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REVIEW AND ANALYSIS OF OIL SHALE TECHNOLOGIES

VOLUME IV
ABOVEGROUND OR SURFACE TECHNOLOGY

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ABSTRACT

This volume presents a technical description and evaluation of retorting methods and scale-up scenarios of four representative methods. The methods described and evaluated include the processes developed by the Bureau of Mines (BOM), the Union Oil Company "B," Petrosix, Paraho, TOSCO II, and the Superior Oil Company. For a future economic analysis, scale-up (ranging from 55,000- to 58,000-bbl/day production rate) scenarios are presented for BOM's Gas Combustion retort (GCR), Union "B," Paraho, and TOSCO II retorting processes. In general, the six aboveground processes selected are in an advanced stage of development as compared to in situ processes and several of them are ready for commercial-scale demonstration. There are, however, a few areas that still need further research and development before demonstration can be undertaken. Specific areas of research cannot be defined at this time because process information needed to identify these areas is mostly proprietary.

The technical evaluation reveals that the aboveground retorting processes are viable with high shale oil recovery yields. The processes, however, have been tested only at the pilot or semiworks scale and need to be demonstrated on full-scale modules. The scale-up scenarios of the representative processes reveal that the logistics of the mining-to-processing operation will be a major problem at high production rates. For example, a nominal crude shale oil production rate of about 50,000 bbl/day will require mining at a rate exceeding present large-scale mining rates. The TOSCO II retorting process is the most energy intensive among Paraho, Union "B," and BOM's GCR because of its complexity, which annuls the benefit of less mining. The TOSCO II process, however, is still an attractive process, providing the technique is used with another technique to enhance resource utilization.

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INTRODUCTION

Research and development investigations of surface or aboveground retorting methods for recovering crude oil from shale have been conducted since 1945. At that time, the Bureau of Mines (BOM) began development of a gas combustion retort (GCR) at Anvil Points in Rifle, Colorado. In the 1950's and 1960's, the Oil Shale Company (TOSCO) and the Union Oil Company investigated aboveground processes for oil shale. A six-company industry group modernized the BOM GCR and then conducted extensive demonstration operations. Development Engineers, Incorporated (DEI), commenced development of the Paraho process in the early seventies. During this same period, TOSCO and Union refined and updated their processes, and Superior Oil Company introduced its Multi-Mineral Oil Shale process for commercial consideration.

Several methods for aboveground retorting have reached the stage of industrial interest in the United States. These methods may be classified by the way heat is supplied to the retorting process. One classification involves methods having a combustion zone within the retort, and another involves methods using an aboveground fuel-fired furnace to generate hot gases or recycle hot solids. Chapter 1 of this volume of the report describes six methods for aboveground retorting. Chapter 2 evaluates the engineering aspects of these methods, focusing on parameters that affect recovery of hydrocarbons from shale. The technical parameters addressed and evaluated include various system design and operation requirements, oil and gas recovery yields, shale bed thickness and grade, particle size, and mechanical complexity or constraints. These factors and conditions are based on the available information from published literature and are subject to change as more proprietary data become available.

Chapter 3 presents scale-up scenarios for the four processes selected as representative of the aboveground technology for extracting shale oil. The scenarios may not reflect an accurate picture of what industry envisions, since some information is not obtainable and best estimates are used. Although some of the projections are mostly speculative, the purpose of the scale-up is to provide a uniform or common cost basis for future economic evaluations.

Principal findings and conclusions derived during the conduct of this study are documented in Chapter 4 to provide additional information on the state-of-the-art of above-ground technology. The chapter also presents RD&D needs and defines data gaps to assist in planning future experiments or redirecting existing experiments.

CHAPTER 1
DESCRIPTION AND STATE-OF-THE-ART OF ABOVEGROUND PROCESSES

Efforts to develop oil shale technologies in the past 33 years have been directed mostly toward aboveground retorting. This method of processing oil shale, therefore, is in an advanced stage of development, and several processes are ready for commercial-scale demonstration. There are, however, some areas that still need further research before demonstration can be undertaken. Specific areas of research cannot be defined at this time because process information needed to identify these areas is mostly proprietary. This chapter presents an overview of the process steps and a detailed description of six retorting methods associated with aboveground oil shale. The process steps are described briefly in the following section and include mining, shale crushing and sizing, retorting, and product recovery. The methods selected and described include the ones being developed by the following companies or government agencies:

- Bureau of Mines (Gas Combustion retort)
- Union Oil Company ("A," "B," and steam gas recirculation)
- Petrobras of Brazil (Petrosix)
- Paraho
- TOSCO II
- Superior Oil Company (Multi-Mineral).

For each of the selected processes, appropriate operating data are provided in the discussion. These data were obtained from interviews with industry and government oil shale experts as well as from the available published reports. In areas where operating data could not be obtained for proprietary reasons, best estimates are used.

1.1 OVERVIEW OF PROCESS STEPS

Aboveground oil shale processing consists of four basic steps. These steps precede the final upgrading and refining of the product as well as handling of the retorted shale:

- Shale is mined and transported to the processing facility.
- Shale is crushed and sized to increase combustion efficiency.
- The crushed and sized shale is ignited, and combustion is sustained to produce the desired hydrocarbons.
- The products are then separated from the by-products and recovered for subsequent upgrading and refining.

The retorted shale handling step involves disposal of the material in an environmentally acceptable manner. These steps are schematically shown in Figure 1, and their general specifications are described briefly in the following sections.

1.1.1 Mining and Handling

Oil shale may be mined by either the open pit (surface) or room-and-pillar (underground) method. Open pit mining requires removal and disposal of whatever overburden is present, followed by mining of the underlying oil shale in a quarry-like operation. The room-and-pillar method requires the mining of 60-ft square rooms with roof supporting pillars between the rooms. The rooms and pillars are 60-ft square with a 60-ft high roof. Seventy-five percent of the oil shale can be mined by this method.

Although room-and-pillar mining is the only method that has been tested on oil shales (Green River Formation), open pit mining may also be a practical method. The open pit method developed for ores and minerals may be applicable to oil shales in certain areas. The key factors in determining whether to apply this technique to an area are overburden storage availability, overburden-to-minable shale ratio, and environmental constraints. Transport of the shale to the crushing and sizing/retort facility would most likely be achieved by truck or belt haulage from the mine.

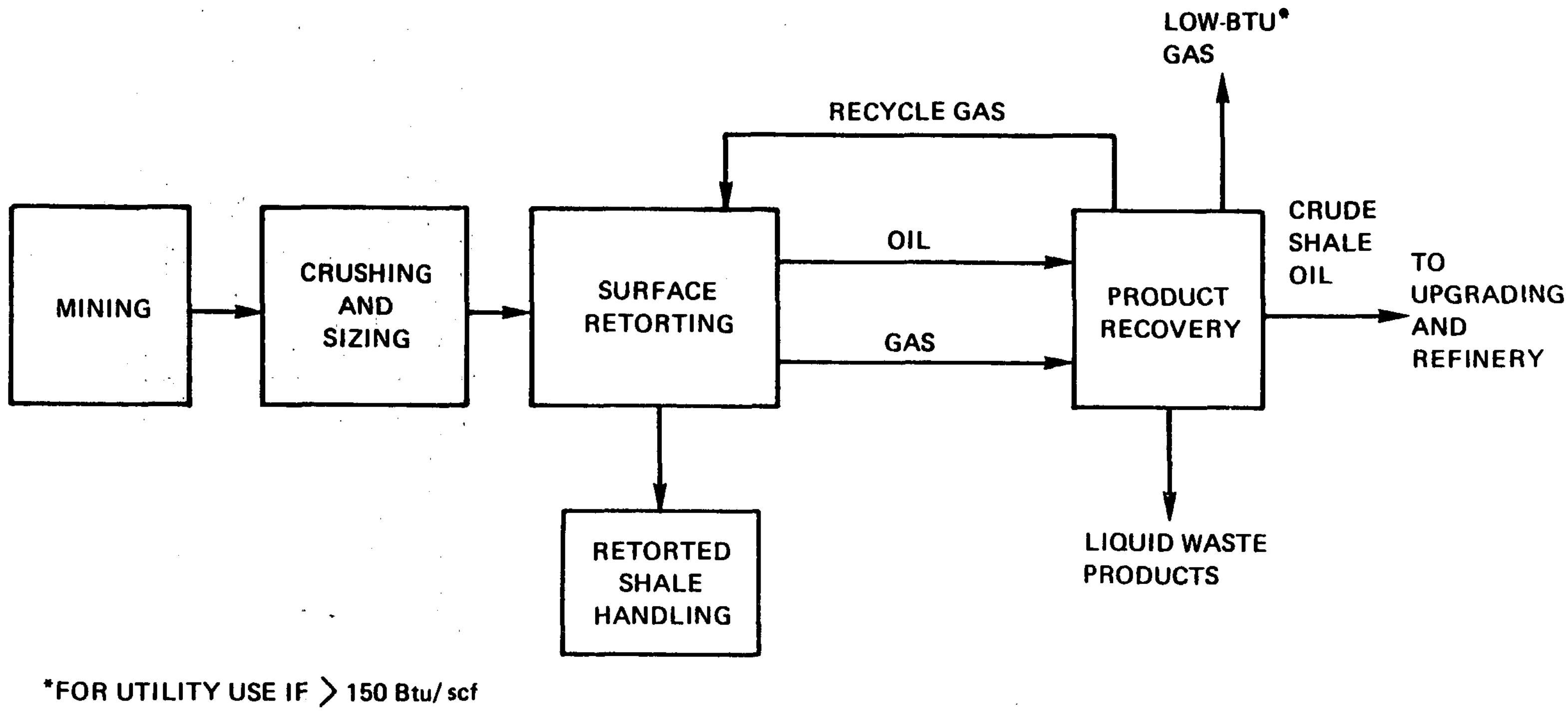

FIGURE 1. ABOVEGROUND OIL SHALE PROCESSING OPERATIONS

1.1.2 Crushing and Sizing

Oil shale consists of a mixture of solid organic materials (kerogen) and minerals. The organic constituents are only slightly soluble at low temperature in common solvents, and most of the oil shale mined would require crushing and sizing prior to retorting. The crushing and sizing equipment is designed to form particles ranging from 1/2 to 3 in. in diameter (average). Crushed and sized shale is subsequently transferred to aboveground retorts by use of continuously moving belts.

1.1.3 Retorting

After the mining, crushing, and sizing operations have been completed, the shale is conveyed to a retort and heated to temperatures ranging from 800° to $1,000^{\circ}F$ at which the kerogen in the shale is converted to gas and oil vapors. Many aboveground retorting processes for oil shale have been patented in the last half century, and new patents continue to be issued. Only a few processes, however, are generally considered to be prime candidates for early commercial use in first-generation retorting plants. All retorting processes have one fundamental characteristic in common; namely, heating the shale to at least the pyrolysis temperature. This is the only practical means known for producing shale oil. Although the major pyrolysis product is oil, both gas and carbonaceous residue also are formed.

1.1.4 Product Recovery

Aboveground retorting processes require provision for effective recovery and separation of the oil and gas products. Typically, this procedure involves transport of a product mixture to a system of available equipment such as impingement-type separators, centrifugal separators, and electrostatic precipitators. Absorbers and similar recovery equipment often used in petroleum refineries also may be used for product recovery. Regardless of the actual components used in the recovery system, the principal function to be served by the system is separation and recovery of oil and gaseous products in relatively clean states. Other products, such as water produced in the retorting process and any particulates that may carry over from the retorts, are trapped in the product recovery system.

1.1.5 Retorted Shale Handling

Depending on the grade of shale being processed, the weight of retorted shale is generally about 80 to 85 percent of that of the originally mined oil shale. The remainder of the original shale weight is accounted for by the oil and gas products evolved during retorting. The volume of retorted material, even after maximum compaction, is expected to be at least 12 percent greater than its in-place volume. This is due to void spaces in the mass of crushed and retorted material which are not present in the shale prior to mining. In practice, final densities would vary considerably depending upon the compaction technique employed and the physical characteristics of the retorted material (e.g., particle size distribution).

Some but not all of the retorted shale can be used as backfill. Consequently, surface disposal will most likely be required. The retorted material may vary in particle size from a fine powder to about 10-in. diameter and could be discharged from the retort as dry material.

1.2 BUREAU OF MINES GAS COMBUSTION RETORT

The Bureau of Mines Gas Combustion retort is a refractory lined vertical kiln in which oil shale flows by gravity from top to bottom. This retort may be characterized as an internal combustion retort in which recycled product gas and carbonaceous residue remaining on retorted shale are burned inside the retort, as shown in Figure 2. The resulting hot gases flow upward, countercurrent to the flow of shale, and heat the crushed shale fragments to the pyrolysis temperature range. The oily vapors are carried out by the gas stream near the top of the retort. Product recovery is accomplished by separating the oil from the product gas, a part of which is recycled to the combustion zone for continued burning (1).

The U.S. Bureau of Mines developed the Gas Combustion retort during an extensive research program in the late 1940's and early 1950's (2). Three experimental plants were built and operated at the Anvil Points Experimental Station near Rifle, Colorado, until 1955. The largest retort had a 150-ton/day capacity.

A second comprehensive R&D program for investigating Gas Combustion retorting was initiated by a consortium of six energy companies (Mobil, Humble, Pan American, Sinclair, Conoco, and Phillips), whicn leased the Anvil Points Facility

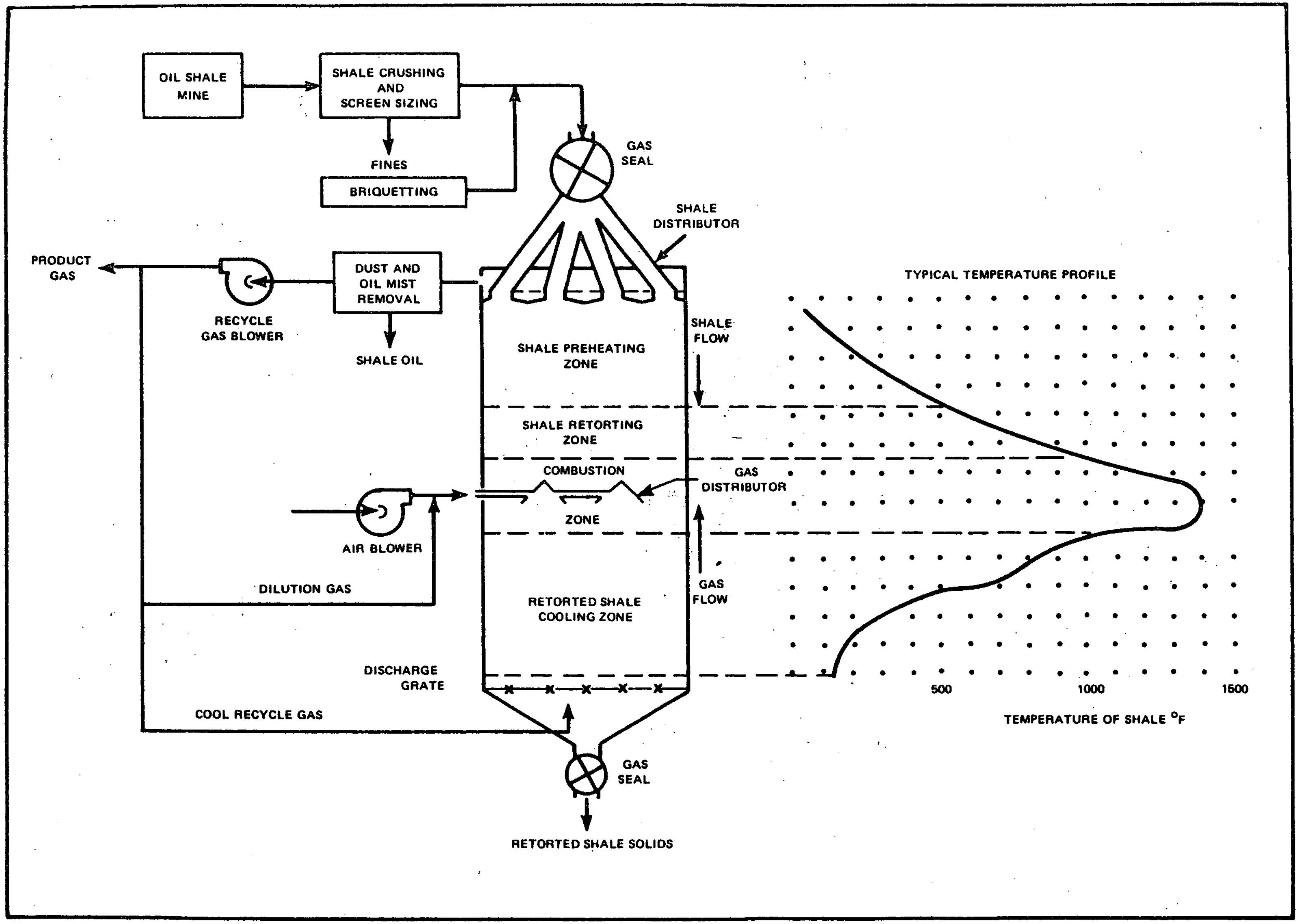

FIGURE 2. THE BUREAU OF MINES GAS COMBUSTION RETORT

from the Bureau of Mines from 1964 to 1967 with the Colorado School of Mines Research Institute as operator. The group modernized the 150-ton retort (with a resultant increase in its capacity to 360 tons/day), installed higher capacity auxiliary equipment, and conducted pilot-scale operations. The existing state of development is close to what is ultimately required in process equipment. However, some operating problems associated with scale-up are still unresolved, such as the even flow of shale in large-diameter retorts and the prevention of channelization of rising gases (3). Also, the Gas Combustion retort suffers from relatively low oil recovery efficiencies as compared to other surface processes. This recovery is on the order of 85 percent.

Nevertheless, the Gas Combustion retort is the most advanced Government-sponsored oil shale retorting process, with many years of process development and refinement. In support of possible commercial development, the Bureau of Mines recently conducted economic analyses of projected scale-ups of the Gas Combustion retorting process to 50,000- and 100,000-bbl/day facilities (4,5). At present, no known private firms are considering this process for development. However, there is great interest in the Paraho Retort and the Petrosix Retort, which are modifications of the Gas Combustion retort.

1.2.1 Mining and Handling

The oil shale for the Gas Combustion retort will probably be extracted from an underground room-and-pillar mine (as described in Chapter 3 of Volume I).

1.2.2 Crushing and Sizing

Run-of-mine oil shale is transported by conveyor belt to receiving hoppers at the crushing plant. There it is crushed to a size of less than 3-in. diameter. This crushed shale is passed through screens that remove particles smaller than 3/16-in. diameter for briquetting. Particles between 3/16- and 3-in. diameter are conveyed to surge bins before retorting (4). It is reported that 1.3 percent of the shale handled during crushing and screening is lost as dust, with half the loss occurring during crushing and transporting and the other half during screening and sizing (6).

1.2.3 Retorting and Product Recovery

As depicted in Figure 2, the retort is equipped with shale charging and discharging devices and gas flow distributors. Crushed oil shale enters the top of the retort and flows downward by gravity along the retort axis. The shale flow rate is controlled by a grate discharge mechanism located in the lower part of the retort. As the bed of shale moves downward, it passes through four zones:

- Preheating Zone - Crushed and sized shale introduced into the top of the retort is initially ignited using an outside energy source. Shale introducted after ignition is preheated by hot gases rising from the combustion zone.

- Retorting Zone - Shale is heated to a pyrolysis level of about 450° to 500°C (850° to 950°F). At this temperature, kerogen decomposes to oily vapor and gas, leaving a carbonaceous residue in the oil shale matrix. When a predetermined amount of shale has been retorted, the outside energy source is shut off and combustion is maintained by injecting air into the retort. Combustion gas leaving the retort may be recycled to control the oxygen of the inlet gas.

- Combustion Zone - Air and recycled product gas are introduced to burn the carbonaceous residue at approximately 1400°F. Thus, heat is transferred to the rising stream of gas for continued pyrolysis.

- Cooling Zone - Recycled product gas may be injected into this zone. If this is done, the gas flows upward from the bottom of the retort, thus heating the gas and cooling the shale. At about 380°F, the retorted shale is mechanically discharged from the retort, moisturized and cooled, and carried by belt conveyor to disposal.

Product recovery may be accomplished by separating entrained hydrocarbon vapors from the produced gas stream. The gas can be directed through a centrifugal separator (Rotoclone) and an electrostatic precipitator. The oil coalesces in the separators and is collected and sent to storage.

The overall oil recovery yields from the Bureau of Mines Anvil Points plants were as follows (3):

- 95 percent of the available shale oil was extracted in the small (6 tons/day) pilot plant
- 87 percent of the available shale oil was recovered in the demonstration (150 tons/day) plant
- 85 percent of the available shale oil was recovered in the 360-ton/day plant.

If this yield relationship is extrapolated to commercial scale (50,000 bbl/day), a further drop to 78 percent of Fischer assay is indicated.

Properties of the crude shale oil produced at the modernized 360-ton/day Gas Combustion retort at Anvil Points are as follows (7):

Gravity (°API)	19.7
Sulfur (wt pct)	0.74
Nitrogen (wt pct)	2.18
Pour Point (°F)	80
Viscosity (SUS at 100°F)	256

By petroleum standards, the raw shale oil is a low-gravity, high-nitrogen, moderate-sulfur crude oil. It can be further refined (upgraded) by standard crude refining procedures. Upgrading is accomplished through distilling, delayed coking, and hydrogenating.

Retort gases produced by the Gas Combustion retort contain high concentrations of nitrogen and carbon dioxide, typical of internal combustion retorts. Retort gas properties are as follows (7):

Nitrogen (vol pct)	62.1
Carbon Monoxide (vol pct)	2.3
Carbon Dioxide (vol pct)	24.5
Hydrogen Sulfide (vol pct)	0.1
Hydrogen (vol pct)	5.7
Hydrocarbons (vol pct)	5.3
Gross Heating Value (Btu/scf)	100
Molecular Weight	30
Yield (scf/bbl of oil)	10,900

Operating conditions and performance data of the modernized (360 tons/day) Gas Combustion retort at Anvil Points are presented in Table 1.

TABLE 1

PERFORMANCE DATA OF THE MODERNIZED 360-TON/DAY GAS COMBUSTION RETORT AT ANVIL POINTS IN APRIL 1967 (8)

Operating Parameters	Average of Nine Runs
Length of Run (hr)	12
Shale Feed Properties	
Average Fischer assay (gal/ton)	25.6
Size range (in.)	1 to 2 1/2
Operating Conditions	
Bed height (ft)	12.5
Feed rate (lb/hr)	27,561
Mass feed rate (lb/hr-ft^2)	500
Air rate (scf/ton)	4,728
Air static pressure (in. H_2O)	120
Air temperature (^oF)	142
Recycle gas rate (scf/ton)	12,722
Recycle gas temperature (^oF)	230
Retort off-gas pressure (in. H_2O)	-0.03
Retort off-gas temperature (^oF)	139
Vent gas rate (scf/ton)	7,243
Vent gas temperature (^oF)	236
Spent shale temperature (^oF)	380
Retort top pressure (in. H_2O)	-0.03
Retort bottom pressure (in. H_2O)	10.2
Blower outlet pressure (in. H_2O)	69
Oil Recovery (water free)	
Shale feed (gal/ton)	21.4
Fischer assay (wt pct)	85.4
Product Oil Properties	
H_2O (wt pct)	5.6
Gravity (^{o}API)	19.7

This low-Btu gas can be used as power plant fuel by combining it with fuel gas generated in the oil upgrading sections (gas stream from hydrogenation and delayed coking units).

1.2.4 Retorted Shale Handling

The Gas Combustion retort yields a coarse retorted shale product containing fragments measuring several inches in size. Relatively few fines are contained in the shale, and some fusing of fragments may be observed. Relatively little organic carbon residue remains in retorted shale particles (9).

The temperature of the retorted shale may be as high as 380°F. As it is discharged through the control grate at the bottom of the retort, the retorted shale is fed into a rotary moisturizing drum cooler for dust control and temperature reduction, then transported by belt conveyor to one of two disposal sites:

- The mined-out areas of an underground mine development (for backfilling)
- A large land disposal site such as a nearby canyon or open pit.

Two disposal sites are necessary because

- The volume of the retorted shale is about twice the volume of the shale in place and cannot be entirely backfilled into the mine.
- The disposal of retorted shale on land is environmentally disadvantageous and should be minimized.

Transport to these disposal areas may be accomplished by a completely enclosed (hooded) belt conveyor. Distribution on the land disposal site can be accomplished by large capacity (150 tons) bottom dump trucks. Compaction to about 100 lb/cu ft can be done by a diesel cat pulling a sheep's foot roller. About 10 to 15 wt pct water is added to reduce dusting and aid in the consolidation of disposal piles. A retaining dam to prevent direct water runoff into the local watershed will be built (4). Other controls to prevent leaching of the pile may also be required.

Backfilling can begin as soon as a large section of the mine can be isolated from active mining, which may not be realized until 5 to 10 years later. However, experiments to prove the feasibility of underground disposal have not been completed.

1.3 UNION OIL COMPANY

The Union Oil Company has developed three retorts:

- The first is the Union Oil "A," an internal-combustion retort in which hot gases, produced by combustion of residual carbon on the retorted shale, are used to heat the raw shale directly.

- The second retort is the Union Oil "B," which uses flowing gas as a heat-transfer medium as does "A." However, "B" is a gas-recycle retort in which hot gases are externally heated before they are injected into the kiln to heat the raw shale directly.

- The third retort is the Union Oil steam gas recirculation (SGR) system. The SGR system uses the "B" retort design as its center, but it includes a separate gasification vessel in which oxygen and steam are passed through the retorted shale to gasify the residual carbon. The hot recycle synthesis gas is then injected into the retort for pyrolysis of incoming shale.

All three retorting processes employ a vertical conically shaped kiln, although "A" is open to the atmosphere at the top and "B" and SGR are not. In all three retorts, coarsely crushed shale is fed up from the bottom of the retort by a rock pump. Shale is heated in the upper zone, pyrolysis occurs in the middle zone, and oil and gas are recovered at the bottom. Retorted shale is removed at the top.

The Union "A" design was developed in the late 1940's and was first demonstrated with a 2-ton/day plant in California, followed by a 50-ton/day pilot plant. The company constructed a 350-ton/day semiworks unit in Parachute Creek Canyon, Colorado, in 1954 and operated it until 1958. During these years the semiworks plant was further developed; it achieved operation at 1,200 tons/day for continuous periods up to 6 weeks. It has been dismantled, and no recent development of the Union Oil "A" process has been reported. However, Union Oil is satisfied that it has the technology to design and operate a single 1,700-ton/day retort, which can be followed by a 3,000-ton/day retort.

Since a commercial-size plant should have a 10,000-ton/day or more retort, the Union Oil technology demonstrated is about one-sixth of commercial scale (3).

The Union Oil "A" process has good potential for commercial exploitation. The 1,200-ton/day retort demonstrated a capacity four times that of the Gas Combustion process over extended periods of continuous operation. Scale-up problems might occur, but it should be possible to establish an efficient commercial-scale facility in a reasonable amount of time.

The Union Oil "B" retort was tested in a pilot plant in California. It has not been field tested on a large scale. Union Oil is currently considering construction of a 10,000-ton/day "B" retort in Parachute Creek Canyon, Colorado. The plant site (bench) would be located at the mouth of a room-and-pillar mine 1,500 ft above the valley floor. Before Union Oil proceeds, it needs Federal support to ensure that court action delays will be avoided and economic incentives provided (10).

Union Oil has operated a 3-ton/day SGR system pilot plant in California since October 1973 (1). This plant extracts 100 percent of the Fischer assayed value of oil from shale, converts about 82 percent of the shale's thermal energy to shale oil and fuel gas, and can produce either low- or high-Btu gas (11) for electrical power generation or auxiliary fuel.

In summary, Union "A" is a relatively simple retort. Oil yields are relatively low, at about 85 percent of Fischer assay. The retort gases are grossly diluted with atmospheric nitrogen and carbon dioxide, and the product gas has a very low heating value. Union "B" is a more complex retort because of the external heater and additional heat transfer equipment, but it has higher oil yields and its product gas has a high heating value. However, in Union "B" the residual carbon on the retorted shale is not recovered. SGR, based on "B," has the high-energy recovery of "A," since it does gasify the residual carbon and has the high oil yield of "B." Surplus synthesis gas from the SGR gasifier is useful for upgrading shale oil, and surplus product gas can be converted to synthetic natural gas and sold. However, engineering and cost studies indicated marginal economics for the SGR system; therefore, further work on this process has been shelved.

1.3.1 Mining and Handling

Oil shale for the Union Oil Company processes can be extracted from surface mines or from room-and-pillar mines as described in Chapter 3, Volume I. Union Oil has proposed that its modular 7,000-bbl/day "B" retort be located on a minemouth bench site of a room-and-pillar mine on the east fork of Parachute Creek, Colorado (12). The room-and-pillar mine should produce a 10,000-ton/day feed of 30 to 35 gal/ton shale.

1.3.2 Crushing and Sizing

The raw shale is crushed by primary and secondary crushers and sized and screened to a maximum size of 2 in. and a minimum size of 1/8 in. (3). All three Union Oil retorts must use a carefully controlled particle size distribution. Particles larger than 2 in. may not be completely retorted as they pass through the kiln, and fine shale particles (smaller than 1/8 in.) may settle in spaces between the coarser particles and create severe gas flow and solids flow problems. Particles smaller than 1/8 in. can be compressed into briquettes and disposed of with the retorted shale or stockpiled in the mine.

1.3.3 Retorting and Product Recovery

In all three retorts, the coarsely crushed shale is conveyed to the feed chute of an oscillating rock pump worked by two hydraulic cylinders at the bottom of the retort, as shown in Figure 3. The rock pump pushes the shale up into the vertical, refractory lined, conically shaped kiln.

Figure 4 shows the Union "A" retort. The top zone of the retort is open to the atmosphere. Incoming air is heated in this zone by contact with hot retorted shale (1). Air is further heated in the next lower zone where oxygen in the air ignites residual carbon on the retorted shale, producing flue gas with a temperature near 2000°F. Suction blowers draw these hot combustion gases down to the raw shale in the next lower zone. Pyrolysis occurs, and product oil vapors and gas are generated. In the bottom zone, feed shale is preheated by the shale oil vapors and the flue gases that are produced by retorting. These gases transfer their heat to the incoming shale as they are leaving the retort near the bottom, and exit as cooled gases and condensed oil to the recovery equipment. Shale ash is scraped from the top of the retort into a chute discharging to a conveyor belt. The entire heat requirement in the Union "A" process is obtained from combustion of residual carbon on the retorted shale.

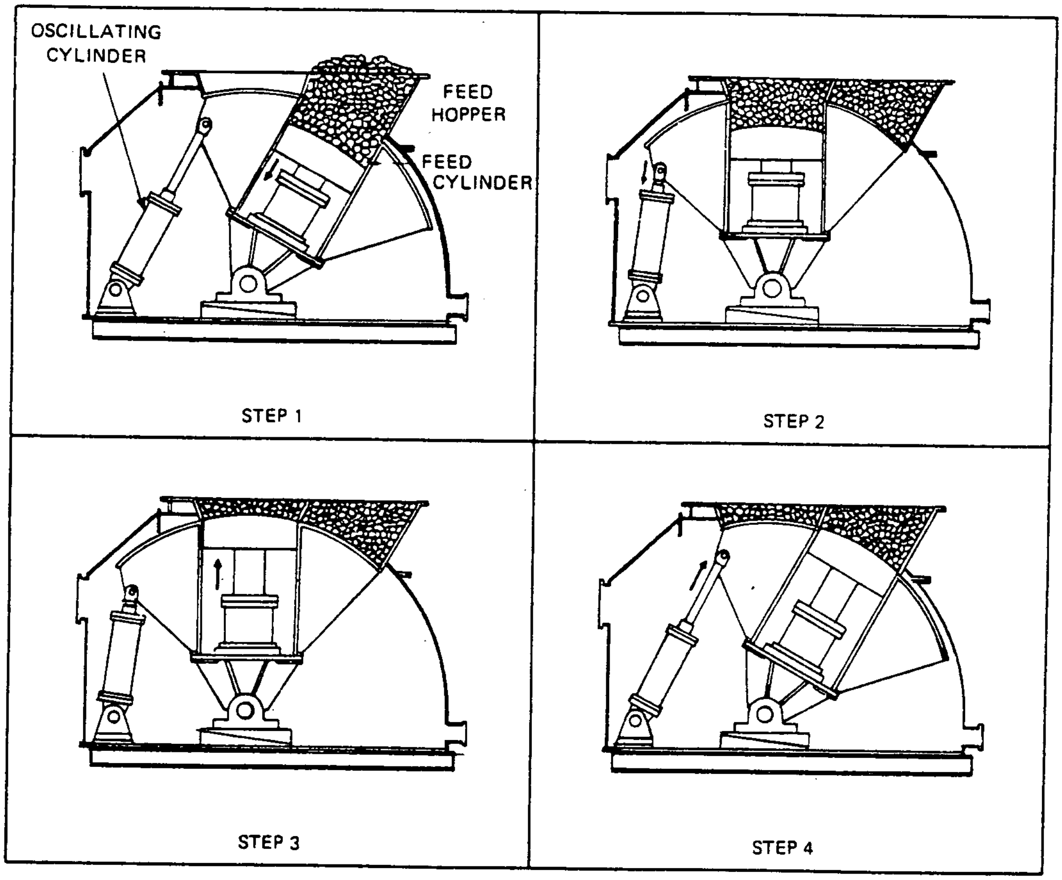

FIGURE 3. UNION OIL ROCK PUMP (9)

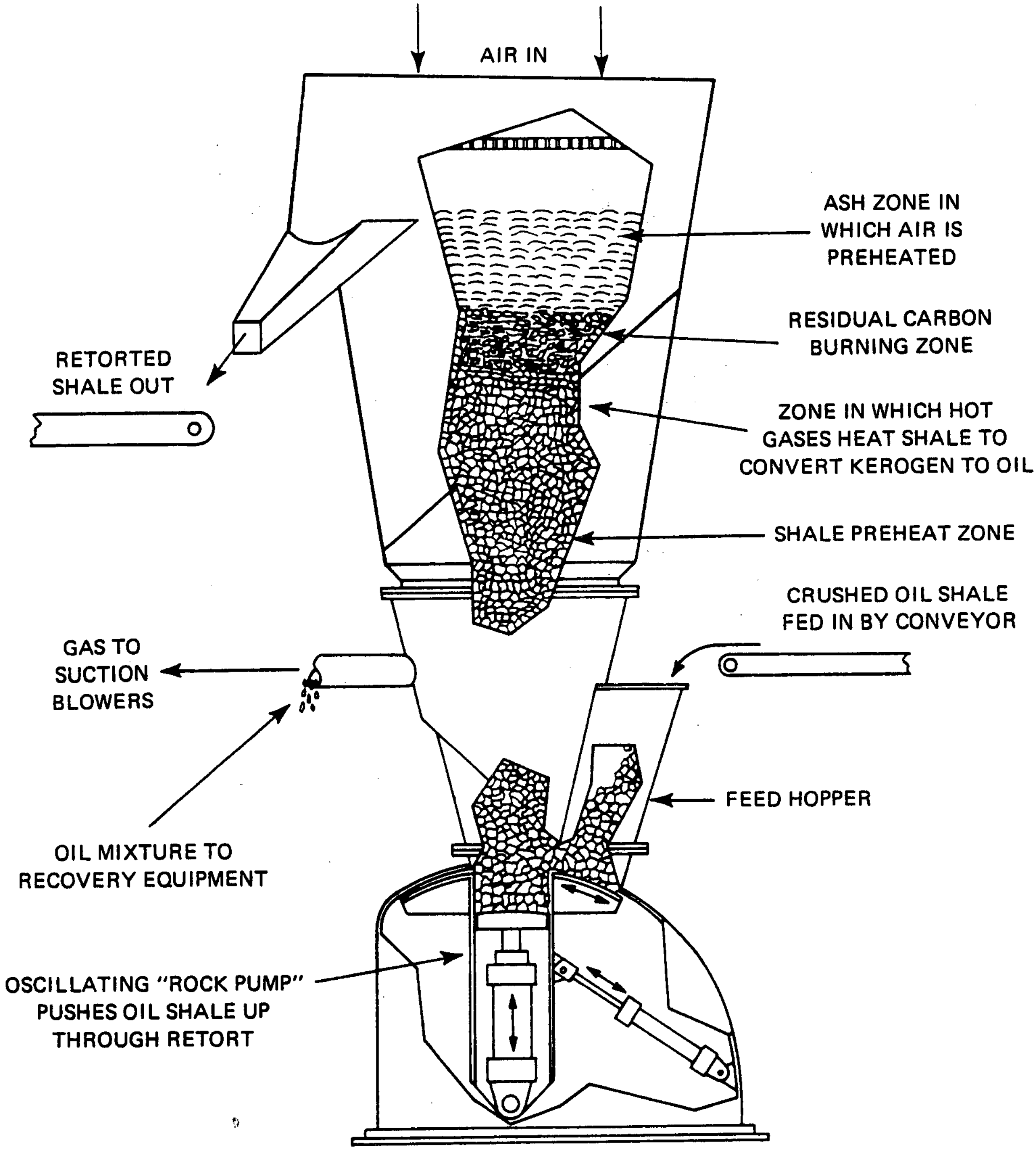

FIGURE 4. UNION OIL COMPANY "A" RETORT (1)

The Union "B" retort and the SGR system are similar to those of "A," but employ external heating and recycling of product gas. As stated previously, the Union "B" retort is the center of the SGR system (see Figure 5). In both retorts, the crushed shale is fed into a rock pump and pushed up through the retort.

In the Union "B" retort, gas is heated in a recycle gas heater and injected into the top of the retort for shale pyrolysis at a controlled temperature of 930° to 970° F. The retorted shale is discharged from the top of the retort and conveyed to a disposal site. In the SGR system, however, the hot retorted shale is conveyed into a separate gasifier (shown in Figure 5). Here is a process unique among American retorts: the gaseous heat carrier is generated by gasification of residual carbon in the retorted shale with recycle gas, steam, and oxygen or air. Part of the hot synthesis gas, which is rich in carbon monoxide and hydrogen, is returned to the retort for oil shale pyrolysis. Surplus synthesis gas from the gasifier and surplus product gas from the retort can be treated and used as plant fuel or converted to synthetic natural gas and sold.

In the Union "A" process, the oil drains from the retort to the bottom of a Rotoclone collector. The gaseous products of retorting also pass through the collector, and large droplets of entrained oil are separated. Smaller oil mist particles are cooled, agglomerated, and separated from the gases in a mist separator. The recovered oil drains into the Rotoclone basin and mixes with the liquid oil from the retort. A sludge ejector removes shale fines and sediment that settle from the product oil. The product oil drains from the collection basin to an inspection tank from which it is pumped to storage (9).

Oil produced in the "B" and SGR versions is collected as a liquid near the base of the retort and treated to remove solids and arsenic. Solids removal is accomplished by two stages of water washing. The shale fines are collected in the water phase and are then recycled to the processed shale quench vessel (12).

The crude shale oil contains 50 ppm of chemically combined arsenic, which will be reduced to about 2 ppm in a proprietary Union process. The oil is reacted with an absorbent that picks up arsenic to about 80 percent of its weight. The oil is then sent to upgrading and sold as synthetic crude.

