
PRE-OP.MINE DEVELOPMENT	195.5	0.0	195.5
MINING	195.0	331.7	526.7
MATERIAL HANDLING	0.0	0.0	0.0
TOTAL MINING AND MAT'L HAND.	390.5	331.7	722.2
M-I-S RETORTING			
AIR COMPRESSION	27.0	0.0	27.0
OXYGEN PLANT	0.0	0.0	0.0
OTHER MIS RETORTING	0.0	0.0	0.0
OIL-WATER-GAS SEPARATION	89.0	0.0	89.0
GAS TREATMENT	270.0	0.0	270.0
TOTAL MIS RETORTING	386.0	0.0	386.0
SURFACE RETORTING			
RETORTS	0.0	0.0	0.0
GAS TREATMENT	0.0	0.0	0.0
TOTAL SURFACE RETORTING	0.0	0.0	0.0
OIL UPGRADING			
DISTILLATION	16.0	0.0	16.0
VISBREAKER	10.0	0.0	10.0
DELAYED COKER	0.0	0.0	0.0
HYDROTREATMENT	76.0	0.0	76.0
HYDROGEN PLANT	46.0	0.0	46.0
TOTAL OIL UPGRADING	148.0	0.0	148.0
UTILITIES AND MISC. OFF-SITES			
STEAM AND POWER GENERATION	334.0	0.0	334.0
OTHER UTILITIES AND OFF-SITES	310.0	0.0	310.0
TOTAL UTILITIES AND OFF-SITES	644.0	0.0	644.0
START-UP COSTS FOR SURFACE FACIL.	35.0	0.0	35.0
WORKING CAPITAL FOR MINE	20.0	0.0	20.0
WORKING CAPITAL FOR SURFACE FACIL.	15.2	0.0	15.2
LEASE BONUS/LAND PURCHASE	0.0	0.0	0.0
OTHER PRE-OP. INVESTMENTS	0.0	0.0	0.0
TOTAL INVESTMENT	1638.7	331.7	1970.4
SPECIFIC INVEST.($/BBL/SD)	36459.8	7380.3	43840.1

Table 4-4. MIS-6 Base Case (Continued)

MINING AND MATERIAL HANDLING INVESTMENTS

YEAR	MINING INVESTMENT	MATERIAL HANDLING INVESTMENT	MINING DEPRECIATION	MATERIAL HANDLING DEPRECIATION
1	32.20	0.0	0.0	0.0
2	52.50	0.0	0.0	0.0
3	62.20	0.0	0.0	0.0
4	28.90	0.0	0.0	0.0
5	19.20	0.0	0.0	0.0
6	39.10	0.0	65.33	0.0
7	15.40	0.0	53.15	0.0
8	15.40	0.0	47.92	0.0
9	15.40	0.0	42.70	0.0
10	15.40	0.0	37.48	0.0
11	15.40	0.0	32.25	0.0
12	15.40	0.0	27.03	0.0
13	15.40	0.0	21.81	0.0
14	15.40	0.0	16.58	0.0
15	15.40	0.0	16.58	0.0
16	15.40	0.0	16.58	0.0
17	15.40	0.0	16.58	0.0
18	15.40	0.0	16.58	0.0
19	15.40	0.0	16.58	0.0
20	15.40	0.0	16.58	0.0
21	15.40	0.0	16.58	0.0
22	15.40	0.0	16.58	0.0
23	15.40	0.0	16.58	0.0
24	15.40	0.0	16.58	0.0
25	15.40	0.0	16.58	0.0

Table 4-4. MIS-6 Base Case (Continued)

DISCOUNTED CASH FLOW CALCULATION AT 15% ROI - ANNUAL AMOUNTS IN MEGA $

YEAR	INVESTMENT	DEPRECIATION	TAXABLE INCOME	TAX	CASH FLOW	PRESENT VALUE
1	32.200	0.0	0.0	0.0	-32.200	-32.200
2	170.300	0.0	0.0	-2.415	-167.885	-145.987
3	356.700	0.0	0.0	-15.717	-340.982	-257.832
4	674.250	0.0	0.0	-34.115	-640.135	-423.399
5	370.050	0.0	0.0	-64.259	-305.791	-174.837
6	74.251	300.825	31.345	-19.663	308.926	153.591
7	15.400	247.710	57.903	26.635	321.480	138.985
8	15.400	224.090	69.713	32.068	316.047	118.814
9	15.400	200.472	81.522	37.500	310.615	101.541
10	15.400	176.853	94.133	43.301	304.814	86.647
11	15.400	153.235	117.752	54.166	293.949	72.660
12	15.400	129.616	141.371	65.031	283.084	60.347
13	15.400	105.997	164.989	75.895	272.220	50.880
14	15.400	82.379	188.608	86.760	261.356	42.478
15	15.400	69.220	201.766	92.813	255.303	35.082
16	15.400	56.061	214.925	98.866	249.250	30.632
17	15.400	42.903	228.084	104.919	243.197	25.989
18	15.400	29.744	241.243	110.972	237.144	22.037
19	15.400	16.585	254.402	117.025	231.091	18.673
20	15.400	16.585	254.402	117.025	231.091	16.238
21	15.400	15.585	254.402	117.025	231.091	14.120
22	15.400	16.585	254.402	117.025	231.091	12.278
23	15.400	16.585	254.402	117.025	231.091	10.677
24	15.400	16.585	254.402	117.025	231.091	9.284
25	-19.751	16.585	254.402	117.025	266.242	9.301
					SUM OF PRESENT VALUE	-0.001

DURING OPERATING PERIOD: REVENUE 616.859
OPERATING EXPENSE 253.343

PRODUCT PRICE FOR 15% ROI.$/BBL 41.781
COST OF CAPITAL.$/BBL 24.622

Table 4-5. Combined MIS/Tosco Base Case

OPERATING EXPENSES:	$/BBL PRODUCT
MINING	8.473
MATERIALS HANDLING	0.084
SURFACE RETORTING	0.803
MIS RETORTING	1.347
OIL UPGRADING	1.509
UTILITIES AND OFF-SITES	2.073
PURCHASED ELECTRICITY	0.698
PURCHASED FUEL	0.0
GROSS OPERATING EXPENSE	14.987
BY-PRODUCT CREDITS - SULFUR	0.223
- AMMONIA	0.441
- COKE	0.080
- ELECT.	0.0
- TOTAL	0.743
NET OPERATING EXPENSE	14.244

Table 4-5. Combined MIS/Tosco Base Case (Continued)

INVESTMENTS: MEGA $
YEAR: 1979
NRC : 732

	PRE-OPERATION INVESTMENT	DEFERRED INVESTMENT	TOTAL INVESTMENT
MINING AND MATERIAL HANDLING			
PRE-OP.MINE DEVELOPMENT	149.6	0.0	149.6
MINING	175.0	266.3	441.3
MATERIAL HANDLING	37.0	6.5	43.5
TOTAL MINING AND MAT'L HAND.	361.6	272.8	634.4
M-I-S RETORTING			
AIR COMPRESSION	16.0	0.0	16.0
OXYGEN PLANT	0.0	0.0	0.0
OTHER MIS RETORTING	0.0	0.0	0.0
OIL-WATER-GAS SEPARATION	60.0	0.0	60.0
GAS TREATMENT	134.0	0.0	134.0
TOTAL MIS RETORTING	210.0	0.0	210.0
SURFACE RETORTING			
RETORTS	97.0	0.0	97.0
GAS TREATMENT	46.0	0.0	46.0
TOTAL SURFACE RETORTING	143.0	0.0	143.0
OIL UPGRADING			
DISTILLATION	29.0	0.0	29.0
VISBREAKER	0.0	0.0	0.0
DELAYED COKER	12.0	0.0	12.0
HYDROTREATMENT	81.0	0.0	81.0
HYDROGEN PLANT	43.0	0.0	43.0
TOTAL OIL UPGRADING	165.0	0.0	165.0
UTILITIES AND MISC. OFF-SITES			
STEAM AND POWER GENERATION	166.0	0.0	166.0
OTHER UTILITIES AND OFF-SITES	275.0	0.0	275.0
TOTAL UTILITIES AND OFF-SITES	441.0	0.0	441.0
START-UP COSTS FOR SURFACE FACIL.	35.0	0.0	35.0
WORKING CAPITAL FOR MINE	20.0	0.0	20.0
WORKING CAPITAL FOR SURFACE FACIL.	15.3	0.0	15.3
LEASE BONUS/LAND PURCHASE	0.0	0.0	0.0
OTHER PRE-OP. INVESTMENTS	0.0	0.0	0.0
TOTAL INVESTMENT	1390.9	272.8	1663.7
SPECIFIC INVEST.($/BBL/SD)	28669.8	5623.1	34292.9

Table 4-5. Combined MIS/Tosco Base Case (Continued)

MINING AND MATERIAL HANDLING INVESTMENTS

YEAR	MINING INVESTMENT	MATERIAL HANDLING INVESTMENT	MINING DEPRECIATION	MATERIAL HANDLING DEPRECIATION
1	27.90	0.0	0.0	0.0
2	49.00	0.0	0.0	0.0
3	56.20	0.0	0.0	0.0
4	24.60	16.00	0.0	0.0
5	17.30	21.00	0.0	0.0
6	34.50	0.80	57.06	9.57
7	12.20	0.30	46.13	7.26
8	12.20	0.30	41.44	6.27
9	12.20	0.30	36.75	5.28
10	12.20	0.30	32.06	4.29
11	12.20	0.30	27.38	3.30
12	12.20	0.30	22.69	2.31
13	12.20	0.30	18.00	1.32
14	12.20	0.30	13.31	0.32
15	12.20	0.30	13.31	0.32
16	12.20	0.30	13.31	0.32
17	12.20	0.30	13.31	0.32
18	12.20	0.30	13.31	0.32
19	12.20	0.30	13.31	0.32
20	12.20	0.30	13.31	0.32
21	12.20	0.30	13.31	0.32
22	12.20	0.30	13.31	0.32
23	12.20	0.30	13.31	0.32
24	12.20	0.30	13.31	0.32
25	12.20	0.30	13.31	0.32

Table 4-5. Combined MIS/Tosco Base Case (Continued)

CISCOUNTED CASH FLOW CALCULATION AT 15% ROI - ANNUAL AMOUNTS IN MEGA $

YEAR	INVESTMENT	DEPRECIATION	TAXABLE INCOME	TAX	CASH FLOW	PRESENT VALUE
1	27.900	0.0	0.0	0.0	-27.900	-27.900
2	144.900	0.0	0.0	-2.092	-142.807	-124.180
3	295.950	0.0	0.0	-13.265	-282.685	-213.750
4	564.449	0.0	0.0	-28.190	-536.259	-352.599
5	322.400	0.0	0.0	-53.560	-268.840	-153.710
6	70.589	256.963	25.255	-17.795	254.678	126.620
7	12.500	210.836	48.318	22.226	272.746	117.916
8	12.500	190.368	58.552	26.934	268.038	100.766
9	12.500	169.899	68.787	31.642	263.330	86.083
10	12.500	149.430	79.021	36.350	258.622	73.517
11	12.500	128.962	98.340	45.236	249.736	61.731
12	12.500	108.492	118.809	54.652	240.320	51.655
13	12.500	88.023	139.278	64.068	230.904	43.158
14	12.500	67.555	159.746	73.483	221.489	35.998
15	12.500	56.772	170.529	78.443	216.529	30.602
16	12.500	45.989	181.312	83.404	211.568	26.001
17	12.500	35.206	192.095	88.364	206.608	22.079
18	12.500	24.423	202.878	93.324	201.648	18.738
19	12.500	13.640	213.661	98.284	196.688	15.893
20	12.500	13.640	213.661	98.284	196.688	13.820
21	12.500	13.640	213.661	98.284	196.688	12.018
22	12.500	13.640	213.661	98.284	196.688	10.450
23	12.500	13.640	213.661	98.284	196.688	9.087
24	12.500	13.640	213.661	98.284	196.688	7.902
25	-22.789	13.640	213.661	98.284	231.977	8.104
					SUM OF PRESENT VALUE	-0.001

DURING OPERATING PERIOD: REVENUE 534.471
OPERATING EXPENSE 226.999

PRODUCT PRICE FOR 15% ROI.$/BBL 33.537
COST OF CAPITAL.$/BBL 19.293

Because of the wide variation in condition and composition of the raw off-gas from the retorts, the gas compression unit was designed for each case and the investment was calculated based on the design. Compression takes place in two stages: the first stage involves compression from retort pressure to 50 psig for charging to the gas treatment units and the second stage involves compression of the clean gas from the desulfurization unit to the pressure required for the hydrogen production plant (325 psig).

The intermediate and product storage investment was calculated on the following basis:

Raw Oil Storage	10 days	Heated and insulated floating roof tanks
Oil Product	20 days	Heated and insulated floating roof tanks
Hydrotreater Charge	20 days	Heated and insulated floating roof tanks
Delayed Coker Charge	7 days	Heated and insulated cone roof tanks
Visbreaker Charge	7 days	Heated and insulated cone roof tanks
Distillate Storage	7 days	Floating roof tank
Ammonia	20 days	Refrigerated tank
Sulfur	20 days	Heated and insulated cone roof tanks

Whenever possible, steam is generated in waste heat boilers throughout the facilities which can be used to fulfill the steam requirement. Power generation and the cooling tower are sized at 20% larger than the requirements for each case. Steam is generated in a boiler fired with the low heating value MIS off-gas and used to run steam turbogenerators; the investment includes the boiler, turbogenerator, cooling tower and accessory electrical equipment.

Investments for the following off-sites were taken directly from an earlier report prepared by TRW.[7]

Site Development

Raw Water Facilities

Access Road

Permanent Rail Spur

Miscellaneous off-sites and general facilities include the following:

Waste Disposal

Interconnecting Piping

Underground Piping

Electrical Distribution

Buildings

Other Utilities

The investment was calculated by taking 22.5% of the process plus utility plus tankage investment; the factor 22.5% was obtained from the above mentioned report.[7]

The product pipeline has been sized for a peak capacity of 150,000 B/D and runs 275 miles from Rifle, Colorado to Casper, Wyoming. The labor-related expenses were based on operators wages of $10.20/hr. The price of purchased electricity is 3¢/kW h and no cost for fresh water is included.* By-product sulfur is priced at $50/LT, ammonia at $125/ST, coke at $10/ST and by-product electricity at 0.6¢/kW h.

The product prices at 15% discounted cash flow rate of return on investment were calculated on the following basis: preoperational mining and material handling investments are depreciated over eight years, double-declining-balance method for the first year and sum-of-years digits method for

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* It is assumed that water will be available from the Colorado river. The capital costs for pumps, pipelines, etc., and operating costs have been included in the economic analysis.

seven years. Deferred mining and material handling investment are depreciated by the straight-line method. The investment for surface facilities is depreciated over thirteen years, double-declining-balance method for the first year and sum-of-years digits method for twelve years.

An investment tax credit of 10% is taken for the surface facilities investment. For the preoperational mining and material handling investment, the 10% tax credit is applied to 75% of the depreciable investment so that the effective tax credit is 7.5%. The deferred mining and material handling investment is assumed to be short term so that no tax credit is taken. Depletion allowance is taken at 15% but is limited to 50% of the taxable income before depletion allowance.

Table 4-3 shows for MIS-5 that the total pre-operational investment is \$1.33 x 10^9 and the deferred investment is \$0.30 x 10^9 for a total investment of \$1.63 x 10^9 for the 20-year operating lifetime of the project. The net operating expense is \$13.68/B of product and the cost of capital is \$20.52/B for a total price of \$34.20/B of refinery feedstock.

Table 4-4 shows that the total pre-operational investment for MIS-6 is \$1.64 x 10^9 and the deferred investment is \$0.33 x 10^9 for a total investment of \$1.97 x 10^9. The net operating expense is \$17.16/B of product and the cost of capital is \$24.62/B. The total product price is \$41.78/B.

As shown in Table 4-5 for the combined MIS/Tosco retorting process, the preoperational investment is \$1.39 x 10^9 and the deferred investment is \$0.27 x 10^9 for a total investment of \$1.66 x 10^6. The net operating expense is \$14.24/B and the cost of capital is \$19.29/B for a total product price of \$33.53/B.

5. PARAMETRIC STUDY

5.1 MIS Retort Yields

Published information on the recovery of liquid product (oil) from large commercial-size MIS retorts is sparse. Occidental Oil Shale Company is the only group currently conducting retorting R&D in the field for vertical MIS retorts. Field research is now being partially sponsored with DOE funding, and more information on yield relationships may become available as work continues in the next couple of years.

Because yield data are important in arriving at conceptual mining and retorting designs matched to the NOSR 1 resource, available data in the public domain were collected and oil yield versus oil shale grade plotted, Figure 5-1. MIS oil shale yields are affected in a complex manner by particle size distribution, variability in the relative position of rich and lean strata, porosity, combustion control, etc. The curves in Figure 5-1 take these factors into account and are based on data generated by Laramie Energy Technology Center (LETC) on the 10-ton and 150-ton batch retorts, the six retorts operated by Oxy at its Logan Wash site, and computer modeling done by Oxy.

The pessimistic, probable, and optimistic oil yield values in Figure 5-1, for different grades of shale, were used in computing the selling price of oil for various retort configurations. Such a parametric approach allows an analysis to be performed, under various limits of oil yield, to determine the optimal operating conditions under which the MIS retorting scheme is economically competitive with surface retorting.

5.2 Retort Configuration

The retort configurations included in the parametric study are shown in Figure 5-2. A total of ten configurations were studied with retort height ranging from 200 to 650 ft and a width ranging from 100 to 325 ft. Cross