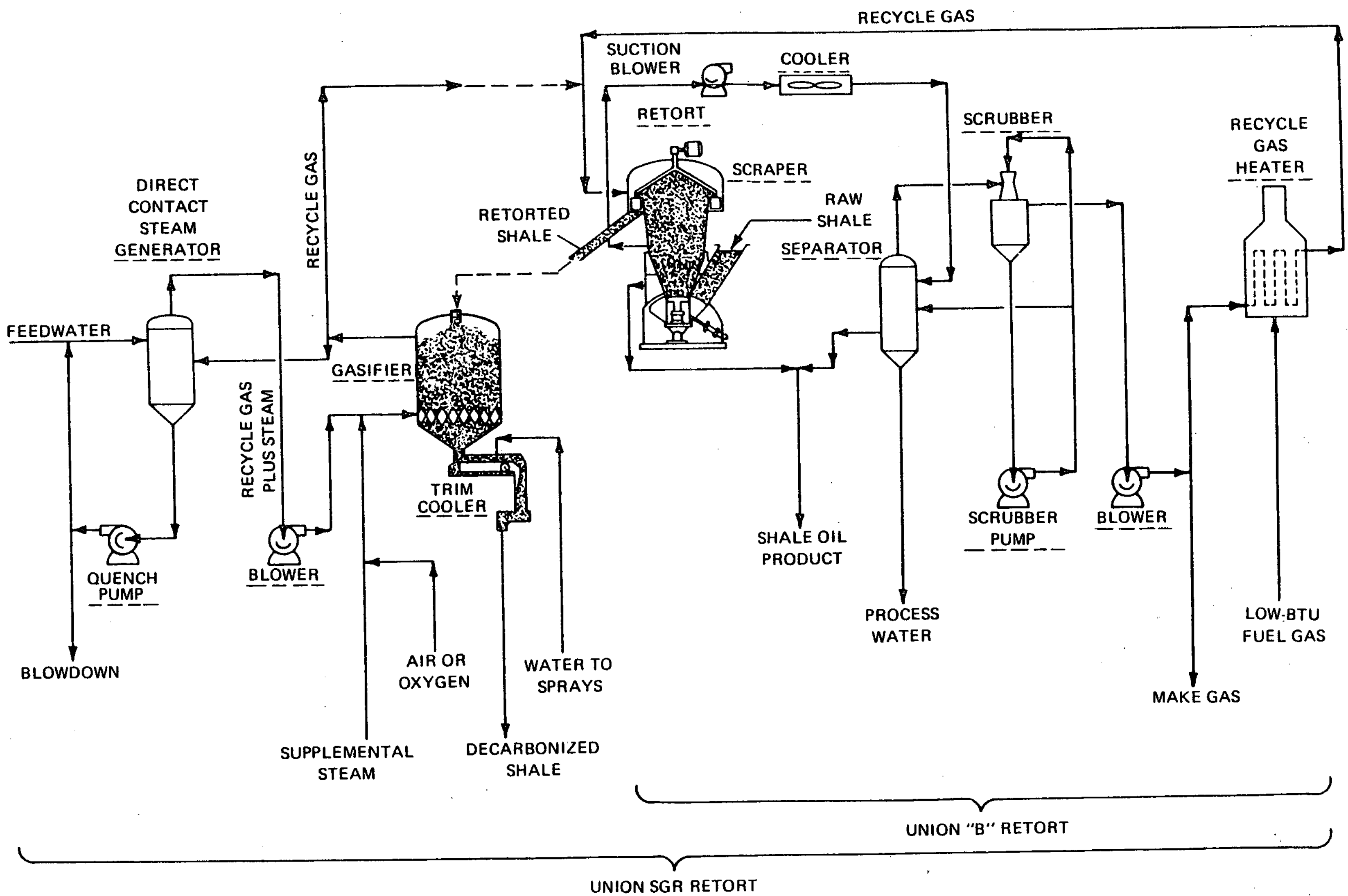

FIGURE 5. UNION "B" AND UNION SGR RETORTS

Oil particles entrained in the gas stream exiting from the retort are separated by a Venturi scrubber that cleans and cools the gas stream. Agglomerated mist plus light ends and water produced by cooling are sent to an oil-water separator. The oil is returned to the retort through the raw shale feed line. Thus, the feeding mechanism is filled with oil, providing a liquid seal that prevents air being drawn into the kiln through the shale feeder (9). After the oil is fed into the retort with the raw shale, it is ready to be drawn off with liquid oil produced during retorting. Water from the oil-water separator is stripped to remove ammonia and recycled to the processed shale quench vessel.

The typical properties of Colorado shale oil produced by the Union "A," SGR, and "B" retort processes are given in Table 2.

TABLE 2

PROPERTIES OF CRUDE SHALE OIL PRODUCED BY UNION RETORTING PROCESSES (1,3,9,13)

Property	Retort Type				
	Union "A"			Union SGR	Union "B"
Gravity (°API)	20.70	17.45	20.70	21.50	22.7
Pour Point (°F)	90	85	90	70	60
Viscosity					
(SUS at 100°F)	223	690	—	—	98.2
(SUS at 122°F)	—	—	113	—	—
Nitrogen (wt pct)	2.01	2.20	1.90	1.80	1.74
Sulfur (wt pct)	0.77	0.80	0.81	0.70	0.81

Retort gases from the Union "A" process are diluted with combustion products (carbon oxides, inert air components) and contain a low heating value of about 80 Btu/scf. Characteristics and yields of retort gases from Union "A" are typical of internal combustion retorts operated at high temperature. Union "B" and SGR retort gases are undiluted and contain higher heating values. Retort gas properties of the Union "A" and "B" processes are given in Table 3.

TABLE 3

GAS PROPERTIES OF THE UNION "A" AND "B" RETORTS (1,3,9)

Property	Retort Type		
	Union "A"		Union "B"
Nitrogen (vol pct)	60.1	56.9	0
Carbon Monoxide (vol pct)	4.7	4.6	7.28
Carbon Dioxide (vol pct)	29.7	30.3	16.48
Hydrogen Sulfide (vol pct)	0.1	0.1	0.96
Hydrogen (vol pct)	2.2	2.2	18.20
Hydrocarbons (vol pct)	3.2	3.0	57.09
Gross Heating Value (Btu/scf)	83.0	80.8	800
Molecular Weight	32.0	—	—
Yield (scf/bbl of oil)	20,560	—	—

Retort gases from the "B" process are scrubbed in a Venturi scrubber and divided into a make-stream and a recycle stream. The recycle stream is compressed and heated prior to injection into the top of the retort. The make-gas is compressed and scrubbed to remove heavy ends and H_2S. (Oil is used to scrub out the heavy hydrocarbons and Stretford solution is used to remove H_2S.) The sweetened make-gas is about 850 Btu/scf and is used as plant fuel. Excess amounts can be converted to synthetic gas and sold.

1.3.4 Retorted Shale Handling

Retorted shale from the Union "A" retort and the SGR system has only a negligible quantity of residual carbon. In the Union "B," the residual carbon remains. The chemical and physical properties of Union Oil retorted shale are given in Tables 4 and 5, respectively.

TABLE 4

CHEMICAL PROPERTIES OF UNION OIL RETORTED SHALE (14)

Components	Retort "A" Shale Ash	SGR Retort Decarbonized Shale	Retort "B" Retorted Shale
SiO_2	35.3	39.2	31.5
CaO	27.2	27.3	19.6
MgO	9.0	8.2	5.7
Al_2O_3	8.5	8.9	6.9
Fe_2O_3	7.3	3.8	2.8
Na_2O	5.5	3.7	2.2
K_2O	2.8	2.7	1.6
SO_3	0.1	1.4	1.9
P_2O_5	2.2	0.5	0.4
Mineral CO_2	1.6	3.1	22.9
Organic C	0.5	0.3	4.3
Trace Elements	< 0.5	0.9	0.5
Nitrogen, Kjeldahl	—	—	0.2
Total	100.0	100.0	100.0
Ignition loss at 950°C (wt pct)	2.1	3.4	26.9
Free Silica—quartz (wt pct)	< 2	2-5	8.0
pH of Slurry	12.5 to 13 (est.)	12.5	8.7

[1]Analyses determined by heating sample to 950°C.

[2]Analyses by Union Research Department.

TABLE 5

PHYSICAL PROPERTIES OF UNION OIL RETORTED SHALE (14)

Property[1]	Retort "B" Retorted Shale Fresh		SGR Retort Decarbonized Shale Fresh		Retort "A" Shale Ash 16 Years Old
	Initial	After Compaction at 12,375 ft-lb/cu ft	Initial	After Compaction at 12,375 ft-lb/cu ft	Composite Sample In Place
Particle Size					
Percent Cobble (1-6 in.)	—	—	—	—	8-28
Percent Gravel (4.76 mm-1 in.)	74	37	75	53	43-57
Percent Sand (0.074-4.76 mm)	16	39	16	14	15-23
Percent Silt (0.005-0.074 mm)	9	17	5	} 33	} 8-13
Percent Clay (- 0.005 mm)	1	7	4		
Soil Grouping (U.S.C. System)	GF-GM	—	GM	—	GW-GM
Texture	Silty gravel	—	Silty gravel	—	Graded gravel to silty gravel
Color	Black	—	Buff	—	Light brown
Solids Density (g/cu cm)	2.59	—	2.69	—	2.36
Dry Bulk Density (lb/cu ft)	61	90.4	—	68.5	60.3-90.5
Unconfined Compressive Strength (psi after 28 days cure at 125°F)	—	13	—	361	—
Field Moisture (wt pct of dry solids)	16	21-23	—	—	12.1-45.0

[1]Analyses by Woodward-Clyde Consultants.

Retorted shale leaving the retort or gasifier goes to a quenching vessel, which cools the shale and adds about 20 wt pct water. Retorted shale is then conveyed to a processed shale disposal site for distribution and compaction to a density of about 90 lb/cu ft (dry basis) with an equilibrium moisture content of about 19 percent (12).

1.4 PETROSIX

The Petrosix oil shale retorting process, developed by Petrobras (Brazil's National Oil Company), is one of the more advanced aboveground retorting processes. Originally conceived for treating Brazilian oil shale, the process is similar in concept to its predecessor, the U.S. Bureau of Mines Gas Combustion process, except for the mode of heat supply. In the Gas Combustion process, heat for the shale pyrolysis is supplied by the combustion reactions occurring in the retort as a result of air injection. The Petrosix retort, however, does not use air injection to obtain the necessary heat. In this system, process heat is obtained by externally heating recycle gas before it is injected into the middle of the retort (3).

The process is characterized by continuous gravity flow of shale with countercurrent flow of gases, and by direct gas to solid heat transfer. The oil produced by shale pyrolysis leaves at the top of the retort as an entrained mist, along with the gaseous stream. The oil is condensed in electrostatic precipitators and part of the resulting noncondensible gas is recycled back into the retort. The portion not recycled is processed for sulfur removal before recovery as a high-Btu gaseous product. Retorted shale discharges through a grate mechanism at the bottom of the retort and is pumped in slurry form to a disposal site. A flow diagram of the process is shown in Figure 6.

Interest in the development of an oil shale industry in Brazil can be traced back to 1950, when a Brazilian government commission was appointed to study the oil shale deposits in Brazil. A pilot plant was constructed a few years later and operated for several years. The decision to proceed with a demonstration plant was made in the early 1960's, but it was almost 10 years before an operating unit was available (12).

The pilot plant has been dismantled, and the demonstration plant has been operating since mid-1972. Both plants are located in the same vicinity, in the southern Brazilian

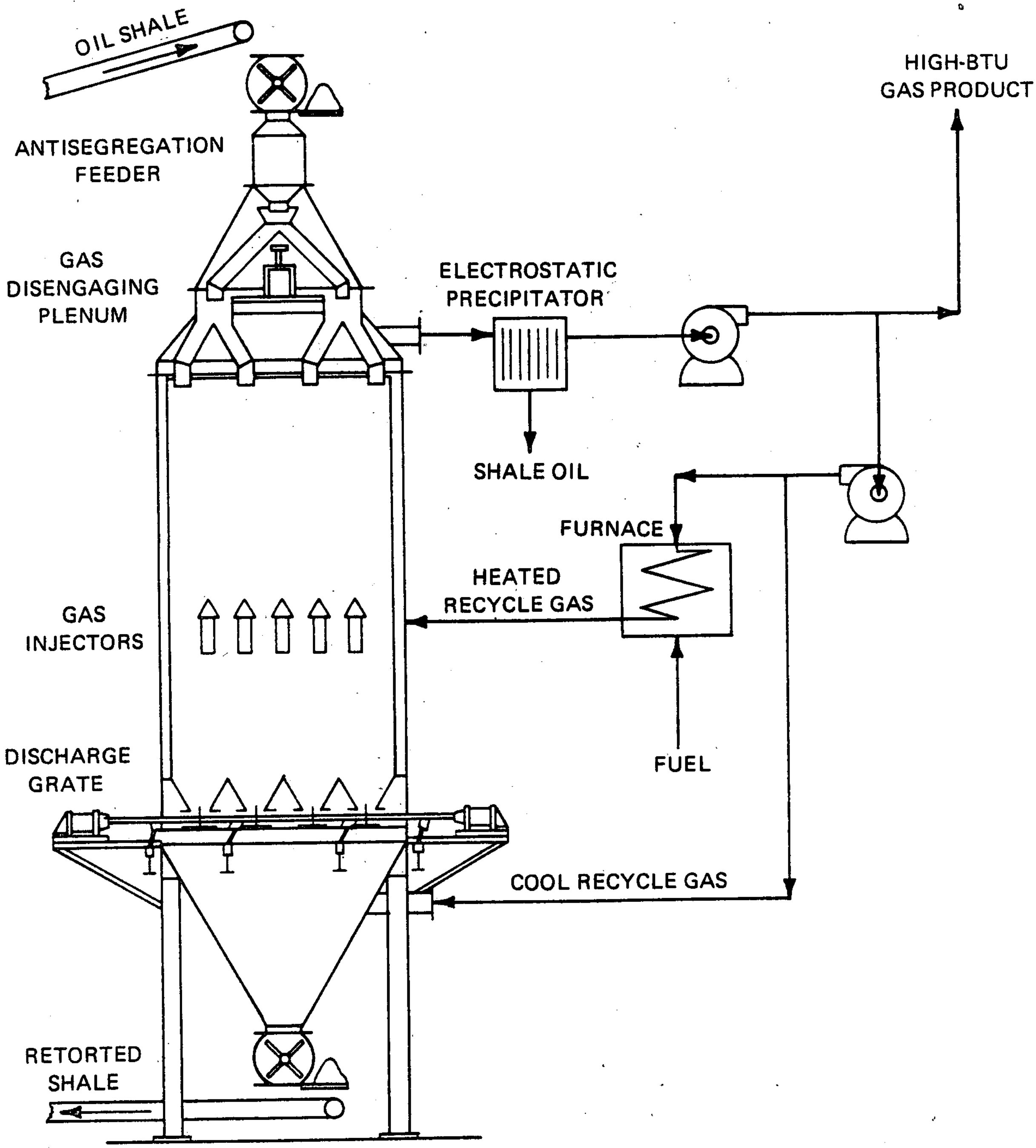

FIGURE 6. PETROSIX PROCESS (3)

State of Parana, near the town of Curitaba. The retort itself has functioned well since the startup of the demonstration unit, but minor problems have been encountered in the operation of the plant. These problems, however, have been mostly associated with auxiliary equipment, such as compressors, crushers, and other materials-handling equipment (12).

The demonstration plant was designed to handle 2,430 tons/day of shale, but it was anticipated that the optimum throughput would be lower. This expectation was confirmed during plant operations. Also, although an oil yield of 100 percent of the Fischer assay was obtained during pilot plant operation, only 90 percent recovery of the Fischer assay was reported with the demonstration unit. This is not a serious problem to Petrobras, whose operators have gained considerable experience with the plant and are confident of their ability to operate it (12).

The shale used in the Petrosix plant is mined from the Irati Formation in Southern Brazil. The Irati Formation displays outcrops for about 900 miles across the Southern Brazilian States of Sao Paulo, Parana, Santa Catarin, and Rio Grande do Sul. It is one of Brazil's most valuable mineral resources because of its extent and shale grade of about 20 gal/ton, which makes it a suitable feedstock for the Petrosix and a variety of other processes.

To meet growing energy demands, the decision to proceed with a commercial oil shale industry in Brazil has been made. The first commercial plant will probably be located close to the demonstration facility near the center of the deposit. The size of the operation is not known at this point, but a retort capacity roughly four times that of the demonstration unit has long been considered to be the goal (12).

The Petrosix process has hitherto been operated on only Brazilian shale. The process will have to be extensively tested on Green River shale before it can be commercialized in the United States. Some confidence can be derived from the success of experiments with the Paraho process, which when operated in the indirect mode is similar to the Petrosix process.

1.4.1 Mining and Handling

As previously mentioned, the source of oil shale for the Petrosix process is the Irati Formation, shown in

Figure 7. The formation typically occurs under the overburden in the following sequence of zones:

Zone	Thickness (Meters)
Upper bituminous shale	5 to 8
Middle limestone and shale	8 to 12
Lower bituminous shale	2 to 4.5

The upper zone of shale yields a dry Fischer assay of 6.1 wt pct; the lower zone of shale, 10 wt pct.

The overburden capping the formation is shallow enough for open pit mining. In fact, the present location is virtually free of intrusions of overburden, in this case an igneous rock (diabase). To locate commercially exploitable lengths of Irati outcrop requires well-planned geologic reconnaissance and core drilling.

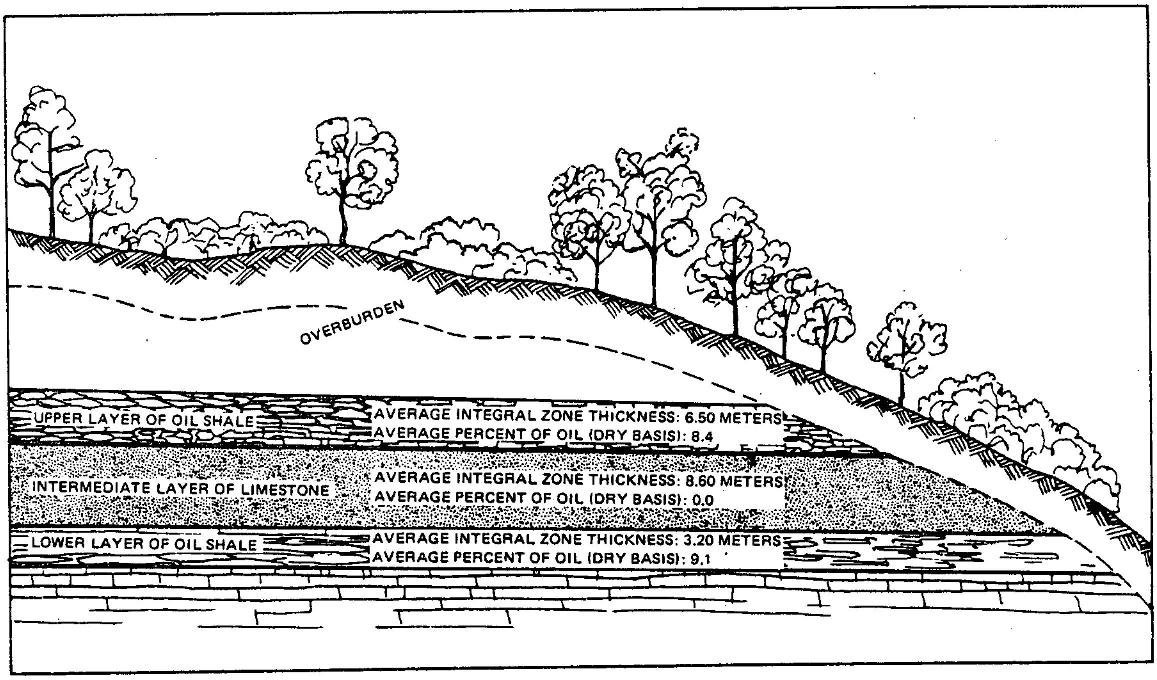

FIGURE 7. TYPICAL CROSS SECTION OF THE IRATI FORMATION (15)

After locating a thick, rich deposit, the overburden is drilled and blasted, and the broken rock is removed by bucket-wheel excavators and trucks to a specially constructed impounding dam. Intermediate partings are also drilled, blasted, and removed. The shale is mined using bucket-wheel excavators and high-speed movable conveyor belts. Overburden and limestone waste is backfilled in the empty pit behind the advancing mine face.

1.4.2 Crushing and Sizing

Petrobras does not appear to have released much information on its crushing plant. There are indications, however, that a particle size range of 1/4 to 3 in. is desirable for optimal operation of retorts of the Petrosix type, which uses an external source of heat (1). Particles larger than 3 in. may not have enough residence time in the retort for complete conversion, and particles smaller than 1/4 in. may hinder the flow of solids and cause an excessive pressure drop in the retort. The production of fines may be minimized by the use of single crushers.

1.4.3 Retorting and Product Recovery

The retort employed in the Petrosix process is a Cameron and Jones Kiln in which crushed shale is fed at the top through an antisegregation feeder, and flow occurs by gravity. The shale moves downward through a product cooling zone, a retorting zone, and a heat recovery zone. As the shale descends in the upper section (the product cooling zone), it meets the rising stream of hot gases and is heated to pyrolysis temperature, simultaneously cooling the gas. At this temperature the kerogen in the shale decomposes and yields oil, gas, and a carbonaceous residue. The oil produced is carried upward in the rising gas stream as an entrained phase while the retorted shale moves downward into the heat recovery zone.

During its passage in the heat recovery zone, the retorted shale transfers part of its sensible heat to the cold recycle gas that is introduced at the bottom. In the process the shale is cooled to about 200° to 300°F before it is discharged through a grate mechanism at the bottom. The discharge grate has annular openings, and a number of hydraulic cylinders (spaced around the circumference of the kiln) move the grate in a circular path to ensure a uniform outflow of the retorted shale (3). The shale is further cooled outside the retort by mixing with water; the slurry is then pumped to a disposal area.

The vapors leaving the retort at the top are passed through electrostatic precipitators where entrained oil is condensed and removed as a liquid stream. The resulting vapor is compressed and sent to a condenser where light oil fractions and water are separated from the noncondensible gases. The remaining gas is divided into three streams: one product stream and two recycle streams. The product stream is treated for sulfur retrieval before being recovered as a high-Btu fuel gas. Of the two recycle streams, one is introduced at the bottom of the retort at 130°F as a cold recycle. The other is heated to 1300°F by an external fuel source before being injected into the center of the retort.

Process heat in the Petrosix retort is obtained from the hot recycle gas stream injected into the middle of the kiln. The source of sensible heat of the recycle gas is fuel oil, which is burned in a recycle gas heater. The use of an external source such as this is thermally inefficient, since there is some combustible carbonaceous residue in the retorted shale effluent from the process. The Gas Combustion process is an example of a process that utilizes the combustion heat available from the retorted shale as a process heat source. There is, however, an advantage in the use of an external heat source, since the product gas is undiluted with nitrogen and consequently has a high heating value. The result is thus a tradeoff.

Data on oil and gas yields of the process are scant, but it has been indicated that the pilot plant did attain 100 percent of Fischer assay oil recovery (12). The demonstration unit, however, gave a lower oil yield, but Petrobras appears to be satisfied with 90 to 100 percent recovery.

The Petrosix process shale oil properties are as follows (9):

Gravity (°API)	19.6
Sulfur (wt pct)	1.06
Nitrogen (wt pct)	0.86
Pour Point (°F)	25
Viscosity (Centistokes) at 38°C	20.76

Operating data have not been released by Petrobras for the Petrosix plant or process. Gas properties and ASTM* distillation data are not available. However, it is expected that at 2,000 tons of raw shale per day input, the

*American Society for Testing Materials.

plant should yield 1,000 barrels of shale oil per day, 1.28 million cu ft of fuel gas per day, and 14 tons of elemental sulfur per day when treating typical Irati Formation shale (9).

1.4.4 Retorted Shale Handling

When the retorted shale is discharged from the Petrosix retort, it is further cooled with river water, which is pumped to the plant. Water is readily available in Brazil but less abundant in the semiarid oil shale regions of the United States. The shale is watered to form a slurry of 40 percent solids and pumped to a disposal pond behind a specially constructed impounding dam.

Since the shale in the Petrosix process is only pyrolyzed and not combusted, and since the particle size is limited and controlled in the process, the retorted shale is about the same size as the raw shale and there is little problem with fines.

The residual carbon content of the retorted shale is high because the process does not employ internal combustion heating.

1.5 PARAHO

Among the recent advances in the surface retorting of oil shale, the Paraho process is a notable development. Originally adapted from the Gas Combustion process technology, by Development Engineers Incorporated (DEI), the process incorporates important features from the Petrosix process as well.

Analogous to its antecedent processes the Paraho concept is essentially one of retorting in a vertical kiln by gravity flow of oil shale and countercurrent flow of gases. In the upper region of the retort, the shale is heated by contact with hot gas, and upon attaining pyrolysis temperature it yields oil, gas, and a carbonaceous residue. The unique feature of the process is that it can be operated either with or without air injection. With air injection, the air is mixed with cold recycle gas and introduced at different levels in the lower part of the retort. Consequently, the operating characteristics in this condition are similar to those of the Gas Combustion retort. When air injection is not used, hot recycle gas is introduced into the retort and the sensible heat of the gas raises the oil shale to pyrolysis temperature. Process heat in this mode of operation is obtained by external heating of recycle gas, and this corresponds to the Petrosix concept (9).

In each of these modes of operation, the oil produced leaves the retort at the top as an entrained phase in the gas stream. The gas is next passed through an electrostatic precipitator where oil is condensed and separated. Part of the resulting gas is recycled, and the remainder is obtained as a fuel gas product. The retorted shale leaving the retort bottom is cooled by mixing with water and is then conveyed to a disposal site. A flow diagram of the process in the air injection mode is shown in Figure 8.

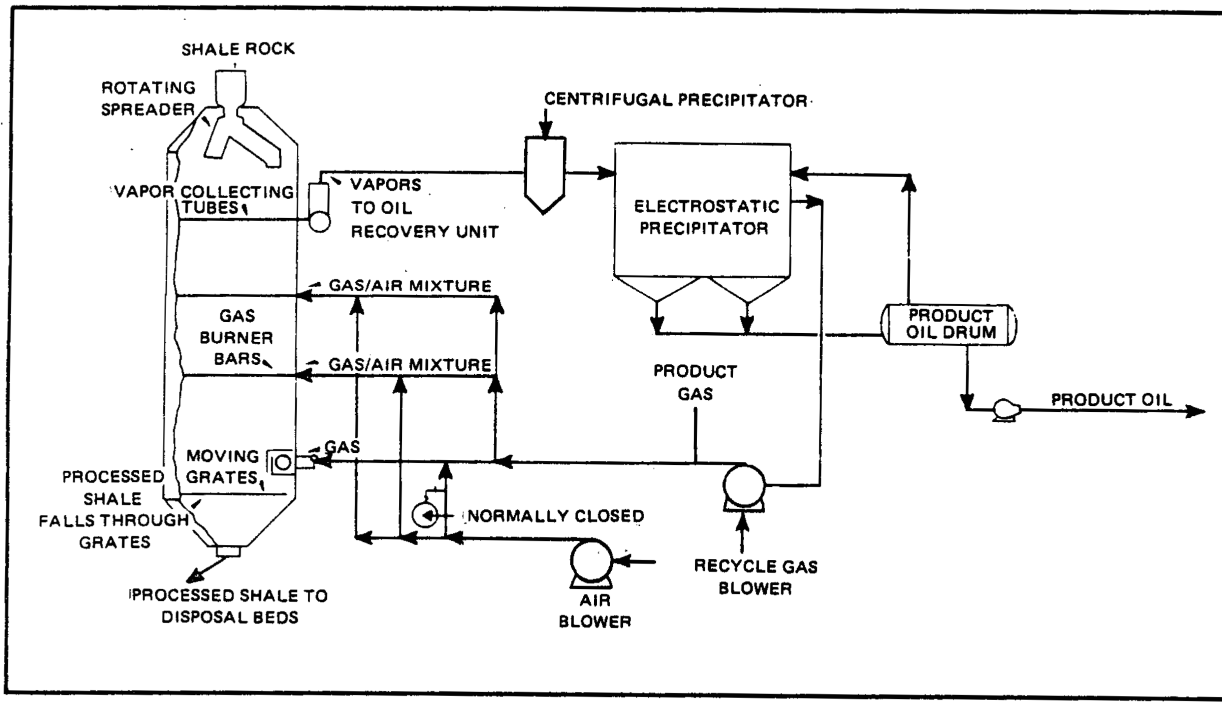

FIGURE 8. PROPOSED VERTICAL-TYPE DH RETORT (16)

Although the Paraho process concept appears to have been borrowed from Gas Combustion and Petrosix technologies, the retort design itself is similar to that of a lime kiln. Prior to the development of the Paraho process, DEI had conducted extensive testing of the Paraho kiln as a limestone calciner, and the tests verified the ability of the hardware to handle high throughputs of hot abrasive solids. Upon completion of the tests, in 1970, DEI acquired a 5-year lease of the Bureau of Mines oil shale facility at Anvil Points, Colorado (1). This was followed by the formation of a consortium of 17 companies, each of which contributed financially to the project.

Experiments with a pilot-scale unit began in mid-1973, and experiments with a semiworks kiln were initiated in mid-1974. The two kilns have been operating successfully. Throughput rates in excess of 400 tons/day of shale have been achieved in the semiworks kiln (1), which has been operated continuously for 56 days. The two retorts have achieved oil recoveries in excess of 95 percent of the Fischer assay, which has averaged about 28 gal/ton for the shale used. The results obtained from the operations have so far been encouraging, and DEI is currently exploring the possibility of constructing a commercial-size module for demonstration purposes. The decision with regard to this step in the process will be taken as soon as the technical and economic feasibility and the environmental impact of a commercial venture have been determined (17).

1.5.1 Mining and Handling

Oil shale for the Paraho process will probably be mined by the room-and-pillar method (described in Chapter 3, Volume I).

1.5.2 Crushing and Sizing

The process of preparing the retort feed requires facilities for crushing, screening, storing, and feeding the retorts. Based on the experience with the two experimental units, a commercial-scale Paraho retort will use a shale feed of rubble size ranging from 1/2 to 3 in. (18). The mined rock will be reduced to this size in two stages. In the first stage, roll crushers will be used to reduce the rubble particle to less than 10 in., which is suitable for transporting on conveyor belts. The primary crushers will be located underground at the mining level or aboveground at the mine portal bench level. The primary crushing facility will also include a control room with dust suppression and collection equipment and a ventilating fan, apron feeders, cranes, and servicing facilities. Crushed rock from the primary crushers will be reduced to the retort feed size in secondary roll crushers, which will be situated aboveground and close to the retort facilities.

To ensure uninterrupted operation of the secondary crushers and the retorts, primary crushed shale will be stockpiled at a convenient location. The mine haulage system and primary crushing operations will be interdependent. If the primary crusher is shut down, haulage from the mine will be stopped and the secondary crusher will be fed from the stockpile (16).

1.5.3 Retorting and Product Recovery

The Paraho process retort is operable in either of two ways: the direct heating (DH) mode and the indirect heating (IH) mode (Figures 9 and 10). When functioning in the IH mode, the process utilizes externally heated recycle gas to supply heat for shale pyrolysis. In the DH mode, in contrast, cold recycle gas, mixed with air, is introduced into the retort. Process heat in this mode is derived from the exothermic combustion reactions occurring in the retort as a result of air injection. These reactions, which occur in the combustion zone, consume carbonaceous residue in the retorted shale and hydrocarbons in the gas stream (17).

As shown in Figure 8, raw shale is fed into a hopper at the top of the retort. The raw shale is then introduced into the retort vessel with the help of a rotating spreader, which is also called a "pants leg" distributor. The linear grade mechanism at the bottom of the retort controls the residence time of the shale by providing a controlled and uniform rate of descent throughout the circular section of the retort. The grade mechanism is probably the most critical factor in retort design, since the performance of the kiln depends on control of the temperature profile along its length (19).

Recycle gases are fed into the kiln at three levels. The bottom level, consisting of gas distributing channels, is incorporated into the linear grate mechanism. At this level cool recycle gas is injected for IH as well as DH modes. As the gas rises in the retort, it gains sensible heat as a result of contact with descending retorted shale, causing the shale temperature to drop to about 350°F. The retorted shale product is then cooled with water and conveyed to a disposal site (17).

The middle and top distributors serve similar purposes and are separated from each other to allow better temperature control in the retort. In the DH mode, recycle gases mixed with air are introduced at these two levels. Combustion reactions occurring in the bed generate sufficient heat to raise the gases above shale pyrolysis temperature. Heat exchange with the rising gases brings the shale to pyrolysis temperature and decomposition follows. As a result of the heat transfer, the gas is cooled to about 140°F before it leaves the bed at the top. Upon leaving the bed, the gases are passed through a centrifugal separator for dust removal and then through an electrostatic precipitator, where

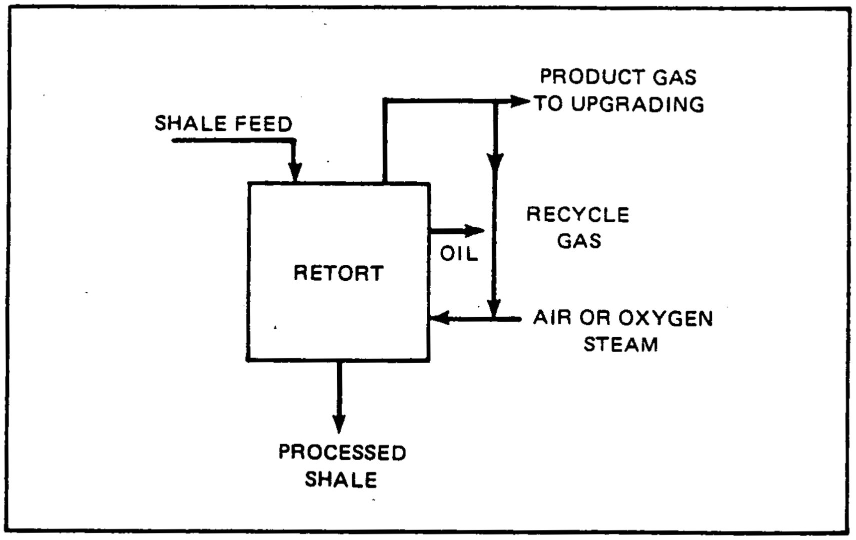

FIGURE 9. DIRECT-HEATED RETORTING SYSTEM

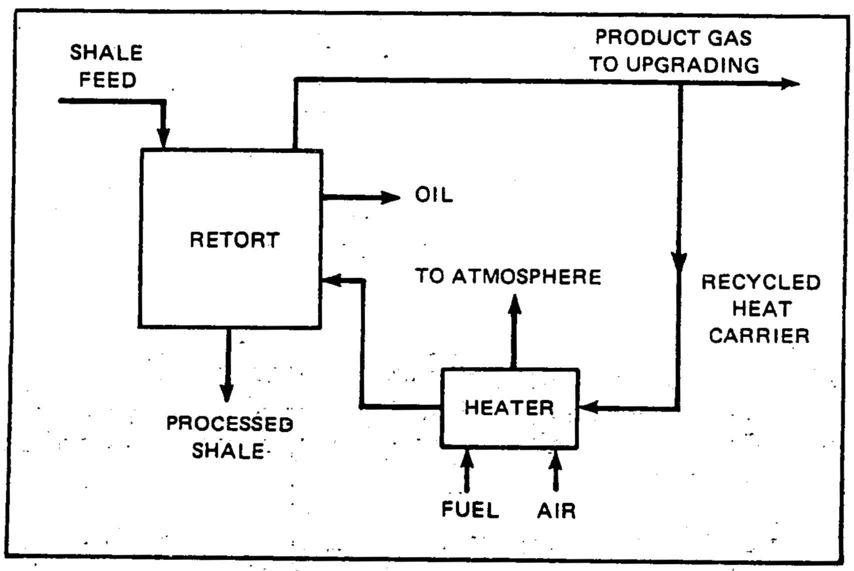

FIGURE 10. INDIRECT-HEATED RETORTING SYSTEM

the oil is condensed and removed as a liquid product stream. Part of the condensible gas is retrieved as a product stream while the remainder is recycled. In the IH mode, recycle gases are preheated in an external heater before being introduced at the middle and top distributors. The heater may be designed to retort off-gas or fuel oil as a heat source. In this mode, gases leave the retort at 280°F and are passed through a similar product recovery system as the DH gas (17).

Collecting tubes in the upper part of the Paraho retort collect not only oil vapors and off-gases but also water vapors and particulates. The product recovery systems in the Paraho process are designed to recover oil and off-gases from the other by-products of retorting. The recovery system is expected to consist of the following equipment:

- Centrifugal precipitator
- Electrostatic precipitator
- Stack gas scrubber
- Gas incinerator
- Recycle gas equipment.

The centrifugal precipitator, the first unit in the recovery system, is normally used to separate particles greater than 25 microns from other products of retorting. The electrostatic precipitator, the second unit, will be used to remove oil from the remaining by-products. The crude oil is collected at the bottom of the electrostatic precipitator. The off-gas and water vapor mixture leaving the precipitator is passed through condensers that separate water from off-gases. The off-gas that is separated out will have to be scrubbed for removal of ammonia and hydrogen sulfide before it can be utilized for power generation or other purposes. The product gas leaving the scrubbers is a low-Btu gas in the DH mode and a high-Btu gas in the IH mode. The low-Btu gas can be used as a power plant fuel after upgrading, and the high-Btu can be economically transported and marketed.

Oil yields of up to 97 percent of the Fischer assay in both DH and IH modes have been reported for the Paraho process (see Table 6). Table 7 lists the properties of the oil produced by the process when operated in the DH and the IH modes. It is observed that the oil from the IH mode is more suitable for pipeline transport because of its lower viscosity and pour point (17).

Gas yields for the two modes of operation are presented in Table 6. For the DH mode the yield is somewhat lower than that of the modernized 360-ton Gas Combustion retort (see Table 1). These yields are, however, expected to improve with further research as more of the problems in operation are resolved.

In addition to producing different quantities of gas, the two modes also produce gas of significantly different composition and properties. Table 8 shows the following significant differences:

- Approximately one-fourth of the gas from the IH mode is hydrogen; the DH mode gas contains only 2.5 percent hydrogen.
- Methane (CH_4), which has high heating value, amounts to 28.7 percent by volume in the IH mode; but only 2.2 percent in the DH mode.
- Nitrogen and carbon dioxide form 90.1 percent of the DH mode gas, but only 15.8 percent of the IH mode gas.
- The IH mode gas contains much higher percentages of H_2S and NH_3 gases.

The higher quantities of methane and hydrogen in the IH mode gas are responsible for its high heating value. At 885 Btu/scf the gas from the IH mode is suitable for pipeline transport. In comparison, the heating value of the DH mode gas is only 100 Btu/scf and is not economical to transport.

1.5.4 Retorted Shale Handling

Retorted shale from the Paraho process has essentially the same size distribution as the raw feed, resulting in minimal fugitive dust during conveying and disposal. Upon discharging from the bottom of the retort, it is transported by conveyors to a holding bin. In a commercial unit a dust collection system will be provided at the discharge points and the retorted shale along with the raw shale fines will be transported to a disposal area. The material will be deposited in a stable manner and moistened to about 22 percent water for dust control and compaction.

TABLE 6

PRODUCT YIELDS OF PARAHO RETORTING (DRY BASIS) (17)

Product	Retort Type	
	DH Mode	IH Mode[1]
Shale Oil		
gal/ton	27.2[2]	27.2[2]
vol pct Fischer assay	97[2]	97[2]
Gas		
scf/ton	6,200[3]	500[3]

[1]Yield for indirect heated retort is gross; fuel for heater must be deducted.

[2]C_5 plus oil.

[3]C_4 minus gas.

NOTE: Yields were obtained with a 28-gal/ton raw shale feed.

TABLE 7

CHARACTERISTICS OF RAW SHALE OIL FROM PARAHO RETORT (17)

Property	Retort Type	
	DH Mode	IH Mode
Gravity (^{o}API)	21.4	21.7
Viscosity		
(SUS at 130^{o}F)	90	68
(SUS at 210^{o}F)	46	42
Pour Point (^{o}F)	85	65
Ramsbottom Carbon (wt pct)	1.7	1.3
Water Content (vol pct)	1.5	1.4
Solids, B.S. (wt pct)	0.5	0.6

TABLE 8

PROPERTIES OF GAS PRODUCED BY PARAHO RETORTING (DRY BASIS) (17)

Component	Retort Type	
	DH Mode	IH Mode
H_2	2.5 vol pct	24.8 vol pct
N_2	65.7 vol pct	0.7 vol pct
O_2	-0-	-0-
CO	2.5 vol pct	2.6 vol pct
CH_4	2.2 vol pct	28.7 vol pct
CO_2	24.4 vol pct	15.1 vol pct
C_2H_4	0.7 vol pct	9.0 vol pct
C_2H_6	0.6 vol pct	6.9 vol pct
C_3	0.7 vol pct	5.5 vol pct
C_4	0.4 vol pct	2.0 vol pct
H_2S	2,660 ppm	3.5 vol pct
NH_3	2,490 ppm	1.2 vol pct
High Heating Value	102 Btu/scf	885 Btu/scf

1.6 TOSCO II

The TOSCO II retorting process, developed by The Oil Shale Corporation (TOSCO), is unique among the surface retorting methods in its mode of heat transfer. Originally developed as a modification of the patented Swedish process Aspeco, to which TOSCO purchased the rights in 1952, the process is characterized by its use of solid-to-solid heat transfer during pyrolysis. This method of heat exchange is accomplished by the use of externally heated ceramic balls as heat carriers in the retort vessel.

Oil shale crushed to less than 3/8 in. is pyrolyzed in an inclined rotating drum into which hot ceramic balls, of about 1/2-in. diameter, are fed. Oil and light hydrocarbon gases produced by pyrolysis leave the retort as hot vapors and are collected in an accumulator, condensed, and fractionated for further processing. Part of the processed gas is used to preheat the shale and ceramic balls. The retorted shale and ceramic balls leaving the retort are separated in a rotating trommel screen, and the retrieved balls are reheated in a ball heater. Retorted shale is cooled, moisturized, and sent to disposal. A flow diagram of the process appears in Figure 11.

Having purchased the rights to the Swedish Aspeco process, TOSCO contracted early developmental work to the Denver Research Institute. This work led to the construction of a 24-ton/day plant at Denver, Colorado, in 1957. Initial research conducted under this contract focused on the retorting system, and both concurrent and countercurrent flows of shale and ceramic balls were investigated. Also studied were various retort gas-scrubbing processes, fluidized-bed combustion of retorted shale, a process for heating the ceramic balls, and some oil shale preheating methods (9).

Encouraged by the progress achieved in the early developmental work, TOSCO, in 1964, formed a joint venture with SOHIO and Cleveland Cliffs Iron Company to demonstrate the retorting of oil shale on the semiworks scale by the TOSCO II retorting process. In this venture, originally called "Oil Shale Venture," a retort was built with a 1,000-ton/day capacity, which was operated in Colorado from 1965 to 1967 and from 1971 to 1972. In 1969, when ARCO joined the venture, the name was changed to Colony Development Company. Later, Ashland Oil Company and Shell Oil Company replaced SOHIO and Cleveland Cliffs (18).

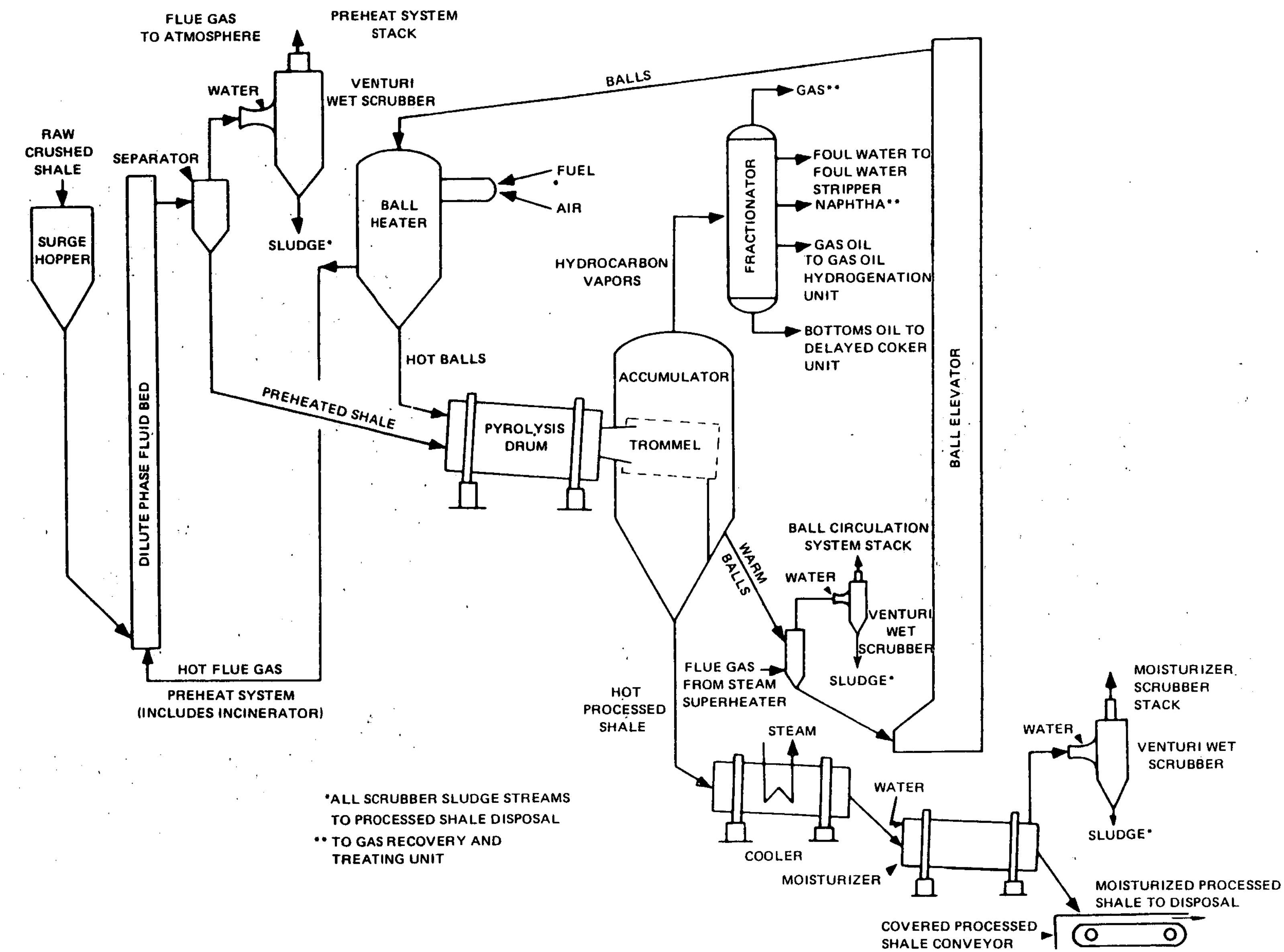

FIGURE 11. PYROLYSIS AND OIL RECOVERY UNIT OF TOSCO II PROCESS (20)

Until 1972, more than 1 million tons of 35-gal/ton oil shale were mined, and about 290,000 tons were retorted during the operation of the semiworks retort and associated pilot room-and-pillar mine. This operation produced some 200,000 barrels of oil (18).

The Colony Development Company is now in the commercialization phase of its project and plans to construct and operate a 50,000-bbl/day commercial-scale plant in Colorado. Construction plans have, however, been at a standstill since 1974 pending initiation of a Federal-sponsored Synfuels Commercialization Program. It is proposed that, when underway, the plant will be located on the Dow West property of the Middle Fork of Parachute Creek, with retorted shale disposal in nearby Davis Gulch. The proposed shale oil complex is illustrated in Figure 12.

An extensive environmental assessment of the proposed plant has been conducted by Colony and the analysis has been published in a 20-volume report (22). A formal Draft Environmental Impact Statement (EIS) by the Bureau of Land Management was issued in December 1975 (21), and hearings on this EIS occurred in January 1976. As yet, final approval has not been granted.

1.6.1 Mining and Handling

Oil shale for the TOSCO II process will probably be mined by the room-and-pillar method (described in Chapter 3, Volume I).

1.6.2 Crushing and Sizing

Run-of-mine shale size will be reduced to minus 1/2 in. before it is fed into the retorting system. This crushing will be done in two stages: primary crushing, which will be performed at the mine portal bench level, and secondary crushing, which will be carried out on the plateau near the retorting facility. A totally enclosed conveyor system will be used to transport crushed shale between the crusher, storage areas, and retort.

Coarse ore from the primary crusher will be discharged to an inclined conveyor system for transport to the final crushing plant. A storage pile of coarse ore will be maintained to ensure a continuous supply to the secondary crushers in the event of a breakdown of the primary crushing facilities. A storage bin for fine crushed ore will also be maintained to provide uninterrupted feed to the retorts in case of short breakdowns of the final crushing unit.

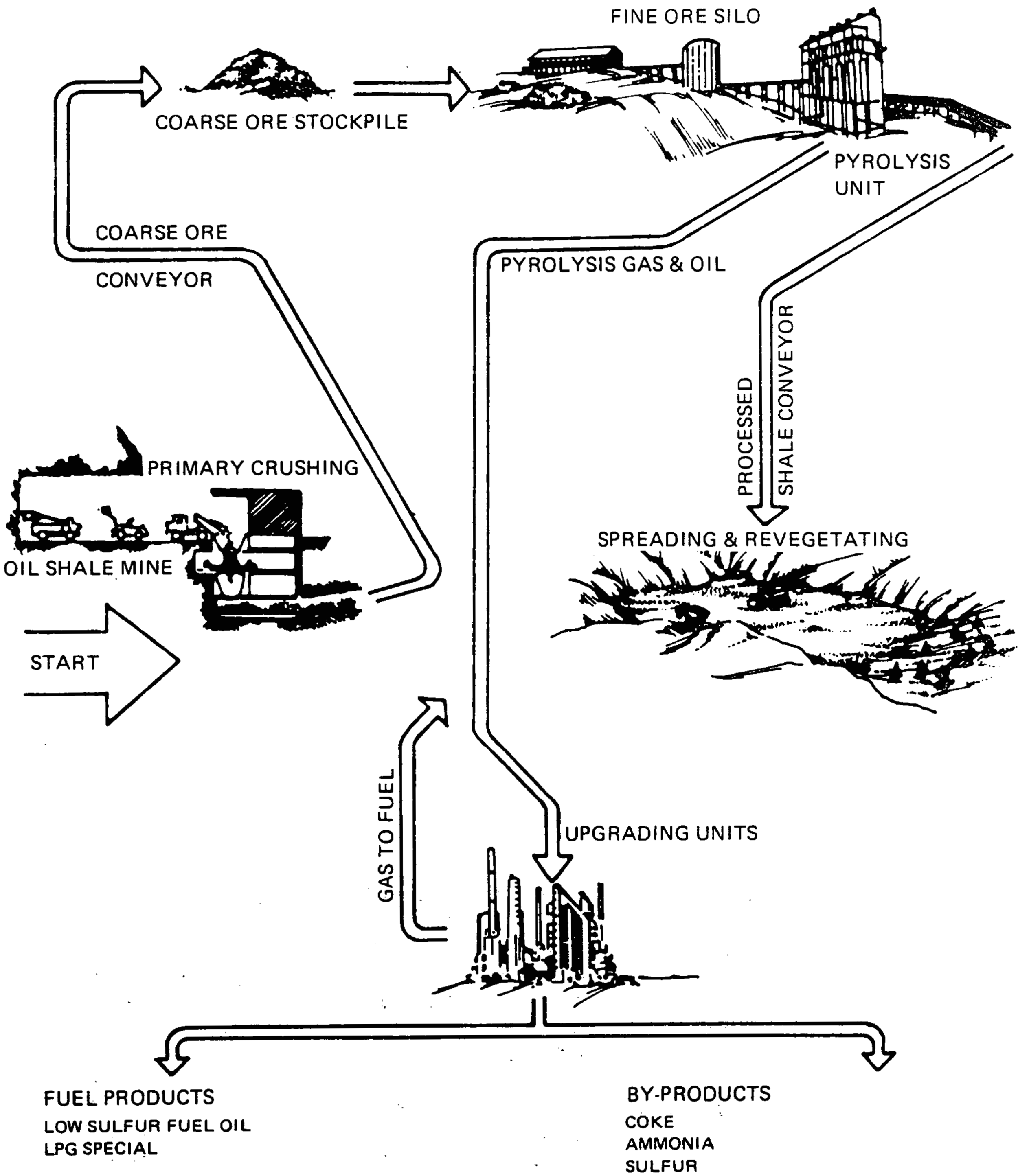

FIGURE 12. TOSCO II OIL SHALE PROCESSING (21)

1.6.3 Retorting and Product Recovery

Unlike its other American counterparts, the TOSCO II process uses a solid heat carrier at a heat source for shale pyrolysis. This heat carrier, in the form of 1/2-in.-diameter ceramic balls, transfers heat to oil shale particles through solid-solid contact between the two species. This heat carrier is more efficient than the gas-solid heat transfer mechanism that is used in most other surface retorting processes.

Referring again to the flow diagram of the process in Figure 11, one can see that raw oil shale, crushed to minus 1/2 in., enters the retorting system through a surge hopper. Upon leaving the surge hopper, the shale is fed to a series of pneumatic lift pipes where a dilute phase fluidized bed of shale is maintained by a stream of hot flue gas from the ball heater. Contact with the flue gas raises the temperature of the shale to about 500°F before it is separated out in settling chambers and cyclones, and fed to a rotating drum retort (pyrolysis vessel) along with a stream of hot ceramic balls. The pyrolysis vessel is essentially an insulated ball mill in which the oil shale and ceramic balls are mixed. As a result of the mixing, good solid-solid heat exchange occurs and the oil shale is heated to the pyrolysis temperature of about 900°F. As the shale pyrolyzes, it loses a large amount of its physical strength and is crushed by the balls to a fine powder. The products of pyrolysis (hydrocarbon vapors) are withdrawn continuously from the rotating drum and recovered in an oil recovery system, leaving behind a mixture of ceramic balls and processed shale.

The retorted shale and ceramic balls leave the pyrolysis drum at about 900°F and enter a perforated rotating trommel. Shale powder passes through the perforations in the trommel and is cooled and conveyed away for disposal. The warm balls leaving the trommel are purged of residual dust by flue gas from a steam superheater, and the dust is removed from the flue gas by means of a high-energy Venturi wet scrubber. The scrubbed gas is then discharged into the atmosphere. The dust-free warm balls are lifted up in a bucket elevator and delivered to the ball heater. In the heater the balls are heated to about 1300°F in a burning mixture of retort gas and air, before being recirculated to the pyrolysis drum.

Oil vapors and gases from the pyrolysis vessel enter the vertical accumulator, then pass on into a fractionator, where they are cooled and separated into gas, naphtha, gas oil, and residue streams. The gas stream, which is obtained as a top product, is sent to the gas recovery and treating unit before being used as plant fuel.

The product recovery system in the TOSCO II process is designed to separate the liquids and gases from the vapor stream that leaves the pyrolysis vessel and further process them into saleable products. The recovery system consists of the following equipment:

- Fractionating column
- Gas desulfurization unit
- Gas recycle equipment.

The gas obtained as an overhead product in the fractionating column is passed through a desulfurization unit for H_2S removal, before being recovered as a high-Btu gaseous product. Part of this gas is recycled for use as fuel in the ball heater.

The TOSCO II process can accept for retort feed shale of a wide Fischer assay range. The Rio Blanco oil shale project Tract C-a will process oil shale with a Fischer assay of 20 gal/ton. The C-b Shale Oil Project plans to process shale averaging 35 gal/ton, as does the Colony Development Operation. The process has also demonstrated high yields, and in one 7-day run in the semiworks unit, a 107.6 vol pct of Fischer assay oil yield was produced (15). A yield of 100 percent is expected for a commercial-scale TOSCO II facility (3). In addition, if the carbon residue left in the retorted shale is used to generate heat for the ball heater, gas production will be enhanced and a higher thermal efficiency will be possible.

Little has been published concerning conventional heat and material balances for the TOSCO II retorting process. Properties of the crude oil from the process are listed in Table 9.

TABLE 9

PROPERTIES OF CRUDE SHALE OIL FROM TOSCO II PROCESS (3)

Oil Properties	
Gravity (^{o}API)	28.0
Sulfur (wt pct)	0.8
Nitrogen (wt pct)	1.7
Pour Point (^{o}F)	75
Viscosity (SUS at 100^{o}F)	120

Inspection of the tabulated data reveals that TOSCO II crude shale oil has a higher gravity (API) than that generally obtained from other surface retorting processes, and is consequently less dense. In addition, the pour point of 75°F is lower than that of shale oils obtained from most of the other processes and hence the TOSCO II shale oil has better pipeline transport characteristics.

Estimated properties of the gas produced by the TOSCO II retorting process are listed in Table 10.

TABLE 10

PROPERTIES OF TOSCO II RETORT GAS (16)

Gas Properties	
Nitrogen (vol pct)	0
Carbon Monoxide (vol pct)	3.3
Carbon Dioxide (vol pct)	19.6
Hydrogen Sulfide (vol pct)	3.9
Hydrogen (vol pct)	19.5
Hydrocarbons (vol pct)	53.7
Gross Heating Value (Btu/scf)	885
Molecular Weight	29
Yield (scf/bbl of oil)	920

Since no combustion air is used in the retort, the produced gas is undiluted with nitrogen and consequently has a high heating value. However, the gas yield is somewhat low, but this is compensated by oil yields in excess of 100 percent of the Fischer assay.

Detailed operating data for the TOSCO II pilot plant or semiworks plant have not been published.

1.6.4 Retorted Shale Handling

Retorted shale from the TOSCO II process consists of finely divided particles in the sand-to-clay size range. Disposal of such fine material requires greater amounts of water for moistening before transportation. Additionally, special care has to be taken in handling the fine processed shale because of the inherent dust problem.

Retorted shale from the TOSCO II retort is prepared for disposal by cooling and moisturizing to about 14 percent water content for dust control and compaction. It is then transported by enclosed conveyors either to a nearby surface disposal area or to trucks for delivery to a remote off-tract surface disposal site. The open pit mining proposed for the Rio Blanco Oil Shale Project, Tract C-a, requires an off-tract disposal site for maximum resource utilization (23).

At the disposal area, retorted shale will be spread in layers and compacted for stability. When it reaches its final elevation, the shale will be contoured in conformance with surrounding topography, covered with overburden and topsoil, and revegetated; or sculptured into planting basins and water harvesting surfaces. In this latter method, each planting basin will contain a trench filled with topsoil, and plants will be placed in these trenches (16). Boulders and crushed rock from mine waste may be deposited as a buffer zone between retorted shale and topsoil to keep toxic elements in retorted shale separate from plant roots.

1.7 SUPERIOR OIL COMPANY

A block diagram of the Superior process is shown in Figure 13. The process uses oil shale containing the minerals nahcolite ($NaHCO_3$) and dawsonite ($NaAl[OH]_2CO_3$) to produce the following four products in one integrated operation (24,25):

- Shale oil
- Raw nahcolite
- Alumina
- Soda ash.

Nahcolite can be physically separated from the raw oil shale because of its differential crushing characteristics. It is proposed that the nahcolite be marketed as a gas-scrubbing agent. Shale oil is recovered by pyrolysis of the shale in a circular traveling grate retort, as conceptually drawn in Figure 14. The process generates high-Btu gas for plant fuel requirements by reacting recycle gas, steam, and air

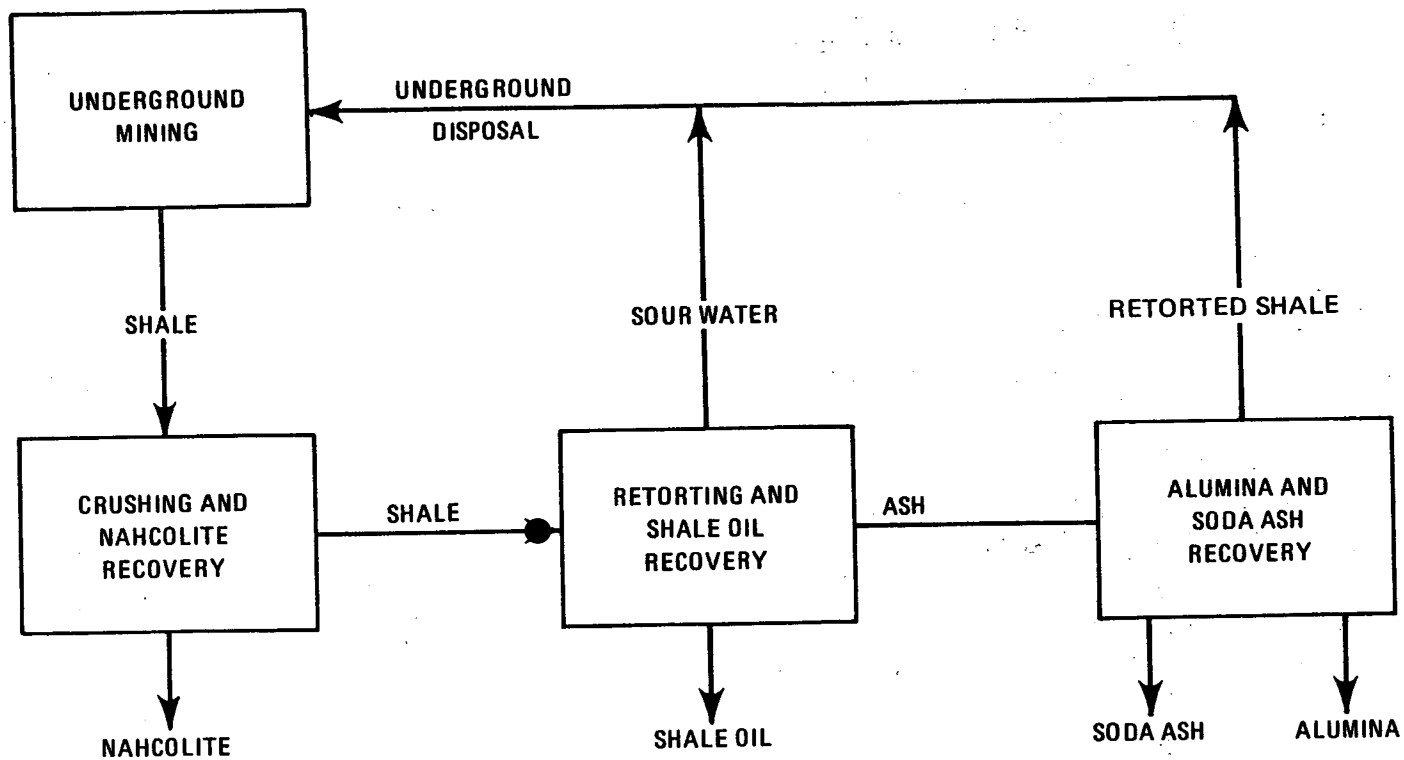

FIGURE 13. BLOCK DIAGRAM OF SUPERIOR'S MULTI-MINERAL OIL SHALE PROCESS (24, 25)

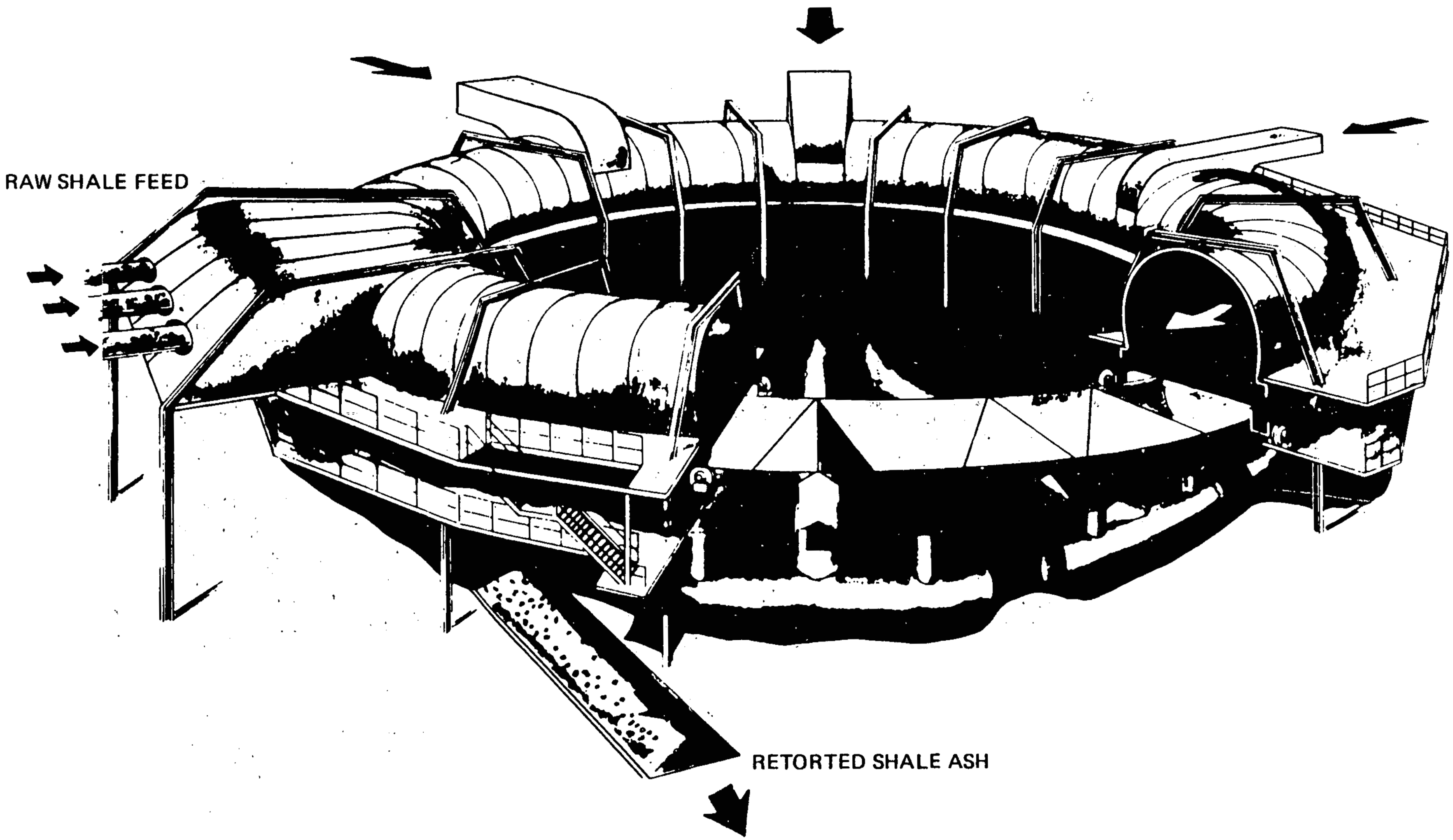

FIGURE 14. CONCEPTUAL DRAWING OF CIRCULAR TRAVELING GRATE RETORT (23)

with the carbonaceous residue in the processed shale. The resulting retorted shale ash is leached to produce alumina (Al_2O_3) and soda ash (Na_2CO_3), and is returned to the mine for disposal.

Superior Oil began the design and testing of this unique multi-mineral oil shale process in 1967 (24). By 1975, the nahcolite recovery system had been tested on commercial-size equipment; the engineering design had been completed for a mine that would produce about 25,000 tons per calendar day of oil shale, nahcolite, and dawsonite; and Superior had successfully pilot tested the viability of the retort and had optimized the process variables. By 1976, the engineering design of a commercial-size retort was initiated, and Superior had successfully tested the alumina and soda ash recovery system at the bench scale. Superior was planning to have pilot testing of the entire process completed in 1976 (24).

The success of future development of the Superior process depends on several factors. One factor is the marketability of the nahcolite product as a scrubbing agent to remove sulfur dioxide from stack gases. The acceptance of the nahcolite product for use as a gas-scrubbing agent is questionable in light of the economics of this scrubbing method and disposal problems for the user (26).

Another factor affecting the development of the process is the outcome of a request by Superior for an oil shale land exchange with the Bureau of Land Management (BLM). Superior owns about 6,500 acres of land on the north end of the Piceance Creek Basin in Colorado, part of which the company wants to exchange (see Figure 15). The exchange is necessary for Superior to block up its holdings into an economic unit suitable for oil shale mining. After 3 years of negotiation with BLM, Superior filed its land swap request in December 1973. The decision on the land swap has already been delayed by almost 4 years, and further delay is expected because BLM is considering preparation of an environmental impact statement (26).

1.7.1 Mining and Handling

The oil shale will probably be extracted from an underground room-and-pillar mine (as described in Chapter 3, Volume I). The proposed mine location depends heavily on the geology of the area; therefore, a brief description of the geology is included.

As shown in Figure 15, large amounts of the sodium minerals, nahcolite and dawsonite, occur with rich oil shale

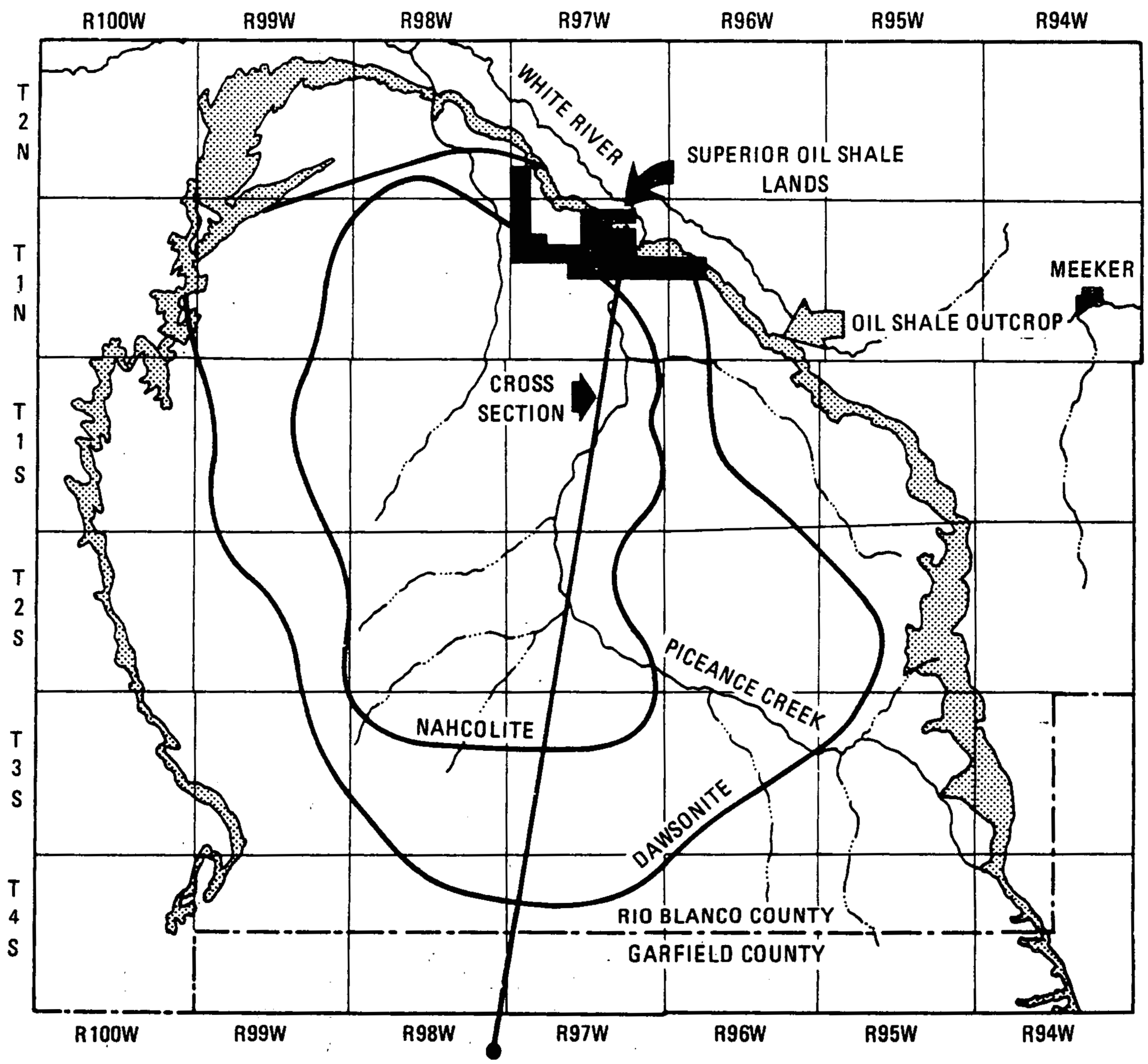

FIGURE 15. PICEANCE CREEK BASIN SHOWING SUPERIOR OIL SHALE LANDS AND AREAS OF NAHCOLITE AND DAWSONITE DEPOSITS (24,26)

in the Parachute Creek member of the Green River Formation. The map also shows the location of a cross section from the north to the south end of the basin. Figure 16 is the cross section showing the Parachute Creek member (25). The minerals nahcolite and dawsonite are found in the Lower Zone, which is composed of nonfractured oil shale. Nahcolite occurs mostly as individual modules of 1 to 3 in., surrounded by oil shale (27).

Overlying the nahcolite-bearing section is the Leach Zone, which is characterized by solution cavities, open fractures, local breccia zones, and intervals of porous earthy marlstone. Most of the nahcolite originally deposited in the Leach Zone has been dissolved and removed by groundwater. Dawsonite occurs as minute crystals, 5 microns or less in size, within the oil shale matrix. Dawsonite has not been dissolved by groundwater and therefore has a greater lateral and vertical distribution than does nahcolite.

To reach the nahcolite-bearing Lower Zone, Superior proposes to drive a 9-degree inclined adit, 2.5 miles long (18). The tunnel is designed to start at an outcrop located below the level of the Leach Zone, and will intercept the mining interval at a point 500 ft beneath the Leach Zone and 2,000 ft beneath the surface. In this manner, Superior will avoid passing through the highly fractured Leach Zone.

Room-and-pillar mining will proceed with special attention to the prevention of subsidence, so that excess water from the overlying Leach Zone will not be allowed a pathway into the mine. To protect against unexpected water flow, the mine is designed to be developed in panels completely enclosed by barrier pillars. If excessive water flow is encountered and cannot be controlled, the panel is sealed at the entrance to protect the remainder of the mine (26).

The mine plan will differ somewhat from that presented in Chapter 1 owing to the thickness of the mineral-bearing oil shale zone. The use of thick zones naturally leads to the potential use of multilevel development (28), or vertical stacking of mine levels. Each level must be properly designed to avoid the transferral of unusual or unnecessary loads to other levels. This is accomplished partly by vertical alignment of corresponding panels and barrier pillars.

Also critical to mine level design is the amount of nahcolite within the shale. Oil shale levels with up to 20 percent nahcolite will be mined with an estimated face height of 40 ft; those levels without nahcolite will have a height of about 60 ft (18).

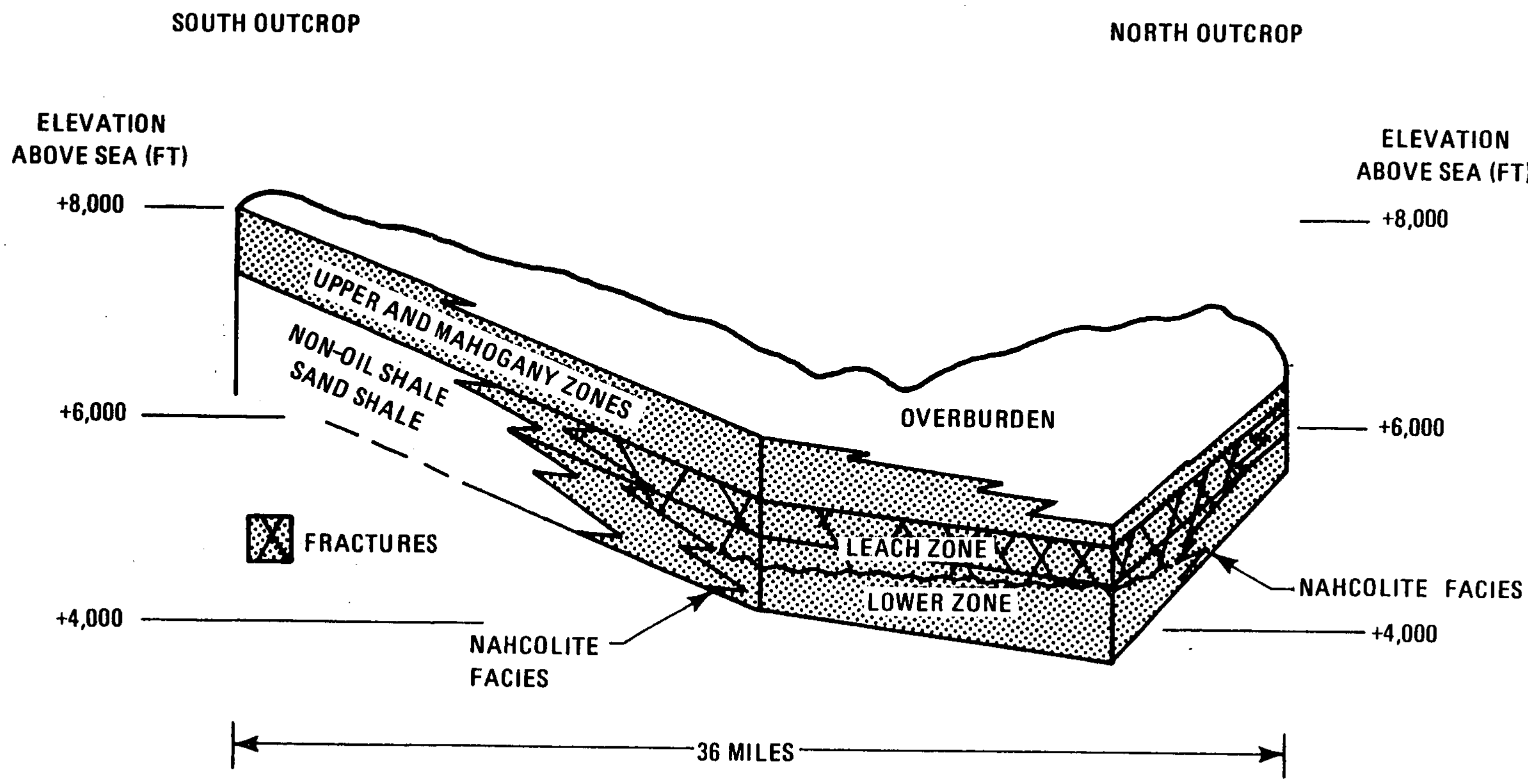

FIGURE 16. SCHEMATIC CROSS SECTION OF PICEANCE CREEK BASIN SHOWING OIL SHALE ZONES IN PARACHUTE CREEK MEMBER (26)

1.7.2 Crushing and Sizing

Run-of-mine oil shale is transported by conveyor belt or haulage truck to the primary crushers, located underground, where the shale is reduced in size to less than 8 in. Secondary crushing can be accomplished at the surface by impact-type crushers. The shale is reduced in size to -3 in., and screened to three size categories: minus 3 in. to plus 2 in., minus 2 in. to plus 1 in., and minus 1 in. to plus 1/4 in.

The nacholite recovery plant operates in conjunction with the secondary crushing facility to remove 80 percent of the nacholite from the shale. The impact-type crushers fracture the very brittle nahcolite modules more readily than the oil shale, and thus the nahcolite can be separated by screening. Additional separation is accomplished by a two-stage photo-sorting system (see Figure 17). The nahcolite is surface oxidized in a low-temperature kiln prior to being fed to the photo-sorters (25). The recovered nahcolite from this plant is expected to be 80 percent pure and is fed to a standard soda ash plant. The unrecovered nahcolite remains with the shale and is calcined to soda ash during retorting, then recovered in a subsequent leaching step.

1.7.3 Retorting and Product Recovery

The Superior process retort is basically a water-jacketed (air tight) doughnut-shaped tunnel through which a flat circular grate travels continually. A cross section of the retort is shown in Figure 18. The retort is divided into five enclosed sections: one each for loading, retorting, residual carbon recovery, shale cooling, and unloading. A commercial-size retort will be about 185 ft in diameter.

Three streams of crushed, sized shale are fed through an air-lock system to the loading zone and positioned on the grate with the fines (minus 1 to plus 1/4 in.) in the middle, and the coarsest fraction (minus 3 to plus 2 in.) on top. The depth of the shale bed is expected to be about 54 in. (18).

In the retorting zone a stream of hot gases is passed down through the raw shale to effect pyrolysis. The gas stream carries the produced hydrocarbon vapors to a separator-condenser system to recover the shale oil. The cooled gases are then recirculated to the retorted shale cooling zone.

In the residual carbon recovery zone, the carbonaceous residue on the retorted shale is reacted with air, steam, and recycled hot gases from the retorted shale cooling zone. The resultant high-Btu producer gas is used for plant fuel requirements.