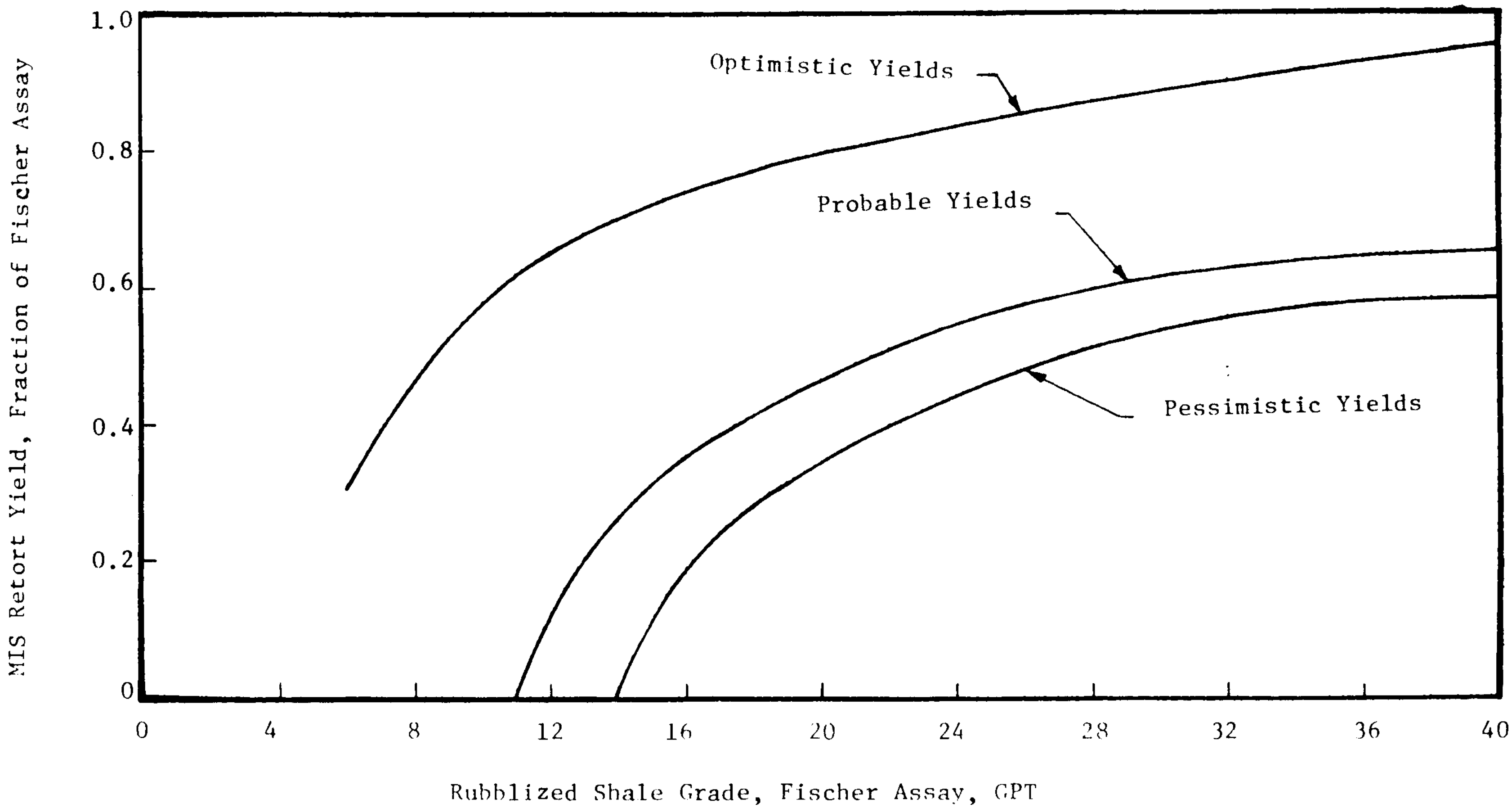

Figure 5-1. Yield of Raw Oil From MIS Retort as Function of Shale Grade

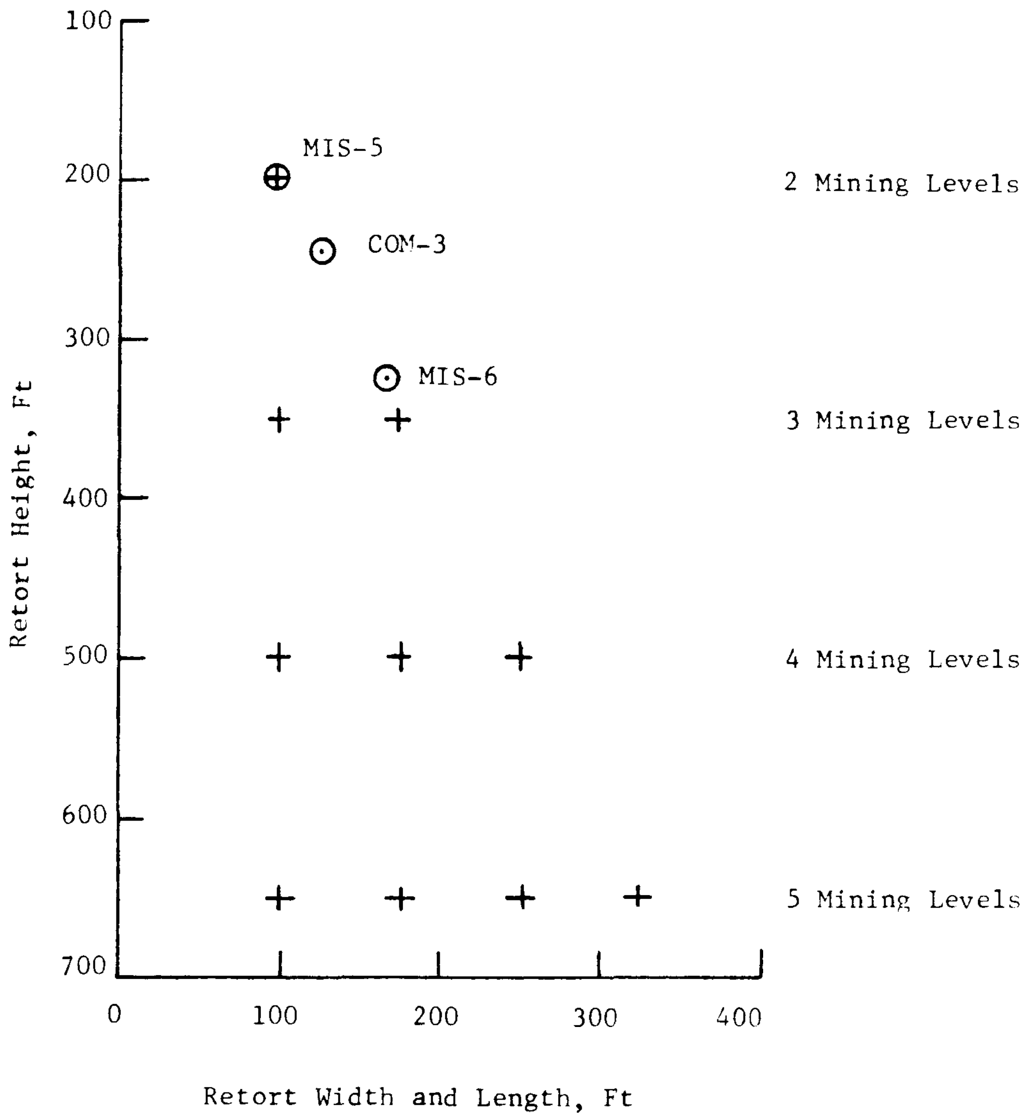

Figure 5-2. Retort Configuration

sectional areas of the retorts are square so that length equals width. The number of mining levels are shown on the margin of Figure 5-2. Also shown in Figure 5-2 are the locations of the three base cases.

An example of the location of the swell zones within the retort volume is shown in Figure 5-3 for the various retort heights. The distances between the swell zones are only approximate since the actual location of the swell zones must correspond with lean oil shale strata. With extraction at 70% for the swell zone levels, voidage is calculated as follows for the 200 ft retort:

$$\text{voidage} = \frac{(32 + 25)\ 0.7}{200} \times 100 = 20\%$$

Voidage for the other retort heights is calculated in a similar manner.

Figure 5-4 shows the retort configurations for the MIS/Tosco cases. The rich oil shale zone is assumed to be at the top of the retort. Voidage is calculated in the same manner as the MIS retorting only cases. Voidage is assumed to be 20%. The proportion of total mined shale in the rich zone is calculated as follows for the 200 ft retort as an example:

$$\text{amount to Tosco retort} = \frac{32}{32 + 25} \times 100 = 56\%$$

The calculations were done similarly for the other retort sizes. For the cases with 24% voidage, the following table was developed by a similar analysis.

	Levels in Rich Zones		Levels in Lean Zones		
Retort Height, ft	Number	Height, ft	Number	Height, ft	Amount to Tosco Retort, %
200	1	36	1	33	52
350	1	36	2	42	30
500	1	36	3	45	21
650	1	36	4	47	16

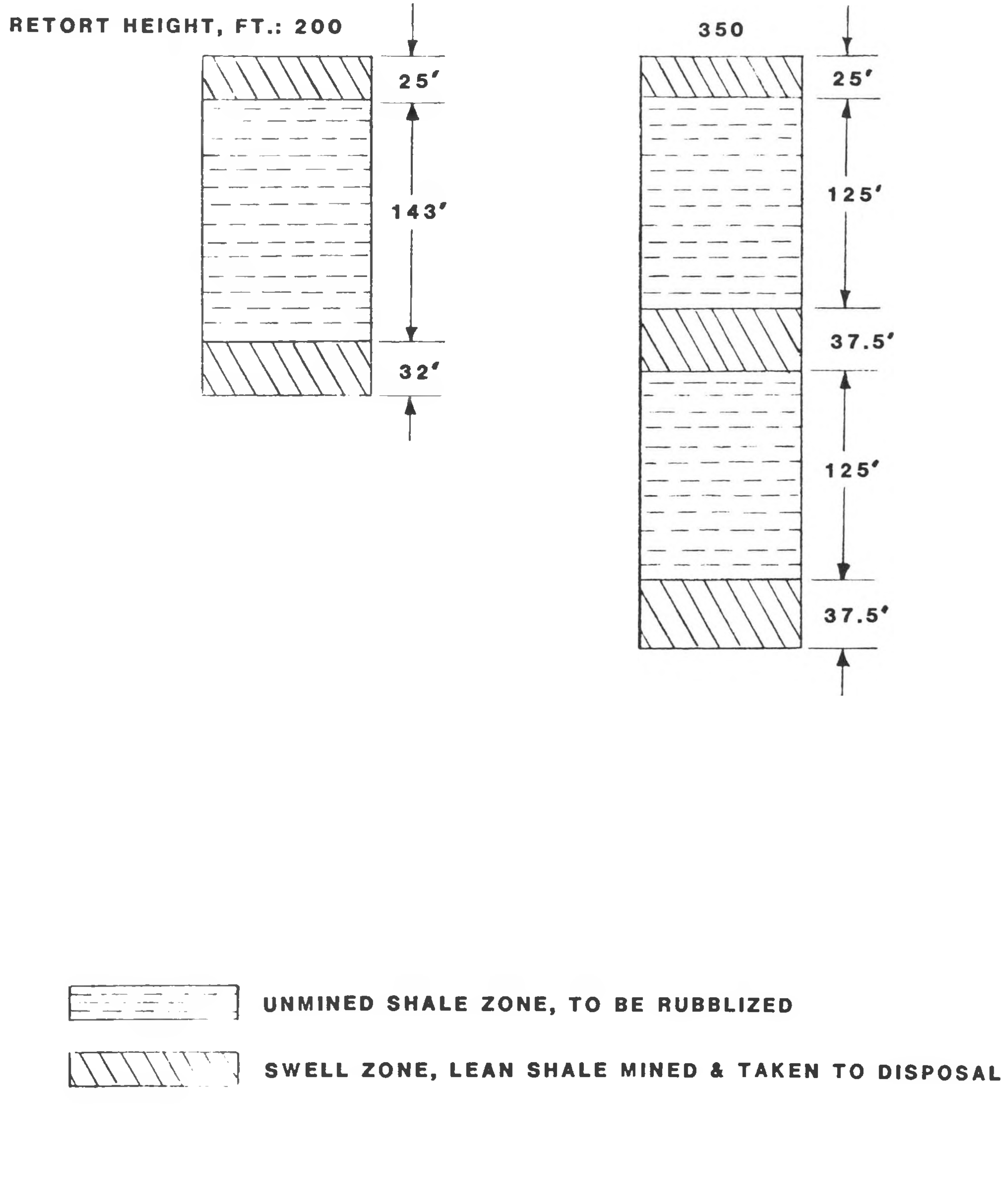

Figure 5-3. MIS Retorting Only:

Retort Configurations

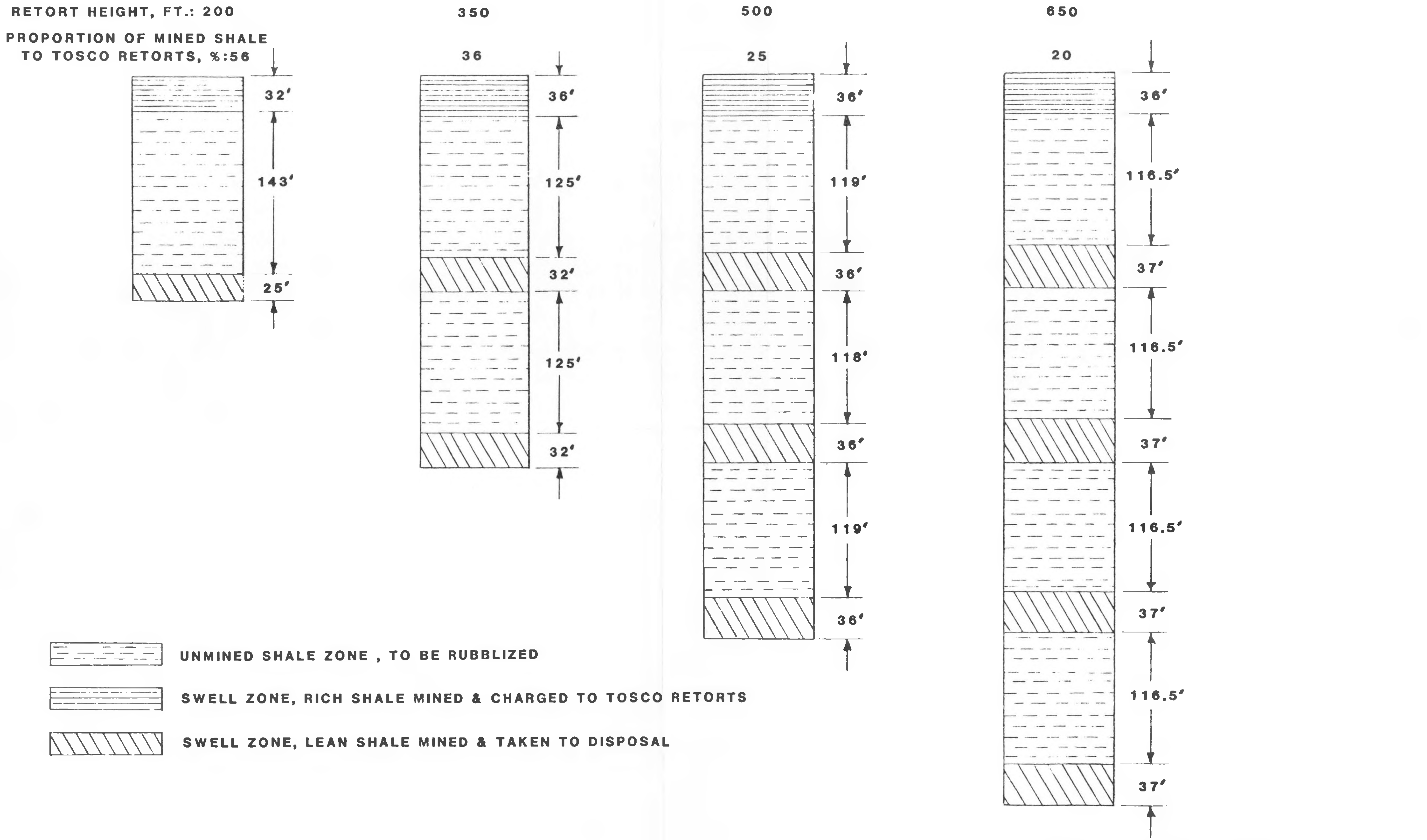

Figure 5-4. MIS/Tosco Retorting: MIS Retort Configurations

5.3 Investment and Economic Basis

The economics for the parametric study were calculated with a computer model designed specifically for modified in situ oil shale retorting economics. The objective function for the study is the product price for 15% discounted cash flow (DCF) rate of return on investment. Details of the basis for the DCF calculations were discussed in Section 4.3. The facility is sized to a nominal capacity of 50,000 B/SD of raw shale oil although the actual capacity depends on using an integral number of in situ retorts.

The yields given in Figure 5-1 were fit to polynomial equations which were inserted into the economic model. This allowed the model to calculate in situ yields automatically as a function of given shale grade.

The sources for the investments for the various processing units were discussed earlier. Investments for mining and material handling were calculated as a function of capacity from previous studies (see Figures 5-5 and 5-6).[1] The exponential factor, 0.85, was assumed based on experience and information on underground mining and other large solids handling systems (for example, see Reference 8). The mining and material handling investments given in the figures are the total investments for the project, i.e., they include both preoperational and deferred investments. The mining investments were divided into two categories: two level mines and 3 or more level mines. Only one point was available for material handling since this category was only required for combined MIS/Tosco retorting. The pre-operational mine development investment has been assumed to be a function of capacity only and independent of other mining parameters, such as number of mining levels. Although this is not strictly correct, the deviation is expected to be small and will not change the conclusions of this study.

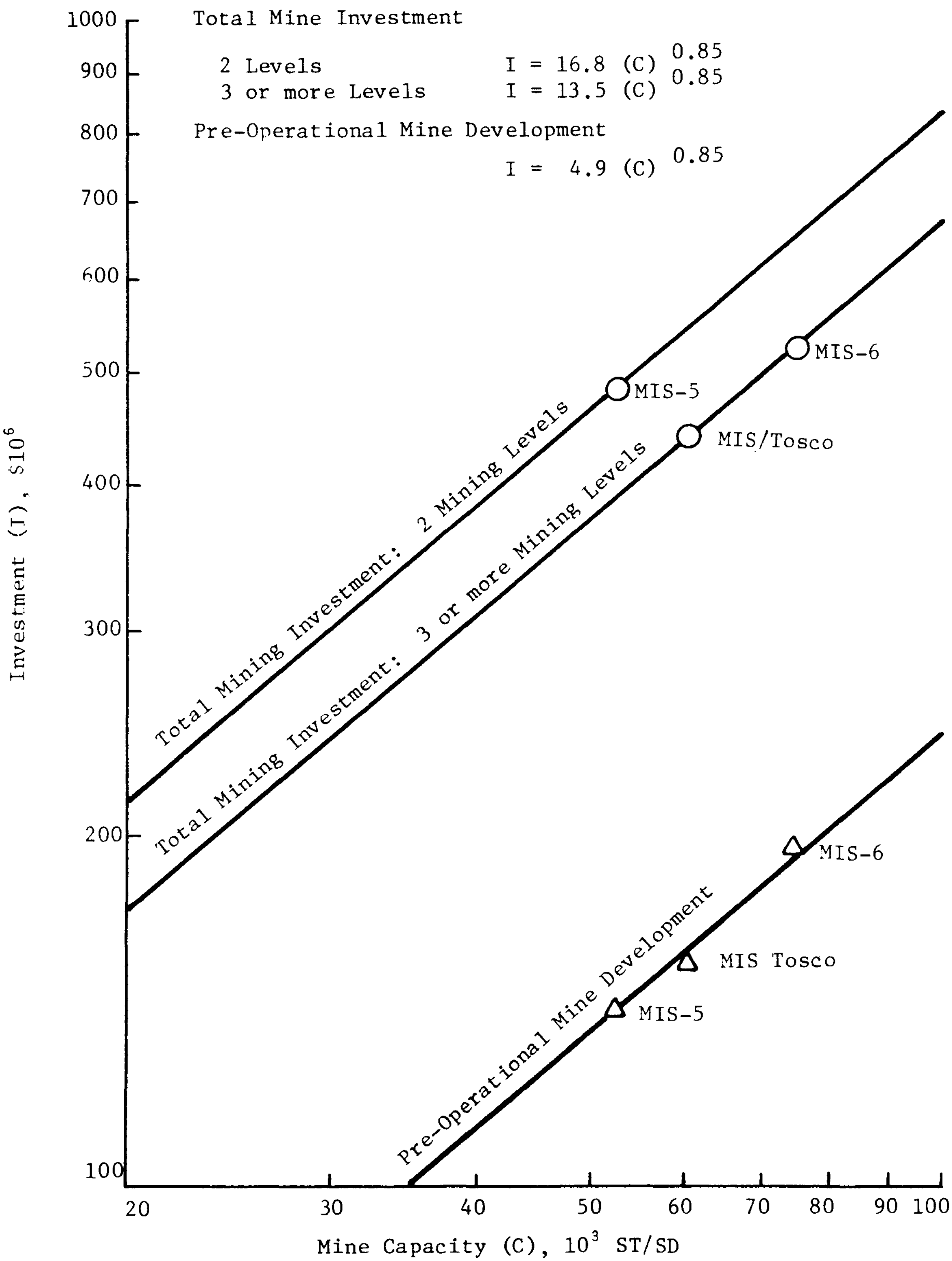

Figure 5-5. Mining and Pre-Operational Mine Development Investments

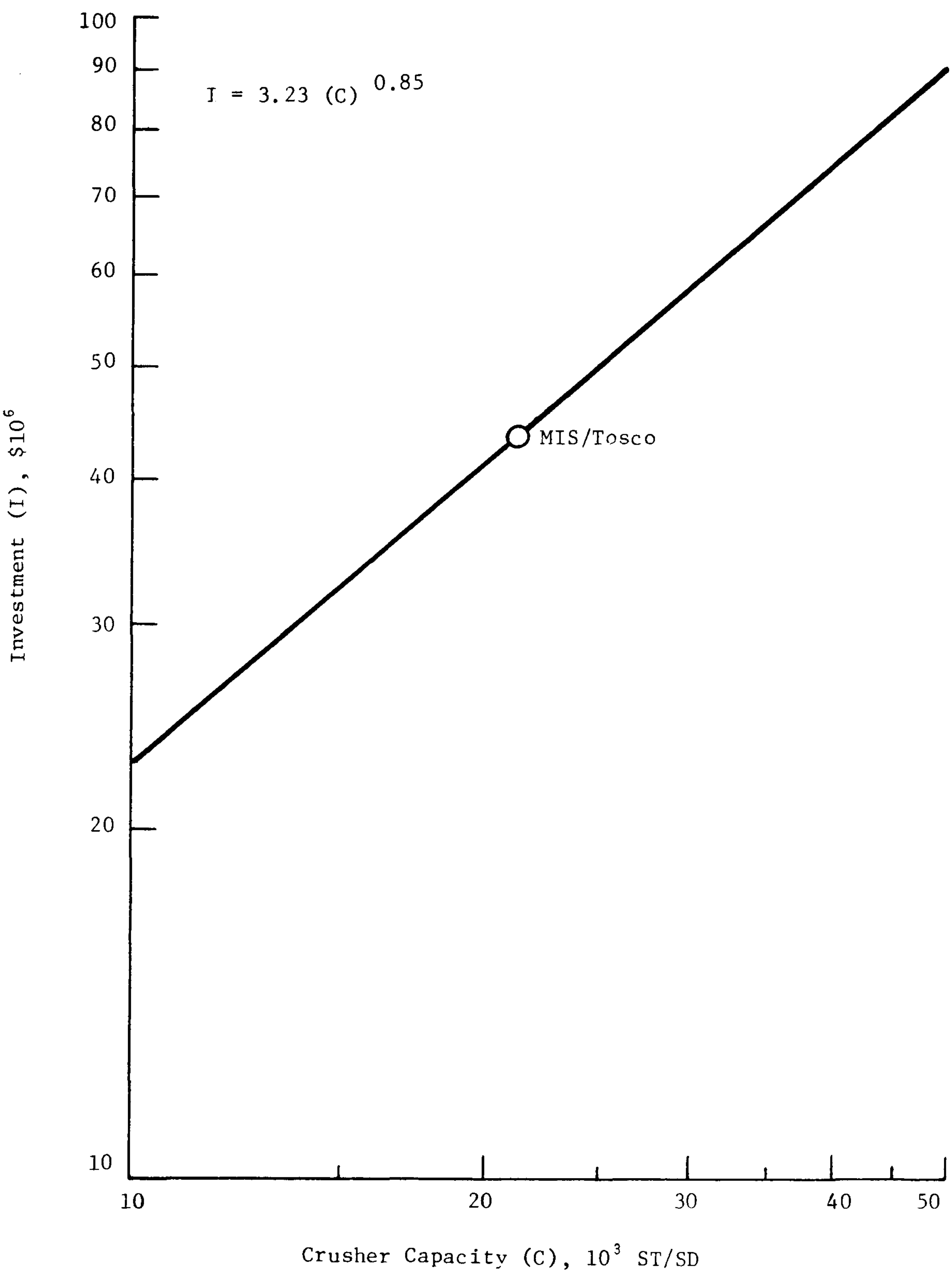

Figure 5-6. Material Handling Investment

6. RESULTS OF PARAMETRIC STUDY

6.1 MIS Retorting Only

Figure 6-1 shows the amount of shale that must be mined to create voidage and Figure 6-2 shows the amount of shale rubblized as a function of shale grade. Probable yields were assumed for these figures. Because the actual production rates may vary somewhat around 50,000 B/SD, the flow rates on the figures are normalized to 50,000 B/SD for consistency. As shown, the amount of shale mined ranges from over 80,000 ST/SD for low shale grades down to 30,000 ST/SD for 40 gpt shale; the amount of shale rubblized ranges from over 300,000 ST/SD down to 90,000 ST/SD. Only the 200 ft retorts are shown on the figures because the larger retorts give similar results.