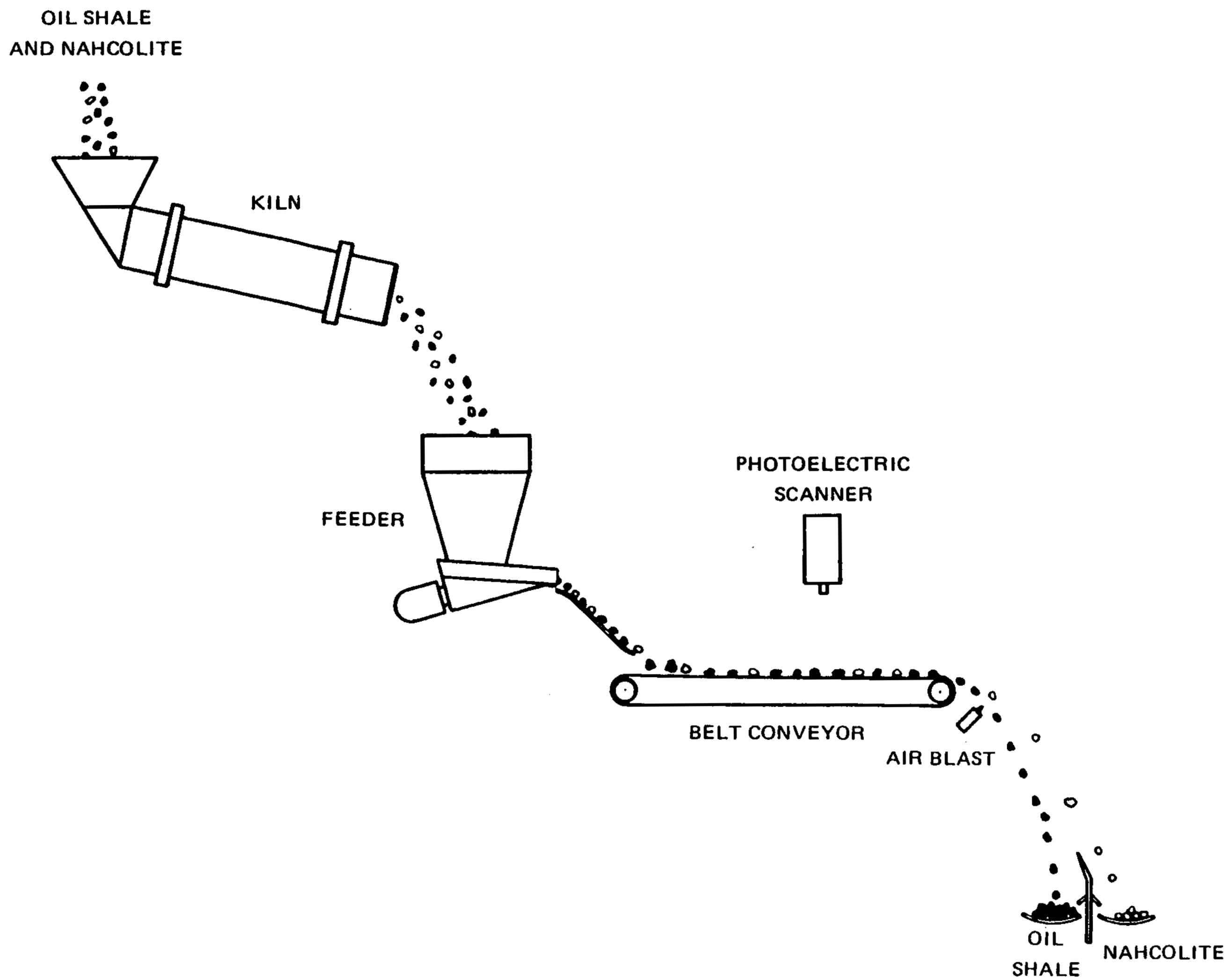

FIGURE 17. PHOTO-SORTING SYSTEM SCHEMATIC (24)

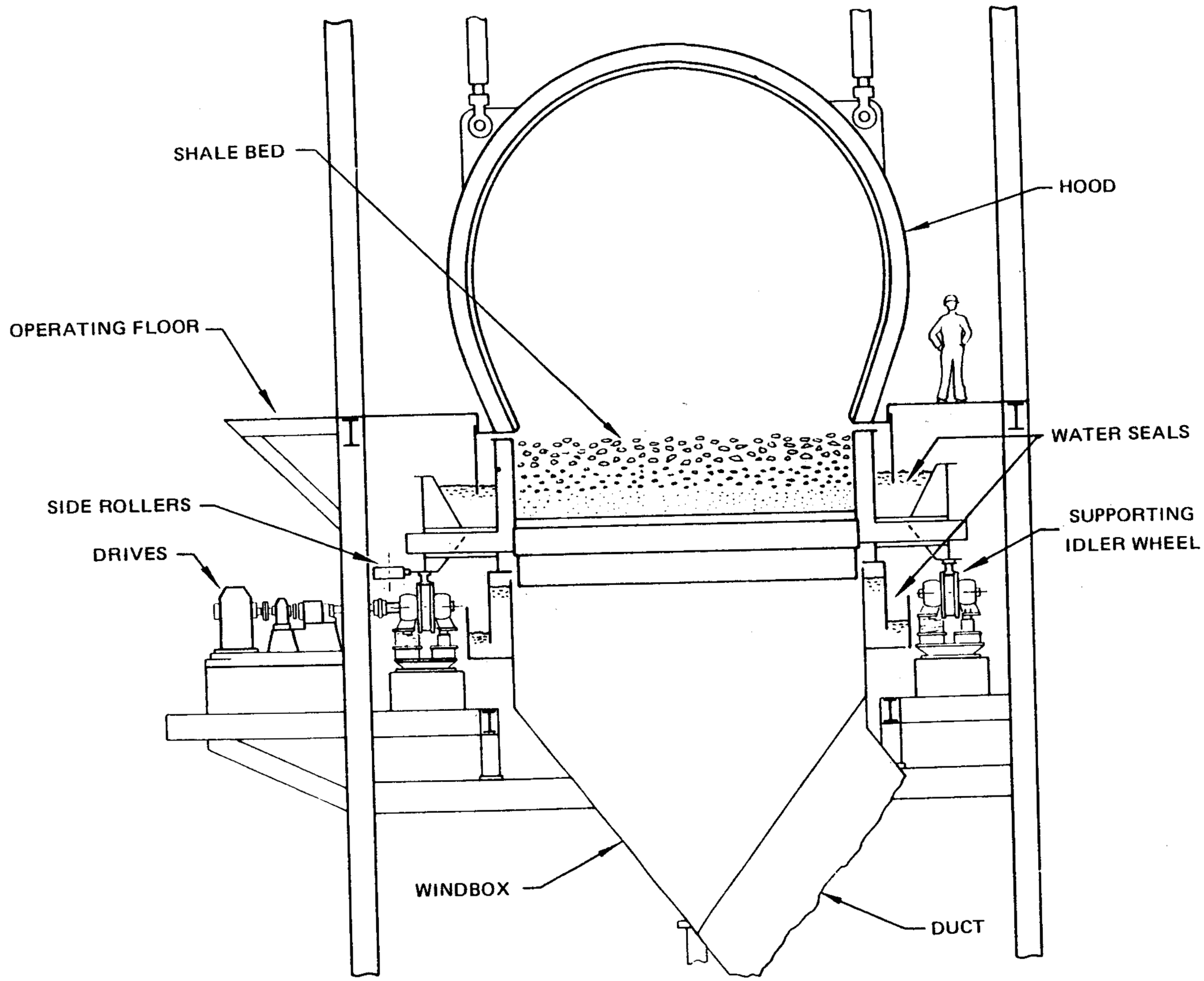

FIGURE 18. CIRCULAR GRATE RETORT CROSS SECTION (24)

The shale ash passes next to the retorted shale cooling zone, where it is cooled in preparation for discharge from the unloading zone. The shale oil from this process is expected to have the following characteristics (18) and will require additional upgrading to be suitable as a refinery feedstock:

Gravity (^{o}API)	26
Pour Point (^{o}F)	70
Sulfur (wt pct)	0.8
Nitrogen (wt pct)	2.0

The recovery of aluminum and sodium compounds actually begins in the retorting zone where the dawsonite is decomposed by heat to alumina and sodium carbonate:

$$2NaAl\ [OH]_2CO_3 \xrightarrow{heat} Al_2O_3 + Na_2CO_3 + CO_2 + H_2O.$$

The temperatures in the retort are controlled to not exceed 1100^{o}F so that the aluminum oxide formed will not become insoluble. The unrecovered nahcolite in the raw shale feed is also decomposed to sodium carbonate by the following reaction:

$$2NaHCO_3 \xrightarrow{heat} Na_2CO_3 + CO_2 + H_2O.$$

These compounds remain in the retorted shale ash discharged from the unloading zone. The retorted shale is crushed and then processed in the alumina and soda ash plants according to the block diagram in Figure 19. The retorted shale is leached in an alkaline solution of recirculated carbonate liquor and make-up water. The water is obtained from the mine dewatering operation or pumped directly from the Leach Zone aquifer (see Figure 16). The alumina in the retorted shale is converted in the shale leach to the soluble compound sodium aluminate:

$$Al_2O_3 + 2NaOH \longrightarrow 2NaAlO_2 + H_2O.$$

The leached retorted shale is separated from the liquor by filtration and is washed, dewatered, and returned to the mine for disposal (see Section 1.7.4). After filtration, the concentrated sodium aluminate liquor is nucleated and carbonated to precipitate aluminum hydroxide:

$$2NaAlO_2 + CO_2 + 3H_2O \longrightarrow Na_2CO_3 + 2Al[OH]_3.$$

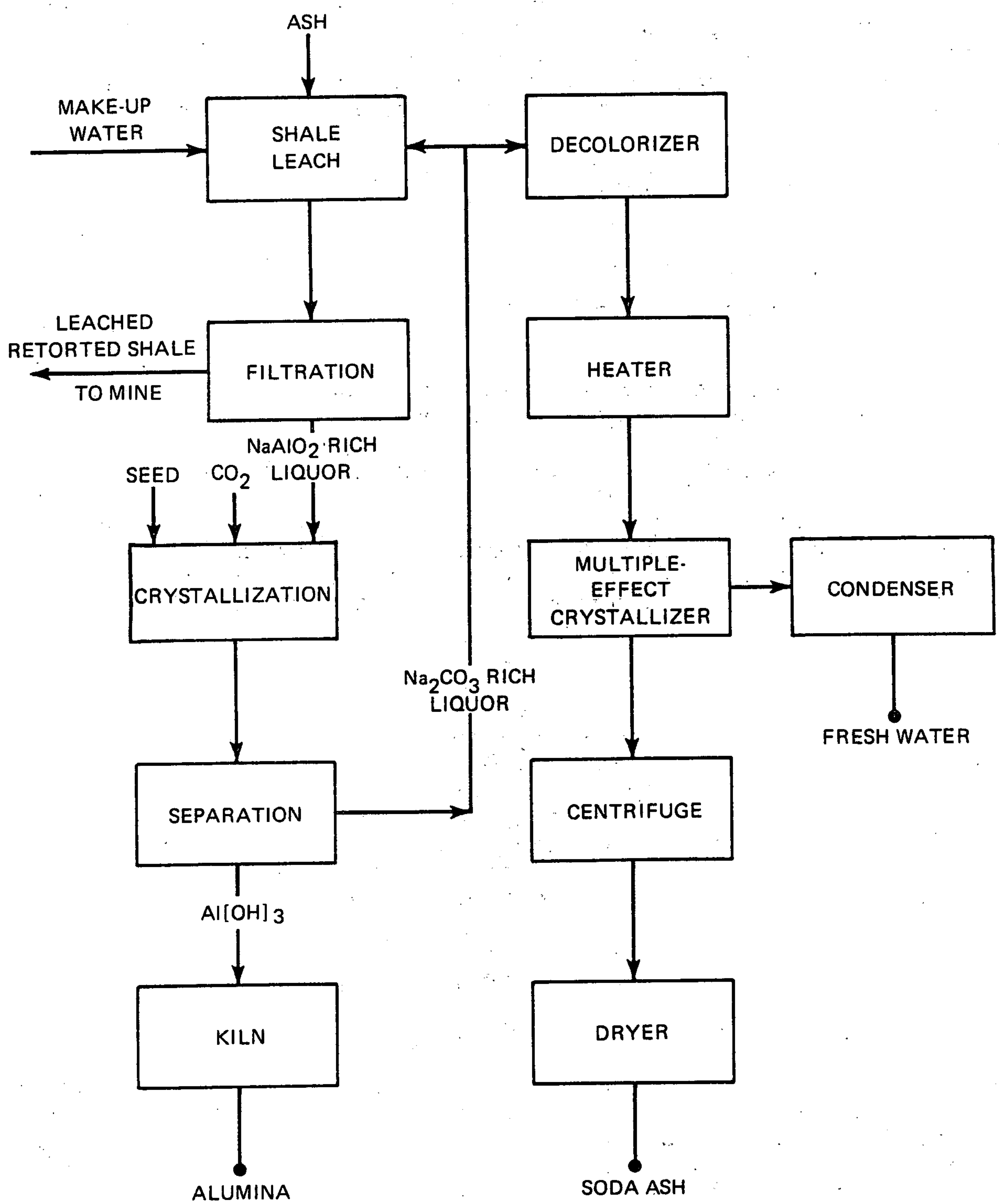

FIGURE 19. BLOCK DIAGRAM OF ALUMINUM AND SODIUM COMPOUND RECOVERY PLANTS (24, 26)

The insoluble aluminum hydroxide is filtered from the sodium carbonate rich liquor and calcined into cell grade alumina for market:

$$2Al[OH]_3 \longrightarrow Al_2O_3 + 3H_2O.$$

The sodium carbonate rich liquor is decolorized and evaporated in multiple-effect crystallizers to remove the water and to precipitate sodium carbonate (soda ash) crystals that are centrifuged from the liquor and dried for market. The remaining liquor is recycled or purged to the retorted shale for underground disposal. Evaporated water is condensed in heat exchangers and recovered as potable water for the plant and support facilities (24).

Contingent on the outcome of Superior's land exchange bid with BLM and on the development of a market for the nahcolite product, Superior proposes to construct a modular oil shale plant designed to permit step-by-step development. Depending on the shale grade and mineral content, one module will process 24,500 tons/day of oil shale and produce the following products (29):

Shale Oil (tons/day)	13,300
Nahcolite (tons/day)	4,500
Alumina (tons/day)	700
Soda Ash (tons/day)	1,500

Water requirements for the proposed plant module are to be met by pumping saline water (5 million gal/day) from the Leach Zone. About 25 percent of this water is consumed during chemical processing and retorted shale disposal. Superior proposes to reinject the remaining 75 percent back into the Leach Zone. Reportedly, the water will be unaltered chemically, although its temperature will be raised to about 120°F (18). Water requirements for this module are summarized as follows:

Plant Requirements (gal/day)	5.04×10^6
Net Consumption (gal/day)	1.26×10^6
Reinject (gal/day)	3.78×10^6
Make-Condensate (gal/day)	0.94×10^6

As noted previously, the make-condensate can be used as freshwater supply, and is equivalent to about 1,000 acre-ft/year.

1.7.4 Retorted Shale Handling

As a result of multi-mineral product recovery, the retorted shale will be reduced in volume and can be returned to the mine for disposal. The retorted shale is slurried and pumped into the mined-out rooms, then compacted by roll packing to within about 8 ft of the top. The top of the room is filled with slurry by a high-speed belt slinger. With the proper moisture content (about 25 percent) and the introduction of an additive, the retorted shale will pack to the roof and partially solidify (26). Excess water draining from the pile is recycled to the slurry plant. Make-up water is obtained from the Leach Zone aquifer.

CHAPTER 2
TECHNICAL EVALUATION

As mentioned previously, aboveground processes for the extraction of shale oil involve the common process steps of mining, shale preparation, retorting and product recovery, and retorted shale disposal. Shale preparation as well as retorting and product recovery systems, however, form the most important components of the aboveground plant and are process specific or differ greatly among the various processes. The establishment of a common basis for evaluating the technical aspects of processes, therefore, is limited to such variables as acceptable shale grade, shale size, oil and gas recovered, and mechanical complexity. This chapter discusses the various factors used for technical evaluation of selected aboveground retorting processes and provides an analysis of these factors.

2.1 BASIS FOR EVALUATION

The factors used to form a common basis for the technical evaluation of each aboveground process are discussed and explained in the following sections. These factors include acceptable shale grade, shale size, oil recovery and quality, gas recovery and quality, retorted shale char utilization, and mechanical complexity.

2.1.1 Acceptable Shale Grade

Most aboveground processes are limited in the maximum shale grade that can be processed. From the economic standpoint a high shale grade is advantageous, since less mining is required. Retort operation, however, is hindered by clinkering (fusing of fragments) at high shale grades. In addition, the higher oil generation rates may cause plugging of the retort, resulting in inefficient operation. Besides being economically disadvantageous, the inability to use the higher grade shale limits the usable resource base to the lower grade shale (although this resource is abundant in comparison to the high grade shale).

2.1.2 Shale Size

The inability of a process to accept a wide range of shale sizes is disadvantageous, since this greatly influences the cost of crushing the shale. Too small a particle size can cause excessive pressure drops and plugging in most retorts. Too large a shale size may result in low conversion efficiency because of inefficient heat transfer. Consequently, the crushing operation has to be well controlled and, depending on the desired size, may require large amounts of power. Also, the low tolerance to fines results in a low efficiency of resource utilization, since the fines are discarded.

2.1.3 Oil Recovery and Quality

The extent of oil recovery is an important measure of retort efficiency and depends on the method used to process the shale. Recovery losses are primarily due to combustion of oil in the vapor phase and the degradation of oil at the high temperatures in the retort. The quality of the oil produced is also an important factor; size and low pour point are desirable from the point of view of upgrading. Most of the existing surface extraction processes, however, produce oil of comparable overall quality, and, consequently, oil quality is a rather weak criterion for a relative evaluation.

2.1.4 Gas Recovery and Quality

The gases produced in retorting operations may be either low Btu or high Btu depending on the mode of heat transfer. In direct-heated (DH) retorts the gas produced is low in heating value, whereas indirect-heated (IH) retorts produce high heating value gas. From the point of view of gas utilization for power production, the high-Btu gas is more economical and therefore preferable.

2.1.5 Retorted Shale Char Utilization

The utilization of retorted shale char to derive part of the heat of retorting is desirable, since it improves the thermal efficiency of the process. The retorted shale char has about 10 percent of the heating value of kerogen and, depending on the fraction of char burned, its utilization can improve the thermal efficiency of retorting from 5 to 10 percent.

2.1.6 Mechanical Complexity

The mechanical complexity of the aboveground system is an important basis for evaluation. For efficient and trouble-free operation, it is desirable to have a system with a minimum of mechanical complexity. Of special concern is the equipment for transporting solids, and high-temperature equipment that may be unique to a given process.

2.2 BUREAU OF MINES GAS COMBUSTION RETORT

Section 2.1 presented a discussion of the key parameters to be used as a basis for the technical evaluation of the aboveground processes. This section presents an evaluation of the Bureau of Mines Gas Combustion retort including an examination of these key factors as they pertain to this process.

2.2.1 Acceptable Shale Grade

The Gas Combustion retort does not operate well with shale assaying more than 30 gal/ton or less than 20 gal/ton. As a result, for a given production level, larger tonnages are required to be mined and processed, and greater quantities of oil shale must be disposed of as retorted shale. The economic and environmental consequences of this limitation are not favorable. Nevertheless, the availability of oil shale assaying 20 to 30 gal/ton is very high in the regions under consideration.

2.2.2 Shale Size

The optimum shale size for economical operation of the Gas Combustion retort is not fully understood. It has been found, however, that a particle-size range of 3/16 to 3 in. is best for smooth retort operation (2). Even very limited quantities of fines (less than 3/16 in. in size) in the feed cause severe retorting problems. As a result, crushing and screening operations must be carefully controlled to reduce the generation of fines. It is estimated that about 5 percent of the run-of-mine shale appears as fines (5). To avoid loss in resource utilization, it has been suggested that the fine shale be briquetted; but the economics of such an operation are not immediately clear and have not been evaluated.

2.2.3 Oil Recovery and Quality

Oil recovery in the Gas Combustion retort is about 85 percent of the Fischer assay, which is rather low in comparison to the 95 to 100 percent recovery obtained in other processes. As a result of the low oil recovery, greater quantities of oil shale must be mined and subsequently disposed of as retorted shale. The low recovery is probably due to the loss of oil by combustion and degradation within the retort. Improved retort design requiring less air per unit mass of shale is thus necessary to reduce oil combustion.

The raw shale oil obtained from the Gas Combustion retort has a pour point of 80°F and a gravity of 19.7°API, both of which are comparable to that of oil produced in other retorts. The viscosity, which is 256 SUS at 100°F, is, however, somewhat higher; and this may increase the need for upgrading.

2.2.4 Gas Recovery and Quality

Retort gases produced by the Gas Combustion retort contain high concentrations of nitrogen and carbon dioxide, which is typical of direct-heated retorts. As a result, the gas has a low heating value, about 100 Btu/scf, and cannot be economically transported. It is, however, possible to use the gas as plant fuel or for on-site power generation.

The amount of gas recoverable is about 10,900 scf per barrel of shale oil, and a total energy of about 1.09×10^6 Btu per barrel of shale oil is obtained in the gas phase. This is somewhat high in comparison to other processes and is related to the utilization of char in the Gas Combustion retort.

2.2.5 Retorted Shale Char Utilization

Retorted shale char is utilized in the Gas Combustion retort to supply part of the heat for retorting the oil shale. Air is injected into the retort, resulting in combustion of the char. The utilization of combustion heat for retorting improves the thermal efficiency of the Gas Combustion retort and is a desirable feature.

2.2.6 Mechanical Complexity

The Gas Combustion process does not use mechanically complex or troublesome equipment. The retort, however, must be well controlled to maintain a steady temperature profile and mass flow within the vessel. There is some inherent difficulty in the uniform distribution of solids throughout the retort cross section. Consequently, the mass velocity of about 500 lb/hr-ft^2 that has been achieved in pilot-scale operation is somewhat low and needs improvement. In addition, there is some uncertainty about the positioning of the gas distributors in the retort to minimize clinkering and gas channeling (18).

2.3 UNION OIL COMPANY "B"

As was done for the Gas Combustion retort (Section 2.2), a technical evaluation of the Union Oil Company "B" retorting process is presented in this section based on the key parameters discussed in Section 2.1.

2.3.1 Acceptable Shale Grade

The Union "B" retort can operate successfully using shale assaying 35 gal/ton. Its ability to process the high-grade shale is economically advantageous, since the mining costs are reduced. The successful operability of the retort at the higher shale grades is due to upward motion of the shale particles. As a result of the upflow of the bed, the retorting zone is located at the top of the retort, so that the stresses are small in this zone. The lowering of the stresses acting in the retorting zone reduces the agglomerative tendency of the high-grade shale, which undergoes substantial plastic deformation upon being retorted (10).

2.3.2 Shale Size

The Union "B" process requires a carefully controlled particle size distribution of between 1/8 and 2 in. Larger particles may not be completely retorted, and fine shale particles create severe gas and solid flow problems. However, 1/8 in. is the smallest size used by any retort except the TOSCO II.

2.3.3 Oil Recovery and Quality

Oil recovery from the Union "B" retort approaches 100 percent of the Fischer assay. This is due to the fact that the oil evolved from the particles is rapidly swept down to the cooler zones so that coking reactions that lead to oil degradation are avoided. Another beneficial effect of the rapid downflow of oil is that the polymerization reactions of the lighter components of the oil are minimized (4), resulting in a low Conradson carbon content of about 1.75 percent (18). The pour point of the oil, which is about 65°F, is comparable to that of TOSCO II oil or Paraho indirect mode oil.

2.3.4 Gas Recovery and Quality

Gas recovery data have not been published for the Union "B" retort, but indications are that the recovery is good. The heating value of the gas is 800 Btu/scf and compares reasonably well with that of the gas from other indirect retorts. The high heating value allows the gas to be used efficiently for plant fuel.

2.3.5 Retorted Shale Char Utilization

The residual carbon in the retorted shale is not utilized in the Union "B" process, resulting in a thermal efficiency of about 70 to 75 percent. This is 5 to 10 percent lower than it would be with char utilization, but Union appears to be satisfied with this system and considers it more economical than the SGR retorting process that does recover the heating value of retorted shale char (10).

2.3.6 Mechanical Complexity

The Union "B" process has the unique feature that oil shale is forced upward in a moving bed. This movement of the bed is realized through the use of a rock pump. Although the rock pump may have mechanical problems, lessening its reliability and durability, Union is satisfied with the results from pilot-scale operation and does not expect any significant problems in commercial operation (10).

2.4 PETROBRAS PETROSIX

This section presents a technical evaluation of the Petrosix retorting process, based on the parameters presented in Section 2.1.

2.4.1 Acceptable Shale Grade

The shale grade range that can be accepted by this process has not been published. It is, however, anticipated that the range will be the same as that of the Gas Combustion retort, which is 20 to 30 gal/ton. Currently, the Petrosix process is being demonstrated on 20 gal/ton shale, since this resource is plentiful in Brazil.

2.4.2 Shale Size

The Petrosix process utilizes shale in the 1/4- to 3-in. range. This range is common among the aboveground processes and, hence, the problems of size control and loss of resource utilization due to the discarding of fines are of some concern in the Petrosix process as well.

2.4.3 Oil Recovery and Quality

The amount of oil recoverable for the Petrosix process is about 90 percent (12). This is somewhat low in comparison with most surface retorts, which approach 100-percent recovery. Since the Petrosix retort is an indirect-heated retort, it is probable that this lower recovery is due to coking reactions occurring in the retorting zone. Some adjustment in retort operation is thus necessary to improve oil yield.

The quality of the oil produced by the Petrosix process is better than that produced by the American processes, except for the sulfur content, which at 1.06 wt pct is a little higher. The American processes generally produce an oil of about 0.8 percent sulfur by weight. The higher amount of sulfur present in shale oil from the Petrosix process is attributed to the high sulfur content of the Brazilian oil shale and is not significantly related to process operation.

The low pour point of the Petrosix oil (25^{o}F) is a very attractive feature. The reason for the low value has not been indicated, but it may be due to the degradation of the heavier components through the coking reactions, which, as explained earlier, lowers the oil yield.

2.4.4 Gas Recovery and Quality

Data on gas recoveries for the Petrosix process have not been reported. It has, however, been anticipated that the 2,000-ton/day demonstration plant should produce 1,000 barrels of shale oil per day and 12.8 million cu ft of retort off-gas per day (9). This expected gas recovery appears to be rather high in comparison to that obtained in other indirect retorts in the United States and partly compensates for the low oil yield of the Petrosix process.

The heating value of the gas has not been reported, but it may be expected to be about 850 Btu/scf, which is typical of indirect-heated retorts. The sulfur content of the gas, at about 33 percent, is rather high due to the high sulfur content of Brazilian oil shale. This is, in fact, a useful feature of the process, since by-product sulfur from the gas desulfurization unit is marketable in Brazil where sulfur is in short supply.

2.4.5 Retorted Shale Char Utilization

Carbonaceous residue in retorted shale is not used for its heating value in the Petrosix process. This lowers the thermal efficiency of the process, since an external fuel is used to supply the heat requirements for retorting.

2.4.6 Mechanical Complexity

The Petrosix retort is similar to the Gas Combustion retort and may be expected to have the same difficulties of gas distribution for minimum clinkering and gas channeling. In addition, the low oil recovery suggests that coking reactions must be reduced through an adjustment in the operation of the retort. The reduction in coking reactions may be difficult to accomplish while attempting to decrease clinkering and gas channeling.

2.5 PARAHO

The Paraho process is similar in technical characteristics to the Gas Combustion and Petrosix retorting processes. A brief technical evaluation containing the unique features of this process is presented in this section.

2.5.1 Acceptable Shale Grade

The Paraho retort has been successfully demonstrated at 28 gal/ton shale. Its operability at shale grades above 30 gal/ton is, however, questionable. Nevertheless, the resource of 28 gal/ton shale is abundant. It may be expected that the Paraho retort has the same range of acceptable shale grade as the GCR, which is 20 to 30 gal/ton.

2.5.2 Shale Size

The Paraho process utilizes shale in the size range of 1/2 to 3 in. (18). This range is similar to that of other processes, which can accept shale of 1/2 to 3/16 in. in the lower limit. Like the other processes, the Paraho process requires good control of the crushing operation to minimize fines generation and the associated loss of resource utilization.

2.5.3 Oil Recovery and Quality

It has been indicated that a 97 percent oil recovery in the IH and DH mode operations of the Paraho process has been obtained (17). This is considerably better than that obtained in the Gas Combustion process and is due to improved retort design. There is still some loss due to coking reactions, but it is possible that with further experience in retort operation improved recovery may be obtained.

The IH mode oil is superior to the oil produced by the DH mode and has a lower pour point of 65°F in comparison to 85°F for the DH mode oil. This suggests that a greater amount of polymerization of the oil occurs in the DH mode because of the higher temperatures existing in this retort.

2.5.4 Gas Recovery and Quality

It has been indicated that gas recoveries of about 775 scf/bbl in the IH mode and about 9,590 scf/bbl in the DH mode have been obtained (17). The yield for the IH mode appears to be somewhat low in comparison to that obtained in other retorts, but more recent improved operation has resulted in up to 30 percent higher yields of high-Btu gas (30).

The heating value of the produced gas is 102 Btu/scf in the DH mode and about 885 Btu/scf in the IH mode. These values are typical of similar aboveground retorts. The total heating value of the retort gas in the DH mode is about 0.98×10^6 Btu/bbl and is somewhat lower than that obtained in the Gas Combustion retort. This is, however, more than adequately compensated for by the higher oil recovery in the Paraho retort.

2.5.5 Retorted Shale Char Utilization

Retorted shale char is burned in the DH mode operation of the Paraho retort to supply the heat of retorting. In the IH mode the char is disposed of in the retorted shale and, hence, the thermal efficiency of this mode is reduced. The retort is versatile and can be operated in either mode. Consequently, depending on the location, the economics and other site-related factors may determine the mode of operation.

2.5.6 Mechanical Complexity

The Paraho process retort is similar to the Gas Combustion retort, but has a more advanced discharge grate system for retorted shale removal. The grate controls the rate of descent of the oil shale bed and must be operable with a high degree of reliability. The control of bed descent is a very effective method for controlling the temperature profile in the retort and has a profound influence on reactor performance. Consequently, the grate mechanism is one of considerable concern and the design must ensure high reliability and minimize wear of moving equipment.

The Paraho retort overcomes some of the problems associated with the distribution of solids (inherent in the Gas Combustion retort) and achieves mass velocities of up to 40 percent higher. The optimal distribution of recycle gas and air in the retort, however, is still an important uncertainty.

2.6 TOSCO II

The TOSCO II retorting process is unique in its mode of heat transfer in the retort and is one of the few techniques that can accept high-grade shale as well as fine particles. It is also in an advanced stage of development and is a promising candidate for commercialization. These facts are discussed in this section, which evaluates the process based on the criteria of Section 2.1.

2.6.1 Acceptable Shale Grade

The TOSCO II retort can accept shale over a wide Fischer assay range. In addition to the low-grade shales (less than 20 gal/ton), the TOSCO II process can accept the higher grade shale of up to 35 gal/ton, which other techniques cannot process. This is primarily due to the continuous pulverization of the shale particles by the ceramic balls in the TOSCO II rotating drum pyrolysis reactor. As a result of this continuous pulverization, the shale particles are prevented from agglomerating to form a clinker.

Since the TOSCO II process can accept the high-grade shale that other processes cannot, the mining requirements are reduced considerably. This is an attractive feature of the process and is economically beneficial.

2.6.2 Shale Size

The TOSCO II process requires shale sizes of less than 3/8 in. This size requirement is necessary to allow pyrolysis in an inclined rotating drum into which 1/2 in. hot ceramic balls are fed.

2.6.3 Oil Recovery and Quality

The oil recovery from the TOSCO II process is expected to be 100 percent of Fischer assay in a commercial-size retort (3). In one pilot-scale operation, a 107 percent recovery was obtained. The high oil recovery of the TOSCO II process is primarily due to the low residence time (about 5 min) and small size of the shale particles. Both these factors tend to minimize coking reactions, which result in oil degradation. The oil from the TOSCO II retort has a somewhat higher pour point (about 75°F) than the oil from the Paraho indirect retort and the Union retorts. This suggests that some polymerization reactions are occurring in the vessel; however, it is not of much concern.

2.6.4 Gas Recovery and Quality

The recoverable gas from the TOSCO II retort is about 920 scf/bbl. The gas has a high-Btu content of about 885 Btu/scf and is usable for power generation or as plant fuel. The total heat obtained in the gas phase is about 0.8×10^6 Btu per barrel of oil and is very close to that obtained in the Fischer assay. It is slightly lower than that of the Gas Combustion or Paraho retorts but is compensated for by the higher oil yield.

2.6.5 Retorted Shale Char Utilization

Retorted shale char is not utilized in the TOSCO II process, which results in a loss in thermal efficiency. Potential, however, does exist for burning pyrolyzed shale in a fluidized bed for heating the ceramic balls, but this has not been attempted as yet.

2.6.6 Mechanical Complexity

The TOSCO II process involves a number of difficult operations that may cause problems in large-scale operation. Of some concern is the operational reliability of the fluid beds used for preheating and simultaneous transport of the raw shale. Good temperature control is required here to avoid any pyrolysis of the shale, which can lead to clinkering of the bed. Control of gas velocity is also important to prevent the slumping and subsequent plugging of the lift pipes. In addition, the potential problems of corrosion and wear may arise in large-scale operation.

Another important uncertainty is the possible coking of the trommel during the separation of retorted shale and ceramic balls. This may occur at the high temperature in the trommel and the result may be detrimental in the long run.

The attrition of ceramic balls is of some concern, since it can be economically detrimental to the process. Attrition may occur in the ball heater as well as in the retort and can lead to plugging in either case. It will also result in loss of attrited balls along with retorted shale in the retorting trommel. Steady and well-controlled operation of the ball heater is essential to reduce attrition. In the retort, attrition can be minimized by a controlled rotation speed, so that cascading of the balls is reduced while still maintaining good heat exchange with the shale particles.

2.7 SUPERIOR OIL COMPANY

This section presents a technical evaluation, based on the key parameters listed in Section 2.1, of the Superior process for the recovery of shale oil and associated minerals.

2.7.1 Acceptable Shale Grade

Shale grade is not known to be a limiting factor, but the Superior process is designed to exploit oil shale deposits containing the minerals nahcolite and dawsonite. Therefore, it may be limited in application to a particular deep-lying zone of the Piceance Creek Basin in which these minerals have not been leached out of the shale. The shale grade in this zone assays at less than 25 gal/ton.

2.7.2 Shale Size

The process requires a shale size range of 1/4 to 3 in. for proper operation. Fines produced during crushing are discarded, which reduces the efficiency of resource utilization.

2.7.3 Oil Recovery and Quality

Oil recovery approaches 100 percent, which is typical of indirect-heated retorts. The oil quality is comparable to that of other retorts, except for the gravity (26^{o} API) which is somewhat better than that of most surface-produced shale oils.

2.7.4 Gas Recovery and Quality

The gas recovery and quality for the Superior process have not been published. However, it has been indicated that a low-Btu gas will be produced which will be used as plant fuel (32).

2.7.5 Retorted Shale Char Utilization

Retorted shale char is utilized in the Superior process by reaction with steam, air, and hot recycle gas. The produced gas thus obtained is used as plant fuel. This is conducted in a separate zone on the moving grate and contributes to the thermal efficiency of the process.

2.7.6 Mechanical Complexity

The Superior process is probably the most complex of the surface oil shale processing methods. The complexity arises from the mechanically intricate grate used for retorting. The grate, which is circular, is divided into five enclosed water-sealed sections that must operate simultaneously yet under vastly different conditions of temperature and pressure. The control of the temperature in the various zones may be anticipated as a potential problem. Furthermore, the continuous rotary motion of the grate may be expected to cause excessive wear and maintenance problems. The reliability of the system is a significant question that can be answered only by long-term testing.

2.8 EVALUATION SUMMARY

It is evident from these evaluations that aboveground processes are in an advanced stage of development and many of them are ready for commercial-scale demonstration. There are, however, some areas where further research is necessary before the demonstration can be undertaken. Possible areas were mentioned in the evaluations; however, since the processes are mostly proprietary it is not certain as to which areas need further pilot or semiworks scale effort. Table 11 provides a summary of the results from the technical evaluation of the six selected aboveground processes.

The Gas Combustion process, which was the predecessor of the Petrosix and Paraho processes, has been surpassed in performance by these retorts. Also, the versatility (IH and DH) of the Paraho retort, as well as its better oil recovery, makes it a more promising candidate for commercial development in the United States than the Petrosix retort, which has been tested only on Brazilian oil shale.

The Union "B" retorting is very attractive as a result of its amenability to the higher grade shales, which reduces mining costs. There is some uncertainty regarding the reliability of Union's rock pump, but it has been indicated that no problems are anticipated. The yield and overall quality of the oil produced are not appreciably different from those of the Paraho or TOSCO II processes.

TABLE 11

TECHNICAL EVALUATION SUMMARY

PROCESS	ACCEPTABLE SHALE GRADE[1]	OPTIMUM SHALE SIZE[2]	OIL RECOVERY AND QUALITY[3]	GAS RECOVERY AND QUALITY	RETORTED SHALE CHAR UTILIZATION	MECHANICAL COMPLEXITY[4]
BUREAU OF MINES' GCR	20-30 GAL/TON	3/16 TO 3 IN.	• ~85% • 80°F	• 10,900 SCF/BBL • ~100 BTU/SCF	• USED FOR RETORTING • T.E.[5] ~75-80%	• NONCOMPLEX
UNION OIL CO. "B"	35 GAL/TON	1/8 TO 2 IN.	• NEAR 100% • 65°F	• UNKNOWN • ~800 BTU/SCF	• NOT UTILIZED • T.E.[5] ~70-75%	• ROCK PUMP
PETROBRAS PETROSIX	20-30 GAL/TON	1/4 TO 3 IN.	• ~90% • 25°F	• 12,500 SCF/BBL • ~850 BTU/SCF	• NOT UTILIZED • UNKNOWN T.E.[5]	• NONCOMPLEX
PARAHO	~25-30 GAL/TON	1/2 TO 3 IN.	• ~97% • 65°F	• 9,590 SCF/BBL • ~102 BTU/SCF	• USED FOR RETORTING • UNKNOWN T.E.[5]	• DISCHARGE GRATE
TOSCO II	<20-35 GAL/TON	3/8 IN. OR LESS	• NEAR 100% • ~75°F	• 920 SCF/BBL • 885 BTU/SCF	• NOT UTILIZED • UNKNOWN T.E.[5]	• FLUID BEDS • RETORTING TROMMEL
SUPERIOR OIL CO. MULTI-MINERAL	~25 GAL/TON	1/4 TO 3 IN.	• NEAR 100% • 65 TO 70°F	• UNKNOWN • UNKNOWN	• USED TO PRODUCE FUEL GAS	• CIRCULAR GRATE

[1]FOR EFFICIENT OPERATION OF RETORT.
[2]SIZE RANGE FOR ECONOMIC OPERATION.
[3]QUALITY PRESENTED AS POUR POINT IN °F.
[4]UNIQUE OR SPECIAL EQUIPMENT LISTED.
[5]T.E., THERMAL EFFICIENCY.

The ability of the TOSCO II retort in handling fine shale is advantageous, since it improves resource utilization. In addition, the mining requirements are reduced because of its acceptance of high-grade shale. This retort appears very attractive for coupling with another process for maximum resource utilization, since fines discard will then be avoided. The complexity of this process in comparison to Paraho or Union "B" is a disadvantage, but TOSCO has not revealed the problems experienced in semiworks-scale operation. The substantially lower mining costs of this process may compensate for the larger operating costs due to its complexity.

The Superior process is unique because of the associated minerals recovery. It employs an intricate and expensive traveling circular grate and the economics of this process relies on the amount and marketability of the minerals recovered. Consequently, the applicability of this process may be limited to the deep-lying zone of the Piceance Creek Basin, which is relatively rich in nahcolite and dawsonite.

CHAPTER 3
SCALE-UP SCENARIO

This chapter presents conceptual commercial-scale designs of four surface retorting processes for the production of about 56,000 bbl/day of crude shale oil. The conceptual designs focus only on the retorting operations of each process and do not include upgrading of the crude shale oil produced. The surface processes selected and discussed include

- Gas Combustion Retort
- Union "B"
- Paraho (Indirect)
- TOSCO II.

For each process a description is given of the uncertainties and assumptions associated with scaling up the retorts currently used in semiworks-scale operation to a full-scale capacity of approximately 10,000 tons/day of oil shale. Then the principal process systems of the retorting process are explained in detailed fashion. Finally, overall resource requirements (land, water, energy, equipment, and materials) necessary to recover the crude shale oil on a commercial basis are presented.

3.1 GAS COMBUSTION RETORT

A conceptual surface oil shale retorting complex using Gas Combustion technology is discussed in this section. The complex produces 58,000 bbl/day of shale oil for its operation. The plant is located in the Piceance Creek Basin and the shale averages 25 gal/ton in the zone of interest.

The proposed complex is expected to require 300 acres of land for surface processing facilities, and 1,800 acres for the disposal site. Over a 20-year period about 9,400 acres of land may have to be mined. The plant may also require about 11,500 acre-ft of water per year for process needs. A block diagram of the facility is presented in Figure 20. A detailed description of the plant and the assumptions used in the design are discussed in the following sections.

3.1.1 Uncertainties and Assumptions

The Gas Combustion retort has been well investigated from the R&D standpoint, but has never been demonstrated on

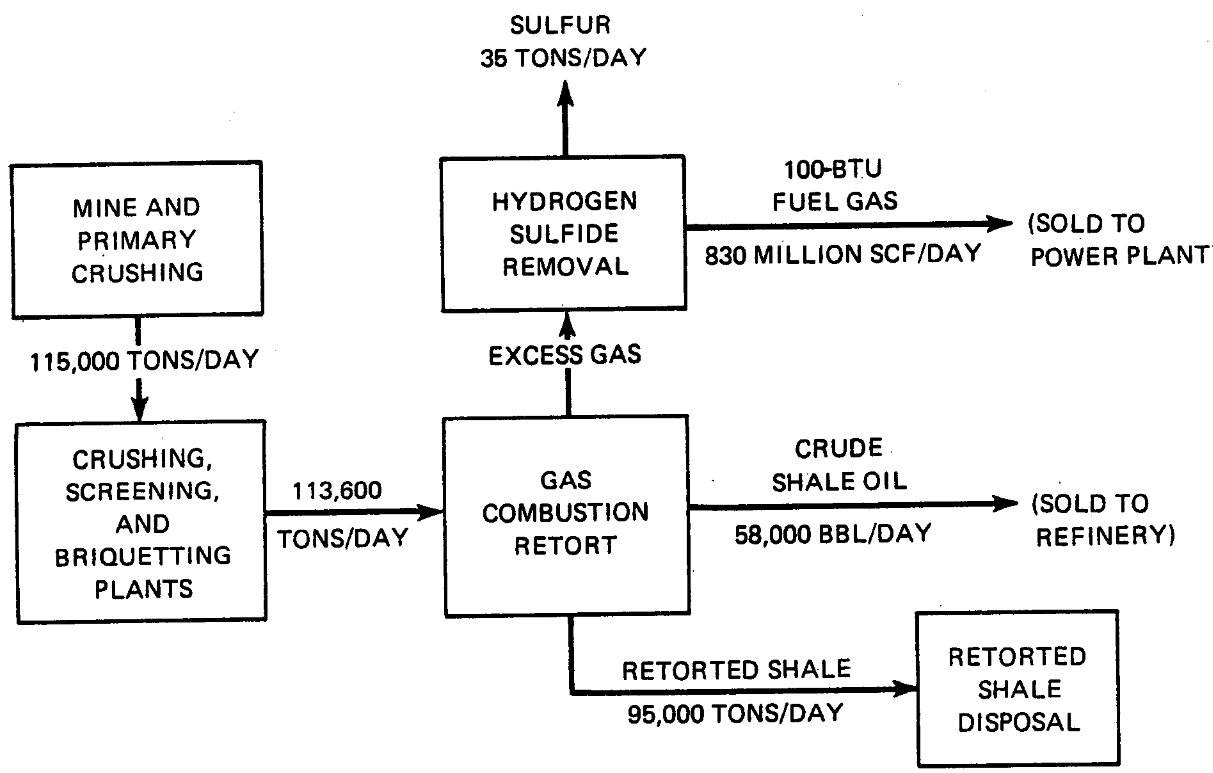

FIGURE 20. BLOCK DIAGRAM FOR A 58,000-BBL/DAY GAS COMBUSTION RETORTING FACILITY

a commercial scale. The following problems remain to be solved before the process can be applied commercially (1,9,32):

- Oil recovery is about 10 percent less than desired, being about 85 percent of Fischer assay.
- Oil recovery decreases with larger retort sizes, indicating potential future decreases with commercial-scale retorts.
- Optimum shale particle-size range for the retort feed is not fully understood.
- Even very limited quantities of fine shale in the feed cause severe operating problems.
- The operation is gas rate limited; that is, raising the gas rate beyond a certain limit creates poor operability.
- Increasing shale rates decreases operability unless compensating changes in gas rates are made.
- Operable gas and shale rates are functions of retort hardware.
- The retort does not work well with shale assaying more than 30 gal/ton or less than 20 gal/ton.
- Retort gas has a heating value of only about 100 Btu/scf and a high sulfur content.

Based on the previously listed uncertainties, the following assumptions regarding the commercialization of the Gas Combustion retorting process are made:

- Oil recovery during retorting is 85 percent of Fischer assay.
- Oil shale grade is 25 gal/ton.
- Oil shale bed thickness is 60 ft.
- Shale feed size range is from 3/16 to 3 in.
- Shale feed rate is 500 lb/hr/sq ft.
- Air feed rate is 4,730 scf/ton shale.

- Gas recycle rate is 15,515 scf/ton shale.
- Dilution gas rate is 2,793 scf/ton shale.
- Retort bed height is 12.5 ft.

If these rates and measures are assumed, then a 58,000-bbl/day crude shale oil production facility using the Gas Combustion retorting method could require a mine production rate of 115,000 tons/day. Fifteen Gas Combustion retorts will be required to meet this production goal.

3.1.2 Process Systems

The systems applicable to a scaled-up Gas Combusion retorting process are discussed in the areas of mining and shale handling, shale crushing and preparation, retorting and product recovery, retorted shale handling, and pollution controls. The scale-up is based on available information; best estimates are used where information is unavailable.

Mining and Shale Handling

This study assumes that a zone of 25 gal/ton oil shale, at least 60 ft thick, outcrops into a canyon in which the retorting plant complex is located. A description of a mining scheme is provided in Chapter 3, Volume I.

Shale Crushing and Preparation

A schematic diagram of the crushing and briquetting plant is shown in Figure 21. As shown in the figure, the mined shale may be conveyed directly to the receiving hoppers, at the crushing plant, where a 24-hr surge storage is maintained. Shale is removed from the bottom of the hoppers at the rate of 115,000 tons/day and conveyed to the primary crusher feed bins, which are sized to provide a holding time of 30 min. The shale is then fed to the primary gyratory crushers, which reduce the shale to less than 10.5 in. After a 24-hr storage, the shale is screened through 4.5-in. openings to the secondary gyratory crushers, where it is reduced to particles smaller than 4.5 in. The shale from the crushers, along with the undersize from the screens, may then be conveyed to the tertiary crusher feed bins, where the procedure is repeated. Here the shale is reduced to less than 3 in. and then conveyed to 72-hr surge storage.

Following the 72-hr storage period, the shale may be further screened to remove particles smaller than 3/16 in.

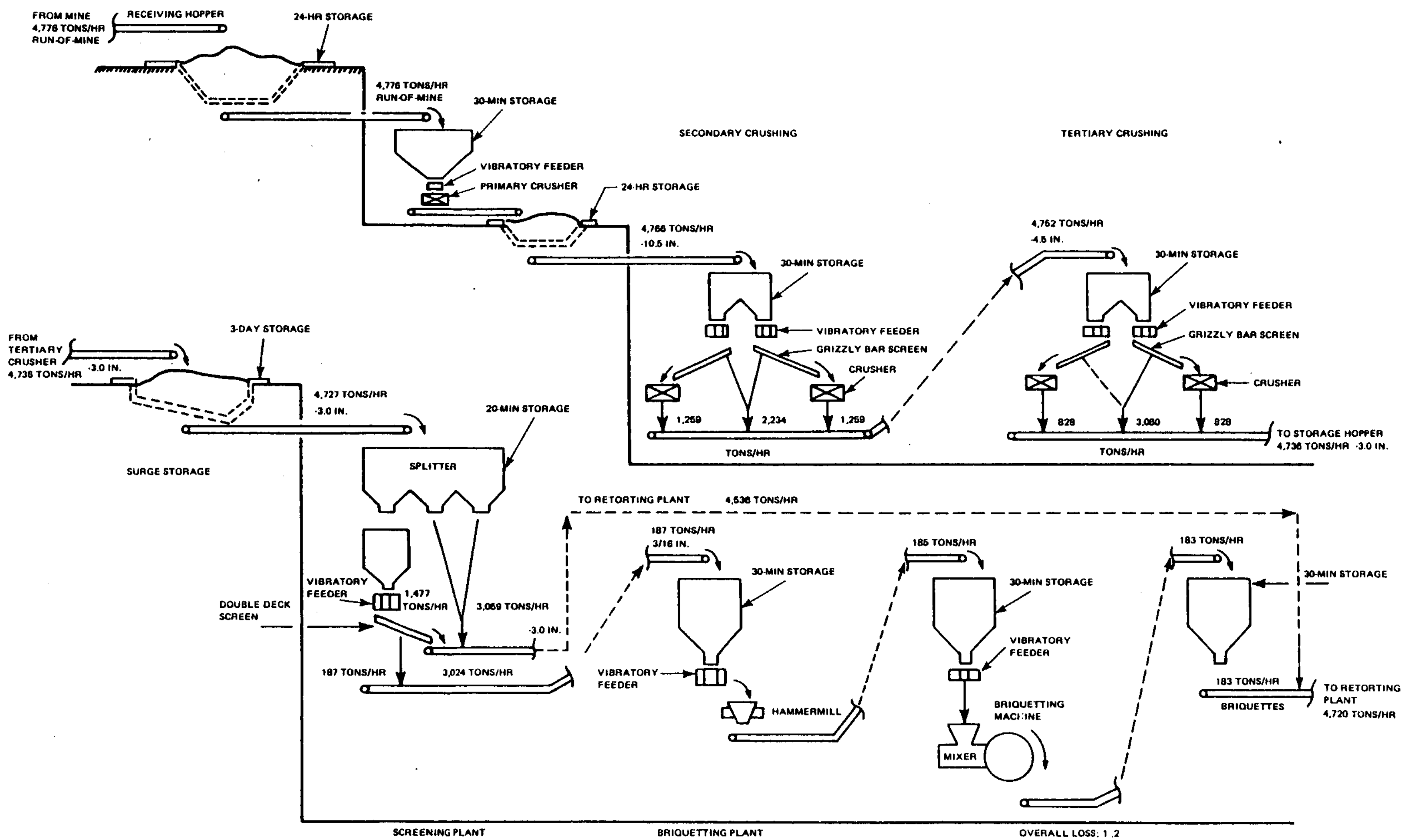

FIGURE 21. SCHEMATIC OF CRUSHING, SCREENING, AND BRIQUETTING OPERATIONS FOR A GCR FACILITY

The fines from the screens are sent to the briquetting plant and the larger size fraction is transported to the retorting plant. The fine shale may be conveyed to briquetting surge bin No. 1 on a 20-in. belt conveyor. The shale is then fed to four parallel hammermills by vibratory feeders where it is reduced to 14-mesh size and conveyed to bin No. 2. A vibratory pan feeder may be used to feed the milled shale to double-paddle horizontal mixers where it is mixed with crude shale oil. The mixture flows from the mixers by gravity to the briquetting machines. The crude shale oil serves as a binder in the briquetting of the fines. The briquettes are sent to surge bin No. 3 before being conveyed back to the retort feed conveyor.

Retorting and Product Recovery

The retorting plant, consisting of fifteen 40-ft-diameter (outside diameter) units, is shown in Figure 22. The shale from 3-hr surge bins may be combined with briquettes from the briquetting plant before entering the retort feed hoppers where it is held for a period of 1 hr. The shale is fed to the retorts by a belt conveyor equipped with an automatic tripper.

Each of the retorts is expected to be 40 ft in diameter (inside diameter) and 15 ft high, to process 7,550 tons/day of shale and briquettes, and produce 3,866 bbl/day of crude shale oil. Each retort also produces 55,440,000 scf/day of excess low-Btu gas and 6,340 tons/day of retorted shale.

The shale bed may be about 12.5 ft deep and solids move through this bed at a superficial velocity of 500 lb/hr/sq ft. After the shale enters the bed and before it moves into the combustion zone, it is preheated by hot gases flowing upward. Air, diluted by recycle gas, is fed into the combustors in this zone and shale is raised to 1300°F by the heat generated by combustion reactions.

The gases leaving the top of the retort flow through rotoclones and electrostatic precipitators that separate entrained oil from the noncondensible gases. The crude oil is then pumped to storage tanks. The gases flow through a rotary blower before being separated into two streams, one of which may be recycled while the other is sent to the purification unit for H_2S removal (see Figure 23). Approximately 18 percent of the recycled gas may be fed into the combustors located in the middle of the retort while the remainder is fed into the bottom of the retort. The recycled gas rising from the retort bottom serves to cool the retorted shale

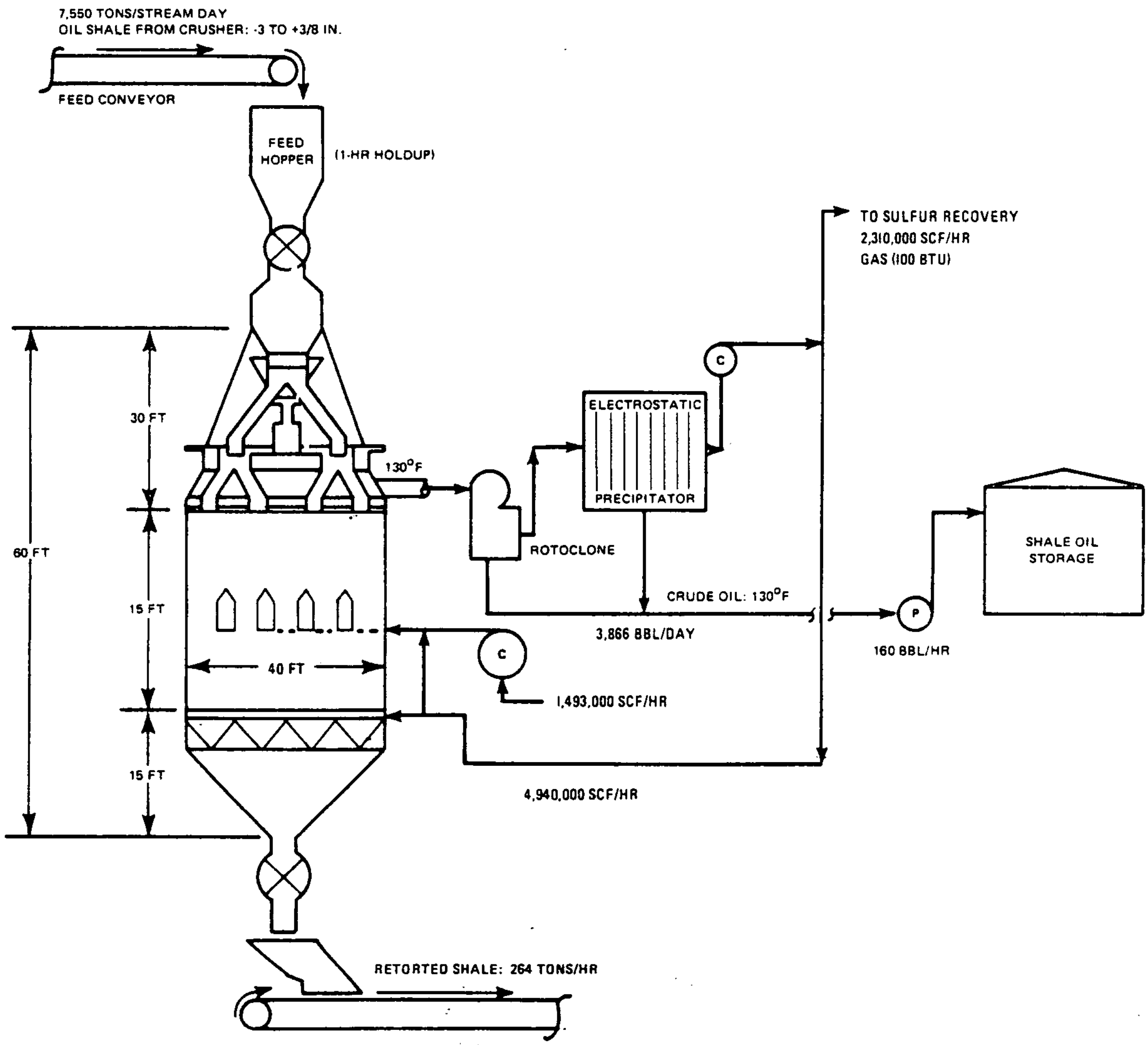

FIGURE 22. GAS COMBUSTION RETORTING SCHEMATIC FLOW DIAGRAM

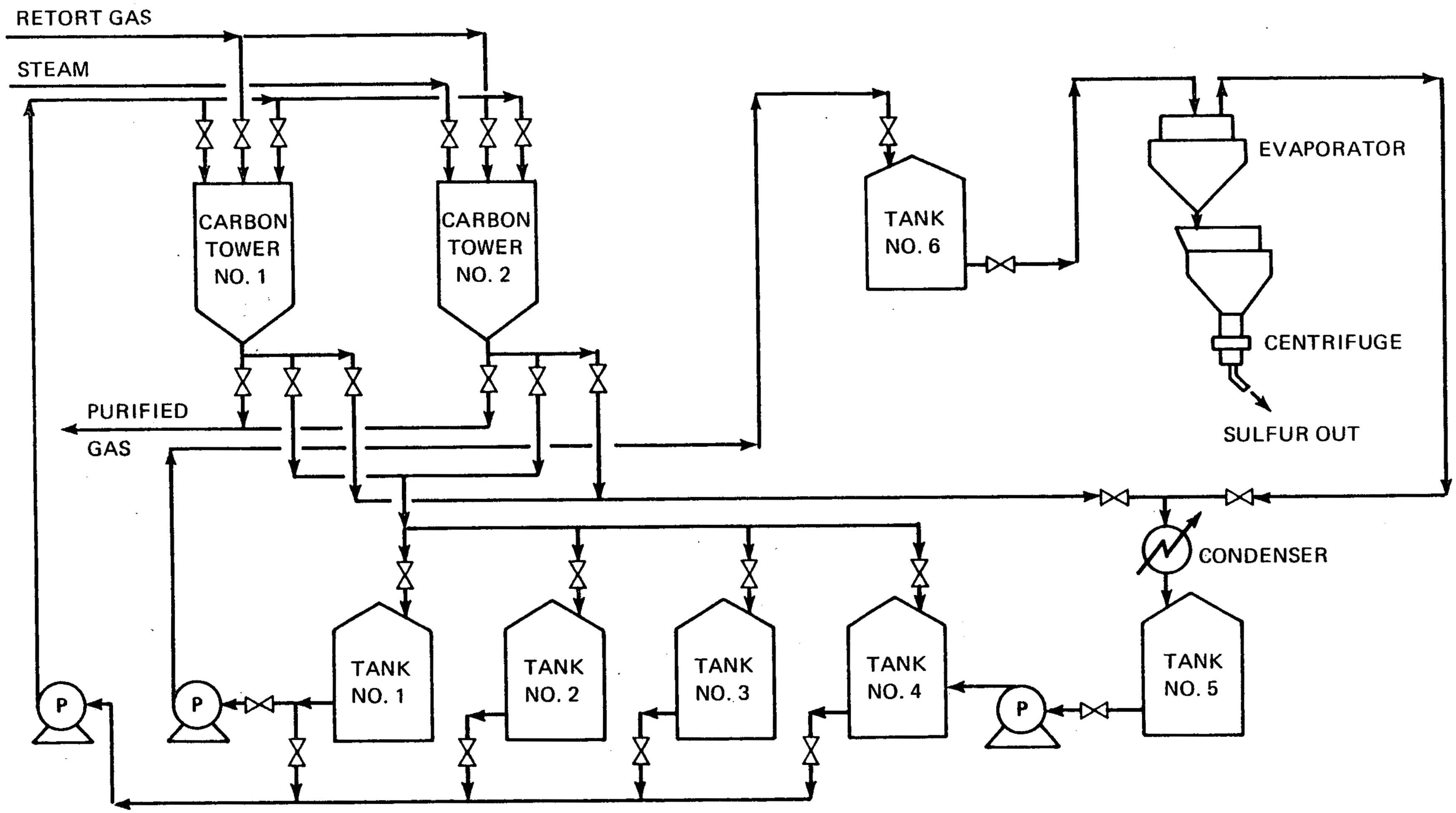

FIGURE 23. SCHEMATIC FLOW DIAGRAM OF HYDROGEN SULFIDE REMOVAL SYSTEM USING ACTIVATED CARBON — GCR FACILITY

as it travels down the bed. (The handling of the retorted shale after it leaves the retort is discussed in the next section.)

The crude oil from the storage tanks is expected to be pumped at the rate of 58,000 bbl/day to the refinery. The gas entering the purification unit is treated for H_2S removal so that it can be sold as a sulfur-free low-Btu plant fuel. H_2S removal from this gas can be accomplished by contacting the gas with activated carbon. The gas, after oil has been separated, flows through activated carbon tower No. 1, and when the bed is saturated, the flow is switched to tower No. 2. While bed No. 2 is in operation, bed No. 1 is regenerated by extraction with 15 percent solution of ammonium sulfide. This is followed by steaming of the bed for residual ammonium sulfide recovery. Four ammonium sulfide tanks may be used and connected in series for stripping the sulfur from the carbon bed before the tower is steamed. The vapors from the tower during the steaming process are condensed and accumulated in the tanks.

As the solutions in the tanks become saturated, they may be successively fed to an evaporator where heating decomposes the polysulfides. Solid sulfur and water are removed from the bottom of the evaporator and the sulfur is separated by a centrifuge. The sulfur, amounting to 35 tons/day, is stored and sold. The purified gas from the carbon towers is sold as a plant fuel.

Retorted Shale Handling and Disposal

Retorted shale is discharged from the bottom of the retort at a temperature of about 380°F. For cooling and moisturizing purposes, the retorted shale may be fed into a rotary moisturizing drum cooler. Dust-laden steam and moist air produced in this step pass through high-efficiency wet scrubbers. Shale dust-water from the scrubbers is expected to be clarified for reuse and the sludge is sent to a disposal site (16). After cooling and moisturizing, the retorted shale is carried on dual 60-in.-wide conveyor belts to the disposal site (assumed to be 1 mile distant). There the retorted shale may be delivered into a truck-loading hopper having three 150-ton compartments. Six 150-ton trucks, each making 5 runs/hr, are expected to distribute the retorted shale on the disposal pile. Other requirements are a grader, bulldozer, and water truck for the purpose of working the pile and reducing fugitive dust emissions.

Pollution Controls

Pollution control systems are necessary for reducing or eliminating emissions of noxious gases, dust, and wastewater associated with development of a commercial oil shale facility using the Gas Combustion retorting process. Details on the expected emission sources and types of control systems were presented in Chapter 4, Volume I. The purpose of this section is to describe the control systems selected specifically for this process.

Dust control during mining, crushing, and shale handling may be accomplished by water sprays and wet suppression techniques. It is estimated that about 1,200 gal/min of water will be required for this purpose. Conveyor belts may be enclosed and crushing devices are expected to require baghouse filters. Diesel-operated underground mining equipment may require catalytic converters or wet scrubbers and be properly maintained to reduce emissions. Gases and dusts emitted during retort feed and discharge operations will most likely have to be scrubbed and the sludge sent to a disposal site. Each retort may be equipped with a Venturi wet scrubber for this purpose, as described in Chapter 4. Gases collected during product recovery are treated to remove H_2S and used as plant fuel without further controls. Contaminated water streams resulting from mining and plant operation will be collected, treated, and reused or consumed according to the wastewater treatment plan presented in Chapter 4, Volume I.

3.1.3 Resource Requirements

A 58,000-bbl/day (net) shale oil facility using Gas Combustion retorting technology will require certain amounts of land, water, power, and other major equipment and material needs. The projected requirements for these resources are presented in Table 12.

Land is required for the shale handling and processing plant complex and the processed shale disposal site. In addition, the land that the mine underlies is included, although the surface may not be disturbed unless severe subsidence occurs. A Gas Combustion commercial facility is expected to require about 300 acres of land and a retorted shale disposal site of 1,800 acres. The land under which mining occurs is expected to be about 470 acres/year, or 9,400 acres over a 20-year period.

TABLE 12

RESOURCE REQUIREMENTS FOR A 58,000-BBL/DAY GAS COMBUSTION RETORTING FACILITY

Land	
Shale Processing Plant	300 acres
Retorted Shale Disposal	1,800 acres
Mining (underground)	9,400 acres (for 20 years)
Total	11,500 acres
Water	
Mining	1,000 gal/min
Crushing and Shale Handling	500 gal/min
Retorting and Product Recovery	2,000 gal/min
Retorted Shale Disposal	3,000 gal/min
General Plant Use	500 gal/min
Total (11,300 acre-ft/year)	7,000 gal/min
Power	
Electric	50 MWe
Diesel	1,600 bbl/day

Water is expected to be used for practically every aspect of the mine and plant complex for this facility. Total consumptive use is estimated at 7,000 gal/min (11,300 acre-ft/year) for normal operations. The major water use categories are as follows:

- Mining (1,000 gal/min for dust control)
- Crushing and Shale Handling (500 gal/min for dust control)
- Retorting and Upgrading (2,000 gal/min for cooling water, steam generation, and upgrading)
- Processed Shale Moisturizing, Cooling, and Disposal (3,000 gal/min for dust control, moisturizing, and revegetation)
- General Plant and Personnel Use (500 gal/min for utility water, fire protection, potable water, and sanitary-wastes water).

Referring to the power requirements in Table 12, the equivalent amount of oil needed to provide for electrical and diesel fuel needs is expected to be about 4,500 bbl/day. Assuming a total shale oil production of 58,000 bbl/day, the net energy production is equivalent to 53,500 bbl/day of crude shale oil.

Major capital equipment and material needs projected for mining and shale handling, crushing and briquetting, retorting and product recovery, processed shale handling, and pollution controls are presented in Tables 13 to 17.

3.2 UNION OIL COMPANY "B"

A scale-up concept for a surface oil shale retorting facility using the Union "B" method is discussed in this section. The assumed production rate of the facility is 55,000 bbl/day of shale oil. An energy equivalent of 2,700 bbl/day of shale oil is expected to be necessary for operation of the facility. The plant is located in the Piceance Creek Basin, where the shale averages 34 gal/ton in the zone of interest.

The facility will probably require 200 acres of land for surface processing facilities, and 1,100 acres for the disposal site, so that over a 20-year period, about 6,000 acres of land will be mined. The facility is also expected to

TABLE 13

PRIMARY CAPITAL EQUIPMENT FOR A SHALE MINE—GCR FACILITY

Heading Jumbo Drill (8 required) Drive: Electric Type: Hydraulic electric with two drills Horsepower: 150	Bulldozer (8 required) Drive: Diesel Horsepower: 700
Bench Jumbo Drill (6 required) Drive: Electric Type: Hydraulic electric with two drills Horsepower: 150	Main Ventilation Fan (2 required) Drive: Electric with 5 blade settings Capacity: 1 million scf/min at 7.6 in., water gauge Horsepower: 800
Powder Trucks (8 required) Drive: Diesel with pneumatic delivery system Capacity: 3 tons Horsepower: 100	Road Grader (2 required) Drive: Diesel 16-ft blade Horsepower: 225
Scaling and Roof Bolting Rig (8 required) Drive: Diesel Aerial Lift Horsepower: 500	Water Truck (6 required) Drive: Diesel Horsepower: 250
Front-End Loader (8 required) Drive: Diesel Bucket Capacity: 20 tons Horsepower: 700	Portable Crushing Plant (8 required) Drive: Electric Horsepower: 100
Haulage Trucks (30 required) Drive: Diesel Capacity: 75 tons Horsepower: 700	Belt Conveyor (2 required) Type: Enclosed Drive: Electric Size: Twelve 900-ft sections, 60 in. wide Horsepower: 1,900
Motor Patrol (4 required) Drive: Diesel Horsepower: 150	Auxiliary Ventilation Fan (40 required) Drive: Electric Capacity: 25,000 scf/min at 7.6 in., water gauge Horsepower: 40
	Power Centers (10 required) Power: 6 kva

TABLE 14

PRIMARY CAPITAL EQUIPMENT FOR A CRUSHING AND BRIQUETTING PLANT—GCR FACILITY

Receiving Hopper (8 required)

Holdup: 24 hr
Capacity: 324,000 cu ft
Size: 90-ft ID x 45-ft s.s.* ht
45-deg conical bottom

Magnetic Vibratory Feeder (16 required)

Load: 300 tons/hr
Model: Syntron FH-45
Horsepower: 2

Conveyor to Primary Crushing (8 required)

Type: Belt, enclosed
Size: 42 in. wide x 200 ft long
Drive: Motor
Horsepower: 15

Primary Crusher Feed Bin (8 required)

Holdup: 30 min
Capacity: 6,750 cu ft
Size: 19-ft ID x 19-ft s.s. ht
60-deg conical bottom

Conveyor to Secondary Crusher (8 required)

Type: Belt, enclosed
Size: 42 in. wide x 200 ft long
Drive: Motor
Horsepower: 15

Secondary Crusher Feed Hopper (8 required)

Holdup: 30 min
Size: 12 ft wide x 24 ft long x
28-ft overall ht
(2-hopper bottom)

Magnetic Vibratory Feeder (16 required)

Load: 300 tons/hr
Model: Syntron F-45
Horsepower: 2

Magnetic Vibratory Feeder (8 required)

Load: 600
Model: Syntron F-66
Horsepower: 2

Primary Gyratory Crusher (8 required)

Drive: Motor
Capacity: 600 tons/hr
Horsepower: 100

Conveyor to Storage (8 required)

Type: Belt, enclosed
Size: 42 in. wide x 200 ft long
Drive: Motor
Horsepower: 15

Surge Storage Hopper (8 required)

Holdup: 24 hr
Capacity: 324,000 cu ft
Size: 90-ft ID x 45-ft ht
45-deg conical bottom

Magnetic Vibratory Feeder (16 required)

Load: 300 tons/hr
Model: Syntron F-45
Horsepower: 2

*Slant side.

TABLE 14

(CONTINUED)

Grizzly Bar Screen (8 required) Load: 600 tons/hr Screen Opening: 4.5 in. Screening Rate: 5 tons/hr/sq ft Screen Area: 120 sq ft Secondary Gyratory Crusher (8 required) Drive: Motor Capacity: 320 tons/hr Horsepower: 50 Conveyor to Tertiary Crusher Feed Bin (8 required) Type: Belt, enclosed Size: 42 in. wide x 200 ft long Drive: Motor Horsepower: 50 Tertiary Crusher Feed Bin (8 required) Same as secondary crusher feed bin Magnetic Vibratory Feeder (8 required) Load: 600 tons/hr Model: Syntron F-45 Horsepower: 2 Grizzly Bar Screen (16 required) Load: 300 tons/hr Screen Opening: 3 in. Screening Rate: 5 tons/hr/sq ft Screen Area: 120 sq ft	Tertiary Crusher (8 required) Drive: Motor Capacity: 210 tons/hr Horsepower: 30 Conveyor to Storage Bin (4 required) Type: Belt, enclosed Size: 54 in. wide x 800 ft long Drive: Motor Horsepower: 60 Surge Storage Bin (24 required) Holdup: 3 days Capacity: 324,000 cu ft Size: 90-ft ID x 45-ft s.s.* ht 45-deg conical bottom Magnetic Feeder (24 required) Load: 300 tons/hr Model: Syntron F-45 Horsepower: 2 Conveyor to Splitter (4 required) Type: Belt, enclosed Size: 54 in. wide x 500 ft long Drive: Motor Horsepower: 50 Splitter (8 required) Holdup: 20 min Size: 11 ft wide x 33 ft long x 11 ft high Construction Material: 1/4-in. steel

*Slant side.

TABLE 14

(CONTINUED)

Magnetic Vibratory Feeder (24 required)

Capacity: 200 tons/hr
Model: Syntron F-440
Horsepower: 2

Conveyor to Retorting Plant (3 required)

Type: Belt, enclosed
Size: 48 in. wide x 750 ft long
Drive: Motor
Horsepower: 150

Conveyor Fines to Briquetting Plant (1 required)

Type: Belt, enclosed
Size: 29 in. wide x 100 ft long
Drive: Motor
Horsepower: 10

Double-Deck Screen (8 required)

Screening Rate: 0.3 ton/hr/sq ft
Size: 44 sq ft
Drive: Motor
Horsepower: 5

Surge Bin No. 1 (1 required)

Capacity: 142.5 tons
Size: 14-ft ID x 20-ft s.s.* ht 60-deg conical bottom
Construction Material: Steel

Vibratory Feeder (4 required)

Capacity: 50 tons/hr
Size: 24 x 42 in.
Model: Syntron F-330
Power: 1 kw

Hammermill (4 required)

Drive: Motor
Capacity: 60 tons/hr
Horsepower: 50

Conveyor to Surge Bin No. 2 (1 required)

Type: Belt, enclosed
Size: 20 in. wide x 100 ft long
Drive: Motor
Horsepower: 10

Surge Bin No. 2 (1 required)

Same as Surge Bin No. 1

Vibratory Feeder (4 required)

Capacity: 142.5 tons
Size: 14-ft ID x 20-ft s.s. ht 60-deg conical bottom
Construction Material: Steel

Mixer and Briquetting Machine (4 required)

Mixer
Type: 2 shaft horizontal paddle
Capacity: 60 tons/hr
Briquetting Machine
Type: Komarek-Greaves Model No. 28-27G
Drive: Motor
Horsepower: 60

Conveyor, Briquettes to Surge Bin No. 3 (1 required)

Type: Belt, enclosed
Size: 20 in. wide x 100 ft long
Drive: Motor
Horsepower: 10

*Slant side.

TABLE 14

(CONTINUED)

<u>Surge Bin No. 3 (1 required)</u> Same as Surge Bin No. 1 <u>Conveyor, Briquettes to Retort Feed Conveyor (1 required)</u> Type: Belt, enclosed Size: 20 in. wide x 500 ft long Drive: Motor Horsepower: 35	

TABLE 15

PRIMARY CAPITAL EQUIPMENT FOR RETORTING AND PRODUCT RECOVERY — GCR FACILITY

Retort (15 required)

Size: 40-ft ID x 15-ft-high retorting section
Type: Bureau of Mines Gas Combustion retort equipped with Cameron and Jones improved feeding and discharge mechanism
Refractory: 9-in. firebrick, 9-in. K-30 insulating brick (retorting section)
Drive: Motor-activated hydraulic
Horsepower: 90 top (feed); 160 bottom (discharge)

Rotoclone (75 required)

Drive: Motor
Capacity: 25,000 scf/min
Head Developed: 12 in. water
Horsepower: 100

Compressor (15 required)

(Recycle and Product Gas)
Type: Centrifugal
Drive: Motor
Horsepower: 1,450

Air Compressor (5 required)

Type: Centrifugal
Drive: Motor
Horsepower: 3,650

Electrostatic Precipitator (15 required)

Size: 13-ft ID x 15-ft ht
Capacity: 180,000 cfm
Power: 16 kw

Shale Oil Pump (15 required)

Drive: Motor
Capacity: 120 gal/min
Horsepower: 2

Feed Hopper on Retort (15 required)

Size: 21-ft ID x 21-ft ht 60-deg conical bottom
Holdup: 1 hr
Construction Material: Steel

Retort Feed Conveyor (1 required)

Type: Belt, enclosed
Size: 60 in. wide x 450 ft long
Drive: Motor
Horsepower: 265

Carbon Tower (60 required, including 30 spares)

Size: 16.5-ft ID x 16.5-ft ht
Catalyst: Two 5.5-ft beds of activated carbon

Solution Tank (6 required)

Size: 6,5000 gal
Construction Material: Steel

Pump (3 required)

Type: Centrifugal
Drive: Motor
Horsepower: 5

Evaporator (10 required)

Size: 6.5-ft ID x 14-ft ht
Steam Required: 9,900 lb/hr

TABLE 15

(CONTINUED)

Centrifuge (5 required) Type: Sharples super D, stainless Drive: Motor Horsepower: 6.5 Condenser (10 required) Type: Spray Size: 9-ft ID x 25-ft ht Crude Rundown Tank (15 required) Type: Cone roof Capacity: 8,000 bbl Crude Storage Tank (5 required) Type: Cone roof Capacity: 80,000 bbl	

TABLE 16

PRIMARY CAPITAL EQUIPMENT FOR RETORTED SHALE HANDLING AND DISPOSAL — GCR FACILITY

Rotary Drum Cooler (15 required)

Drive: Electric motor
Unit Size: 5,750 tons/day
Horsepower: 30

Belt Conveyor (2 required)

Type: Enclosed
Drive: Electric motor
Size: Six 900-ft sections, 60-in. belt
Horsepower: 2,250 (total)

Truck Loading Hopper (1 required)

Size: 450 tons
Three 150-ton compartments

Haulage Truck (6 required)

Drive: Diesel
Size: 150 tons
Horsepower: 1,000

Bulldozer (1 required)

Drive: Diesel
Horsepower: 700

Grader (1 required)

Drive: Diesel
Horsepower: 250

Water Truck (1 required)

Drive: Diesel
Horsepower: 250

TABLE 17

PRIMARY CAPITAL EQUIPMENT FOR POLLUTION CONTROLS—
GCR FACILITY

Baghouse Filter—Crushing and Briquetting Units (25 required)

Type: Induced draft
Drive: Motor
Horsepower: 40
Filter area: 1000 sq. ft.
Capacity: 3000 cfm

Wet Scrubber—Retort Feed Hopper and Processed Shale Moisturizer (15 required)

Type: Venturi
Drive: Motor
Horsepower: 70
Capacity: 12,500 cfm

Wastewater Holding Tank—Surge Attenuation, Sedimentation, and Gravity Separation (5 required)

Size: 500 gal

Wastewater Treatment Unit (1 required)

Flotation: 25,000 gal/day
Biological Oxidation: 35,000 gal/day
Filtration: 35,000 gal/day
Reverse Osmosis: 7,000 gal/day

require about 8,000 acre-ft of water per year for process needs. A block diagram of a commercial-scale facility is presented in Figure 24. A detailed description of the plant and the assumptions used in the design are discussed in the following section.

3.2.1 Uncertainties and Assumptions

The Union "B" retort has never operated at the demonstration or commercial plant level. Also, industry oil shale personnel have expressed concern that Union's rock pump may experience mechanical difficulties at higher throughputs and continuous operating conditions. Nevertheless, Union has a high degree of confidence in the technology, and is convinced that the rock pump "... will be a dependable, low-operating-cost component of the oil shale complex" (10). This confidence is based on months of testing pilot- and demonstration-scale pumps.

Also unknown are the actual dimensions and operating conditions for a 10,000-ton/day facility using a Union "B" retort. Although most of the information needed to scale-up this process is proprietary, communication with Union Oil personnel revealed the approximate specifications of the retort and rough estimates of some, but not all, of the operating conditions. To form a basis for conducting an economic evaluation of a commercial-scale Union "B" facility, the following specifications are assumed:

- Oil shale grade: 34 gal/ton
- Oil shale bed thickness: 60 ft
- Oil shale feed size range: 1/8 to 2 in.
- Oil shale fines discard: 7.5 wt pct
- Oil recovery during retorting: 97 percent of Fischer assay
- Processing rate of each retort: 10,000 tons/day
- Retort dimensions: 38-ft ID x 25-ft bed height
- Oil shale mass feed rate: 735 lb/hr/sq ft
- Recycle gas rates: 20,000 scf/ton of shale
- Gas production rates: 750 scf/ton of shale.