The fuel balance, electrical power balance and low pressure steam balance are shown in Table 6-1. As discussed previously, MIS retorting produces a large amount of low heating value fuel gas which is used for satisfying the fuel requirements of the facility but the excess is used for generating electrical power in steam boiler power plants. The electrical power is used to satisfy the needs of the facility but the excess is sold as a by-product to a power grid.

The water requirements are shown in Figure 6-3. The lower curve does not include the water requirements for the electrical power plant; the water requirements for this curve were calculated in the same way as the water balances shown in Figures 4-4 and 4-6 for the base cases. If the water for the power plant is included, the upper curve results. It can be seen that the power plant requires as much water by itself as the rest of the facility.

Figures 6-4, 6-5, and 6-6 show the results of the MIS retorting for probable, optimistic and pessimistic yields respectively. Also shown in Figure 6-4 is the MIS-5 and MIS-6 base cases. As shown in the three figures, the size of the retort affects the product price very little. Only the 200 ft and 650 ft retorts are shown in the figures; the other retort sizes lie in between the two lines shown. The shale grade has a large effect on the product price but this effect tends to decrease as the shale grade is increased.

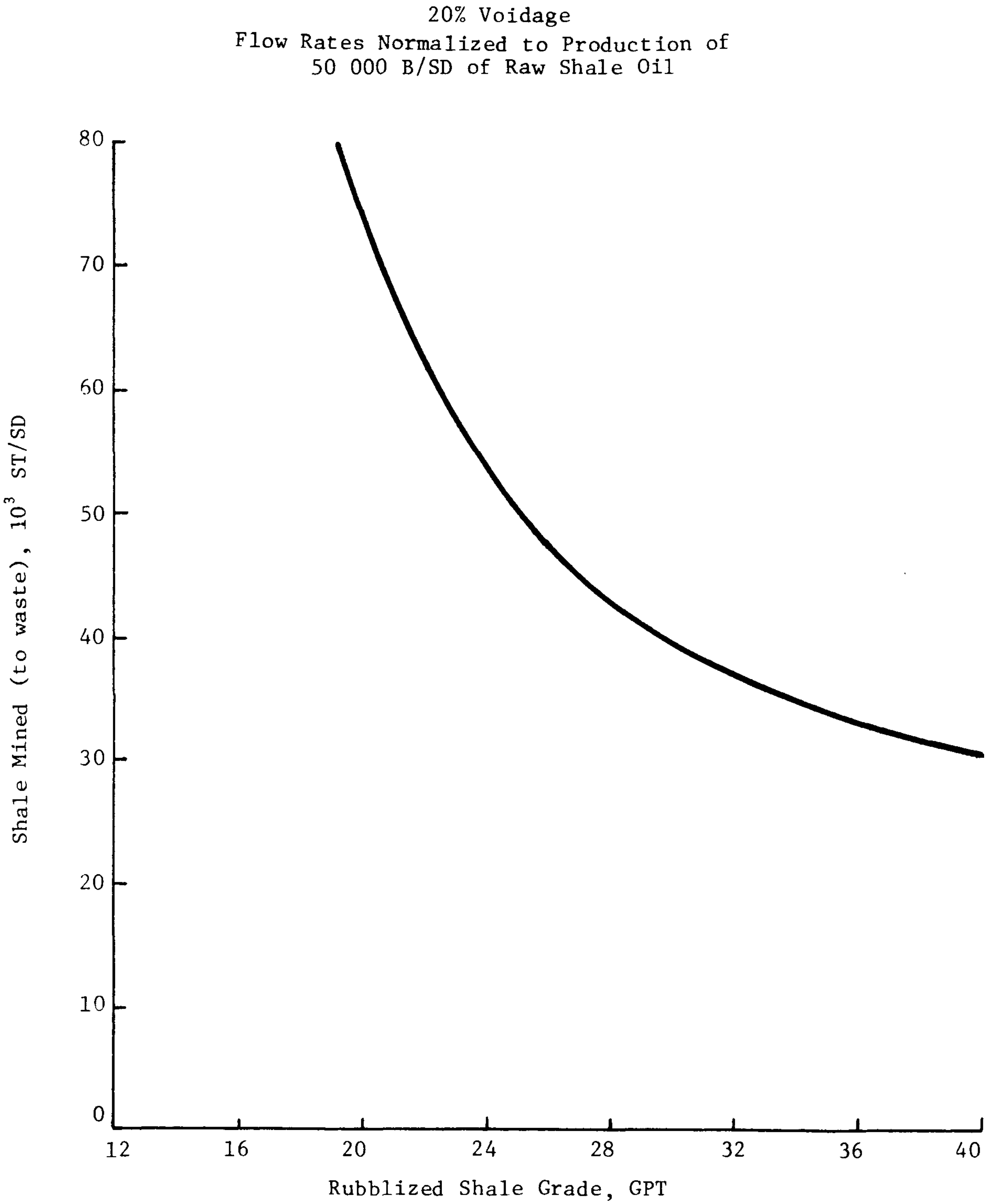

Figure 6-1. MIS Retorting Only: Effect of Shale Grade on Amount of Shale Mined - 200-Foot Retorts

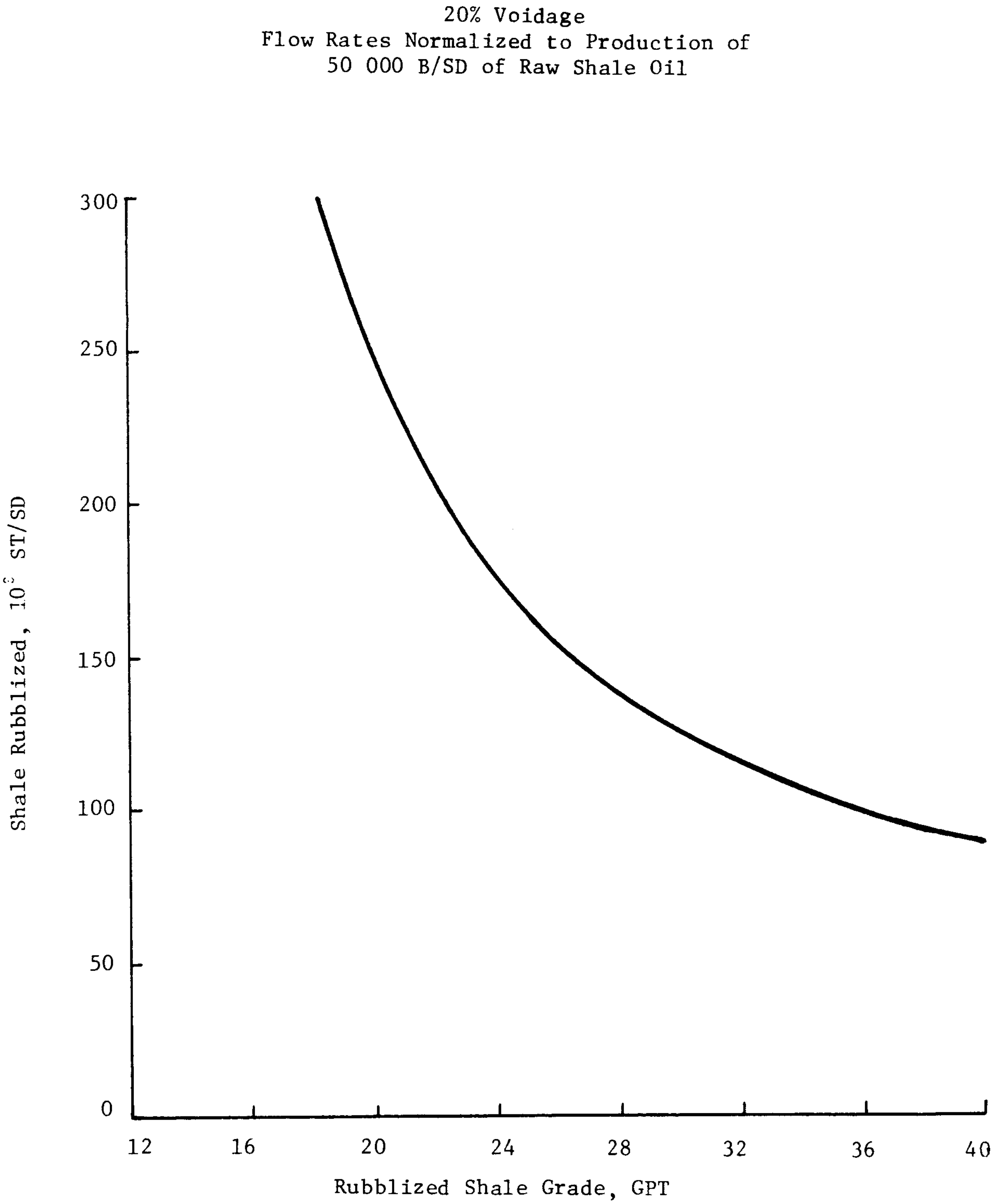

Figure 6-2. MIS Retorting Only: Effect of Shale Grade on Amount of Shale Rubblized - 200-Foot Retorts

Table 6-1. Effect of Rubblized Shale Grade on Utilities for MIS Retorting

MIS Retort Height = 200 ft
Raw Shale Oil Produced = 50,000 B/SD[a]

Rubblized Shale Grade, gpt, F.A.	16	20	24	32	40
Fuel Gas Balance, 10^6 Btu/hr					
Steam and Power Generation	18010	11160	8110	5610	4600
Process Fuel Requirements	1300	990	850	750	700
Fuel Produced from Off-Gas	19310	12150	8960	6360	5300
Electrical Power Balance, MW					
Power Generated	1239	765	554	381	311
Power Required	900	568	420	299	250
Power Sold	339	197	134	82	61
Steam Balance, 10^3 lb/hr					
Retort Steam	3735	2313	1679	1159	950
Other Steam Requirements	433	376	351	331	323
Total Steam Requirement	4168	2689	2030	1490	1273
Steam Plant	3937	2458	1799	1259	1042
Process Waste Heat Boilers	231	231	231	231	231
Total Steam Generated	4168	2689	2030	1490	1273

[a]All flow rates are normalized to production of 50,000 B/SD of raw shale oil.

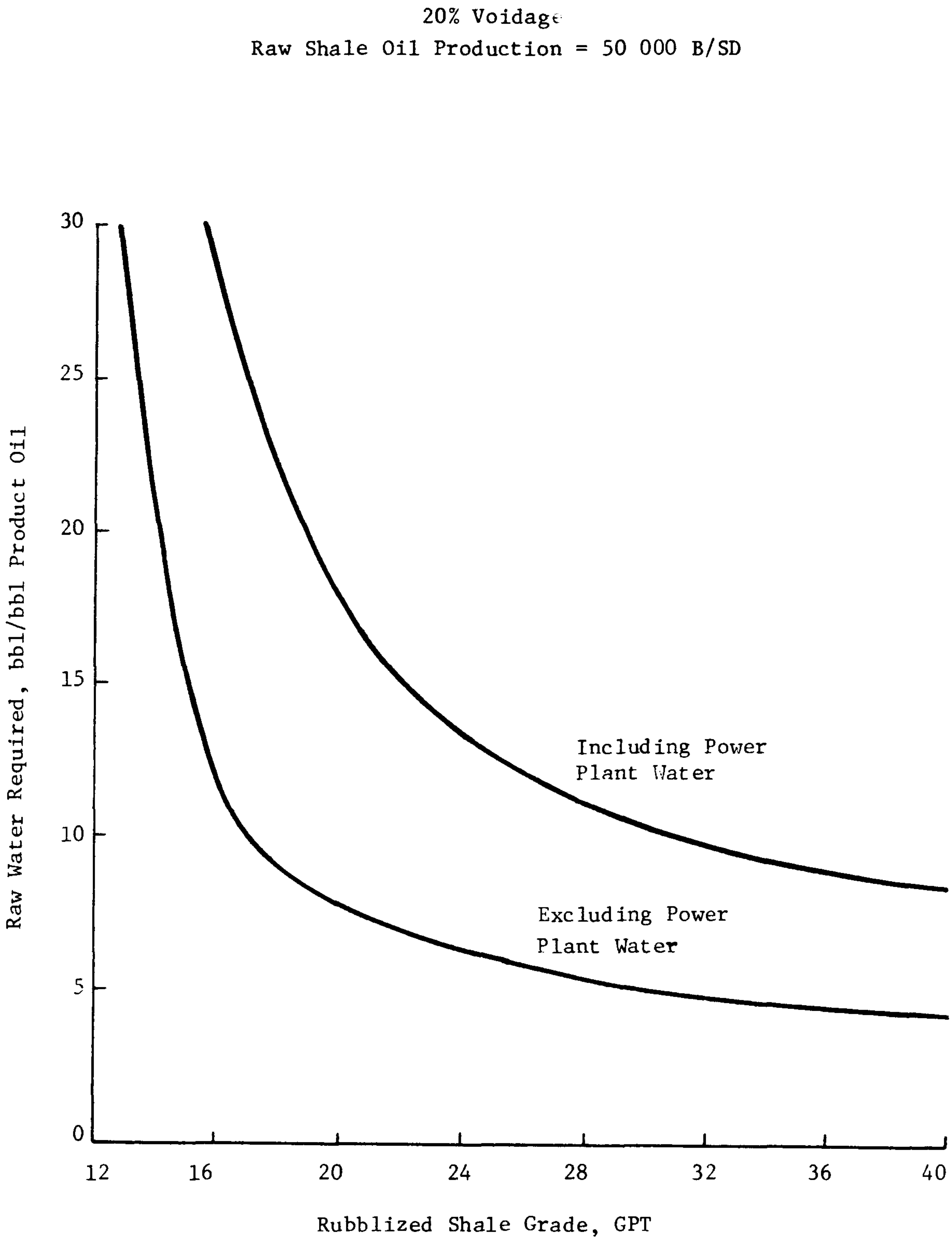

Figure 6-3. MIS Retorting Only: Effect of Shale Grade on Water Requirement - 200-Foot Retorts

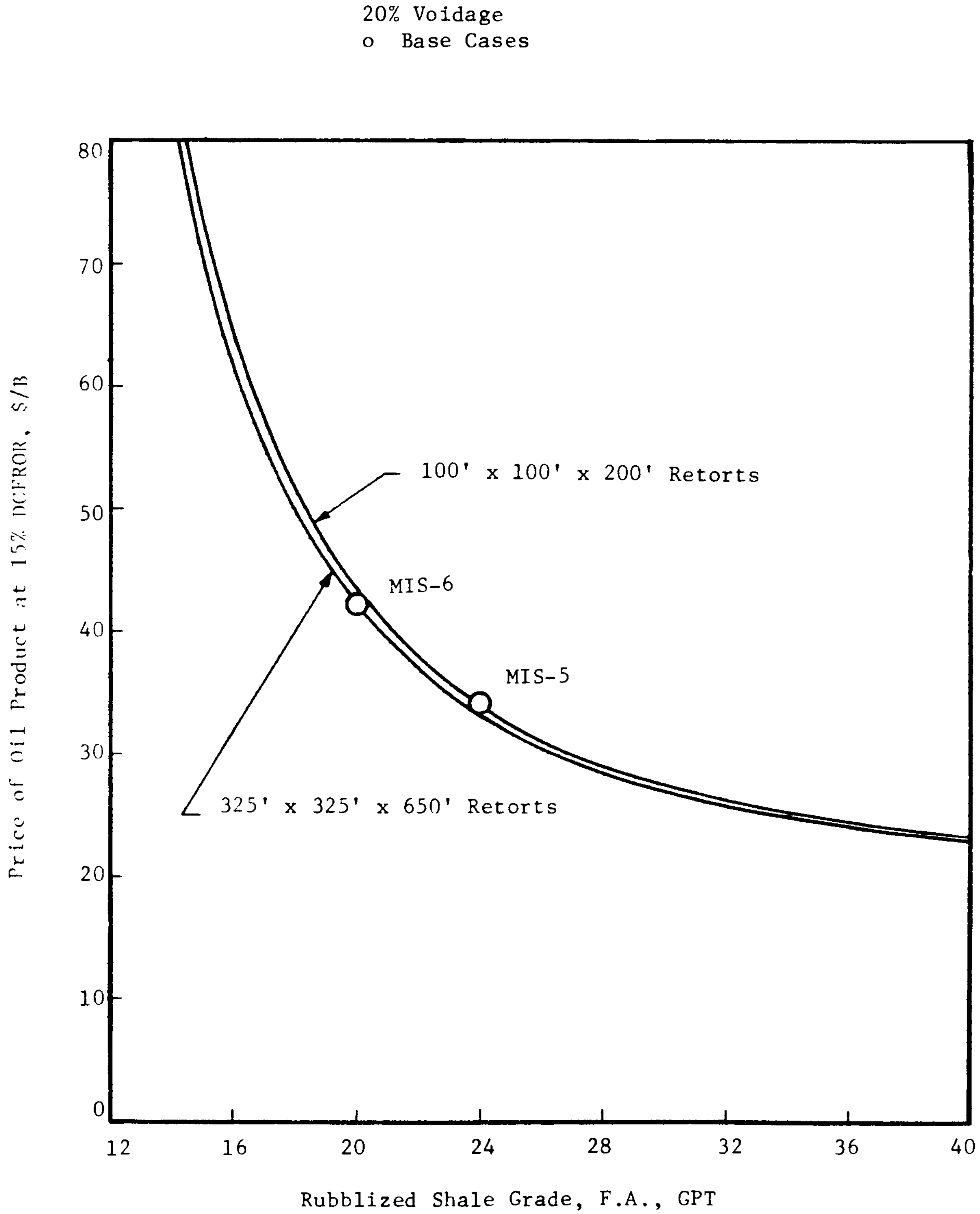

Figure 6-4. MIS Retorting Only: Effect of Shale Grade on Product Price with Probable MIS Yields