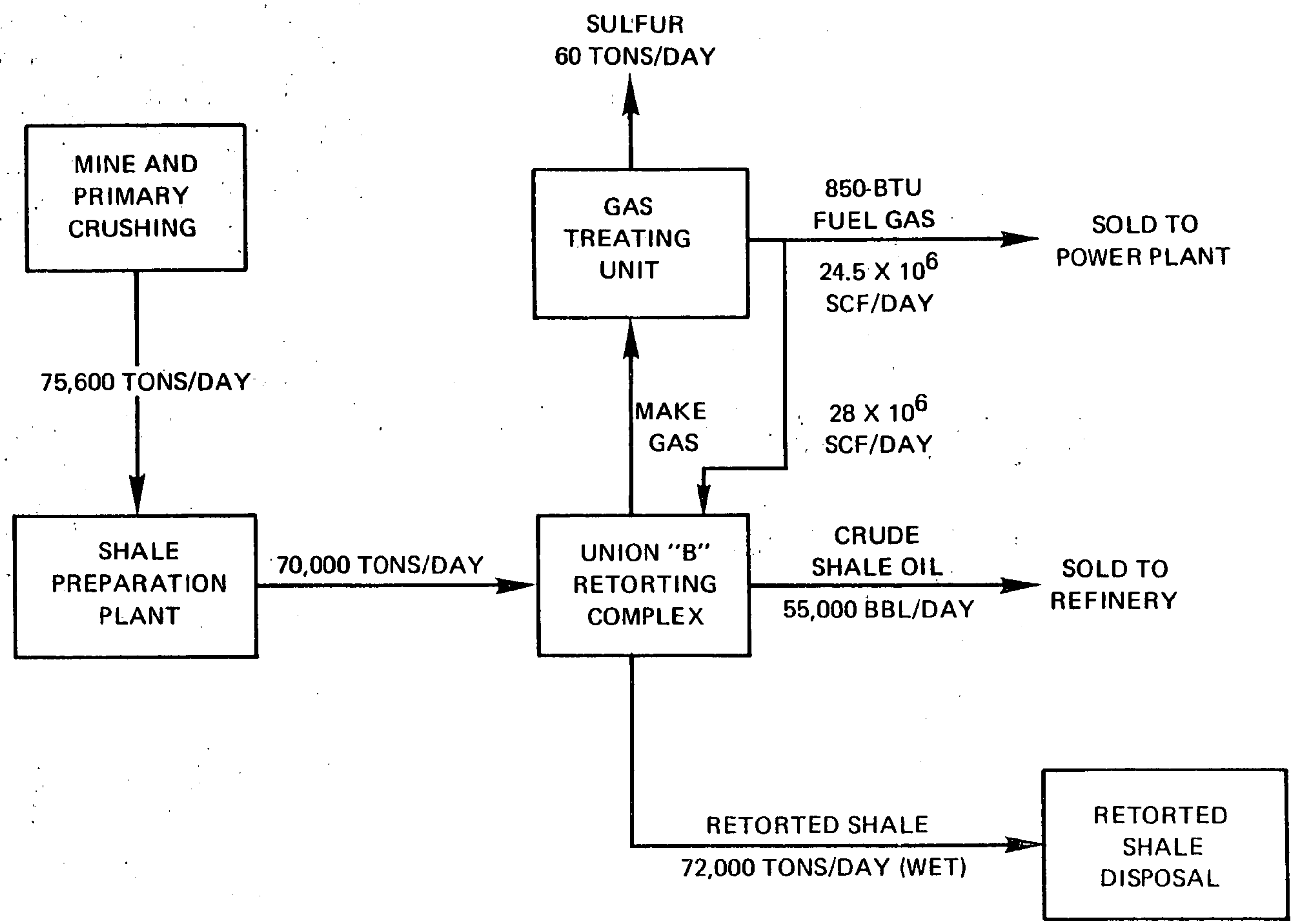

FIGURE 24. BLOCK DIAGRAM FOR A 55,000-BBL/DAY UNION "B" RETORTING FACILITY

With the preceding assumptions, a total of seven Union Oil "B" retorts are expected to be required for a facility producing 55,000 bbl/day of crude shale oil. The mine production rate is estimated to be 75,600 tons/day to supply these retorts.

3.2.2 Process Systems

The appropriate process system requirements for a commercial-scale Union "B" retorting facility are described in the following scenario.

Mining and Shale Handling

The mining phase of the Union "B" scale-up assumes that mine development will take place on Union Oil property at East Parachute Creek north of Grand Valley, Colorado. This mine is expected to open to a bench at 7,000-ft elevation, or about 1,500 ft above the Parachute Creek Valley floor. Production mining is expected to be done by the room-and-pillar method as described in Chapter 3, Volume I. The production rate of this mine is estimated to be 75,600 tons/day of 34 gal/ton oil shale. It is assumed that haulage trucks will transport the run-of-mine shale to a primary crushing plant located at the minemouth bench. There, toothed-roll crushers will be used to reduce the shale to less than 10 in. in size. An ore pass will transport the primary crushed shale from the 7,000-ft elevation bench to the 5,500-ft elevation valley floor of the shale processing complex.

Shale Crushing and Preparation

Run-of-mine oil shale is expected to be transferred from the base of the ore pass by belt conveyor to the primary crushed ore stockpile. This stockpile may contain a 5-day supply of about 380,000 tons of primary crushed oil shale in an elongated windrow-shaped pile. The pile may be stacked by a swinging-boom stacker and reclaimed by a crawler-mounted bucketwheel. The stacker travels on rails alongside the stockpile, as shown in Figure 25. The bucketwheel reclaimer deposits oil shale from the stockpile onto a conveyor belt for transfer to the secondary crushing facility featuring roll-type crushers.

Figure 26 presents a typical secondary crushing and screening operation (cross section). In this operation the facility is enclosed in a ventilated building, which has baghouse filters to control particulate emissions. Secondary crushed oil shale may be further sized at a tertiary screening facility in a second building. Undersized material (less than 1/8 in.) may be discarded to the mine and properly sized material (2 to 1/8 in.) may be carried by belts to the retort feed storage bunker. The bunker should have a working capacity of about 150,000 tons, or 2 days' storage for the "B" retorts. Reclaim facilities for this bunker are expected to consist of a rotary plow feeder, which travels on rails underneath the storage bunker and continuously withdraws the ore from the bottom onto a conveyor belt for movement to the retort feed hopper. Each feed hopper is expected to provide surge storage of 1 hr, or about 420 tons. A flow chart of the entire shale crushing and preparation system for a Union "B" facility is shown in Figure 27.

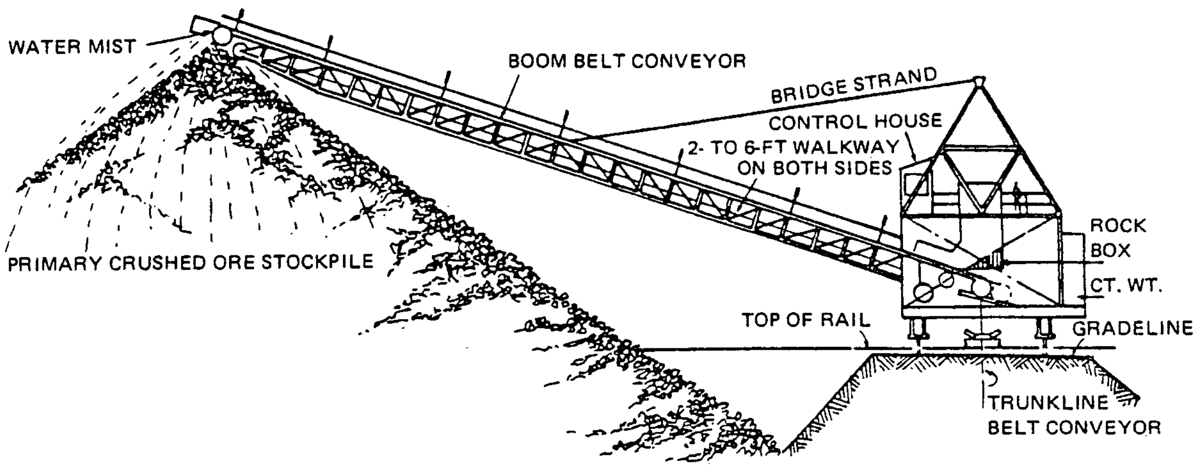

FIGURE 25. TRAVELING STACKER—
UNION "B" FACILITY (21)

Retorting and Product Recovery

A typical Union Oil "B" retort is shown in Figure 28. Oil shale from this retort's feed hopper flows through two feed chutes to the solids pump. The shale oil product acts as a hydraulic seal in the feed chutes to maintain the retort pressure (10). The solids pump consists of two piston and cylinder assemblies that alternately feed shale to the retort. The pump is immersed in oil and is mounted on a hydraulically operated carriage that moves horizontally on tracked wheels.

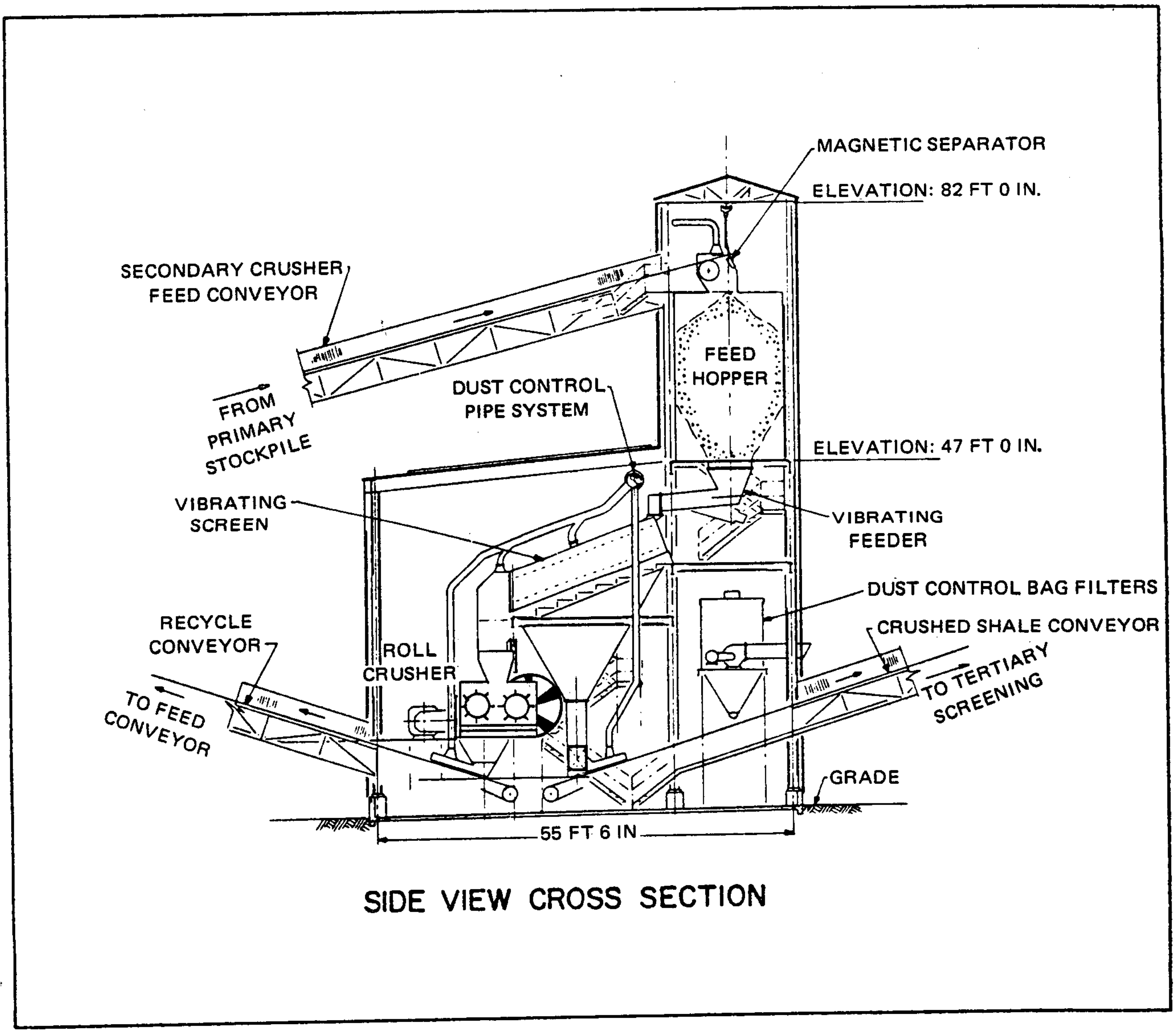

FIGURE 26. CROSS SECTION OF A SECONDARY CRUSHING AND SCREENING OPERATION—UNION "B" FACILITY (23)

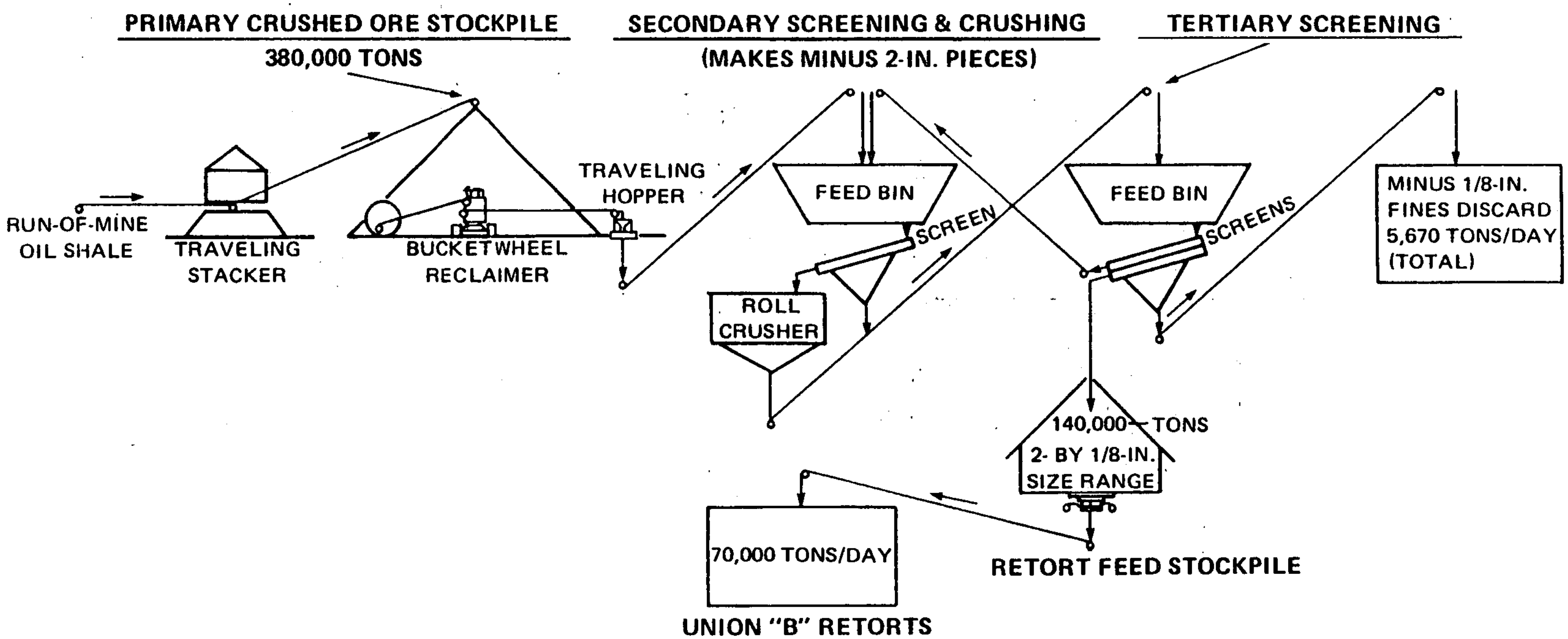

FIGURE 27. FLOW CHART OF A SHALE CRUSHING AND PREPARATION OPERATION—UNION "B" FACILITY (23)

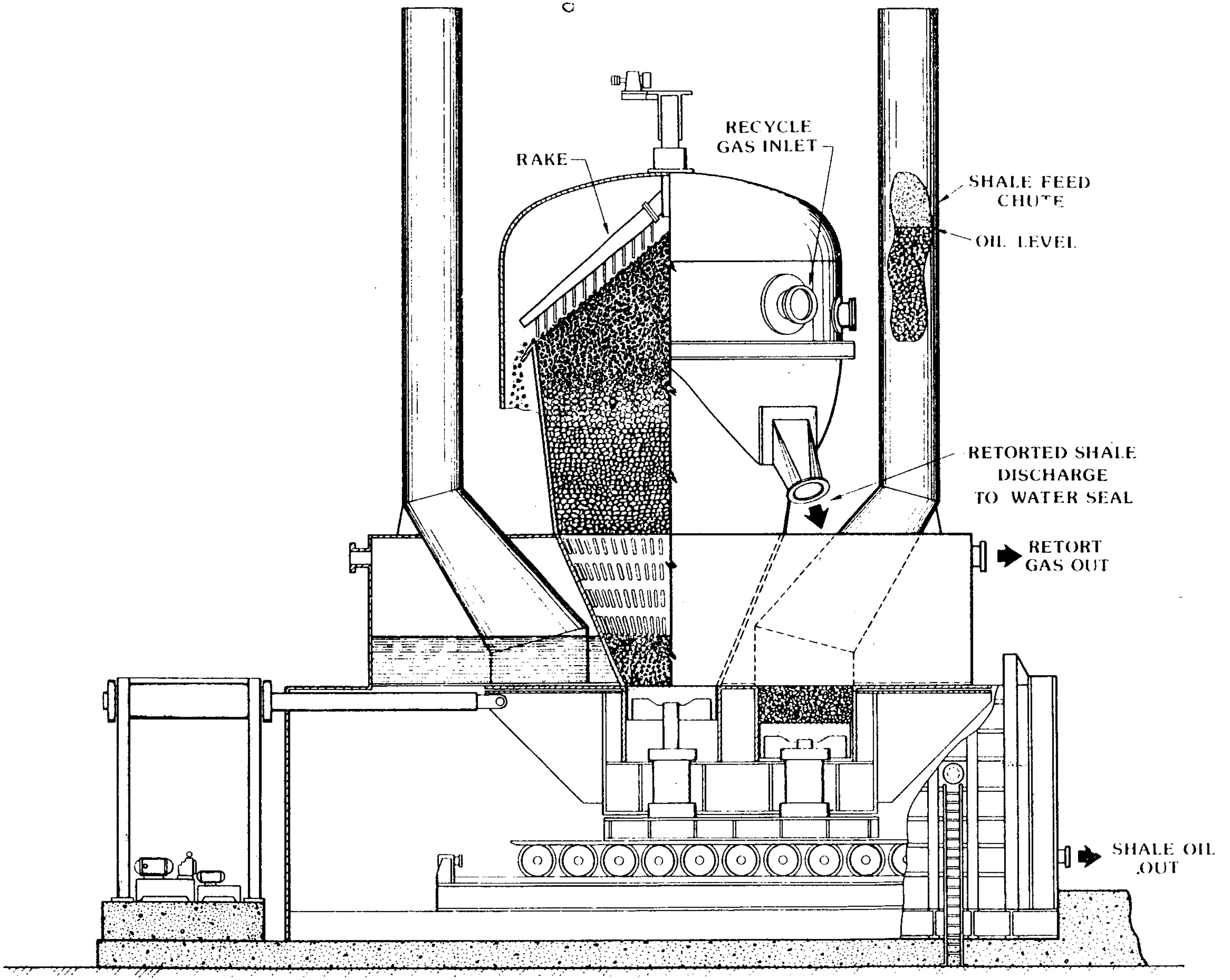

FIGURE 28. UNION OIL COMPANY "B" RETORT (10)

As the shale is pumped upward through the retort, it is met by a countercurrent stream of heated (950° to 1000°F) recycle gas introduced at the top of the retort. This operation, therefore, provides heat for the retorting process to decompose the oil shale kerogen. The resulting liquid and gaseous hydrocarbon products are forced downward by the recycle gas stream, and into a solid carbonaceous residue that remains on the retorted shale. The gas and liquid cool on contact with the rising bed of oil shale and are separated from the shale in the lower slotted wall (disengaging) section of the retort cone.

The retorted shale rises within the retort cone until it stands above the upper cone lip, at which time it either falls off or is dislodged by a rotating rake operating just above the surface of the pile. The retorted shale slides down chutes and through outlets of the dome-topped retort to the quench vessel as shown in Figure 29. A drag-chain conveyor removes the cooled shale from the water seal for disposal. Steam produced in the quench vessel may be condensed and returned to the cooling vessel for reuse.

Gases from the disengaging section may be scrubbed and cooled in a Venturi scrubber. The scrubbed gas is divided into a make-stream and a recycle stream. The make-gas production rate is estimated to be 750 scf/ton of shale. The recycle stream may be compressed and heated for reinjection into the top of the retort. The retort make-gas may be treated by compression and scrubbing to remove heavy ends and hydrogen sulfide. Oil is expected to be used to scrub out heavy hydrocarbons and a Stretford unit may be used to remove hydrogen sulfide. The sweetened make-gas, now at 850 Btu/scf, may be recycled and used as a gas heater fuel and the excess make-gas may be sold as power plant fuel.

The rundown oil product is treated to remove solids by two stages of water washing. The oil also contains about 50 ppm of chemically combined arsenic which is expected to be reduced to about 2 ppm in a Union Oil "B" process (10). In the Union Oil "B" process, this oil is reacted with an absorbent, which removes up to about 80 percent (by weight) of the arsenic. Once arsenic has been removed, the shale oil is then upgraded and refined.

Retorted Shale Handling and Disposal

The Union "B" retorted shale is expected to be a coarse gravel-sized material similar to that produced by the Bureau of Mines and the Paraho retorting processes. The shale will

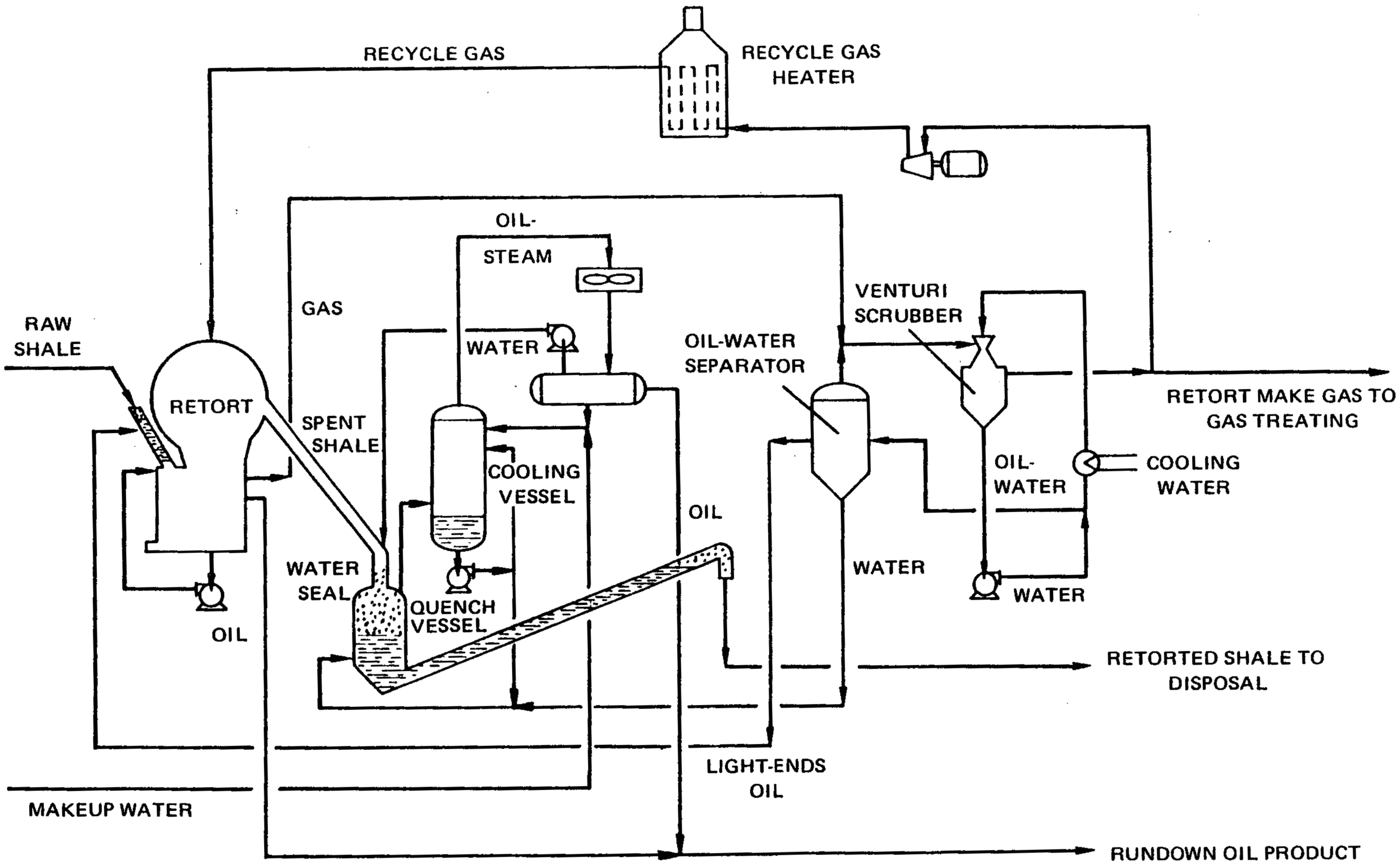

FIGURE 29. RETORT "B" FLOW DIAGRAM—UNION OIL COMPANY (10)

most likely be a black carbon residue, having a pH of about 8.7, and very little tendency for cementation. The dry bulk density of retorted shale from the "B" retort has been reported as 61 lb/ cu ft (14). Assuming a weight loss of 15 percent during retorting, the volume of the retorted shale can be calculated as

$$(0.85 \times 70{,}000 \text{ tons/day} \times 2{,}000 \text{ lb/ton}) \div (61 \text{ lb/cu ft} \times 27 \text{ cu ft/cu yd}),$$

or about 72,250 cu yd/day. This material can be compacted to a density of about 90 lb/cu ft (dry basis), with an equilibrium moisture content of about 19 percent (10). The final disposal volume is found by multiplying 72,250 cu yd/day by (61 lb/cu ft ÷ 90 lb/cu ft), which is equal to 49,000 cu yd/day, or about 18 million cu yd/year. Thus, a disposal area of about 1,100 acres may be required, to which a depth of 10 ft/year of retorted shale can be added.

The retorted shale may be transferred by conveyor belt from the quench vessel to the disposal site (assumed to be 1 mile distant). There the shale is delivered into a truck-loading hopper having three 150-ton compartments. A total of four 150-ton trucks, each making 5 runs/hr, will most likely be required to distribute the retorted shale on the disposal pile. Also required are a bulldozer and a segmented-wheel (sheep's-foot) roller to work the pile and a water truck to control dust.

Pollution Controls

Pollution control systems are expected to be required for reducing or eliminating emissions of noxious gases, dust, and wastewater from a commercial oil shale facility using the Union "B" retorting process. The expected emission sources and types of control systems are discussed in Chapter 4, Volume I. The purpose of this section is to describe the control systems needed specifically for this process.

Dust control during mining, crushing, and shale handling may be accomplished by water sprays and wet suppression techniques. It is estimated that about 750 gal/min of water may be required for this purpose. Conveyor belts may have to be enclosed and crushing devices will most likely require baghouse filters.

Diesel-powered underground mining equipment may be equipped with catalytic converters or wet scrubbers to properly maintain a reduced air emissions level.

Gases collected during product recovery may be scrubbed in a Venturi scrubber and divided into a make-stream and a recycle stream. The recycle stream may be compressed, heated, and reinjected into the retort and the make-stream may be treated initially in a Stretford sulfur unit to remove H_2S, then burned as plant fuel without further control. Sulfur recovered from the Stretford unit is expected to amount to about 67 tons/day, assuming a concentration of 3 percent H_2S in the make-gas stream.

Contaminated water streams resulting from mining and plant operation will be collected, treated, and reused or consumed according to the wastewater treatment plan presented in Chapter 4, Volume I.

3.2.3 Resource Requirements

A 55,000-bbl/day shale oil facility using Union "B" retorting technology will require certain amounts of land, water, power, and other major equipment and material needs. These resource requirements are presented in Table 18.

The facility is expected to require about 200 acres of land for the shale handling and processing plant and 1,100 acres for shale disposal. The land under which mining occurs is expected to be about 300 acres/year, or 6,000 acres over a 20-year period.

Water requirements are estimated at 2,800 gal/min (8,000 acre-ft/year), of which 2,250 gal/min may be recycled to the processed shale disposal operations. The remainder is considered or assumed to be consumptively lost in the process.

The major water-use categories for a Union "B" facility are expected to be as follows:

- Mining (650 gal/min for dust control)
- Crushing and Shale Handling (350 gal/min for dust control)
- Retorting and Upgrading (1,500 gal/min for cooling water, steam generation, and upgrading)
- Retorted Shale Moisturizing, Cooling, and Disposal (2,250 gal/min for dust control, moisturizing, and revegetation)

TABLE 18

RESOURCE REQUIREMENTS FOR A 55,000-BBL/DAY UNION "B" RETORTING FACILITY

Land (acres)	
Oil Shale Processing Plant	200
Retorted Shale Disposal	1,100
Underground Mining (for 20 years)	6,000
Total	7,300
Water (gal/min)	
Mining	650
Crushing and Shale Handling	350
Retorting and Product Recovery	1,500
Retorted Shale Disposal[1]	2,250
General Plant Use	300
Total (8,000 acre-ft/year)	5,050
Power	
Electric (MWe)	23
Diesel (bbl/day)	1,400

[1]Recycled wastewater.

- General Plant and Personnel Use (300 gal/min for utility water, fire protection, potable water, and sanitary-wastes water).

As shown in Table 18, the power requirements for the facility are expected to be 23 MWe and the diesel fuel needs are estimated to be 1,400 bbl/day. Thus, the total equivalent amount of oil to provide for electrical and diesel fuel needs is about 2,700 bbl/day. If the total shale oil production is 55,000 bbl/day, the net energy production is equivalent to 52,300 bbl/day of crude shale oil.

The expected major capital equipment and material needs for the mining, shale crushing and preparation, retorting and product recovery, retorted shale handling, and pollution control systems of a Union "B" facility are presented in Tables 19 to 23.

3.3 PARAHO (INDIRECT)

The assumptions used to conceptually scale-up the Paraho (indirect) process are based on a total crude oil production rate of 56,000 bbl/day, of which an equivalent of 3,000 bbl/day of shale oil are required for energy to operate the facility. In addition, the facility is assumed to be located in the Piceance Creek Basin, where the shale averages 28 gal/ton in the zone of interest.

The commercial-size Paraho facility will probably require 200 acres of land for surface processing systems and support structures and 1,400 acres for the disposal site. Approximately 7,350 acres of land are expected to be mined over a 20-year period. The facility is also expected to need about 7,350 acre-ft of water per year for process and utility use. A block diagram of a scaled-up facility is presented in Figure 30, and a detailed description of the assumptions used in the design is presented in the following sections.

3.3.1 Uncertainties and Assumptions

The Paraho retorting process, though successfully demonstrated at the pilot and semiworks level, has not been tested on a commercial scale. For this study, the conceptual design of a full-scale module is based on the assumption that the large-size retorts needed for commercial-scale operations will be similar to the small-size retorts. The scale-up, therefore, represents a linear extrapolation of small-scale data. In applying this approach, inaccuracies may occur and a factor of uncertainty prevails in the scale-up model. Also,

TABLE 19

PRIMARY CAPITAL EQUIPMENT FOR A SHALE MINE - UNION "B" FACILITY

Heading Jumbo Drill (6 required) Drive: Electric Type: Hydraulic electric with two drills Horsepower: 150	Bulldozer (5 required) Drive: Diesel Horsepower: 700
Bench Jumbo Drill (4 required) Drive: Electric Type: Hydraulic electric with two drills Horsepower: 250	Main Ventilation Fan (1 required) Drive: Electric with 5 blade settings Capacity: 1 million scf/min at 7.6 in., water gauge Horsepower: 800
Powder Trucks (5 required) Drive: Diesel with pneumatic delivery system Capacity: 3 tons Horsepower: 100	Road Grader (2 required) Drive: Diesel 16-ft blade Horsepower: 225
Scaling and Roof Bolting Rig (5 required) Drive: Diesel Aerial Lift Horsepower: 500	Water Truck (4 required) Drive: Diesel Horsepower: 250
Front-End Loader (8 required) Drive: Diesel Bucket Capacity: 10 tons Horsepower: 700	Auxiliary Ventilation Fan (20 required) Drive: Electric Capacity: 25,000 scf/min at 7.6 in., water gauge Horsepower: 40
Haulage Trucks (25 required) Drive: Diesel Capacity: 75 tons Horsepower: 700	Power Centers (7 required) Power: 6 kva
Motor Patrol (4 required) Drive: Diesel Horsepower: 150	

TABLE 20

PRIMARY CAPITAL EQUIPMENT FOR A CRUSHING AND PREPARATION PLANT—UNION "B" FACILITY

Grizzly Bar Screen (6 required)

Load: 600 tons/hr
Screen Opening: 42 in.
Screen Area: 120 sq ft

Primary Crusher Feed Bin (6 required)

Capacity: 300 tons
Size: 20-ft ID x 20-ft s.s. ht
60-deg conical bottom

Magnetic Vibratory Feeder (6 required)

Load: 600 tons/hr
Model: Syntron F-66
Horsepower: 2

Primary Toothed-Roll Crusher (6 required)

Type: McClanahan
Size: 48 in. wide x 72 in. long
Capacity: 600 tons/hr
Drive: Electric
Horsepower: 300

Conveyor to Ore Pass (2 required)

Type: Belt, enclosed
Size: 60 in. wide x 200 ft long
Drive: Electric
Horsepower: 30

Conveyor to Primary Stockpile (1 required)

Type: Belt, enclosed
Size: 60 in. wide x 900 ft long
Drive: Electric
Horsepower: 200

Stacker for Primary Stockpile (1 required)

Type: Fixed-rail swinging-boom traveling stacker
Drive: Diesel
Capacity: 3,500 tons/hr
Horsepower: 1,100

Reclaimer for Primary Stockpile (1 required)

Type: Crawler-mounted rotary bucketwheel reclaimer
Capacity: 3,500 tons/hr
Drive: Diesel
Horsepower: 700

Conveyor to Secondary Crusher (1 required)

Type: Belt, enclosed
Size: 60 in. wide x 600 ft long
Drive: Electric
Horsepower: 90

Secondary Crusher Feed Hopper (6 required)

Capacity: 300 tons
Size: 20-ft ID x 20-ft s.s. ht
60-deg conical bottom

Magnetic Vibratory Feeder (6 required)

Load: 600 tons/hr
Model: Syntron F-66
Horsepower: 2

Grizzly Bar Screen (6 required)

Load: 600 tons/hr
Screen Opening: 10 in.
Screen Area: 120 sq ft

TABLE 20

(CONTINUED)

Secondary Toothed-Roll Crusher (6 required)

Type: McClanahan
Size: 48 in. wide x 72 in. long
Capacity: 600 tons/hr
Drive: Electric
Horsepower: 100

Double-Deck Screen (6 required)

Size: 44 sq ft
Drive: Electric
Horsepower: 5

Conveyor to Retorting Plant (2 required)

Type: Belt, enclosed
Size: 60 in. wide x 500 ft long
Drive: Electric
Horsepower: 100

Retort Feed Storage Bunker (1 required)

Type: Underground
Capacity: 150,000 tons
Size: 250-ft ID x 85-ft ht

Retort Feed Storage Reclaimer (1 required)

Type: Rotary plow feeder on fixed rails
Capacity: 3,000 tons/hr
Drive: Diesel
Horsepower: 700

Conveyor to Retort Feed Hopper (7 required)

Type: Belt, enclosed
Size: 42 in. wide x 200 ft long
Drive: Electric
Horsepower: 15

Retort Feed Hopper (7 required)

Capacity: 420 tons
Size: 25-ft ID x 25-ft ht
60-deg conical bottom

Magnetic Vibratory Feeder (7 required)

Load: 420 tons/hr
Model: Syntron F-66
Horsepower: 2

TABLE 21

PRIMARY CAPITAL EQUIPMENT FOR RETORTING AND PRODUCT RECOVERY—UNION "B" FACILITY

Retort (7 required) Size: 38-ft ID x 25-ft ht retorting section Capacity: 10,000 tons/day Type: Union Oil Company Retort "B" with hydraulic solids pump Horsepower: 200 Processed Shale Quench Vessel (7 required) Type: Water seal with drag-chain conveyor discharge Size: 35-ft ID x 25-ft ht Cooling Water Vessel (7 required) Size: 10,000 gal Pump (28 required) Type: Centrifugal Drive: Electric Horsepower: 5 Water Tank (7 required) Size: 5,000 gal Venturi Scrubber (7 required) Capacity: 150,000 scf/min Drive: Electric Horsepower: 400	Oil Dearsenating System (1 required) Proprietary Oil-Water Separator (7 required) Size: 10,000 gal Recycle Gas Compressor (7 required) Type: Centrifugal Drive: Electric Horsepower: 1800 Recycle Gas Heater (7 required) Type: Gas-fired burner Heat Transfer Surface: 1,750 ft^2 Air Blower (1 required) Type: Centrifugal Drive: Motor Horsepower: 3,200 Crude Rundown Tank (20 required) Capacity: 5,800 bbl Type: Cone roof Crude Storage Tank (5 required) Capacity: 60,000 bbl Type: Cone roof

TABLE 22

PRIMARY CAPITAL EQUIPMENT FOR RETORTED SHALE HANDLING AND DISPOSAL—UNION "B" FACILITY

<u>Conveyor to Disposal Site (1 required)</u>

Type: Belt, enclosed
Size: 60-in. width x six 900-ft sections
Drive: Electric
Horsepower: 1,800

<u>Truck Loading Hopper (1 required)</u>

Capacity: 450 tons
Three 150-ton compartments

<u>Haulage Truck (4 required)</u>

Capacity: 150 tons
Drive: Diesel
Horsepower: 1,000

<u>Bulldozer (1 required)</u>

Drive: Diesel
Horsepower: 700

<u>Segmented-Wheel Compactor (1 required)</u>

Drive: Diesel
Horsepower: 500

<u>Water Truck (1 required)</u>

Drive: Diesel
Horsepower: 250

TABLE 23

PRIMARY CAPITAL EQUIPMENT FOR POLLUTION CONTROL—UNION "B" FACILITY

<u>Baghouse Filter—Shale Crushing and Preparation Units (32 required)</u>

Type: Induced draft
Drive: Electric
Horsepower: 40

<u>Hydrogen Sulfide Removal—Make-Gas Stream (1 required)</u>

Type: Stretford sulfur unit
Capacity: 40,000 scf/min
Production: 60 tons/day sulfur

<u>Wastewater Holding Tank—Surge, Sedimentation, and Gravity Separation (5 required)</u>

Size: 500 gal

<u>Wastewater Treatment Unit (1 required)</u>

Flotation: 25,000 gal/day
Biological Oxidation: 35,000 gal/day
Filtration: 35,000 gal/day
Reverse Osmosis: 7,000 gal/day

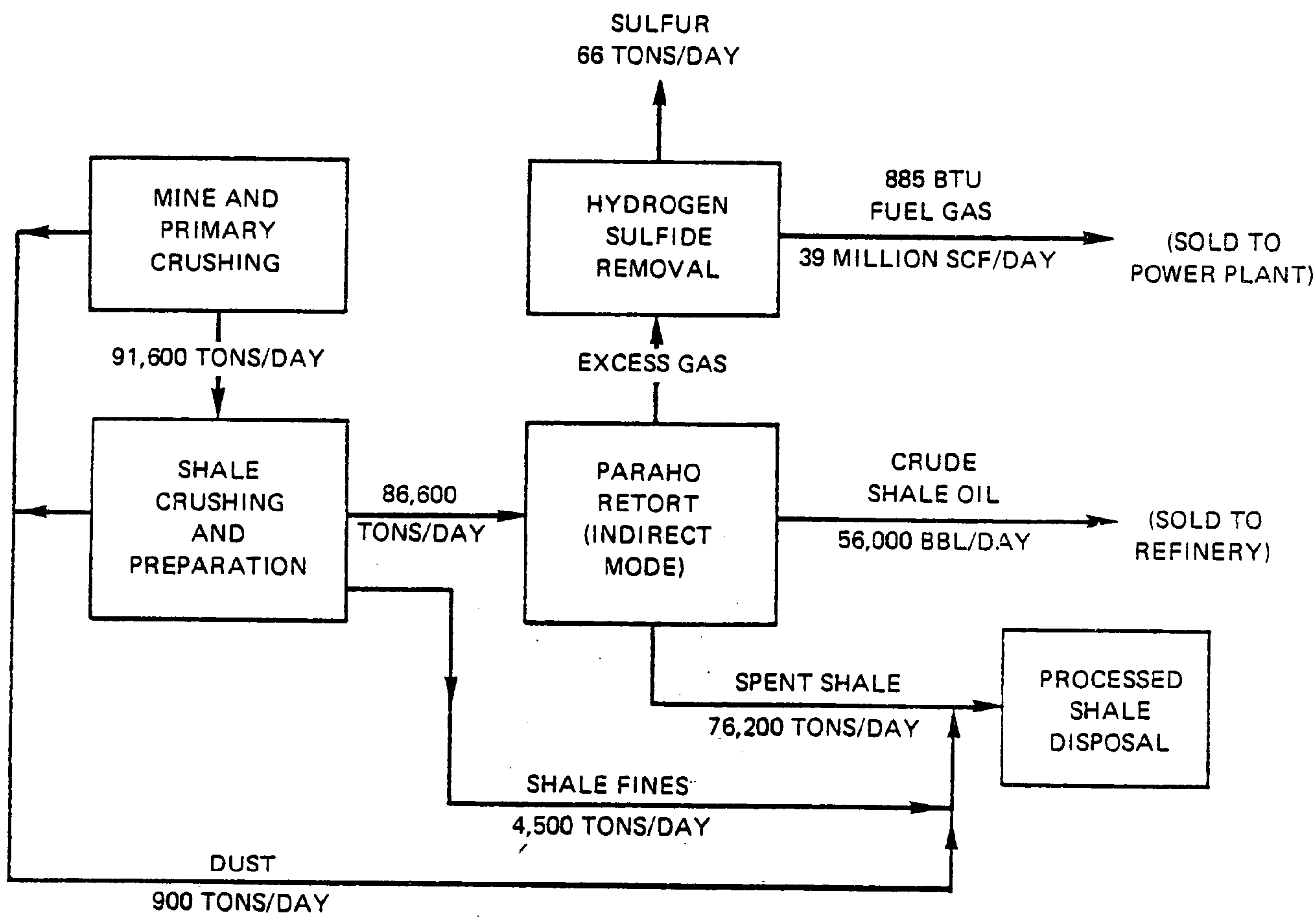

FIGURE 30. BLOCK DIAGRAM FOR A 56,000-BBL/DAY PARAHO (INDIRECT) FACILITY

the quality of data used (especially where limited data are available) affects the accuracy of scale-up. The following variables were considered independent of retort size in the scale-up of the Paraho process:

- Residence time of the shale in the bed
- Acceptable range of shale grade
- Superficial velocity of the shale
- Superficial velocity of the gas
- Acceptable particle-size range
- Bed porosity
- Temperature distribution
- Pressure distribution
- Oil yield.