20% Voidage

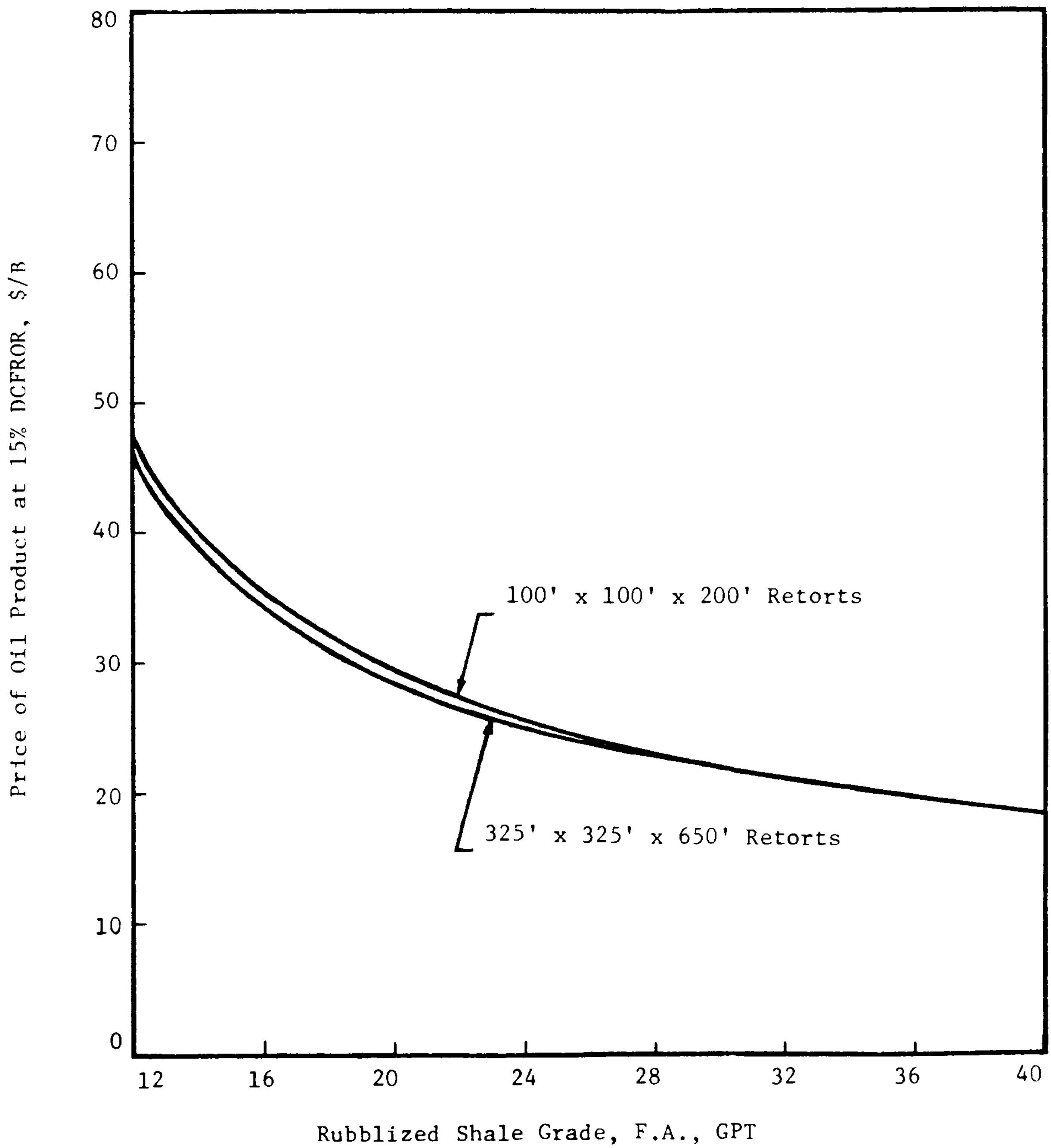

Figure 6-5. MIS Retorting Only: Effect of Shale Grade on Product Price with Optimistic MIS Yields

20% Voidage

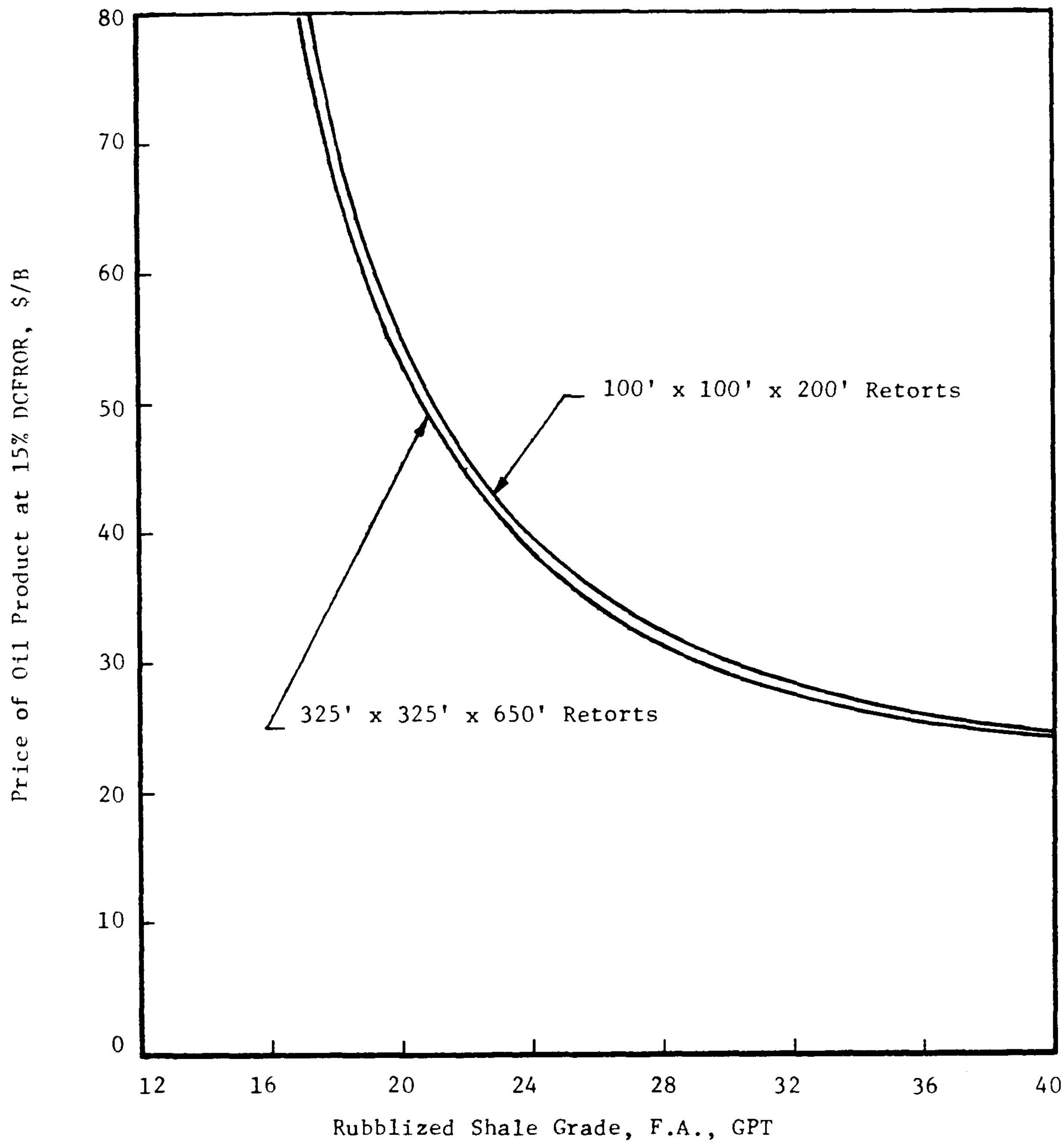

Figure 6-6. MIS Retorting Only: Effect of Shale Grade on Product Price with Pessimistic MIS Yields

The differences in product price between the probable, optimistic and pessimistic yield cases tend to decrease with an increase in shale grade. This is shown more clearly in Figure 6-7 which shows the product price plotted as a function of retort yield for five shale grades. The curves extend from the pessimistic to the optimistic yields.

The product prices were calculated on the assumption that water can be supplied to the facility at no cost; however, in the absence of prior water rights, should it become necessary to purchase water, Figure 6-8 shows the incremental product price of oil when water is purchased at $40¢/10^3$ gal and $80¢/10^3$ gal. The impact of purchasing water at these rates is minor on the price of oil.

6.2 MIS/Tosco Retorting

Figures 6-9 and 6-10 show the amount of shale that must be rubblized when the MIS retorts are 200 ft and 650 ft high, respectively. Figures 6-11 and 6-12 show the total amount of shale that must be mined to create the retorts and the amount of shale charged to the Tosco retorts for the 200 and 650 ft high retorts. The curves for the other retort heights lie between the 200 and 650 ft retort curves.

The amount of shale retorted in the Tosco retorts when the retorts are 200 ft high is more than twice that when the retorts are 650 ft high because the proportion of shale in the rich zone is so much greater for the smaller retorts (see Figure 5-4). This, in turn, requires more total shale to be mined and more shale to be rubblized.

Figure 6-13 shows the proportion of raw shale produced by the MIS and Tosco retorts for 200 ft MIS retorts and Figure 6-14 shows the proportion of raw shale oil for the 650 ft MIS retorts. For 200 ft MIS retorts, Figure 6-13 shows that the amount of raw shale oil from the Tosco retorts is about equal with the amount from the MIS retorts at low grades of rubblized shale, but decreases to about 20% of the total as the rubblized shale grade increases. For the 650 ft MIS retorts, Figure 6-14 shows that the amount of

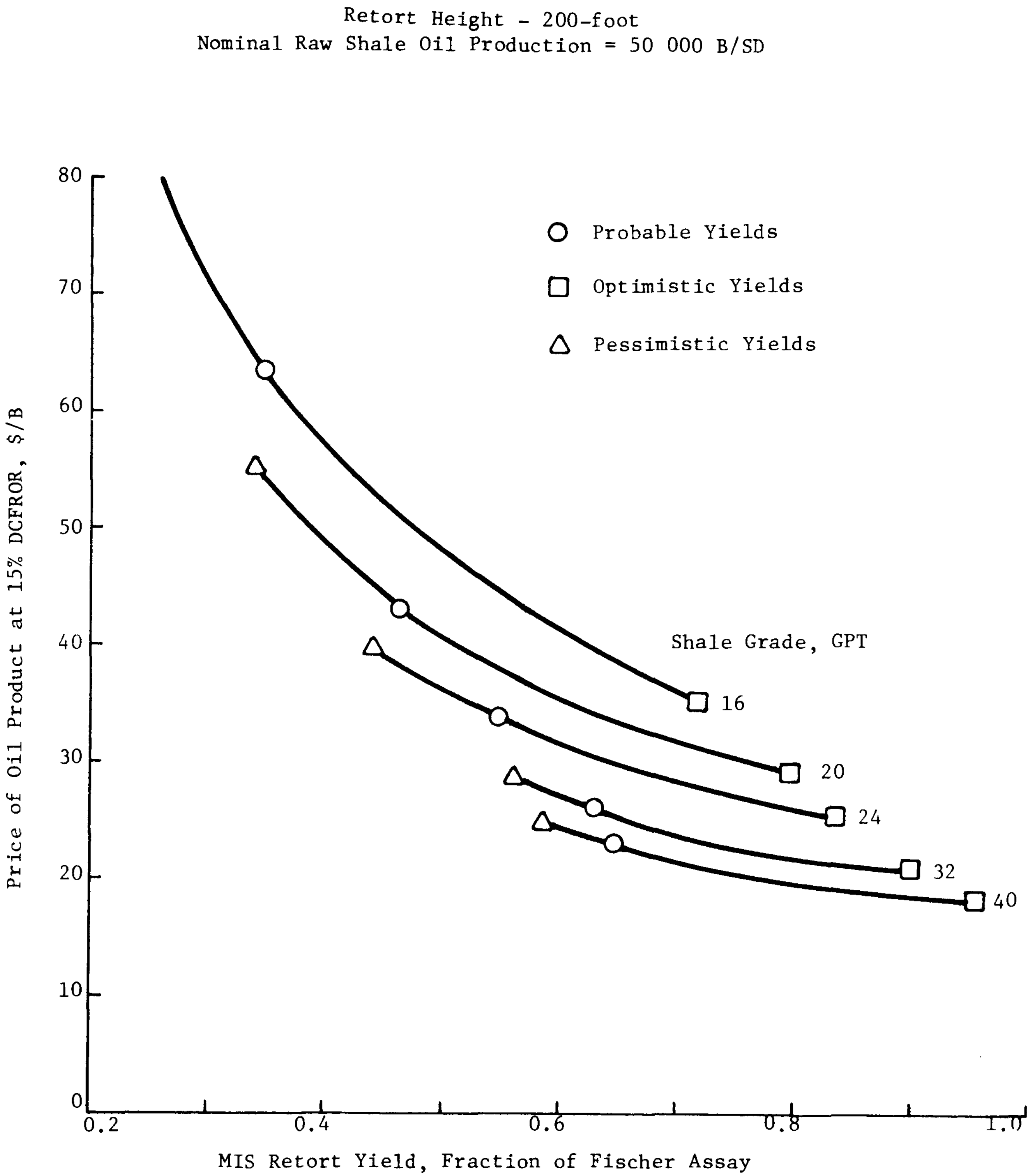

Figure 6-7. MIS Retorting Only: Effect of Shale Grade and Yield on Product Price

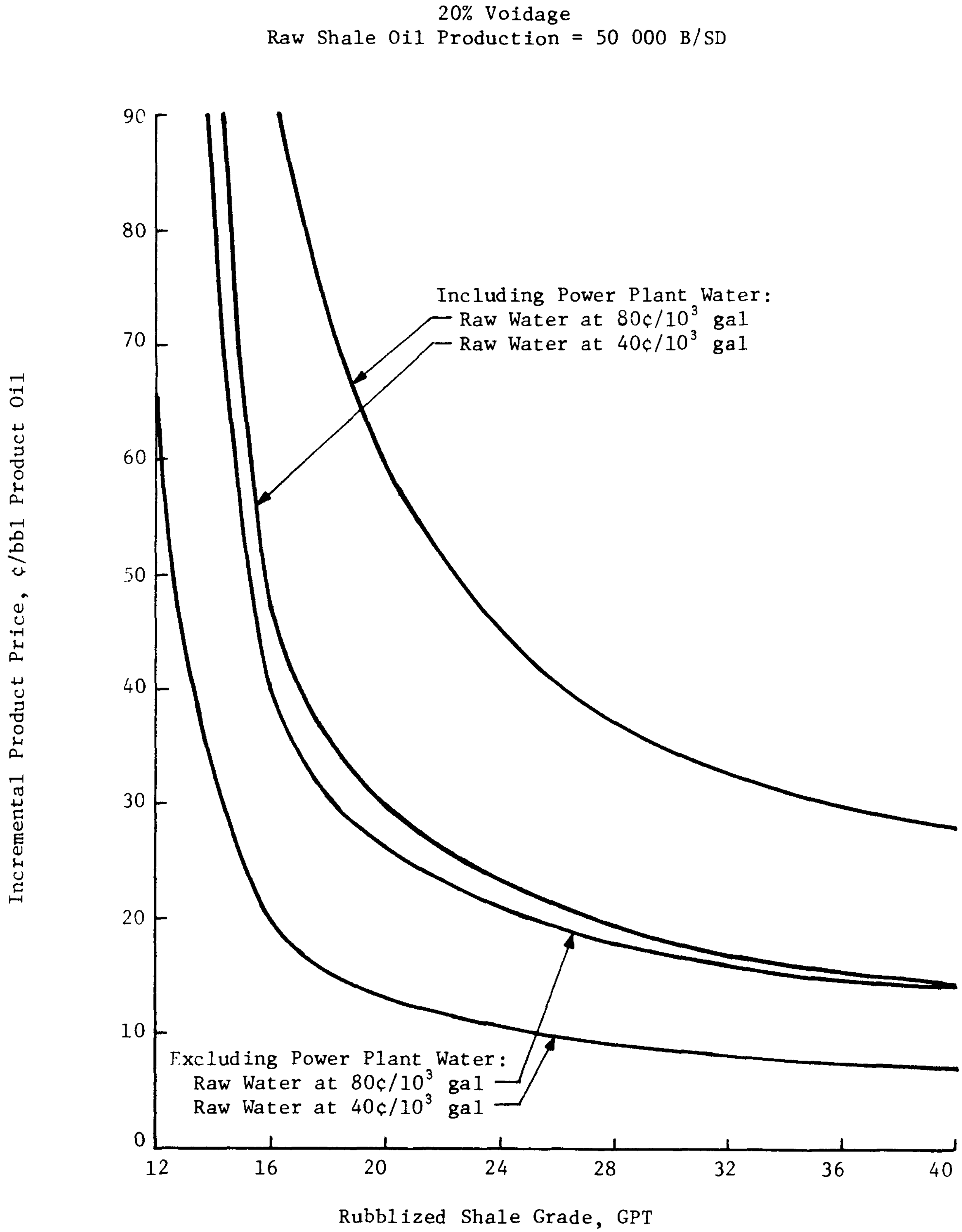

Figure 6-8. MIS Retorting Only: Effect of Price of Raw Water on Product Price - 200-Foot Retorts

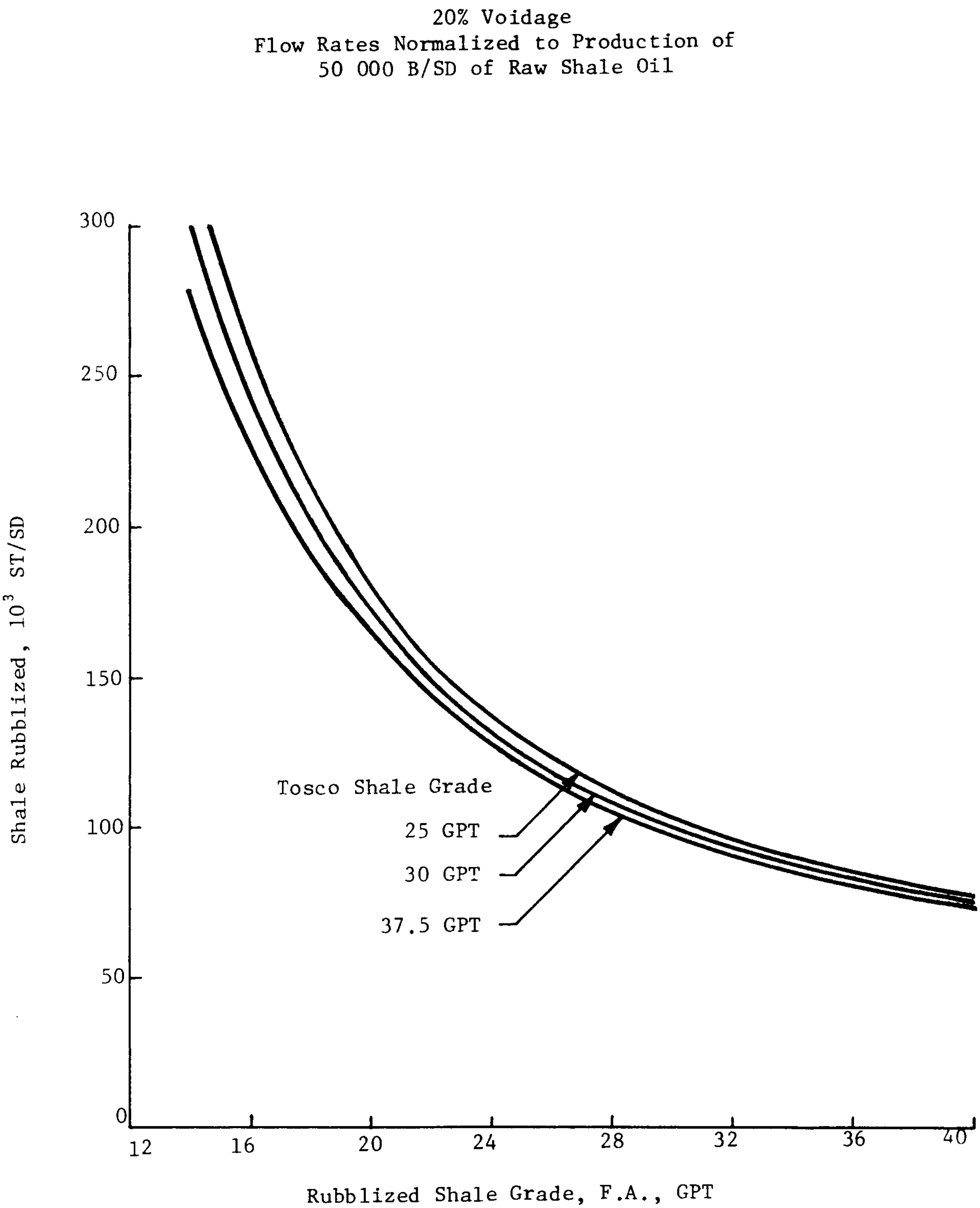

Figure 6-9. MIS/Tosco Retorting: Effect of Shale Grade on Amount of Shale Rubblized - 200-Foot MIS Retorts

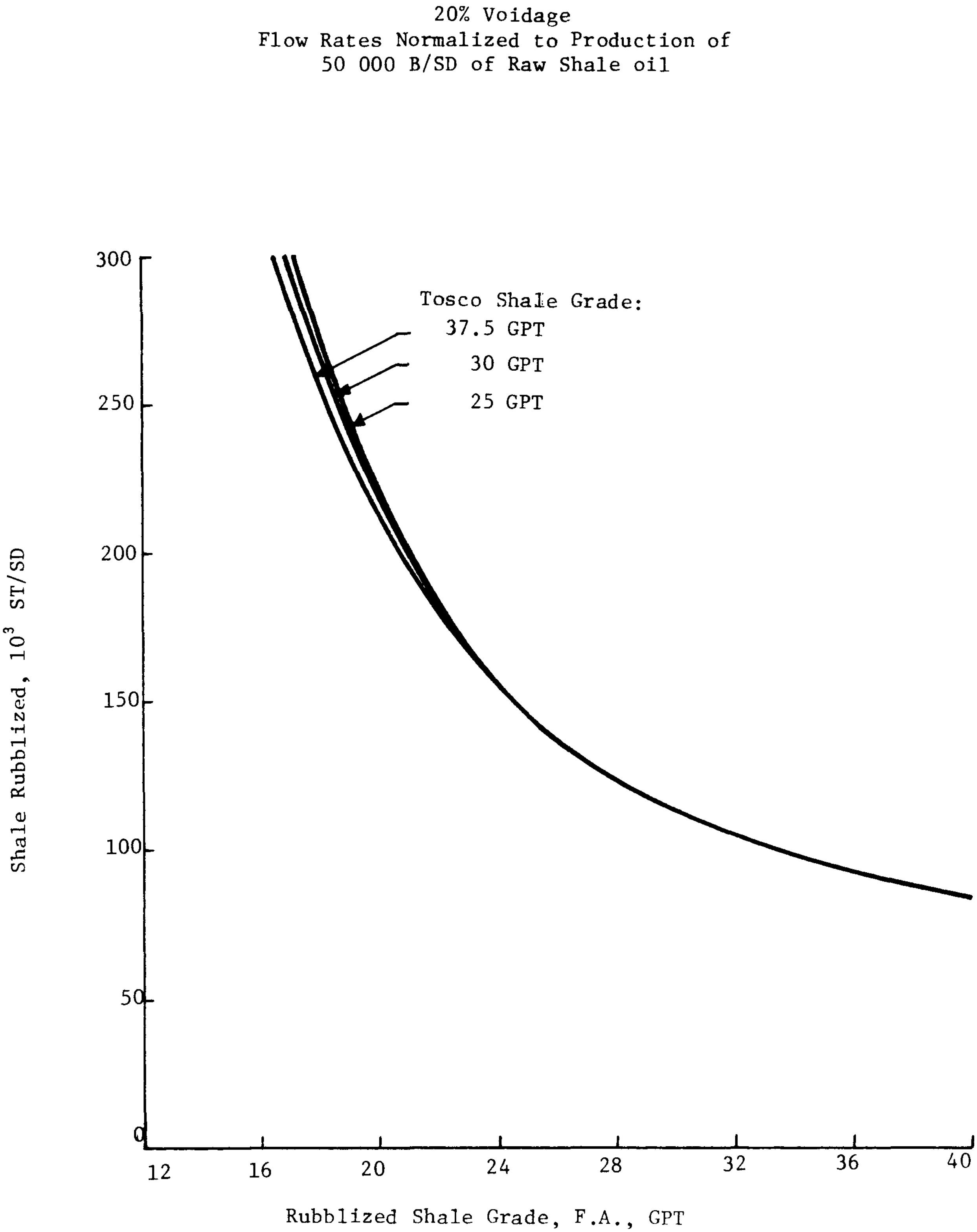

Figure 6-10. MIS/Tosco Retorting: Effect of Shale Grade on Amount of Shale Rubblized - 650-Foot MIS Retorts

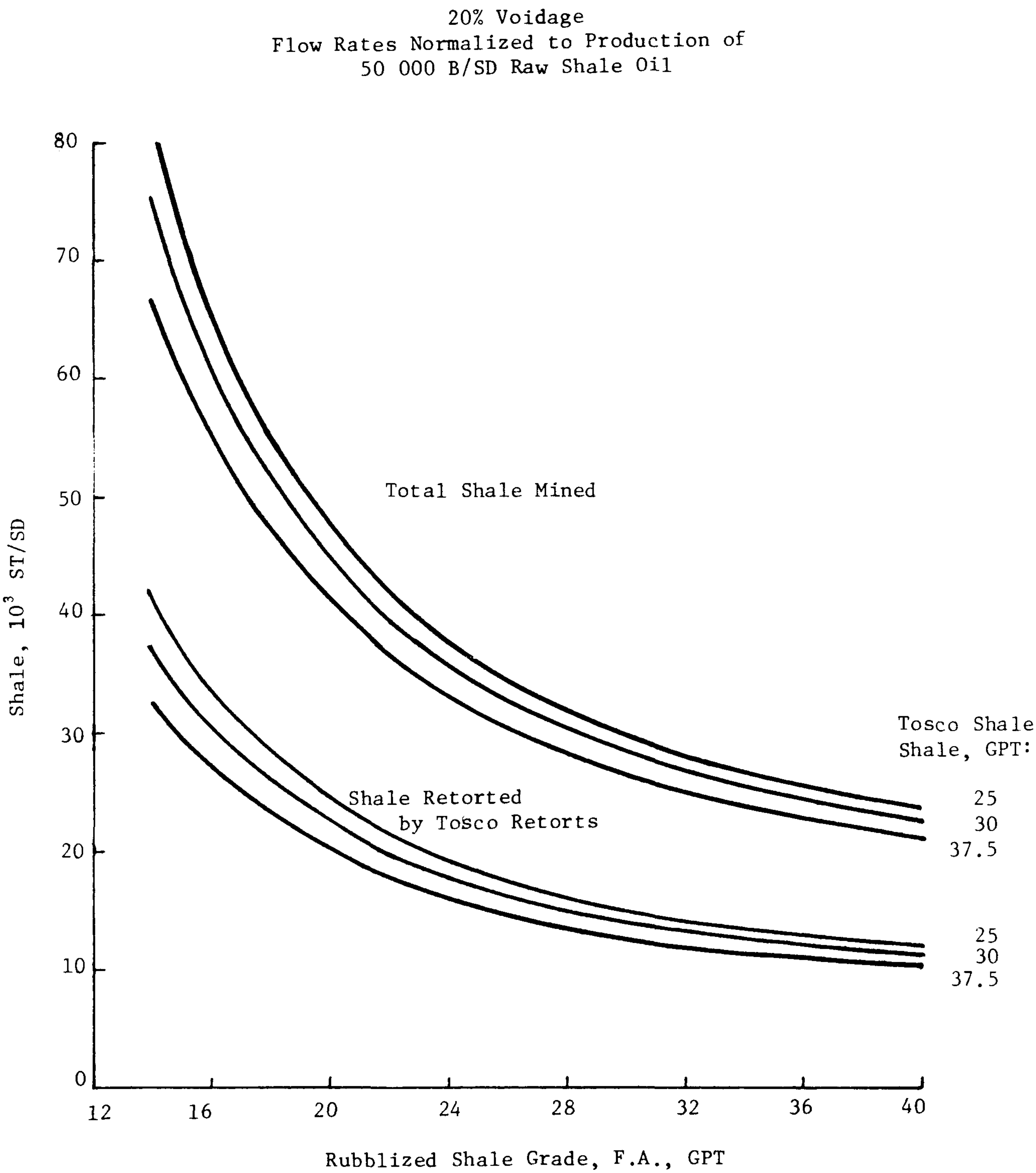

Figure 6-11. MIS/Tosco Retorting: Effect of Shale Grade on Amount of Shale Mined and Retorted in Tosco Retorts - 200-Foot MIS Retorts

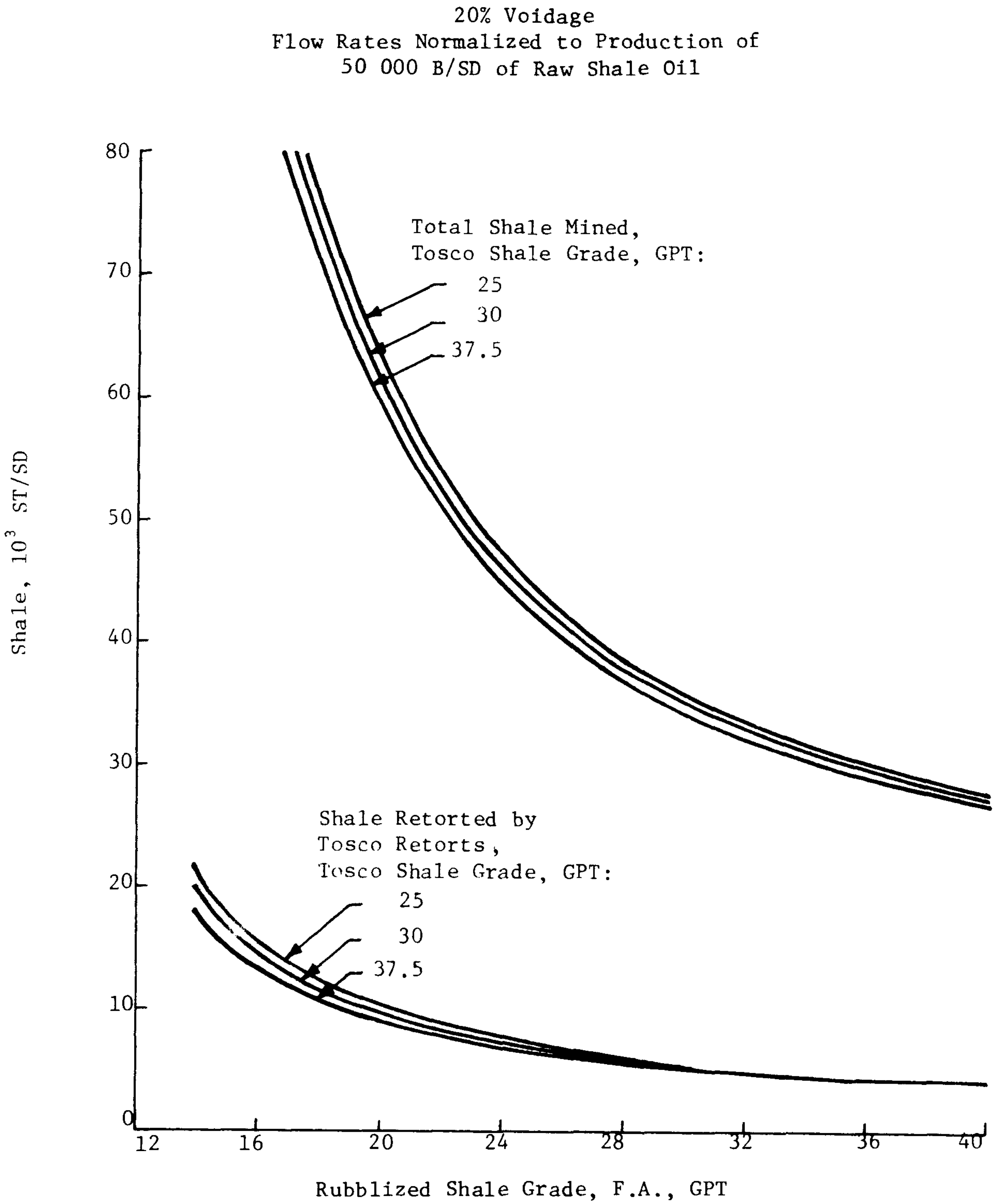

Figure 6-12. MIS/Tosco Retorting: Effect of Shale Grade on Amount of Shale Mined and Retorted in Tosco Retorts - 650-Foot MIS Retorts

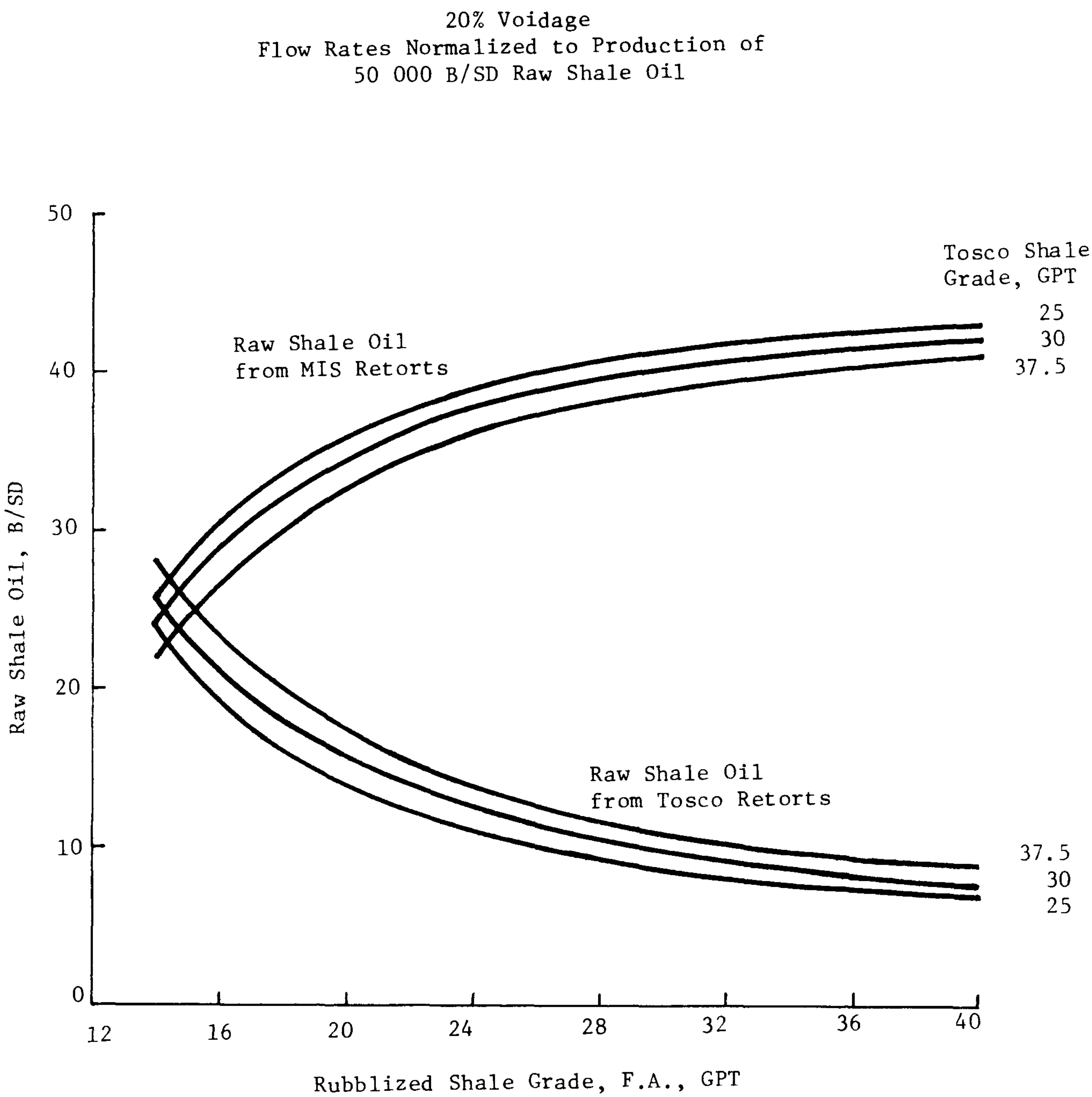

Figure 6-13. MIS/Tosco Retorting: Effect of Shale Grade on Production of Raw Shale Oil from MIS and Tosco Retorts - 200-Foot MIS Retorts

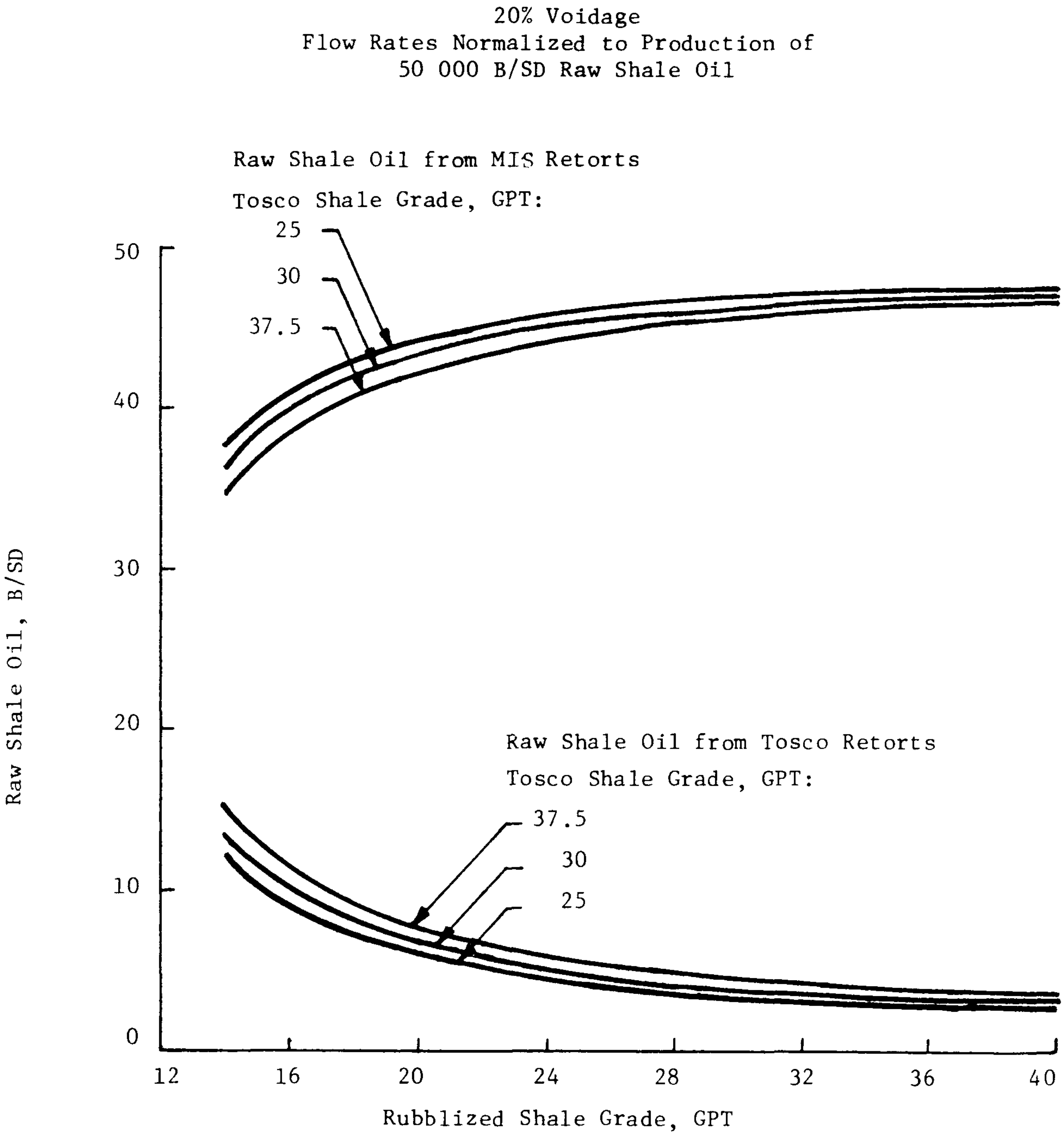

Figure 6-14. MIS/Tosco Retorting: Effect of Shale Grade on Production of Raw Shale Oil from MIS and Tosco Retorts - 650-Foot MIS Retorts

shale from the Tosco retorts is about 30% for low grades of rubblized shale but decreases to less than 8% of the total as the rubblized shale grade increases.