Based on available process data (17,18,19) and best estimates developed for site specific parameters (16), the following specifications were assumed with regard to these variables:

- Shale grade: 28 gal/ton
- Oil shale zone thickness: 55 ft
- Overburden thickness: 850 ft
- Bed height: 35 ft
- Superficial velocity of shale: 660 lb/hr/ sq ft
- Gas rate in retort: 22,500 scf/ton shale
- Cold gas recycle rate: 15,825 scf/ton
- Hot gas recycle rate: 6,000 scf/ton shale
- Hot recycle gas temperature: 1300°F
- Retort off-gas temperature: 280°F
- Retorted shale: 88 percent by weight of raw shale
- Oil yield: 97 percent Fischer assay.

3.3.2 Process Systems

The process systems scaled-up for the Paraho retorting process are discussed in the same categories as the Gas Combustion retort and the Union "B" processes. These categories include mining and shale handling, crushing and screening, retorting and product recovery, retorted shale handling, and pollution controls.

Mining and Shale Handling

In scaling-up the Paraho process, it is assumed that all activities will take place in the Uinta basin, immediately south of the White River. In addition, the mine supplying the shale is expected to be open at an elevation of 5,500 ft and to extend into the Mahogany Zone about 850 ft below the surface. This zone has a thickness of approximately 55 ft and an average oil yield of 28 gal/ton shale (16), which is considered suitable for use in the Paraho process, since the process has been successfully demonstrated on a 28 gal/ton shale at the semiworks level (17).

Mining will most likely be done by the room-and-pillar method at a rate of 92,000 tons/day. The mined shale is expected to be transported by haulage trucks to a primary crushing plant located at the mining level. At this point shale may be received by the primary crusher feed bins, which should be designed to provide a 30-min holdup. From these bins, shale is transferred by means of apron feeders to roll crushers, which reduce the run-of-mine shale to less than 10 in. in size. The primary crushed shale is then transferred to conveyors by means of belt feeders, and transported to the surface. Figure 31 depicts the shale flow during its passage through the primary crushing system and the stockpile.

Shale Crushing and Preparation

Primary crushed shale, upon being transported to the surface, may be transferred by inclined conveyors to a set of tripper conveyors for delivery to the stockpile. The stockpile should be designed to store about 450,000 tons or approximately 5 days' supply of shale for the secondary crushers. Consequently, any short-term shutdown of the mine or the primary crushers will not result in stoppage of the retorting operation.

A schematic of a typical secondary crushing unit appears in Figure 32. Shale from the stockpile may be transferred by apron feeders to the coarse ore reclaim conveyor, which carries the shale to a vertical conveyor. The conveyor transports the shale to the secondary crusher feed bins, which are sized for a 30-min holdup of shale. Shale is removed from the bottom of the bins by means of belt feeders and sent to single-deck vibrating screens, which screen the shale through a 3-in. opening. Particles larger than 3 in. are fed directly to the secondary roll crushers, which reduce the shale to the 3-in. size. The crushed product, along with the undersize from the screens (which consists of particles smaller than 3 in.), is next sent to double-deck vibrating screens where it is successively screened through a 1-1/2-in. opening and a 1/2-in. opening. Particles smaller than 1/2 in. in size cannot be processed by the Paraho retort and are therefore discarded. The coarse product (particles in the size range of 1/2 to 3 in.) is delivered to the retorting plant by a 500-ft-long belt conveyor. At the retorting

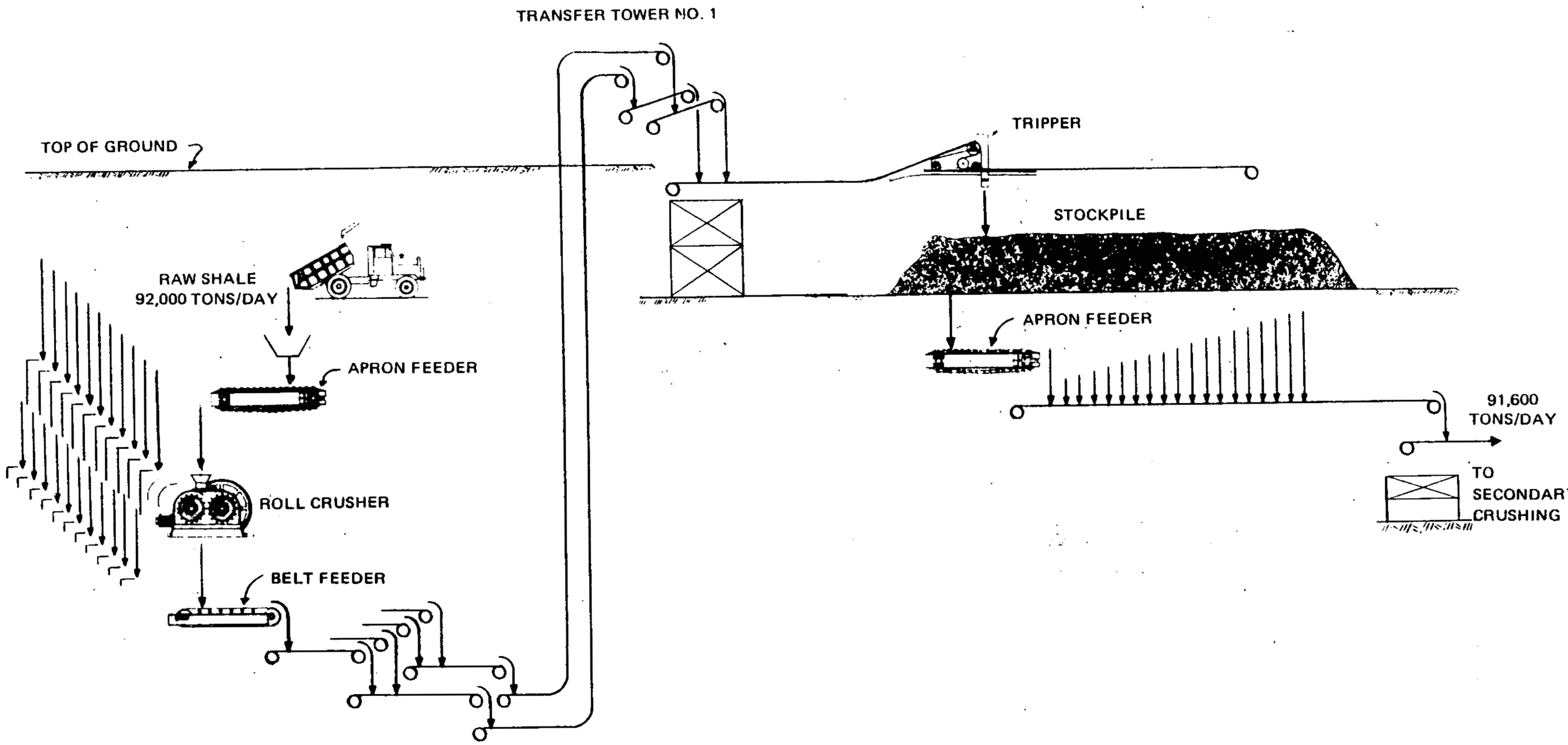

FIGURE 31. PRIMARY CRUSHING AND STOCKPILING OPERATIONS—PARAHO (INDIRECT) FACILITY

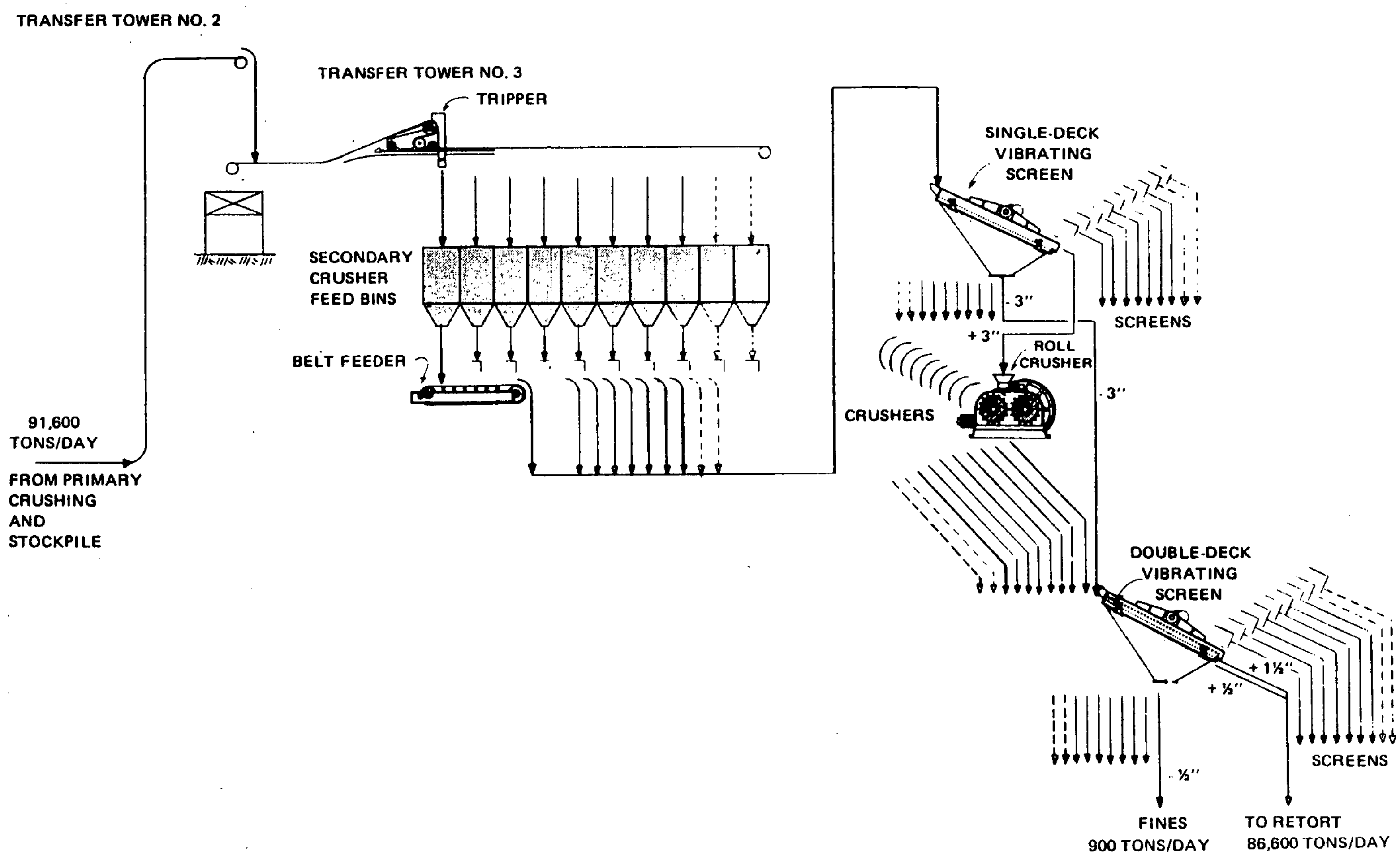

FIGURE 32. SECONDARY CRUSHING OPERATION—PARAHO (INDIRECT) FACILITY

plant, shale may be transferred from the conveyor to the retort feed storage bunker, which has a capacity of 175,000 tons. Shale may then be reclaimed from the bunker by a rotary plow feeder, which is mounted on rails and continuously withdraws shale from the bottom of the bunker.

Retorting and Product Recovery

A typical Paraho indirect-heating retort, consisting of nine parallel retorts, is shown in Figure 33. In this retort shale from the rotary plow feeder is conveyed to the top of the retort where it enters the feed hoppers in which a holding time of 1 hr is provided. Each of the retorts is expected to be 40 ft in diameter with a bed height of 35 ft. About 9,620 tons of raw shale per day can be processed by each retort, resulting in the production of 6,220 bbl of oil. In addition, it is estimated that each retort will also produce 4,330,000 scf/day of excess high-Btu gas and 8,465 tons/day of retorted shale.

In the Paraho process, shale enters the retort from the bottom of the feed hoppers and moves down at a superficial velocity of 660 lb/hr/sq ft. Shale is heated by contact with rising hot gas in the upper part of the retort and reaches pyrolysis temperature before it moves into the pyrolysis zone in the middle of the retort. Hot recycle gas is introduced at the center of the retort and is mixed with the cooler gas rising up from the retort bottom.

The gases leaving the top of the retort are passed through a cyclone separator where dust and entrained particles are removed from the gas stream. In addition, tar and other heavier hydrocarbons are condensed from the gas stream in this unit. The gases next enter an electrostatic precipitator where shale oil is condensed and removed as a liquid stream. The crude oil may then be pumped to storage tanks where a holding time of about 5 days is provided. Gases leaving the retort are passed through a blower before being divided into three streams: one is the product stream and the other two are recycled back into the retort. One of the two may be injected as a cold recycle at the bottom of the retort and part of the other may be mixed with air and burned in a recycle gas heater. The heat generated serves to preheat the rest of this stream to about 1300°F before it is introduced into the retort vessel through the gas distributors.

The product gas stream obtained from the retorting operation is undiluted with nitrogen and consequently has a

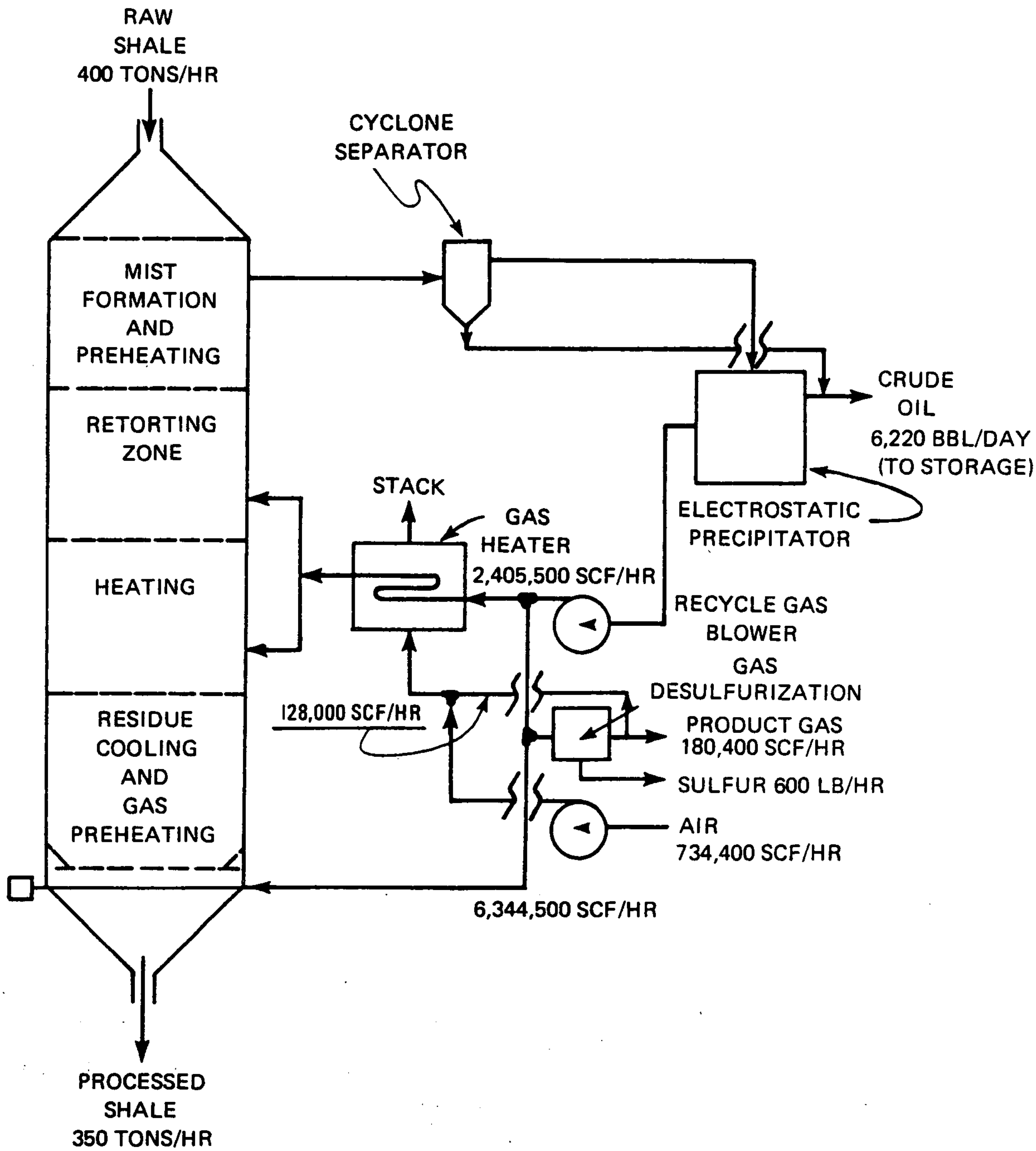

FIGURE 33. SCHEMATIC FLOW DIAGRAM OF THE PARAHO (INDIRECT) PROCESS

high-Btu content (roughly 885 Btu/scf). The gas, however, has to be desulfurized before it is acceptable as a clean fuel. Desulfurization may be accomplished by means of a Stretford unit, which strips the H_2S from the gas and produces elemental sulfur as a by-product. A flow scheme of a typical Stretford process is shown in Figure 34 (3).

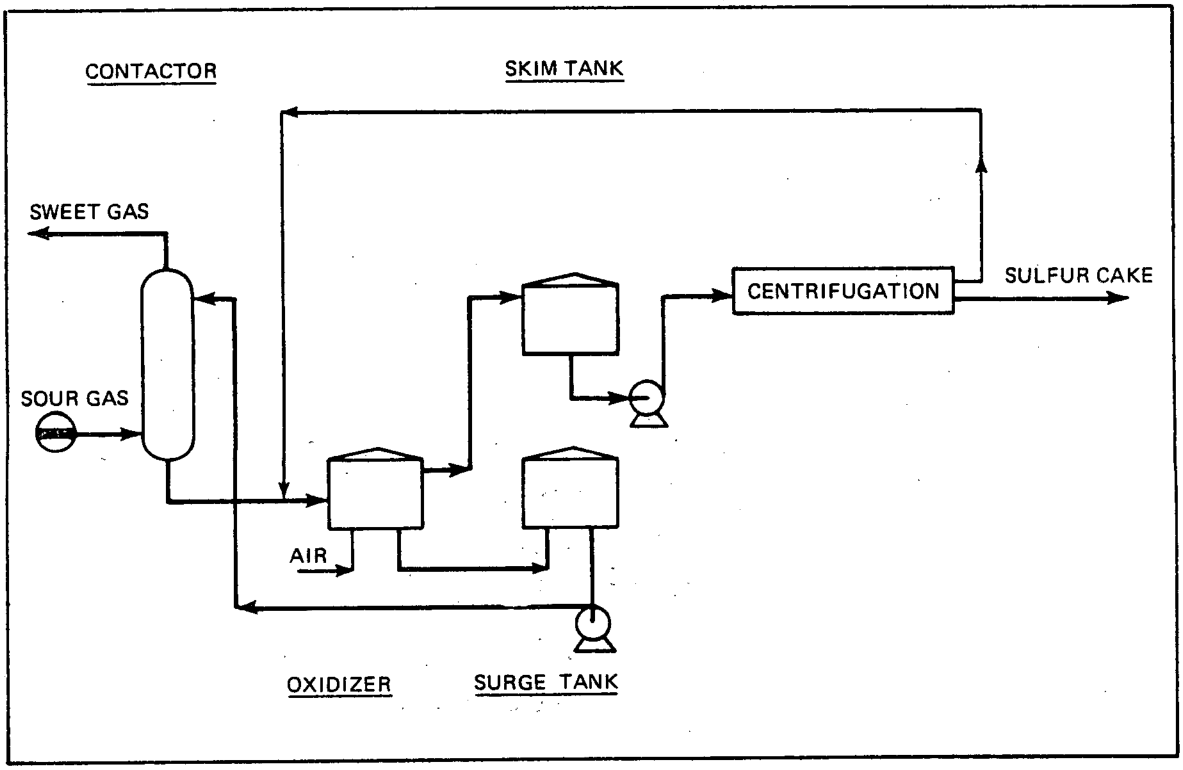

FIGURE 34. STRETFORD PROCESS FOR GAS DESULFURIZATION—PARAHO (INDIRECT) FACILITY

In the Stretford process, the sour gas entering the unit is first washed with an aqueous solution containing sodium carbonate, sodium vanadate, and anthraquinone disulfonic acid (ADA). The solution reaches an equilibrium with respect to the CO_2 in the gas, and only relatively small amounts of CO_2 are removed by the process (33). The H_2S dissolves in the alkaline solution and the sweetened gas leaving the contactor may be sold to a power-generating plant. The hydrogen sulfide formed reacts with the 5-valent state vanadium and is oxidized to elemental sulfur. The liquor is regenerated by air blowing, and the reduced vanadium is restored to the

5-valent state through a mechanism involving oxygen transfer via the ADA. The sulfur may be removed by froth flotation, producing a scum which is centrifuged for sulfur retrieval. Sulfur is then recovered in the form of coke at the rate of 66 tons/day and can be sold as a by-product.

Retorted Shale Handling and Disposal

The scale-up of the Paraho process assumes that retorted shale is discharged from the bottom of the retort at a temperature of about 350°F and fed into a quench vessel. Dust-laden steam and moist air produced in this step pass through high-efficiency wet scrubbers in which shale dust-water from the scrubbers is clarified for reuse and the sludge is sent to processed shale disposal (16). After cooling and moisturizing, the processed shale may be carried on dual 60-in.-wide conveyor belts to a disposal site (assumed to be a mile away). At the disposal site, the retorted shale may be loaded into a hopper with three 150-ton compartments. A total of five 150-ton trucks, each making 5 runs/hr, are the expected requirements to distribute the retorted shale on the disposal pile. A grader, bulldozer, and water truck to work the pile and reduce dusting are other equipment needed at the disposal site.

Pollution Controls

For a commercial-scale Paraho facility, pollution control systems are expected to be necessary for reducing or eliminating emissions of noxious gases, dust, and wastewater. The expected emission sources and types of control systems are presented in detail in Chapter 4, Volume I. The control systems selected specifically for this process are described in the following discussion.

Dust control during mining, crushing, and shale handling is expected to be accomplished by water sprays and wet suppression techniques. It is estimated that about 750 gal/min of water will be required for this purpose. Conveyor belts will most likely be enclosed and crushing operations will need to have baghouse filters, as indicated in Chapter 4, Volume I.

Diesel-operated underground mining equipment will probably require the use of catalytic converters or wet scrubbers, which should be maintained continuously to reduce emissions. Gases and dusts emitted during the retort feed and discharge operations will most likely have to be scrubbed with the sludge sent to a disposal area. Each retort will need to be equipped with a cyclone separator for this purpose, as illustrated in Figure 34. Gases collected during product recovery should be treated to remove H_2S and may be sold to a utility company for power generation. A typical gas purification system was described previously in the Retorting and Product Recovery section.

Contaminated water streams resulting from mining and plant operation will have to be collected, treated, and reused or consumed according to the possible wastewater treatment plan presented in Chapter 4, Volume I.

3.3.3 Resource Requirements

A 56,000-bbl/day (net) shale oil facility using the Paraho indirect retorting process will require certain amounts of land, water, power, and other major equipment and material needs. Table 24 presents a listing of the projected resource requirements for this facility.

A commercial-scale Paraho facility is expected to require about 200 acres of land for the shale handling and processing plant operations and 1,400 acres for a retorted shale disposal site. The land requirements under which mining occurs are expected to be about 370 acres/year, or 7,400 acres over a 20-year period. This land that the mine underlies is not considered to be disturbed (unless severe subsidence occurs) if it can be reclaimed or used for other purposes.

Water is expected to be used for practically every aspect of the mine and plant operations associated with this facility. Total consumptive use is estimated at 4,575 gal/min (7,350 acre-ft/year) for normal operations. The major water-use categories are as follows:

- Mining (400 gal/min for dust control)
- Crushing and Shale Handling (150 gal/min for dust control)
- Retorting and Product Recovery (750 gal/min for cooling water, steam generation, and upgrading)
- Retorted Shale Moisturizing, Cooling, and Disposal (3,000 gal/min for dust control, moisturizing, and revegetation)
- General Plant and Personnel Use (275 gal/min for utility water, fire protection, potable water, and sanitary-wastes water).

TABLE 24

RESOURCE REQUIREMENTS FOR A 56,000-BBL/DAY PARAHO FACILITY

Land (acres)	
Shale Processing Plant	200
Retorted Shale Disposal	1,400
Underground Mining (for 20 years)	7,350
Total	8,950
Water (gal/min)	
Mining	400
Crushing and Shale Handling	150
Retorting and Product Recovery	750
Retorted Shale Disposal	3,000
General Plant Use	275
Total (7,350 acre-ft/year)	4,575
Power	
Electric (MWe)	31
Diesel (bbl/day)	1,300

As shown in Table 24, the electrical power needs for a Paraho commercial-scale facility are estimated to be 31 Mwe and the diesel fuel needs are about 1,300 bbl/day. Thus, the total equivalent amount of oil needed to satisfy both electrical and diesel fuel needs is about 3,000 bbl/day. For a total production rate of 56,000 bbl/day of crude shale oil, the net production is 53,250 bbl/day of crude shale oil.

The projected major capital equipment and material needs for the mining and shale handling, crushing and preparation, retorting and product recovery, retorted shale handling, and pollution control operations of a commercial-scale Paraho facility are presented in Tables 25 to 29.

3.4 TOSCO II

The scale-up specifications for the TOSCO II process discussed in this section are based on the overall assumption that the facility produces 56,000 bbl/day of shale oil, requires an equivalent of 3,250 bbl/day of shale oil for energy, and is located in the Piceance Creek Basin, which contains an average of 35 gal/ton of shale in the zone of interest.

The facility is expected to require 250 acres of land for surface activities and 1,100 acres for use as a disposal site. Over a 20-year period, about 5,700 acres of land are expected to be mined. Overall water needs for the plant are expected to be about 6,050 acre-ft/year. A block diagram of a possible TOSCO II commercial facility is presented in Figure 35 and details of the scale-up assumptions used in the design are defined in the following sections.

3.4.1 Uncertainties and Assumptions

In the scenario for scaling up the TOSCO II process (20, 21), the gas and oil vapor mixture emerging from the retort is assumed to be directly fractionated into naphtha, diesel fuel, heavy residue, and other streams. Both the gas and oil products may be upgraded and further processed at a refinery. Oil is also expected to be present in or mixed with gases in cyclones and electrostatic precipitators. This oil may be condensed from these separators and sold to a refinery for further processing.

The exact location of the commercial retorting facility is assumed to be the same as that anticipated for the Colony Development Project, i.e., the Dow West property of Middle Fork of Parachute Creek, which includes a retorted shale

TABLE 25

PRIMARY CAPITAL EQUIPMENT FOR A SHALE MINE—
PARAHO (INDIRECT) FACILITY

Heading Jumbo Drill (6 required)

Drive: Electric
Type: Hydraulic electric with two drills
Horsepower: 150

Bench Jumbo Drill (3 required)

Drive: Electric
Type: Hydraulic electric with two drills
Horsepower: 150

Powder Trucks (6 required)

Drive: Diesel with pneumatic delivery system
Capacity: 3 tons
Horsepower: 100

Scaling and Roof Bolting Rig (6 required)

Drive: Diesel
Aerial Lift
Horsepower: 500

Front-End Loader (10 required)

Drive: Diesel
Bucket Capacity: 10 tons
Horsepower: 700

Haulage Trucks (20 required)

Drive: Diesel
Capacity: 75 tons
Horsepower: 700

Motor Patrol (4 required)

Drive: Diesel
Horsepower: 150

Bulldozer (6 required)

Drive: Diesel
Horsepower: 700

Main Ventilation Fan (1 required)

Drive: Electric with 5 blade settings
Capacity: 1 million scf/min at 7.6 in., water gauge
Horsepower: 800

Road Grader (2 required)

Drive. Diesel
Horsepower: 225

Water Truck (5 required)

Drive: Diesel
Horsepower: 250

Auxiliary Ventilation Fan (20 required)

Drive: Electric
Capacity: 25,000 scf/min at 7.6 in., water gauge
Horsepower: 40

Power Centers (8 required)

Power: 6 kva

Primary Crusher Feed Bin (10 required)

Holdup: 30 min
Size: 12 ft wide x 24 ft long x 20 ft high

Apron Feeders (10 required)

Capacity: 400 tons/hr
Horsepower: 15

TABLE 25

(CONTINUED)

<u>Roll Crusher (10 required)</u> Capacity: 400 tons/hr Horsepower: 200 Drive: Motor <u>Belt Feeder (8 required)</u> Load: 500 tons/hr Horsepower: 4 <u>Collecting Conveyor (4 required)</u> Type: Belt Size: 60 in. wide x 25 ft long Belt Speed: 250 ft/min Horsepower: 5	<u>Transport Conveyor (2 required)</u> Type: Belt Size: 60 in. wide x 50 ft long Belt Speed: 450 ft/min Horsepower: 10 <u>Transfer Conveyor (2 required)</u> Type: Belt Size: 60 ft wide x 900 ft long Belt Speed: 450 ft/min Horsepower: 2,000 Drive: Motor

TABLE 26

PRIMARY CAPITAL EQUIPMENT FOR CRUSHING AND PREPARATION PLANT—PARAHO (INDIRECT) FACILITY

Incline Conveyor (2 required)

Type: Belt
Size: 60 in. wide x 20 ft long
Belt Speed: 450 ft/min
Horsepower: 25
Drive: Motor

Tripper Conveyor (2 required)

Type: Belt
Size: 60 in. wide x 100 ft long
Belt Speed: 450 ft/min
Horsepower: 22
Drive: Motor

Apron Feeder (15 required)

Capacity: 250 tons/hr
Horsepower: 10

Coarse Ore Reclaim Conveyor (1 required)

Type: Belt
Size: 2 sections, 60 in. wide x 900 ft long
Belt Speed: 450 ft/min
Horsepower: 225
Drive: Motor

Secondary Crusher Feed Conveyor (2 required)

Type: Belt
Size: 60 in. wide x 250 ft long
Belt Speed: 450 ft/min
Horsepower: 60
Drive: Motor

Tripper Conveyor (2 required)

Type: Belt
Size: 60 in. wide x 100 ft long
Belt Speed: 450 ft/min
Horsepower: 22
Drive: Motor

Secondary Crusher Feed Bin (6 required)

Holdup: 30 min
Size: 12-ft width x 24-ft length x 30-ft overall ht

Belt Feeder (6 required)

Load: 625 tons/hr
Horsepower: 5

Single-Deck Vibrating Screen (6 required)

Load: 625 tons/hr
Screen Opening: 3 in.
Size: 100 sq ft
Horsepower: 15
Drive: Motor

Roll Crusher (6 required)

Capacity: 500 tons/hr
Horsepower: 100
Drive: Motor

Double-Deck Vibrating Screen (6 required)

Load: 625 tons/hr
Size: 50 sq ft
Horsepower: 5
Drive: Motor

Conveyor to Retorting Plant (2 required)

Type: Belt
Size: 60 in. wide x 750 ft long
Belt Speed: 450 ft/min
Horsepower: 100
Drive: Motor

TABLE 26

(CONTINUED)

Retort Feed Storage Bunker (1 required)	Retort Feed Storage Reclaim (1 required)
Type: Underground Capacity: 175,000 tons Size: 250-ft ID x 100-ft ht	Type: Rotary plow feeder on fixed rails Capacity: 3,625 tons/hr Horsepower: 700 Drive: Diesel

TABLE 27

PRIMARY CAPITAL EQUIPMENT FOR A RETORTING AND PRODUCT RECOVERY PLANT—PARAHO (INDIRECT) FACILITY

Retort (9 required)

Size: 39.33-ft ID x 35-ft ht retorting section
Type: Vertical kiln equipped with retorting "pants leg" spreader and hydraulically operated discharge grate mechanism
Refractory: 9-in. firebrick, 9-in. K-30 insulating brick (retorting section)
Drive: Motor-activated hydraulic
Horsepower: 125 top, 200 bottom

Cyclone Separator (36 required)

Capacity: 37,600 scf/min
Drive: Motor
Horsepower: 100

Blower (3 required) (Recycle and Product Gas)

Type: Centrifugal
Drive: Motor
Horsepower: 1,870

Air Blower (2 required)

Type: Centrifugal
Drive: Motor
Horsepower: 2,800

Recycle Gas Heater (9 required)

Type: Gas-fired Burner
Heat Transfer Surface: 20,000 ft^2

Electrostatic Precipitator (18 required)

Size: 10.4-in. ID x 15-ft ht
Capacity: 75,200 cu ft
Power: 7.5 kw

Shale Oil Pump (9 required)

Capacity: 182 gal/min
Drive: Motor
Horsepower: 3.25

Feed Hopper on Retort (9 required)

Size: 27.5-ft ID x 27.5-ft ht 60-deg conical bottom
Holdup: 1 hr
Construction Material: Steel

Retort Feed Conveyor (1 required)

Type: Belt
Size: 72 in. wide x 450 ft long
Drive: Motor
Horsepower: 200

Process Shale Quench Vessel (8 required)

Type: Water seal with drag chain conveyor discharge
Size: 35-ft ID x 25-ft ht

Cooling Water Vessel (8 required)

Size: 10,000 gal

Cooling Water Pump (8 required)

Type: Centrifugal
Drive: Motor
Horsepower: 2

Water Tank (8 required)

Size: 5,000 gal

TABLE 27

(CONTINUED)

<u>Stretford Unit for Gas Purification (1 required)</u> Capacity: 40,000 CfM, 3.5% H_2S Power Consumption: 400 kw Sulfur Production: 66 tons/day <u>Crude Rundown Tank (20 required)</u> Capacity: 6,000 bbl Type: Cone roof	<u>Crude Storage Tank (5 required)</u> Capacity: 60,000 bbl Type: Cone roof

TABLE 28

PRIMARY CAPITAL EQUIPMENT FOR RETORTED SHALE HANDLING AND DISPOSAL—PARAHO (INDIRECT) FACILITY

Conveyor to Disposal Site
(1 required)

Type: Belt, enclosed
Size: 60-in. width x six 900-ft sections
Drive: Motor
Horsepower: 2,000

Truck-Loading Hopper
(1 required)

Capacity: 450 tons
Three 150-ton compartments

Haulage Truck
(5 required)

Capacity: 150 tons
Drive: Diesel
Horsepower: 1,000

Bulldozer
(1 required)

Drive: Diesel
Horsepower: 700

Segmented-Wheel Compactor
(1 required)

Drive: Diesel
Horsepower: 500

Water Truck
(1 required)

Drive: Diesel
Horsepower: 250

TABLE 29

PRIMARY CAPITAL EQUIPMENT FOR POLLUTION CONTROL—PARAHO (INDIRECT) FACILITY

<u>Baghouse Filter—Shale Crushing and Screening Unit (25 required)</u>

Type: Induced draft
Drive: Electric
Horsepower: 40

<u>Wastewater Holding Tank—Surge, Sedimentation, and Gravity Separation (5 required)</u>

Size: 500 gal

<u>Wastewater Treatment Unit (1 required)</u>

Flotation: 25,000 gal/day
Biological Oxidation: 35,000 gal/day
Filtration: 35,000 gal/day
Reverse Osmosis: 7,000 gal/day

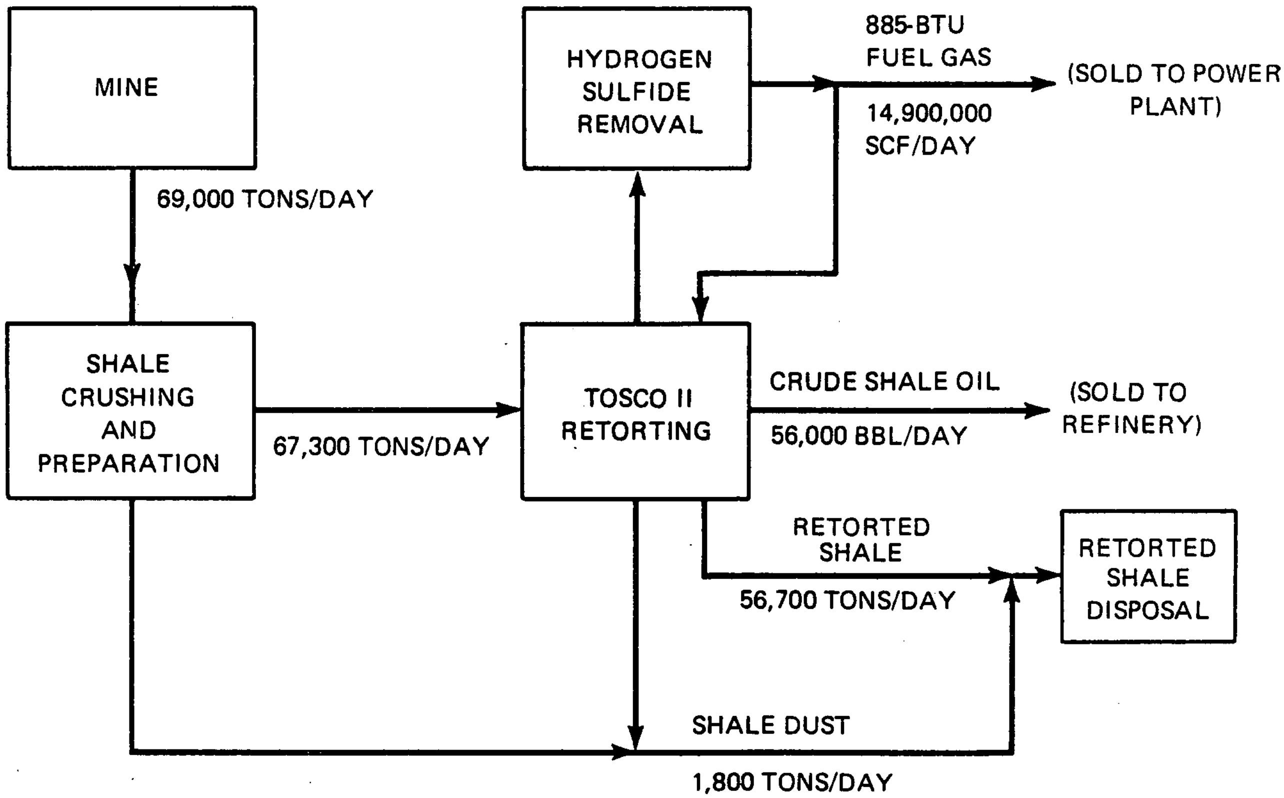

FIGURE 35. BLOCK DIAGRAM FOR A 56,000-BBL/DAY TOSCO II FACILITY

disposal site at nearby Davis Gulch. This commercial facility is expected to produce 56,000 bbl/day of shale oil and use electricity and diesel fuel purchased from external sources. Other assumptions regarding the scale-up parameters of the TOSCO II process are based on available data (9,18,23) and include

- Shale grade: 35 gal/ton
- Flow rate of ceramic balls: 2 tons/ton of shale
- Preheated shale temperature: 500°F
- Temperature of balls: 1300°F
- Retort exit temperature: 900°F
- Retort capacity: 11,000 tons/day
- Gross heating value of gas: 885 Btu/scf.

3.4.2 Process Systems

The probable process systems of a commercial-scale TOSCO II facility are discussed below and divided into the same categories as the previous process scale-ups.

Mining and Shale Handling

Since commercial development is expected to take place in the Dow West property of Middle Fork of Parachute Creek, mining will most likely be done by using the conventional room-and-pillar technique (described in Chapter 3, Volume I). Based on a production rate of 56,000 bbl/day, about 69,000 tons/day of oil shale will need to be mined for processing. The shale mined is expected to have an average grade of about 35 gal/ton and be transported by haulage trucks directly to the primary crushing units. Mine access is expected to be from a portal bench constructed in the Middle Fork Canyon of Parachute Creek at the level of the Mahogany Zone outcrop. Parking facilities, offices, haulage equipment, mine water and fuel supply, service stations, and other support facilities will need to be provided at the bench surface.