The fuel gas balance, electrical power balance and low pressure steam balance are shown in Table 6-2 for the 200 ft and 650 ft MIS retorts. Fuel gas is produced by the MIS retorts, the Tosco retorts and the upgrading units. The high heating value fuel gas from the Tosco retorts is used to make hydrogen for hydrotreating. Fuel gas is also used by the Tosco retorts and the other process units. The fuel gas in excess of that required for the facility is used to generate steam and electricity. As shown in the table, excess power is generated only for low grades of rubblized shale. If insufficient power is generated, the remaining electricity requirements are purchased.

Figure 6-15 shows the water requirements for MIS/Tosco retorting. The water requirements for the curves in which the power plant water is excluded is calculated by the same analysis as shown in Figure 4-9. The upper curves result when the water required for the power plant is added.

Figure 6-16 shows a combined MIS/Tosco case in which the MIS retort voidage is 24%, as in the combined MIS/Tosco base case. The shale retorted by the Tosco retort is 37.4 gpt and probable yields are assumed. Also shown in the figure is the base case for reference. All other combined MIS/Tosco cases are at 20% retort voidage.

Figures 6-17, 6-18, and 6-19 show the product prices resulting from assuming probable MIS retorting yields and shale grades of 37.4, 30 and 25 gpt, respectively, for the Tosco retorted shale. At low grades of in situ retorted shale, the retort size appears to have an effect on the product prices but the effect is actually due to the amount of mined shale that can be taken to the surface for retorting. For the 200 ft retorts, more than 50% of the mined shale is retorted aboveground whereas with the 650 ft retorts, as little as 20% of the mined shale is retorted aboveground.

Table 6-2. Effect of Rubblized Shale Grade on Utilities for MIS/Tosco Retorts

MIS Retort Height = 200 ft
Proportion of Mined Shale Retorted by Tosco Retorts = 56%
Grade of Shale Retorted on Tosco Retorts = 37.4 gpt, F.A.
MIS Retort Voidage = 20%
Total Raw Shale Oil Produced = 50,000 B/SD[a]

Rubblized Shale Grade, gpt, F.A.	16	20	24	32	40
Fuel Gas Balance, 10^6 Btu/hr					
Tosco Retorts	1087	815	653	494	420
Hydrogen Manufacture	1386	1395	1399	1402	1404
Steam and Power Generation	8808	6318	4832	3362	2682
Other Process Fuel Requirements	1239	1119	1049	982	946
Fuel Produced from Off-Gas	12520	9647	7933	6240	5452
Electrical Power Balance, MW					
Power Generated	534	370	272	175	131
Power Required	506	383	309	237	203
Purchased (Sold) Power	(28)	13	37	62	72
Steam Balance, 10^3 lb/hr					
MIS Retort Steam	2010	1510	1211	915	780
Other Steam Requirements	643	529	461	394	363
Total Steam Requirement	2653	2039	1672	1309	1143
Steam Plant	2431	1836	1481	1129	968
Process Waste Heat Boilers	222	203	191	180	175
Total Steam Generated	2653	2039	1672	1309	1143

[a]All flow rates are normalized to production of 50,000 B/SD of raw shale oil.

Table 6-2. Effect of Rubblized Shale Grade on Utilities for MIS/Tosco Retorts (Continued)

MIS Retort Height = 650 ft
Proportion of Mined Shale Retorted by Tosco Retorts = 20%
Grade of Shale Retorted in Tosco Retorts = 37.4 gpt, F.A.
MIS Retort Voidage = 20%
Total Raw Shale Oil Produced = 50,000 B/SD[a]

Rubblized Shale Grade, gpt, F.A.	16	20	24	32	40
Fuel Gas Balance, 10^6 Btu/hr					
Tosco Retorts	542	369	278	202	166
Hydrogen Manufacture	1402	1407	1410	1411	1412
Steam and Power Generation	12814	8314	6017	3975	3111
Other Process Fuel Requirements	1402	1197	1090	998	955
Fuel Produced from Off-Gas	16160	11287	8795	6586	5644
Electrical Power Balance, MW					
Power Generated	827	522	365	227	168
Power Required	695	476	363	264	222
Purchased (Sold) Power	(132)	(46)	(2)	37	54
Steam Balance, 10^3 lb/hr					
MIS Retort Steam	2875	1951	1479	1061	883
Other Steam Requirements	487	387	338	295	272
Total Steam Requirement	3362	2338	1817	1356	1155
Steam Plant	3179	2170	1655	1199	1004
Process Waste Heat Boilers	183	168	162	157	151
Total Steam Generated	3362	2338	1817	1356	1155

[a]All flow rates are normalized to production of 50,000 B/SD of raw shale oil.

20% Voidage
Raw Shale Oil Production = 50 000 B/SD
Tosco Shale Grade = 37.4 GPT

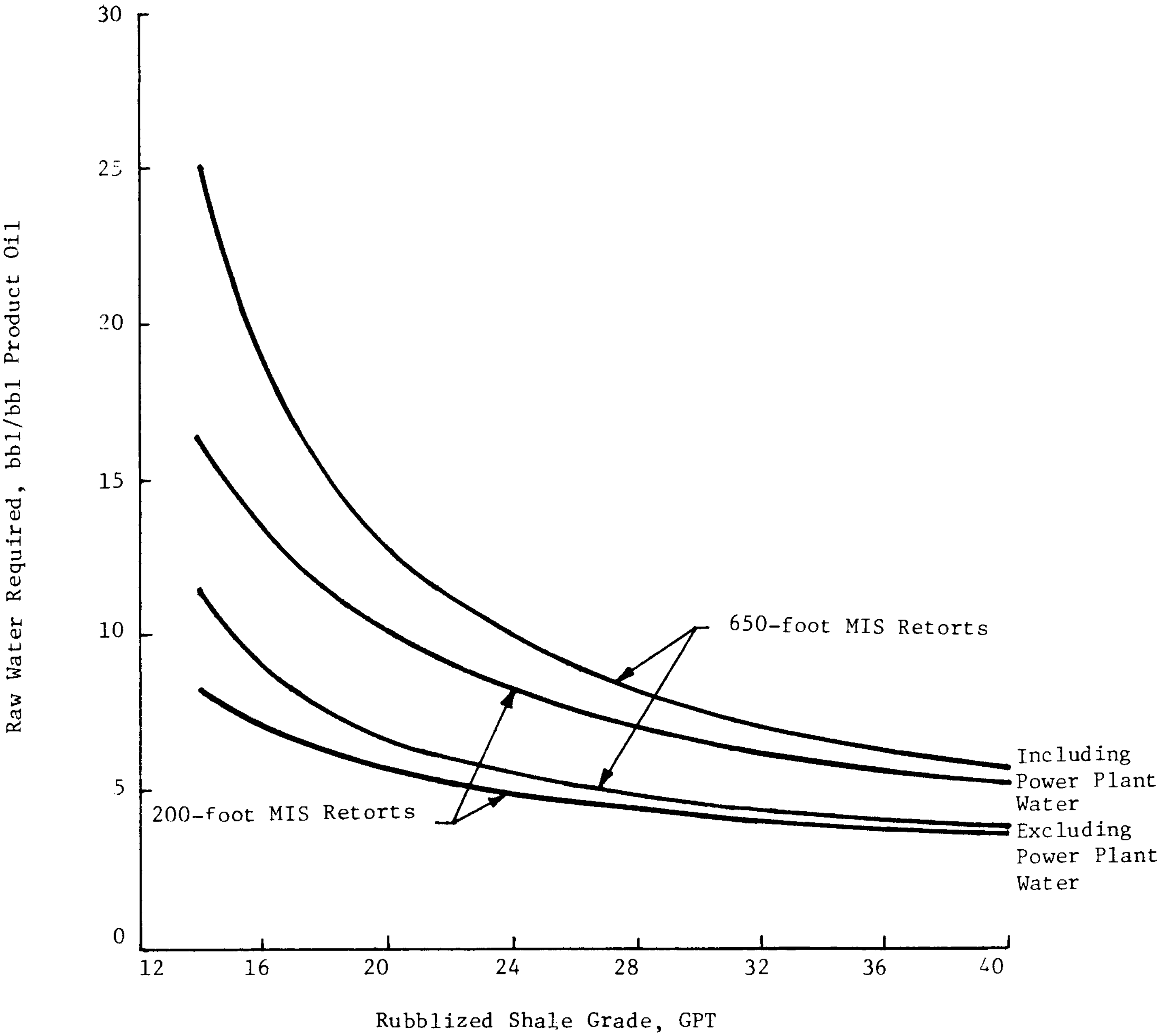

Figure 6-15. MIS/Tosco Retorting: Effect of Shale Grade on Water Requirement

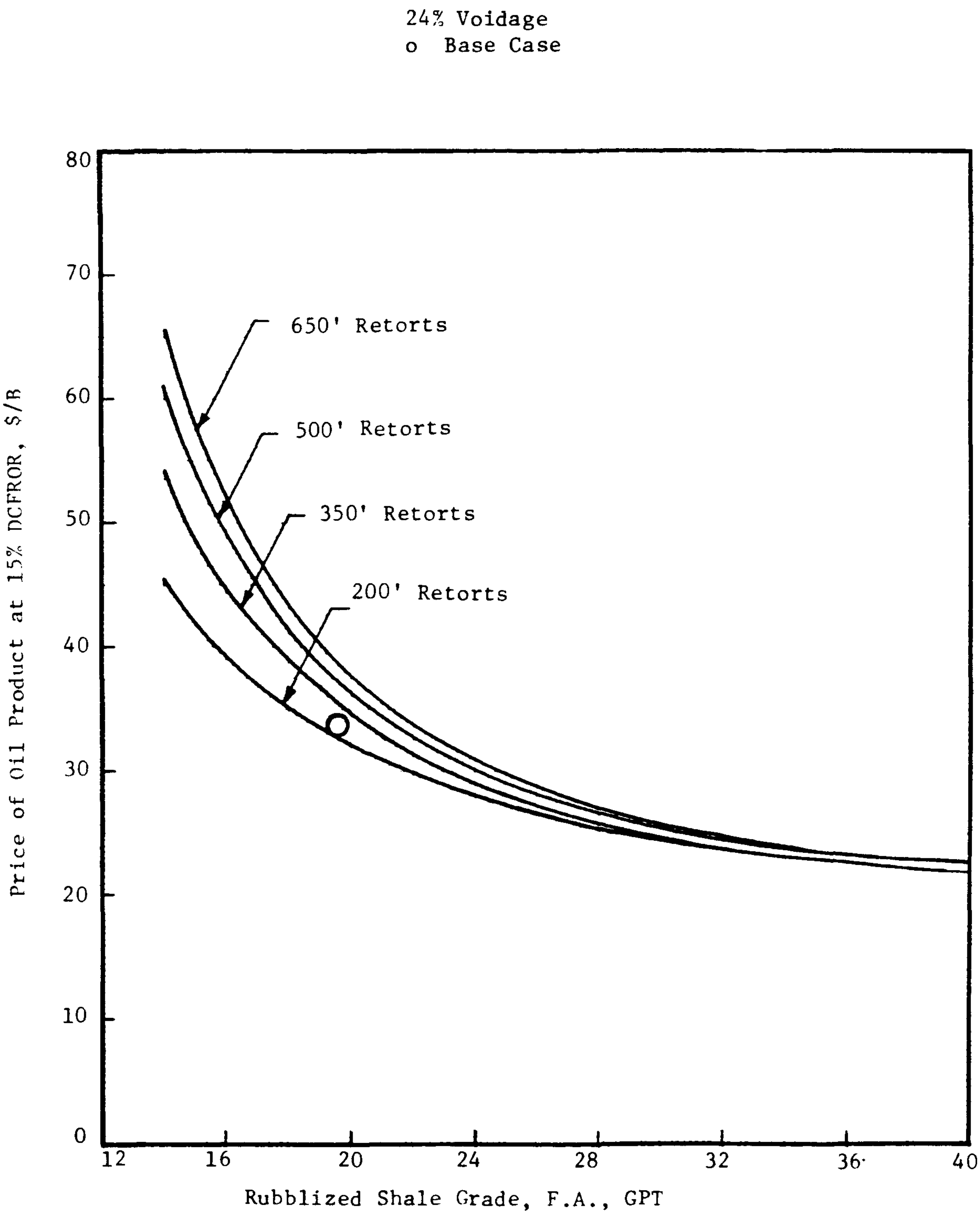

Figure 6-16. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Probable MIS Yields and Tosco Retorted Shale Grade at 37.4 GPT

20% Voidage

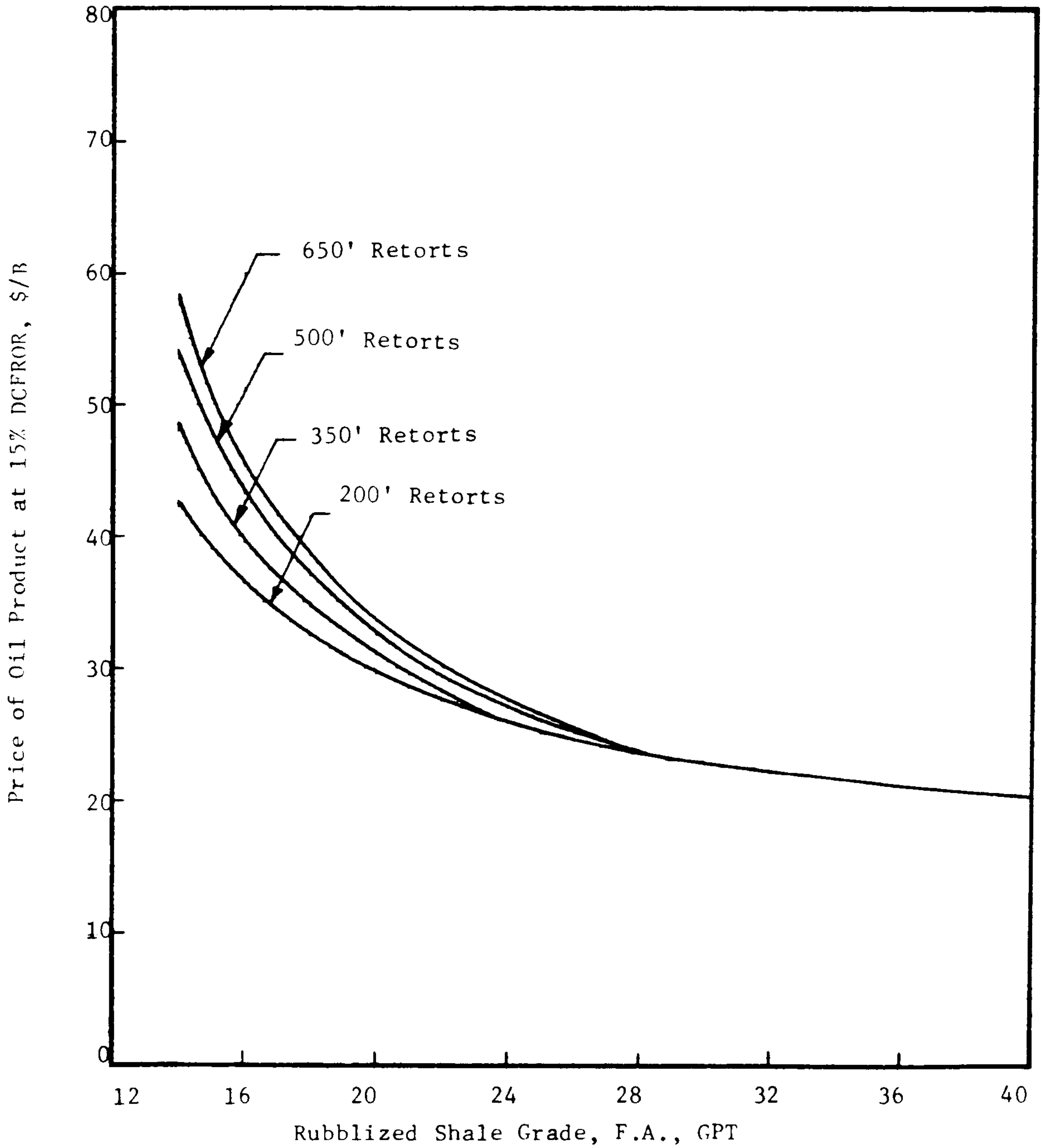

Figure 6-17. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Probable MIS Yields and Tosco Retorted Shale Grade at 37.4 GPT

20% Voidage

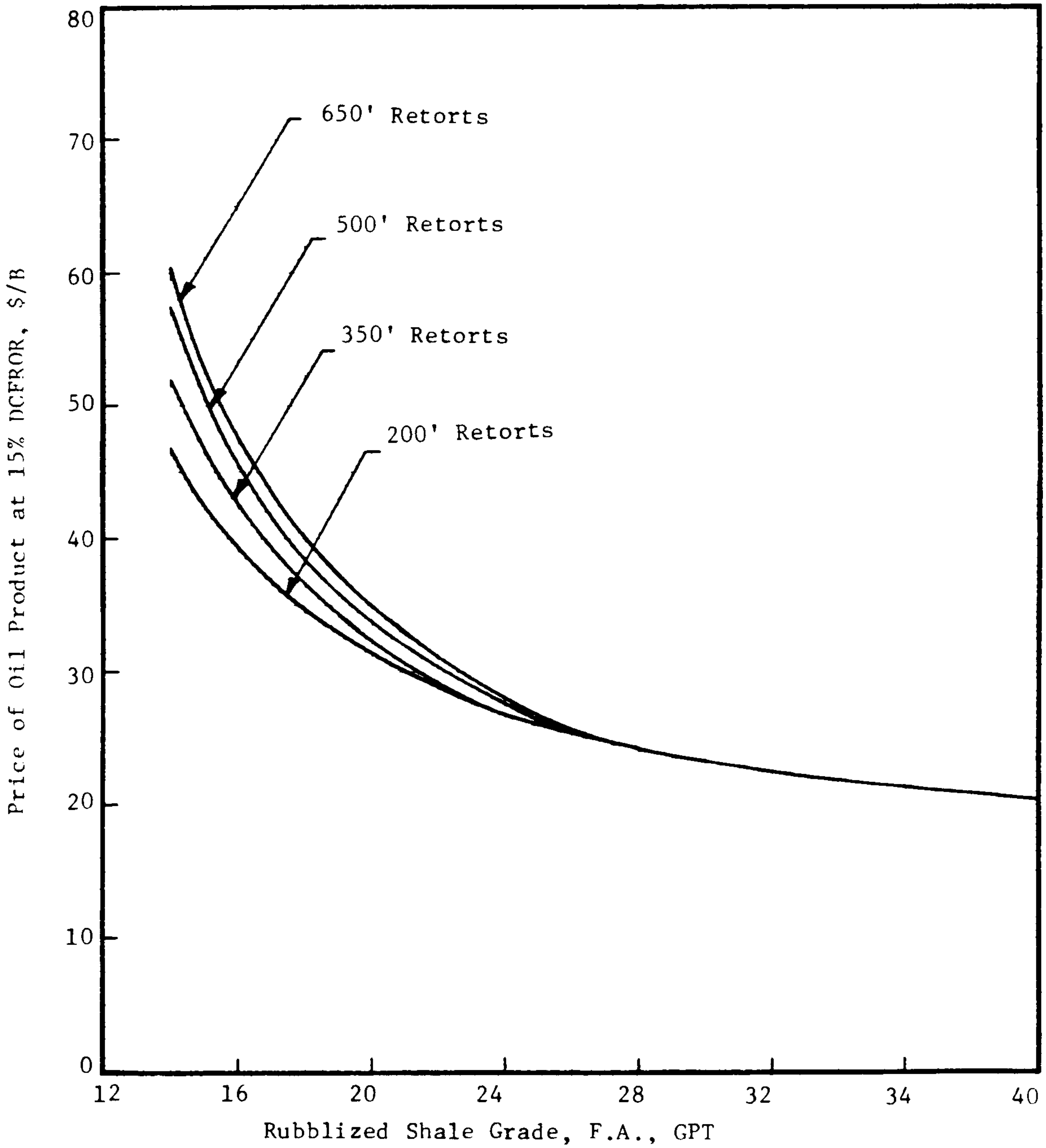

Figure 6-18. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Probable MIS Yields and Tosco Retorted Shale Grade at 30 GPT