Shale Crushing and Preparation

The typical facilities for primary and secondary crushing are illustrated in Figures 36 and 37. In these types of facilities, run-of-mine shale is fed directly to the primary crushing unit at the rate of 69,000 tons/day. The primary crushing unit, consisting of five gyratory crushers, reduces the shale to a nominal size of 10 in. before further crushing is carried out. The crushed shale leaving the gyratory crushers enters surge storage bins and is held for a period of about 30 minutes. Upon leaving the surge storage

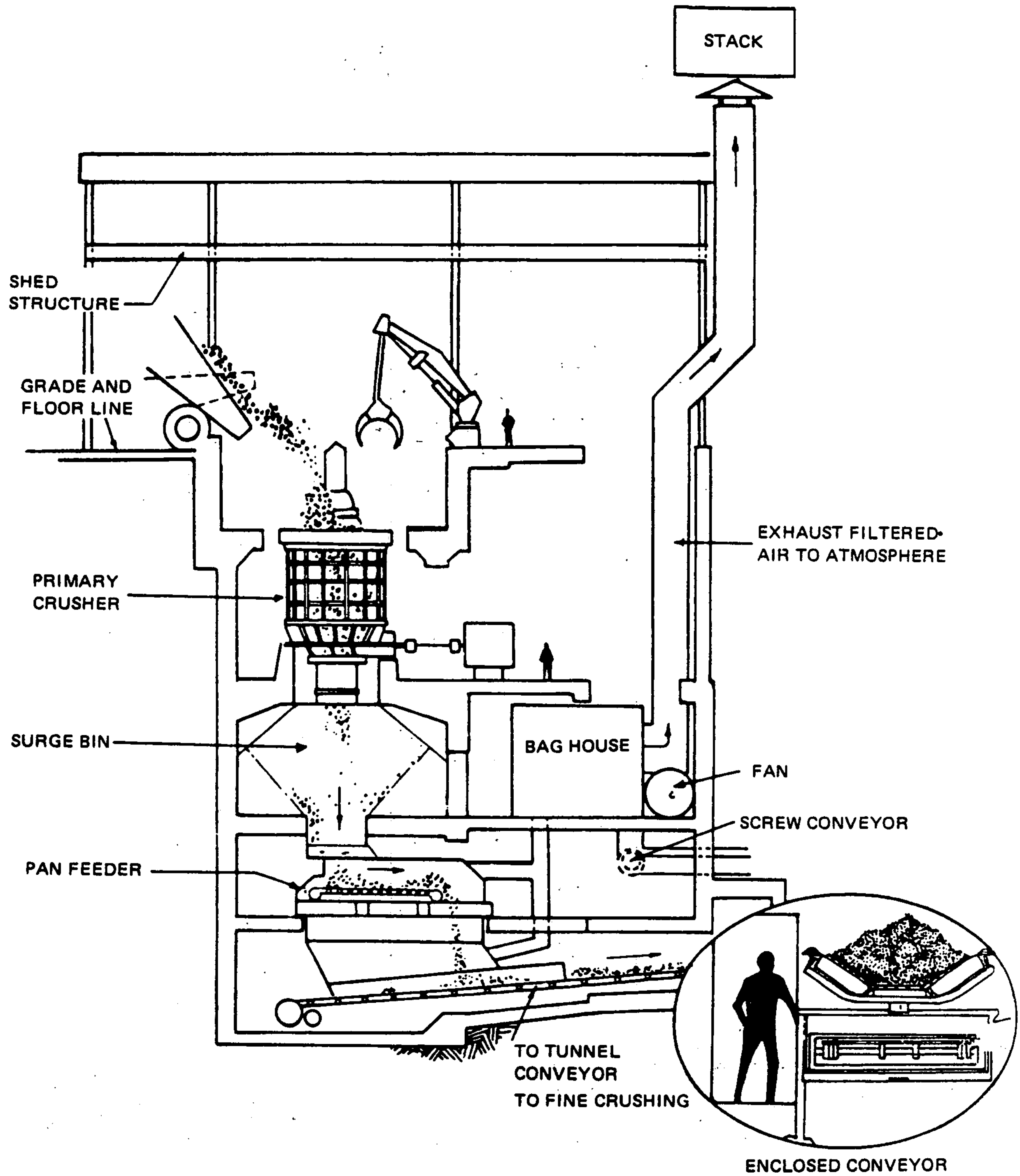

FIGURE 36. PRIMARY CRUSHER (WITH DUST CONTROL)—
TOSCO II FACILITY (21)

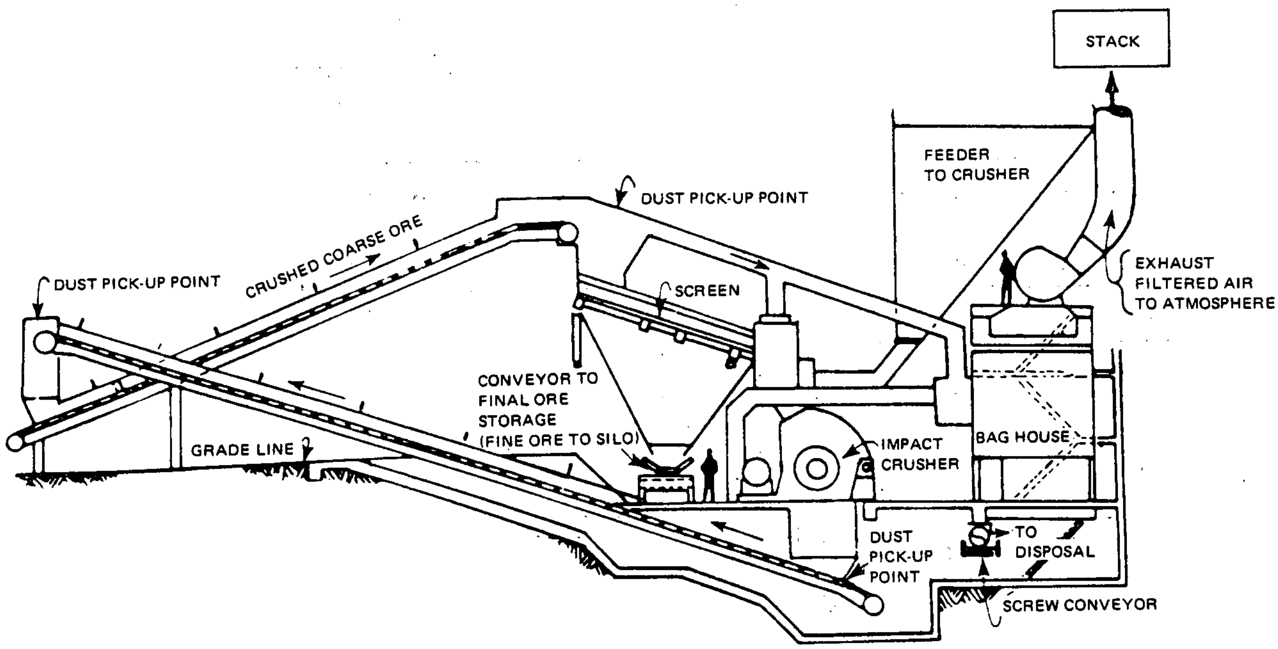

FIGURE 37. FINAL CRUSHER (WITH DUST CONTROL)—
TOSCO II FACILITY (21)

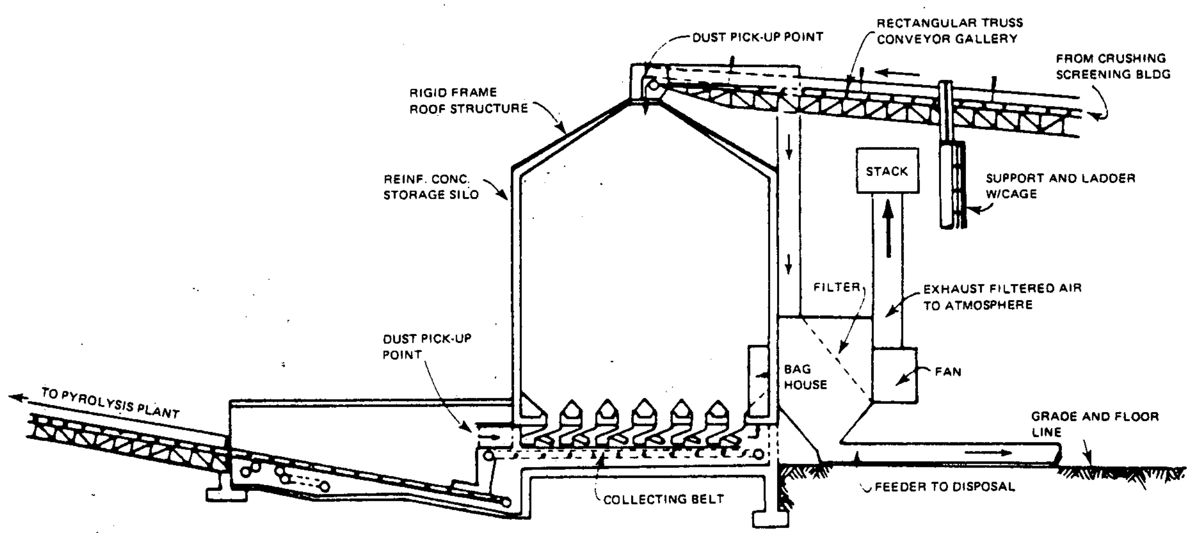

FIGURE 38. FINE ORE STORAGE (WITH DUST CONTROL)—
TOSCO II FACILITY (21)

bins, the shale may be transferred by means of pan feeders to a system of inclined conveyors for transport to the secondary crushing units. A baghouse filter may be installed in the unit for dust collection.

To allow uninterrupted operation of the secondary crushers in case of a breakdown in the mine or in the primary crushing unit, a storage pile of coarse crushed ore will need to be maintained. This stockpile can store sufficient shale to feed the downstream facilities for a total period of 1 month. Normally, the coarse shale from the primary crushers is fed directly to the final crushing plant at the rate of about 2,850 tons/hr. During periods when the coarse ore production exceeds the feed requirements of the final crusher, the excess can be diverted to the coarse ore storage area. A coarse ore reclaim system, consisting of apron feeders and belt conveyors, can be included in the operations to maintain a uniform feed rate to the final crusher.

Ten crushers in the secondary crushing facility are expected to have the capability of producing minus 1/2-in. shale at a rate of 2,825 tons/hr on a continuous basis. Primary crushed shale may be fed into hoppers where a holdup of 30 minutes is provided before the solids enter a set of impact crushers. The shale leaving these crushers may then be transported by a series of belt conveyors to a screen with a 1/2-in. opening. In this operation, undersized particles from the screen are conveyed to fine ore storage and particles larger than 1/2 in. are recycled into the impact crushers along with fresh coarse ore.

Fine ore leaving the secondary crushing facility may be transported to storage silos, which can hold the ore for a time of 5 hr. The ore is removed from these silos at a rate of 67,300 tons/day and conveyed to the retorting plant. A baghouse filter will most likely have to be installed in the storage unit for dust collection. Figure 38 depicts a typical fine ore silo and the dust removal equipment that may be used in this operation.

Retorting and Product Recovery

A flow diagram for a TOSCO II pyrolysis plant is given in Figure 39. The commercial facility consists of six parallel trains each of which processes 11,200 tons of shale per day. Raw oil shale conveyed from the fine ore silo enters a surge hopper and is held for 30 minutes. From the surge hopper, shale is fed into a fluidized-bed vessel, where it

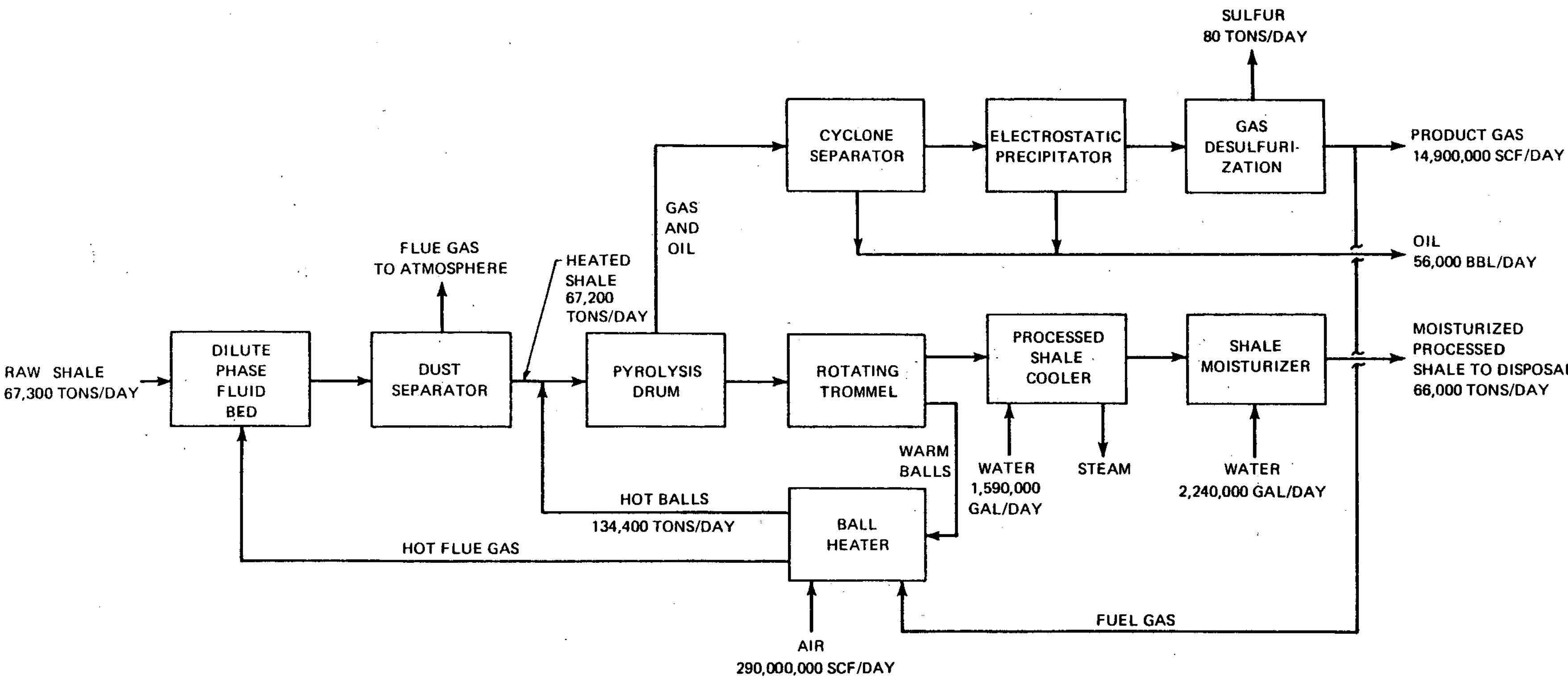

FIGURE 39. FLOW DIAGRAM OF TOSCO II COMMERCIAL PYROLYSIS PLANT

gains heat by contact with flue gas from the ball heater. As a result of the heat exchange, shale is preheated to a temperature of about 500°F before it is separated from the gas in a settling chamber. The flue gas is further cleaned in a Venturi wet scrubber before it is discharged into the atmosphere. Preheated shale enters the pyrolysis vessel along with hot ceramic balls, and solid-solid heat exchange occurs.

Six pyrolysis vessels are expected to be required to retort the 67,200 tons/day of oil shale. The vessels will also accept 134,400 tons/day of hot ceramic balls, which serve as the source of heat for shale pyrolysis. Rotation of the pyrolysis drum promotes solid-solid mixing, which results in good heat exchange between the two solid species and raises the shale temperature to 900°F. The pyrolyzed shale and ceramic balls leaving the rotating drum reactor are fed into a revolving trommel with a sieve size of 1/2 in. Retorted shale is sieved and collected at the bottom of an accumulator while the ceramic balls are collected in a separate stream.

The hot retorted shale leaving the accumulator enters a rotating drum cooler where sensible heat of the shale is used to generate steam by heat exchange with water. About 1,590,000 gal/day of water is fed to the rotating drum cooler for shale cooling and steam production. Shale then enters a moisturizing vessel, which is also a rotating drum, and is moisturized to about 14 percent water by weight before it is conveyed to a disposal site at Davis Gulch. The moisturized process is expected to use 2,240,000 gal/day of water.

Warm balls separated out in the trommel are elevated in a vertical bucket elevator to a ball heating system. In this system the ceramic balls are heated to temperatures of 900° to 1300°F by burning fuel gas with air. The hot ceramic balls are then fed into the pyrolysis vessel along with preheated shale. The vapors leaving the pyrolysis vessel are passed successively through cyclone separators and electrostatic precipitators where oil is condensed out and removed as a liquid stream at the rate of 56,000 bbl/day. Gases are expected to leave the electrostatic precipitators at the rate of 51,520,000 scf/day and further processed to remove sulfur.

A Stretford sulfur removal unit may be used for the desulfurization of the gases. In this process, sulfur cake is produced at the rate of 80 tons/day and may be sold as obtained. Part of the sweetened gas may be recycled back and used as fuel for the ball heating system. The remainder is considered a high-Btu fuel, which is produced at the rate of 14,900,000 scf/day.

Retorted Shale Handling and Disposal

Retorted shale discharged from the pyrolysis vessels at 900°F may be cooled by water in rotating drums and moisturized with water to about 14 percent (by weight). In this operation, dust-laden steam and air produced in the moisturizing step is passed through high-efficiency wet scrubbers. The water from the scrubbers may be clarified for reuse and the sludge is sent to a shale disposal site (18). After cooling and moisturizing, the retorted shale may be transported to the disposal site (about a mile away) on dual 60-in.-wide conveyor belts. At the disposal site, the retorted shale is loaded into a hopper that has two 150-ton compartments. A total of four 150-ton trucks, each making 5 runs/hr, are expected to be required to distribute the retorted shale in the disposal area. In addition to the trucks and hopper, a grader, bulldozer, and water truck will be needed to handle the retorted shale.

Pollution Controls

For a TOSCO II commercial-scale facility, pollution control systems will be necessary for reducing or eliminating emissions of noxious gases, dust, and wastewater. Additional details pertaining to emission sources and types of control systems are presented in Chapter 4, Volume I, of this report.

As indicated for the other processes in the previous sections, dust may be controlled during mining, crushing, and shale handling by water sprays and wet suppression techniques. Water requirements for this purpose are to be 575 gal/min. Conveyor belts will need to be enclosed and crushing devices will probably require baghouse filters, as indicated in the Shale Crushing and Preparation discussion. Underground mining equipment with diesel engines will most likely have to be installed with catalytic converters or wet scrubbers. These controls will need to be properly maintained to reduce emissions. Gases and dusts emitted during retort feed and discharge operations will probably require scrubbing. The sludge from the scrubbing system is expected to be transported to the shale disposal site. Each retort is expected to be equipped with a cyclone separator for this purpose, as shown in Figure 39. Gases collected during production recovery will need to be treated to remove H_2S. A part of the gases may be recycled as plant fuel and the remainder may be sold to a utility for electrical power generation.

For contaminated water streams resulting from mining and plant operations, the wastewater treatment plan presented in Chapter 4, Volume I may be implemented to collect, treat, and reuse or discharge the wastewater.

3.4.3 Resource Requirements

As specified in the scale-ups for the other processes, a 56,000-bbl/day TOSCO II facility will require certain amounts of land, water, power, and other major equipment and material. The facility is expected to require about 250 acres of land for shale processing and 1,100 acres for a disposal site. The land under which mining operations will be conducted is about 285 acres/year, or 5,700 acres over a 20-year period.

Water is expected to be needed and used for numerous mine and plant activities and operations. The total consumptive use estimated for normal operations is 3,750 gal/min (6,050 acre-ft/year). The major water-use categories are as follows:

- Mining (500 gal/min for dust control)
- Crushing and Shale Handling (200 gal/min for dust control)
- Retorting and Product Recovery (1,200 gal/min for cooling water, steam generation, and upgrading)
- Processed Shale Moisturizing, Cooling, and Disposal (1,575 gal/min for dust control, moisturizing, and revegetation)
- General Plant and Personnel Use (275 gal/min for utility water, fire protection, potable water, and sanitary-wastes water).

The estimated electrical power requirements for the facility are shown in Table 30, estimated to be 39 Mwe. The table also shows diesel fuel needs to be about 110 bbl/day. In terms of equivalent amount of oil for these requirements, the total is about 3,250 bbl/day. Since total shale oil production has been set at 56,000 bbl/day, the net production rate is equivalent to 52,750 bbl/day of crude shale oil.

TABLE 30

RESOURCE REQUIREMENTS FOR A 56,000-BBL/DAY TOSCO II FACILITY

Land (acres)	
Shale Processing Plant	250
Retorted Shale Disposal	1,100
Underground Mining (for 20 years)	5,700
Total	7,050
Water (gal/min)	
Mining	500
Crushing and Shale Handling	200
Retorting and Product Recovery	1,200
Retorted Shale Disposal	1,575
General Plant Use	275
Total (6,050 acre-ft/year)	3,750
Power	
Electric (Mw)	39
Diesel (bbl/day)	1,110

Primary capital equipment and material needs projected for mining and shale handling, crushing and preparation, retorting and product recovery, processed shale handling, and pollution control operations for a TOSCO II commercial-scale facility are presented in Tables 31 to 35. The purpose of these tables is to provide a basis for costing the facility for a future economic analysis.

TABLE 31

PRIMARY CAPITAL EQUIPMENT FOR A SHALE MINE— TOSCO II FACILITY

<u>Heading Jumbo Drill (4 required)</u>

Drive: Electric
Type: Hydraulic electric with two drills
Horsepower: 150

<u>Bench Jumbo Drill (2 required)</u>

Drive: Electric
Type: Hydraulic electric with two drills
Horsepower: 150

<u>Power Trucks (4 required)</u>

Drive: Diesel with pneumatic delivery system
Capacity: 3 tons
Horsepower: 100

<u>Scaling and Roof Bolting Rig (4 required)</u>

Drive: Diesel
Aerial Lift
Horsepower: 500

<u>Front-End Loader (8 required)</u>

Drive: Diesel
Bucket Capacity: 10 tons
Horsepower: 700

<u>Haulage Trucks (20 required)</u>

Drive: Diesel
Capacity: 75 tons
Horsepower: 700

<u>Motor Patrol (4 required)</u>

Drive: Diesel
Horsepower: 150

<u>Bulldozer (4 required)</u>

Drive: Diesel
Horsepower: 700

<u>Main Ventilation Fan (1 required)</u>

Drive: Electric with 5 blade settings
Capacity: 1 million scf/min at 7.6 in., water gauge
Horsepower: 800

<u>Road Grader (2 required)</u>

Drive: Diesel
Horsepower: 225

<u>Water Truck (4 required)</u>

Drive: Diesel
Horsepower: 250

<u>Auxiliary Ventilation Fan (20 required)</u>

Drive: Electric
Capacity: 25,000 scf/min at 7.6 in., water gauge
Horsepower: 40

<u>Power Centers (8 required)</u>

Power: 6 kva

TABLE 32

PRIMARY CAPITAL EQUIPMENT FOR CRUSHING AND PREPARATION PLANT—TOSCO II FACILITY

Primary Gyratory Crushers (5 required)

Capacity: 600 tons/hr
Drive: Motor
Horsepower: 100

Surge Bin (5 required)

Hold up: 30 min
Capacity: 8,400 cu ft
Size: 20-ft ID x 25-ft ht

Pan Feeder (5 required)

Capacity: 600 tons/hr
Horsepower: 5
Drive: Motor

Enclosed Conveyor (2 required)

Type: Belt
Size: 60 in. wide x 900 ft long
Belt Speed: 300 ft/min
Horsepower: 800
Drive: Motor

Tripper Conveyor (1 required)

Type: Belt
Size: 60 in. wide x 500 ft long
Belt Speed: 450 ft/min
Horsepower: 100

Apron Feeder (10 required)

Capacity: 300 tons/hr
Horsepower: 10

Secondary Crusher Feed Conveyor (2 required)

Type: Belt
Size: 60 in. wide x 500 ft long
Belt Speed: 300 ft/min
Horsepower: 100

Inclined Conveyor (2 required)

Type: Belt
Size: 60 in. wide x 500 ft long
Belt Speed: 300 ft/min
Horsepower: 300
Drive: Motor

Tripper Conveyor (1 required)

Type: Belt
Size: 60 in. wide x 100 ft long
Belt Speed: 450 ft/min
Horsepower: 25
Drive: Motor

Feed Hopper (10 required)

Hold up: 30 min
Capacity: 4,200 cu ft
Size: 17-ft ID x 20-ft ht
60-deg conical bottom

Impact Crusher (10 required)

Capacity: 300 tons/hr
Drive: Motor
Horsepower: 75

Inclined Conveyor (10 required)

Type: Belt
Size: 48 in. wide x 100 ft long
Belt Speed: 100 ft/min
Horsepower: 30
Drive: Motor

Inclined Conveyor (10 required)

Type: Belt
Size: 48 in. wide x 75 ft long
Belt Speed: 100 ft/min
Horsepower: 20
Drive: Motor

TABLE 32

(CONTINUED)

Vibrating Screen (10 required) Load: 300 tons/hr Screen Opening: 1/2 in. Size: 100 sq ft Horsepower: 10 Drive: Motor Fine-Ore Silo (10 required) Capacity: 40,000 cu ft Size: 30-ft ID x 65-ft ht Material: Reinforced concrete	Conveyor to Fine Ore Storage (10 required) Type: Belt Size: 48 in. wide x 500 ft long Belt Speed: 100 ft/min Horsepower: 70 Drive: Motor

TABLE 33

PRIMARY CAPITAL EQUIPMENT FOR A RETORTING AND PRODUCT RECOVERY PLANT—TOSCO II FACILITY

Retort (6 required)

Size: 18-ft ID x 34-ft length
Type: Rotary kiln, with 9-in. insulation
Material: Steel
Drive: Motor
Horsepower: 1,500
Ceramic Balls: 5,000 tons initial charge (total)

Trommel (6 required)

Capacity: 33,000 tons/day
Sieve Size: 1/2 in.
Drive: Motor
Horsepower: 500

Accumulator (6 required)

Size: 29-ft ID x 58-ft ht
60-deg conical base
Material: Steel

Dust Separator (6 required)

Size: 10-ft ID x 20-ft ht
Capacity: 11,500 tons/day

Venturi Wet Scrubber (18 required)

Capacity: 80,000 scf/min
Drive: Electric
Horsepower: 250

Processed Shale Cooler (6 required)

Type: Rotating drum
Size: 10-ft diam. x 20-ft length
Horsepower: 250
Material: Steel

Shale Moisturizer (6 required)

Type: Rotating drum
Size: 10-ft diam. x 20-ft length
Horsepower: 250
Material: Steel

Ball Elevator (1 required)

Height: 150 ft
Drive: Motor
Horsepower: 1,050

Ball Heater (6 required)

Type: Gas-fired burner
Heat Transfer Surface: 2,500 ft^2

Fluid Bed Vessel (6 required)

Size: 7-ft ID x 150-ft ht
Material: Steel

Settling Chamber (6 required)

Size: 5 ft long x 5 ft wide x 15 ft high
Material: Steel

Venturi Wet Scrubber (6 required)

Capacity: 120,000 scf/min
Drive: Motor
Horsepower: 250

Surge Hopper (6 required)

Size: 19-ft ID x 25-ft ht
Hold up: 30 min

Cyclone Separator (1 required)

Capacity: 36,000 scf/min
Drive: Motor
Horsepower: 100

Electrostatic Precipitator (1 required)

Capacity: 36,000 scf/min
Size: 9-ft ID x 11-ft ht
Power: 4 kw

TABLE 33

(CONTINUED)

Shale Oil Pump (10 required) Capacity: 165 gal/min Drive: Motor Horsepower: 3.25 Stretford Unit for Gas Purification (1 required) Capacity: 36,000 scf/min, 3.9% H_2S Power Consumption (electric): 450 kw Sulfur Production: 80 tons/day Crude Rundown Tank (20 required) Capacity: 6,000 bbl Type: Cone roof Crude Storage Tank (5 required) Capacity: 60,000 bbl Type: Cone roof Cooling Water Vessel (6 required) Capacity: 12,000 gal Cooling Water Pump (12 required) Type: Centrifugal, single stage Drive: Motor Horsepower: 10 Water Tank (6 required) Size: 5,000 gal	Air Compressor (6 required) Type: Centrifugal Capacity: 43,000 cu ft/min Drive: Motor Horsepower: 2,750 (sea level rating) Compressor (1 required) (Recycle and Product Gas) Type: Centrifugal Capacity: 55,600 cu ft/min Drive: Motor Horsepower: 2,300

TABLE 34

PRIMARY CAPITAL EQUIPMENT FOR PROCESSED SHALE HANDLING AND DISPOSAL—TOSCO II FACILITY

<u>Conveyor to Disposal Site</u>
<u>(1 required)</u>

Type: Belt, enclosed
Size: Six sections, 60 in. wide x 900 ft long
Drive: Motor
Horsepower: 1,500

<u>Truck-Loading Hopper</u>
<u>(1 required)</u>

Capacity: 300 tons
Three 150-ton compartments

<u>Haulage Truck</u>
<u>(4 required)</u>

Capacity: 150 tons
Drive: Diesel
Horsepower: 1,000

<u>Bulldozer</u>
<u>(1 required)</u>

Drive: Diesel
Horsepower: 700

<u>Segmented-Wheel Compactor</u>
<u>(1 required)</u>

Drive: Diesel
Horsepower: 500

<u>Water Truck</u>
<u>(1 required)</u>

Drive: Diesel
Horsepower: 250

TABLE 35

PRIMARY CAPITAL EQUIPMENT FOR POLLUTION CONTROL—
TOSCO II FACILITY

<u>Baghouse Filter—Shale Crushing and Screening Unit (30 required)</u>

Type: Induced draft
Drive: Electric
Horsepower: 40

<u>Wastewater Holding Tank—Surge, Sedimentation, and Gravity Separation (5 required)</u>

Size: 500 gal

<u>Wastewater Treatment Unit (1 required)</u>

Flotation: 25,000 gal/day
Biological Oxidation: 35,000 gal/day
Filtration: 35,000 gal/day
Reverse Osmosis: 7,000 gal/day

CHAPTER 4
ABOVEGROUND PROCESSES
PRINCIPAL FINDINGS AND CONCLUSIONS

This chapter presents the findings and conclusions drawn from a review and analysis of aboveground processes for oil shale extraction. Also included are findings derived from the technical evaluation and the scale-up of selected surface retorting processes. In addition, R&D needs for surface processes have been identified.

Since the majority of the surface processes are proprietary, there is some degree of uncertainty in the state-of-the-art for these processes. It is also possible that some of the published data may be obsolete. This uncertainty was taken into account in the formulation of the R&D needs and in drawing conclusions from analyses based on the data.

4.1 TECHNICAL FINDINGS

Based on the technical evaluation and scale-up of the surface retorting processes, a number of findings relevant to process operations were made. These findings are discussed from the point of view of mining, shale crushing and preparation, and retorting and product recovery.

4.1.1 Mining

The scale-up of the surface processes to a plant producing about 50,000 bbl/day of shale oil shows that, depending on the specific process, the amount of shale needed may be from 66,000 tons/day to more than 100,000 tons/day. The mining of such large quantities of solids from a single operation is a difficult task and far exceeds the mining rates achieved in present-day operations. At the required rates of production, the logistics of removing the shale from the mine and the return trip by the haulage trucks will be overwhelming. Nevertheless, these rates will have to be achieved if a commercial operation is to be conducted. In a larger operation requiring higher production rates, the problem will be even more acute. It may be ameliorated by employing two or more mines instead of one, but this will substantially increase costs. Consequently, the optimum production capacity of an aboveground oil shale plant may be greatly influenced by operational logistics.

The presence of local aquifers in the vicinity of the mining zone is of considerable concern, since inflows of water into the mine can cause mine safety and stability problems. This inflow can result from the transport of groundwater through natural fractures encountered during mining, or through fractures induced by blasting operations during mining. To avoid the problems associated with excessive mine water intrusion, any groundwater in the area may have to be pumped out. This will increase the operating cost slightly but may be justifiable when compared with the operational and safety risks involved.

An examination of the requirements of a scaled-up facility reveals that TOSCO II may require the least amount of mining (69,000 tons/day) followed by Union "B" (76,000 tons/day) and Paraho (92,000 tons/day). Thus, the mining costs are expected to be significantly lower for the TOSCO II than for the others. However, the complexity of the TOSCO II and Union systems may increase the operating costs to the same range as that of the Paraho process.

4.1.2 Shale Crushing and Preparation

The operations of crushing and preparation are not expected to pose any major problems, since these are standard operations in other industries requiring high input rates of solids. The stockpiling of large amounts of solids in between mining and crushing steps is, however, of some concern, since fugitive dust created by winds may create an environmental air quality problem. The accompanying erosion of the stockpile is also detrimental in that it leads to a loss of resource utilization.

The crushing systems, which will be required to handle high rates of shale, will be subject to severe mechanical stresses for extended periods. The maintenance of these systems is, therefore, a demanding and expensive operation, since continuous attention will be required.

4.1.3 Retorting and Product Recovery

An important finding for most surface processes is that no use is made of the carbonaceous residue present in retorted shale. The recovery of the heating value of the char can improve the thermal efficiency of these processes by 5 to 10 percent. Even though the retorts may not be designed to utilize the char, the possibility of utilizing an external unit for gasifying the char should be studied.

The properties and oil yield of the various retorts depend heavily on good control of the temperature profile. A discharge grate is used in the Paraho process to control the bed movement and the temperature profile, but the operation is mostly empirical and not much understanding of the control system has been achieved. In the Union and TOSCO II retorts as well, a knowledge of the control aspects appears to be lacking.

Aboveground retorting is not expected to achieve maximum thermal efficiency. In addition, there are specific areas for each process where improvement through energy conservation is possible (excluding retorted shale char utilization, which has been mentioned). An example is the recovery of sensible heat in retorted shale in the Union and Paraho processes. Currently, retorted shale is cooled by quenching in water and the moisturized shale is conveyed away for disposal. Retorted shale sensible heat recovery could be achieved by Union or Paraho through feed-effluent heat exchange, with shale feed or with recycle gas.

Most processes accept shale in the size range of 1/4 to 3 in., thus resulting in fines discard. TOSCO II, however, utilizes shale of less than 1/2-in. size. It, therefore, appears that the combination of a TOSCO II retort with another process is an attractive concept to maximize resource utilization through the retorting of fines. However, because of the complexity of the TOSCO II process, there may be an economics of scale involved which limits the minimum plant capacity at which this can be conducted.

Based on the results of the scale-ups, a comparison of the energy requirements of the various processes reveals that Union "B" is the least energy consuming. An analysis of the electric power and diesel requirements of these processes indicates that Union "B" consumes the equivalent of 4.9 percent of its production for its energy requirements, whereas Paraho, TOSCO II, and Gas Combustion consume 5.4, 5.8, and 7.8 percent, respectively. The Gas Combustion process is the least energy efficient because of its relatively low recovery of oil and its ability to process only low-grade shale. In spite of its low mining requirements, TOSCO II consumes more energy than Union "B" and Paraho, primarily owing to its complexity. The inclusion of an upgrading facility along with the retorting plant may, however, affect the relative picture through the use of make-gas as plant fuel, and internal heat recovery.

The Superior process uses a mechanically intricate retorting system and extracts nahcolite and dawsonite from the oil shale. As a result, the process capital and operating costs are high, and the process depends on production of the inorganic chemicals for its economic viability. Consequently, the resource base for this process is the nahcolite- and dawsonite-rich zone of the Piceance Creek Basin.

4.2 RESEARCH AND DEVELOPMENT NEEDS

Most of the aboveground processes are now well developed and have been tested at the semiworks scale. Since system information on these processes is proprietary, the specific R&D needs for any processes are uncertain. Some general needs regarding retort control and energy conservation, as well as the need for testing of large-scale modules, are evident and are brought out in this section. These are listed below:

- Retort operation control
- Retorted shale char gasification
- Retorted shale heat recovery
- Improved crushing systems
- Improved utilization of low-Btu gas
- Large-scale module demonstration.

4.2.1 Retort Operation Control

Control of the retorts is of considerable importance in all the processes, since it greatly influences oil and gas yields and properties and the thermal efficiency of the system. In the Paraho process, retort control is achieved through proper gas distribution and by the discharge grate mechanism that controls bed movement. Before commercial application is possible, however, a better understanding of the control systems involved must be gained through theoretical and further experimental research.

The Union "B" retort is controlled by means of regulation of the bed movement by the rock pump. In the TOSCO II retort, control may be achieved through changes in drum rotation speed and in shale/ceramic balls ratio in the retort feed.

A knowledge of the transient behavior of the retorts is lacking. Such a knowledge is essential for the control of retorting, especially for retorts of the internal combustion type.

4.2.2 Retorted Shale Char Gasification

Except for the Superior process, the processes using indirect heating do not recover the heating value of the carbonaceous residue in retorted shale. Recovery of this heating value should be given some consideration, since it can result in improvement of the thermal efficiency by 5 to 10 percent. Research should thus be conducted in spouted or fluidized-bed oxidation of the char and the utilization of the heat thus released for the heat of retorting. As an alternative, the char may be gasified by steam-air mixtures to form producer gas. In either case, considerable energy savings can be achieved.

4.2.3 Retorted Shale Heat Recovery

In Paraho and Union processes, retorted shale leaves the retort at about 350°F. Considerable sensible heat is lost in cooling the retorted shale to ambient temperature by quenching in water. Research must be conducted on efficient heat exchangers for the recovery of this sensible heat, which may then be used to generate steam for process use or for preheating shale feed. In either case, the thermal efficiency of the system may be appreciably improved.

4.2.4 Improved Crushing Systems

Because of limitations on the shale size range that is acceptable to most surface processes, there is some loss of resource utilization through the discard of fines generated in crushing. This loss can amount to as much as 10 percent, depending on the shale size range required by the process. To minimize the generation of fines, some research must be devoted to the development of improved crushing techniques. At present, fines minimization is achieved through the use of roll crushers, but as mentioned, approximately 10 percent of the feed is discarded as fines. Research in improving these crushing systems and developing more efficient ones should thus be conducted.

4.2.5 Improved Utilization of Low-Btu Gas

Low-Btu gases are generated in direct-heated processes such as Gas Combustion or Paraho. In addition, the gasification of retorted shale char, as in the Superior process, can result in the production of low-Btu gas. The utilization of low-Btu gas (~100 Btu/scf) for power generation, however, is presently inefficient, since most gas turbines are designed to operate on medium or high heating value gas. Research into improving the operability of gas turbines to reduce energy wastage in burning low-Btu gases can result in considerable energy conservation.

4.2.6 Large-Scale Module Demonstration

None of the surface retorts has yet been demonstrated at the commercial scale. Although success has been achieved in the demonstration of pilot- and semiworks-scale retorts, there is considerable risk in the commercial application of the technologies unless the testing of large-scale retorts is conducted. At the commercial scale the problems of retort control and the accompanying losses in oil yield through coking and combustion may be enhanced. Difficulty may also be expected in the uniform distribution of gas and solids in the retort. Consequently, the demonstration of commercial-scale retorts must be carried out to present an opportunity for further research on the feasibility of surface processing of oil shale.

4.3 SUMMARY AND CONCLUSIONS

From a technical standpoint, aboveground retorting is a viable technology and is characterized by high yields. The technology, however, has been tested only at the pilot or semiworks scale, and it needs to be demonstrated on full-scale modules. Work is also needed in the area of retort control, char gasification, and low-Btu gas utilization.

A scale-up of the processes indicates that the logistics of transporting the raw shale from the mine to the facilities will be a major problem at the high production rates projected. For a nominal crude shale oil production rate of about 50,000 bbl/day, the output tonnage rate for a shale mine will exceed the rates for most other existing large-scale mines. Thus, the production of larger quantities of shale oil (e.g., 100,000 bbl/day) may require the use of two or more mines even though this may increase the cost.

The TOSCO II retorting process is the most energy intensive among Paraho, Union "B," and TOSCO II. This is primarily due to its complexity, which annuls the benefit obtained for requiring less raw shale and, thus, less mining. The inclusion of an upgrading plant along with the retorting plant may, however, change the relative situation owing to internal heat recovery. The TOSCO II process is still an attractive process for operation in conjunction with another technique. The process can accept fines and, thus, resource utilization can be maximized.

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