20% Voidage

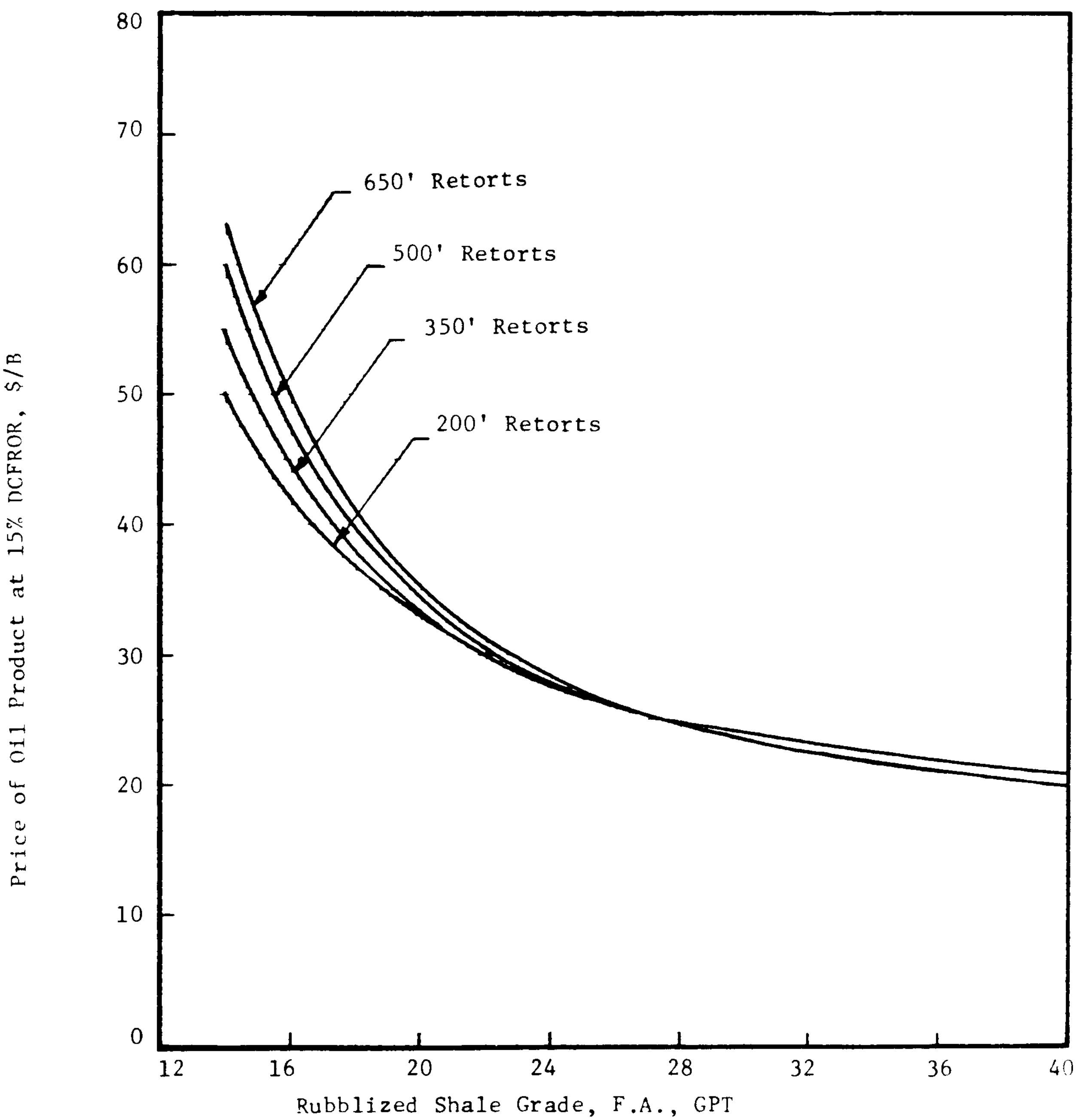

Figure 6-19. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Probable MIS Yields and Tosco Retorted Shale Grade at 25 GPT

The figures show that there is an advantage for higher shale grades for the shale retorted by the Tosco retorts when the rubblized shale is low grade. However, the effect of the product price due to amount and quality of shale retorted aboveground disappears as the in situ retort shale grade is increased; all three figures tend to converge to a product price of about $20/B at an in situ shale grade of 40 gpt.

In comparing Figures 6-16 and 6-17, the advantage of 20% versus 24% voidage is seen to be about $2 to $6/B.

Figures 6-20, 6-21, and 6-22 show the cases where optimistic in situ yields are assumed and Figures 6-23, 6-24, and 6-25 show the cases where pessimistic in situ yields are assumed. For the optimistic yields, shale grade is the only parameter that significantly affects the economics. All three figures converge to about $17/B at an in situ retort grade of 40 gpt, about $3/B lower than the corresponding price for the probable yields. As expected, much larger differences in the effect of the amount and quality of shale retorted aboveground are shown by the cases where pessimistic in situ yields are assumed.

Figures 6-26 and 6-27 show the incremental increase in product price due to raw water prices of $40¢/10^3$ gal and $80¢/10^3$ gal.

20% Voidage

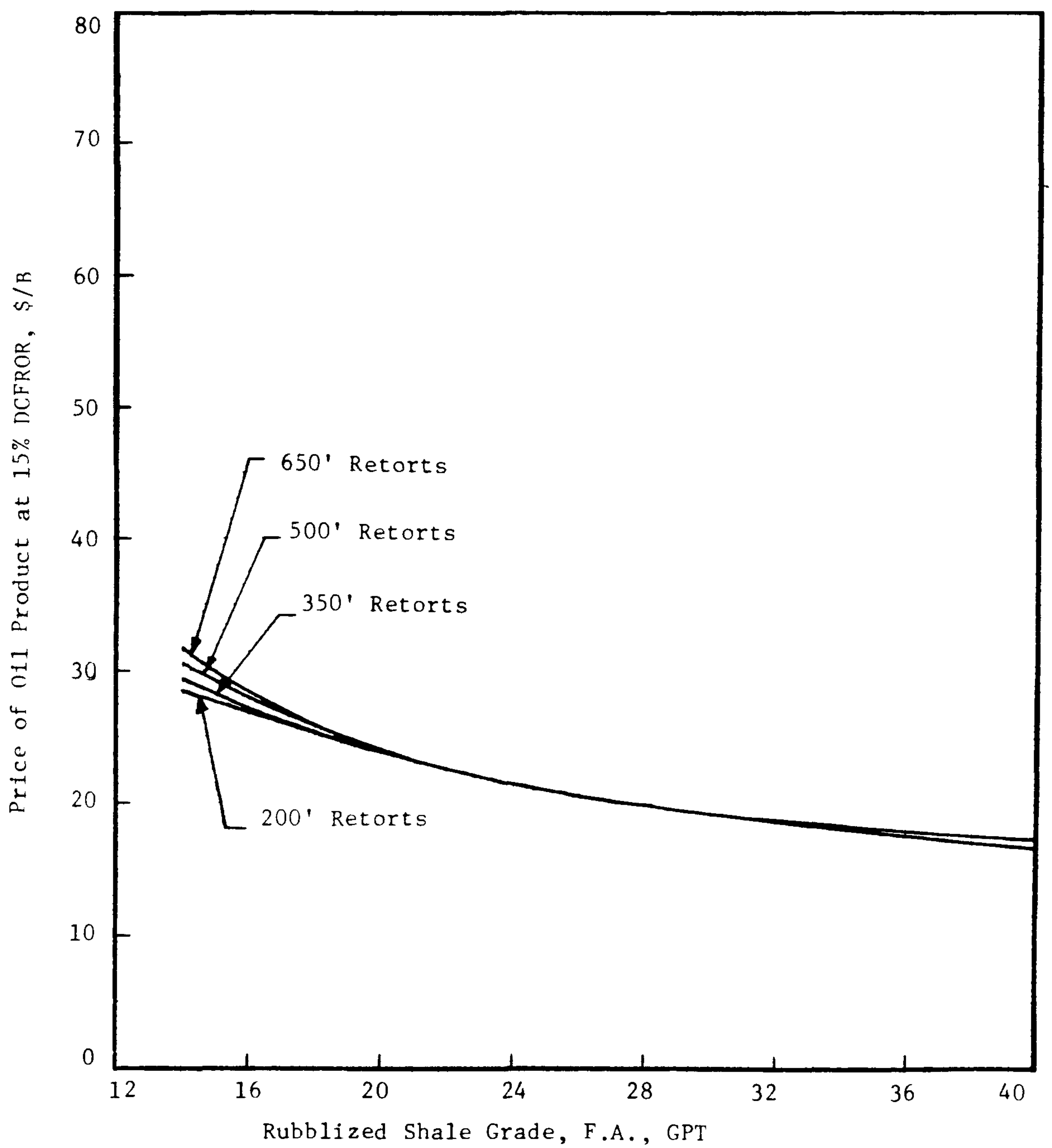

Figure 6-20. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Optimistic MIS Yields and Tosco Retorted Shale Grade at 37.4 GPT

20% Voidage

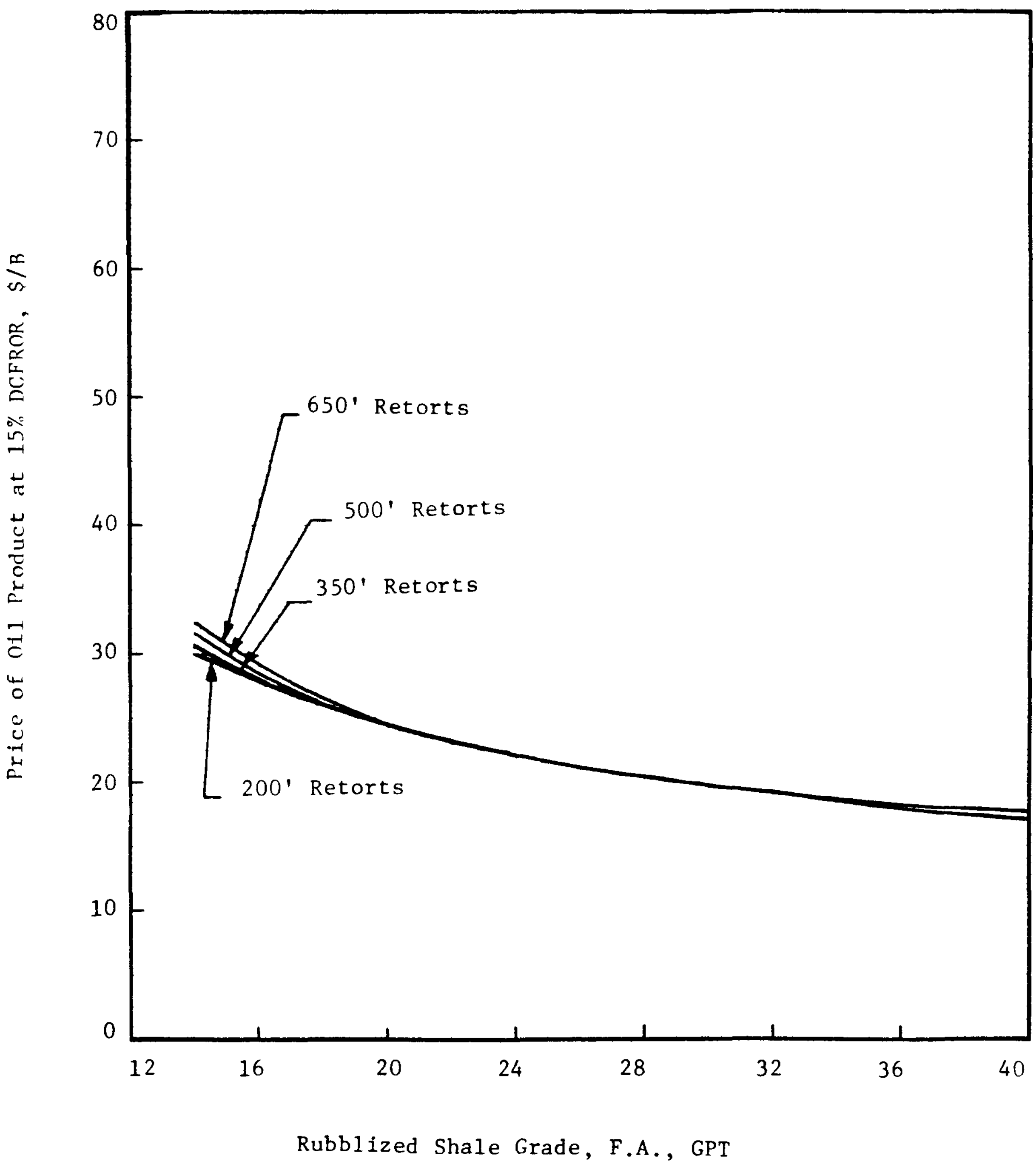

Figure 6-21. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Optimistic MIS Yields and Tosco Retorted Shale Grade at 30 GPT

20% Voidage

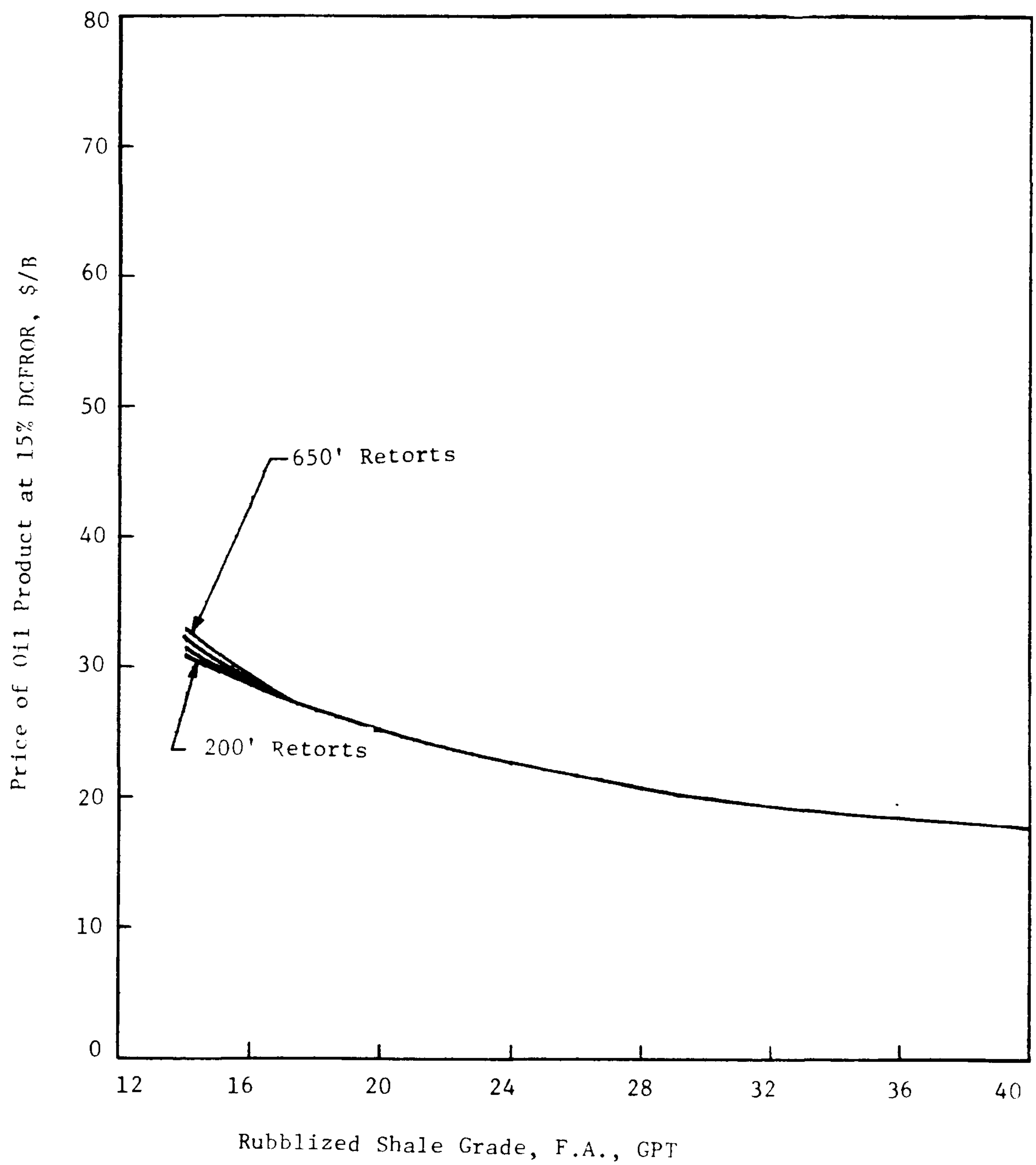

Figure 6-22. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Optimistic MIS Yields and Tosco Retorted Shale Grade at 25 GPT

20% Voidage

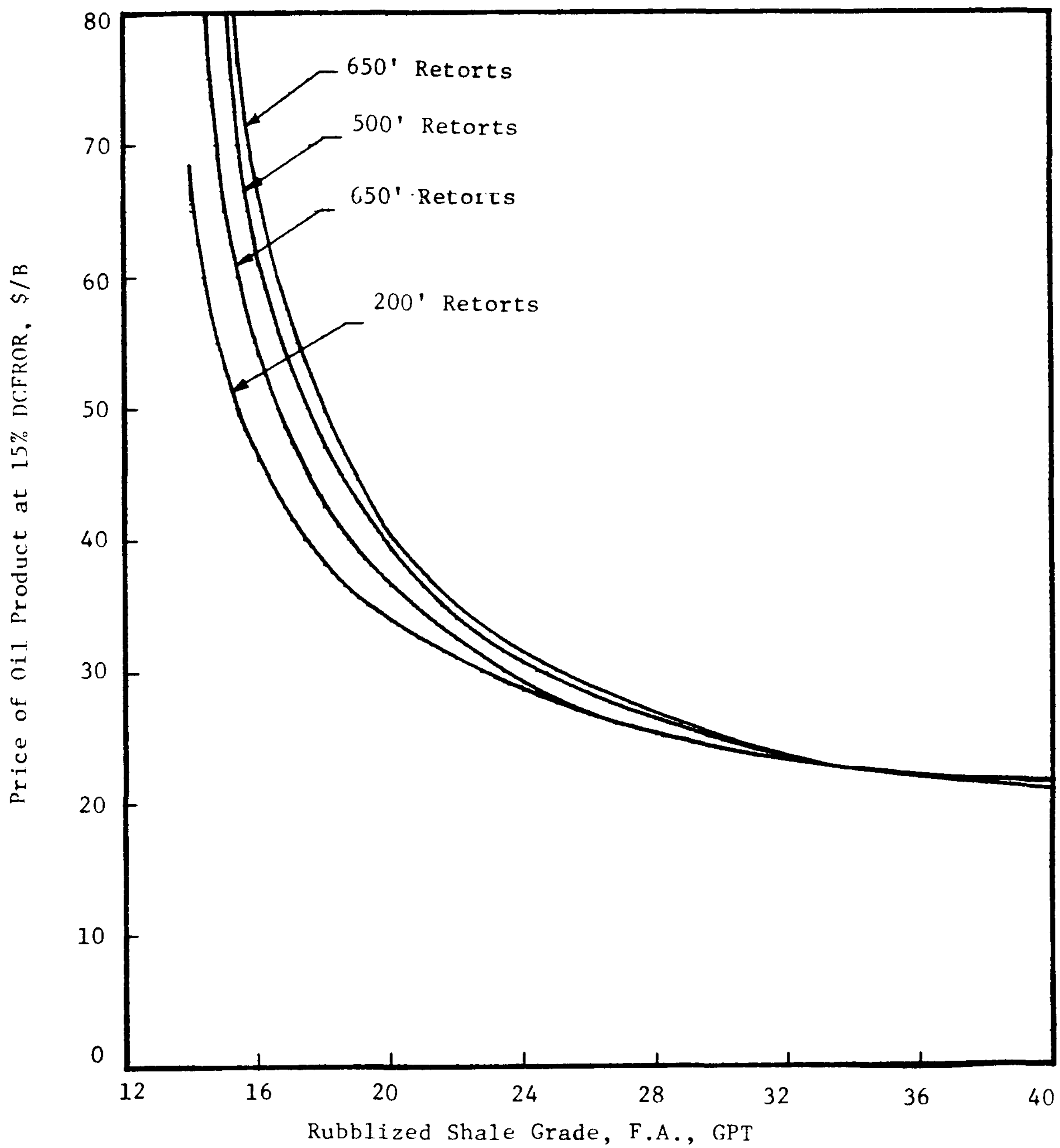

Figure 6-23. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Pessimistic MIS Yields and Tosco Retorted Shale Grade at 37.4 GPT

20% Voidage

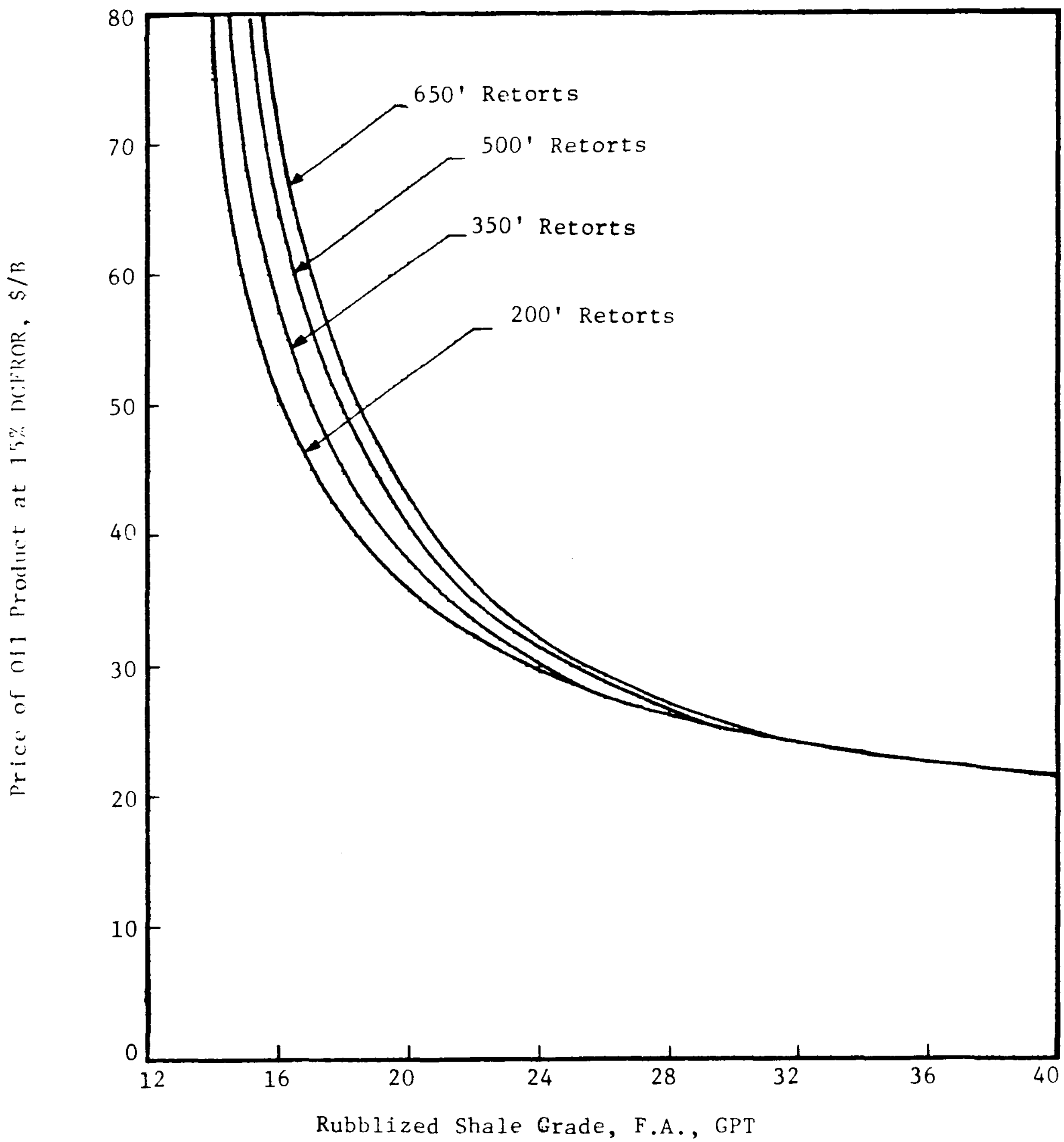

Figure 6-24. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Pessimistic MIS Yields and Tosco Retorted Shale Grade at 30 GPT

20% Voidage

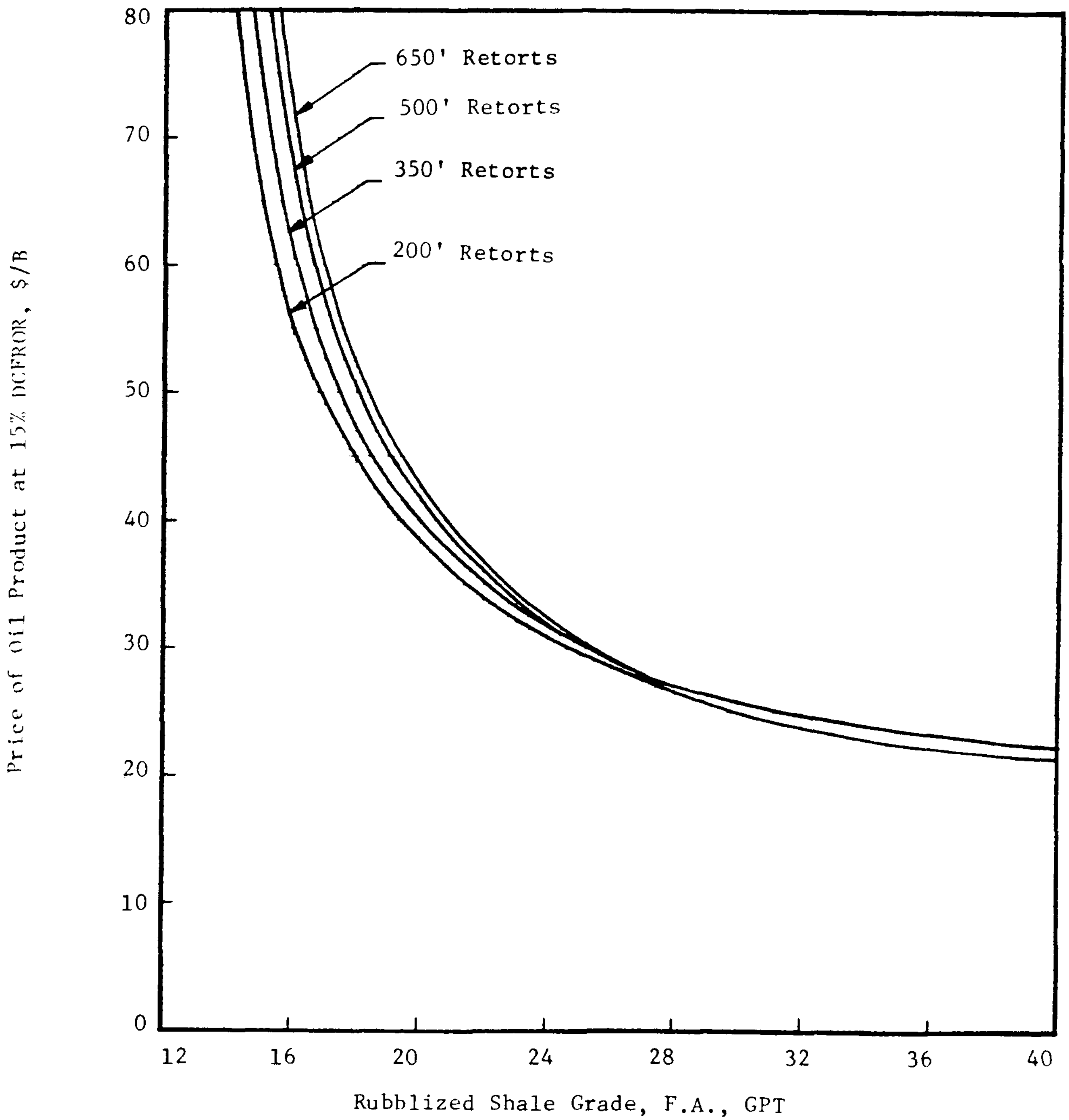

Figure 6-25. MIS/Tosco Retorting: Effect of Shale Grade on Product Price with Pessimistic MIS Yields and Tosco Retorted Shale Grade at 25 GPT

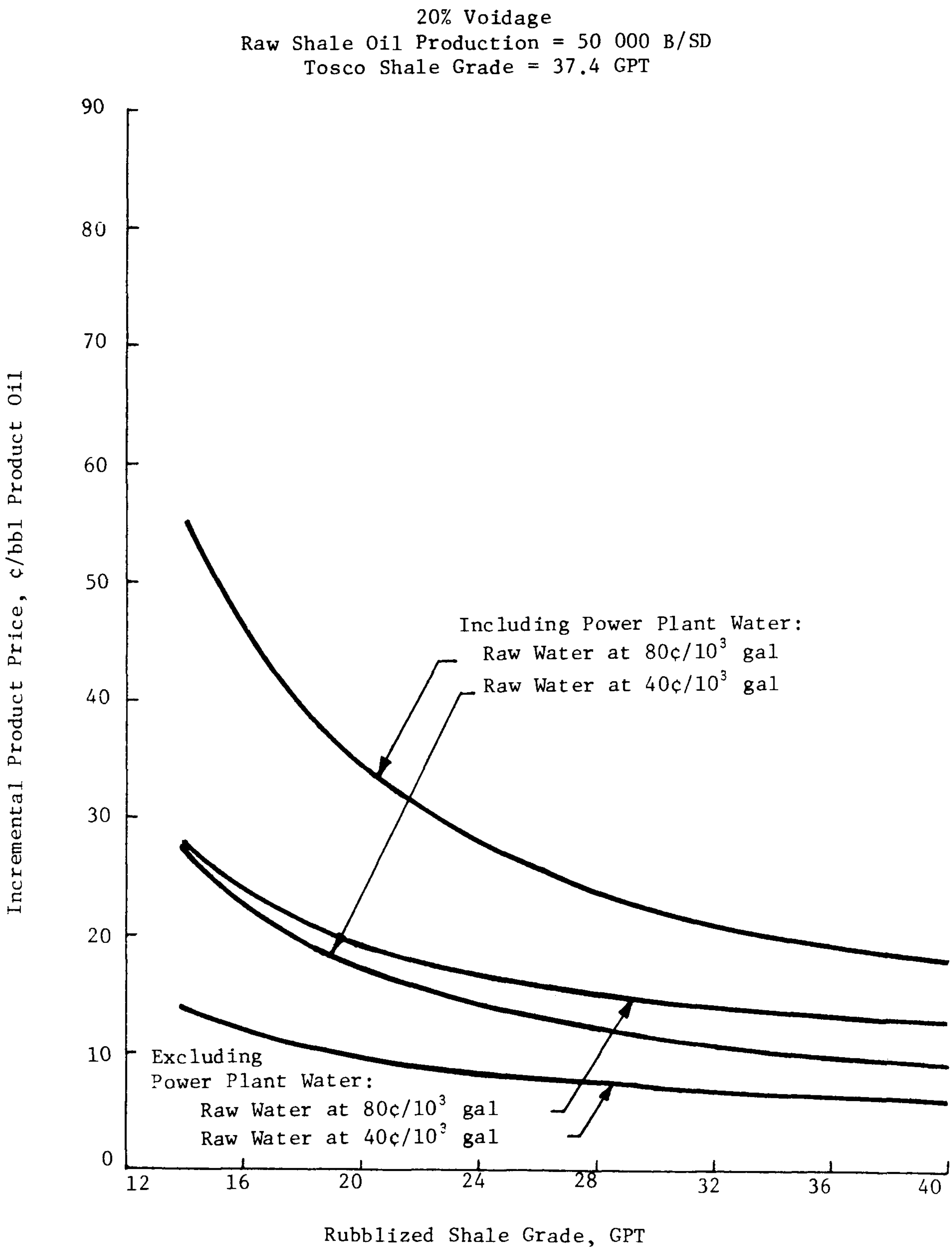

Figure 6-26. MIS/Tosco Retorting: Effect of Price of Raw Water on Product Price - 200-Foot MIS Retorts

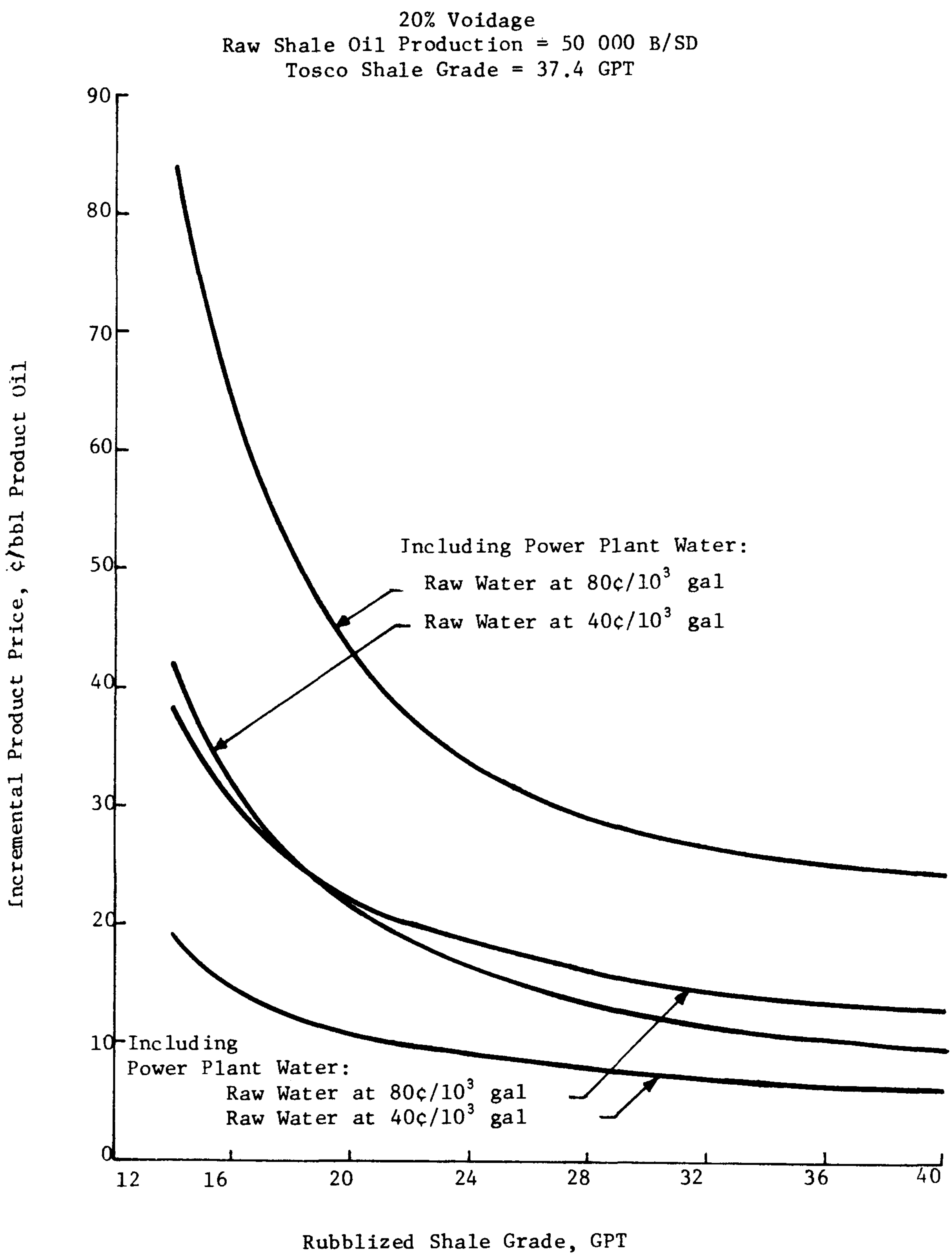

Figure 6-27. MIS/Tosco Retorting: Effect of Price of Raw Water on Product Price - 650-Foot MIS Retorts

7. RESULTS

A comprehensive analysis has been performed in evaluating the MIS technologies as a function of retort configuration, shale grade, oil yields, costs and resource compatibility. Two basic retorting scenarios were evaluated: MIS retorting only and MIS/surface retorting combination. Major results of this study are discussed below:

7.1 MIS Case Only

- The water requirements for retorting 24 gpt shale (MIS-5 case) are 6.1 B/B oil assuming a probable oil yield of 55%. This water requirement reflects the assumption that retort waters are disposed and not recycled for steam generation. Wastewater treatment of MIS retort waters is expected to be prohibitively expensive. Further, the above water requirements do not reflect the water needs for power generation. When power plant water is added to this value, total water requirements calculate to be 13.3 B/B oil. The large water values for power generation reflect losses associated with the cooling tower.

  The addition of water for power generation approximately doubles the total plant water requirements for MIS retorting of shales 20 gpt and richer. The ratio is much higher for the lower grade shales because of the large amounts of power generated from low Btu gas from the retorts.

- Based on the results of 10 retort configurations in which the height of the retorts was varied from 200 feet to 650 feet, the retort height-to-base width ratio varied between 2 and 6, as many as 5 mining levels for retorts 650 feet height, and shale grades varying from 16 gpt to 40 gpt, it can be shown that the effect of retort configuration on the product oil price is small (about 5%).

This is due to the fact that the total mining investments amount to only about 35-38% of the total investment, and incremental changes in mining costs, due to increased height of the retorts, are small.

The small effect of retort configuration on selling price of oil is true for all yields of oil: pessimistic, probable and optimistic.

- The product selling price decreases as the grade of shale retorted increases, and/or as the yield of oil from the retorts increase. For a 24 gpt shale, oil yields greater than 80% are needed to make the MIS process competitive with surface retorting at $25/B. An average selling price of $25/B oil (at 15% DCF-ROR) reflects the most expensive surface retorting option evaluated. The bases (economical and financial) for comparing MIS retorting with surface retorting are the same.

  This analysis further shows that the in situ shale grade has to be 30 gpt and richer with a minimum of 60% oil yield from the retorts to be competitive. High yields (93-95%) or high in situ grades of shale (40 gpt) will reduce the selling price of oil to about $18/B.

- Should water rights not be available to the NOSR project, the cost of purchasing raw water at 40¢/10^3 gal and 80¢/10^3 gal will add a maximum of 45¢/B to the selling price of oil.

7.2 MIS/Surface Retorting Case

- When retorting an average of 20 gpt shale in situ and 37.5 gpt shale in the surface retorts, the water requirements calculate to be 5.9 B/B oil, assuming no water for power generation. With power generation, this value increases to 9.9 B/B oil. As in the MIS case, the retorting waters are not reused for steam generation due to expected high costs for wastewater treatment.

- At lower grades of in situ retorted shale, the retort configuration appears to have an effect on the product prices; however, this effect is actually due to the amount of shale mined for surface retorting.

For the 200 ft retorts, more than 50% of the mined shale is retorted aboveground; whereas with the 650 ft retorts, about 20% of the mined shale is retorted aboveground. For the 650 ft retorts, about 40% more shale has to be mined than for the 200 ft retorts.

- Results of the combined MIS/surface retorting case show that there is an advantage (in product selling price) in retorting higher grade shale aboveground, especially when the rubblized shale grade is low. This advantage disappears as the rubblized shale grade increases; all product oil prices tend to converge to $20/B at an in situ shale grade of 40 gpt.

- The product selling price decreases as the grade of rubblized shale increases, and/or the in situ oil yield increases. Because of the larger number of variables involved - retort height, oil yields, surface retort shale grades, and rubblized in situ shale grades - it is not possible to represent these results in a simple diagram like Figure 6-7. However, limiting cases can be analyzed for impacts.

  For a 20 gpt rubblized shale grade, and 37.5 gpt shale grade to the surface retorts, in situ oil yields of about 80% must be realized for this combination system to be competitive with surface retorting only at $25/B.

  For the case when 25 gpt of shale is retorted on the surface, an average in situ shale grade of 27 gpt (with a probable oil yield of 59%) is needed for the combination system to be competitive at $25/B. If optimistic yields are assumed, a 20 gpt rubblized shale grade with 80% oil yield is required to be competitive.

  Surface retorting of shales below 25 gpt is not currently considered to be economically feasible.

Under the most optimistic scenario, 19 gpt rubblized shale grade and 37.5 gpt shale grade for surface retorting will give a product selling price of $25/B. The oil yield from the in situ retorts for this case has to be 78-79%.

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