CHAPTER 3 : OVERVIEW OF SELECTED SYNTHETIC FUEL CONVERSION PROCESSES

Section No. Page

3.1 General Synfuel Processes. 3-1

3.2 Coal Gasification. 3-2

3.3 Coal Liquefaction. 3-8

3.3.1 General 3-8
3.3.2 Liquid Solvent Refined Coal (SRII) 3-11
3.3.3 Exxon Donor Solvent 3-14
3.3.4 H-Coal. 3-17
3.3.5 Fischer-Tropsch Process 3-21
3.3.6 Methanol Process. 3-26

3.4 Oil Shale Retorting. 3-31

3.4.1 General 3-31
3.4.2 Surface Retorting 3-31
3.4.3 Modified In Situ Retorting. . . 3-36

3.5 Comparison of the various Synfuel Systems With Respect to Resource Requirements 3-40

Chapter 3: OVERVIEW OF SELECTED SYNTHETIC FUEL CONVERSION PROCESSES

3.1 General Synfuel Processes

The General term " synfuel processes" applies to the following:

1. Upgrading of coal. to gaseous, liquid or solid products with improved characteristics.
2. creversion of the kerogen in oil shale to gaseous or liquid fuels or products.
3. Recovery of petroleum crudes from non-conventional oil resources such as heavy oils and tar sands.

Upgrading of coal by subjecting it to a reaction with steam at high temperatures and pressures in the presence of air or oxygen, or to hydrogen, with or without a catalyst, is called conversion. The coal can be converted to gaseous (gasification) or liquid (liquefaction) hydrocarbons. The products have a much lower content of sulfur than the original coal. Oil shale can be retorted by subjecting it to high temperature and pressure, also producing gaseous or liquid hydrocarbons . Catalysts are used in synfuel processes when there is need to accelerate the reaction rates and affect the product state.

In this report, the following processes are included:

1. Coal gasification

   - to medium Btu gas: generic
   - to high Btu gas: generic

2. Coal Liquefaction

   - by pyrolysis (none included)
   - by solvent extraction: liquid solvent refined coal (SRC II)
     Exxon donor solvent (EDS)
   - by catalytic liquefaction: H-coal
   - by indirect liquefaction: Fischer-Tropsch (FT) Methanol

3. Oil shale retorting using:

   - true in situ retorting (none included)
   - modified in situ: generic
   - surface retorting: generic

3.2 Coal Gasification

The process by which coal is gasified involves reactions of devolatization of coal with steam at elevated pressures and temperatures to produce CO and H_2O. Gasification of coal involves basically the following reaction between steam and carbon:

$$c + \text{Air or Oxygen} + H_2O \quad co + H_2 + \text{Heat}$$

There are many processes by which coal can be gasified producing low-, medium- or high-Btu gas. The definitions of the heat content of each of then are not rigorous. Low-Btu gas is a mixture of carbon monoxide, hydrogen and nitrogen. It has a heating value of less than 300 Btu per standard cubic foot[1] (Reference No. 25)=. This gas is of interest to industry either as a combustible fuel or as a raw material from which ammonia, methanol, and other compounds may be synthesized. Due to the low heating value, it cannot command high enough prices to justify long distance transport. Medium-Btu gas is a mixture of methane carbon monoxide, hydrogen, and other gases. It has a heating value between 300 and 700 Btu per standard cubic foot (Reference No. 25) . It is suitable as a fuel for industrial consumers, but because of its low heating value, is not economic to transport over great distances. High-Btu gas consists essentially of methane. It has a heating value of appro approximately 1000 Btu per standard cubic foot, and is compatible with natural gas in that it can be substituted for natural gas in existing pipeline systems.

Coal gasification processes can be divided into three major process types, according mainly to the way in which the feedstock coal, steam, and the product gases are contacted. They are:

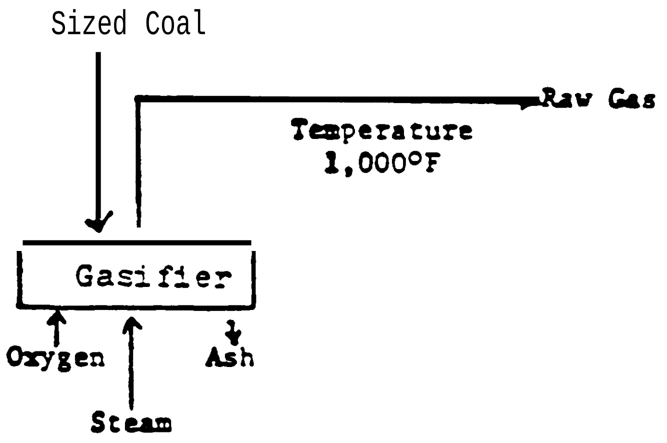
1. Fixed bed gasification in which the crushed, sized coal is fed from the top of the reactor vessel. Steam, air or Oxygen are blown upwardly.
2. Fluidized bed gasification in which the finely sized coal particles are "fluidized" by the steam, air or oxygen, which are piped through them.
3. Entrained bed gasification: in which the even finer coal particles are blown into the reacting gas stream prior to entry into the reactor. The coal particles are suspended in the gas phase, and are filtered and recycled until a product gas with a suitable heating value is produced.

Figure 3.1 (Reference No. 31) describes the main features of these three processes.

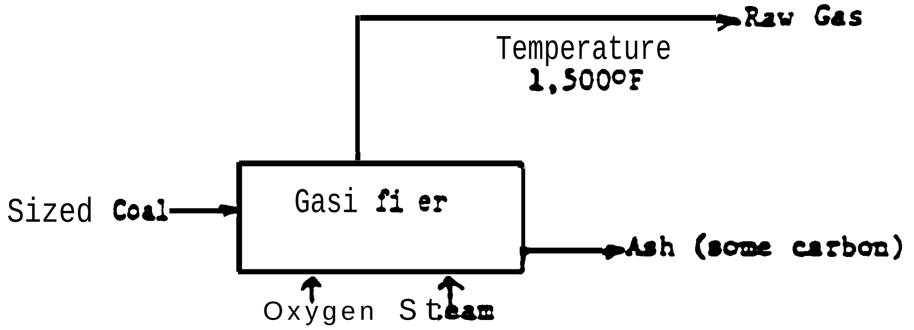
---

[1] Usually, low-Btu gas has a heating value below 200 Btu per SCf; and medium-Btu gas ranges in heating value between 300 - 350 Btu per Scf .

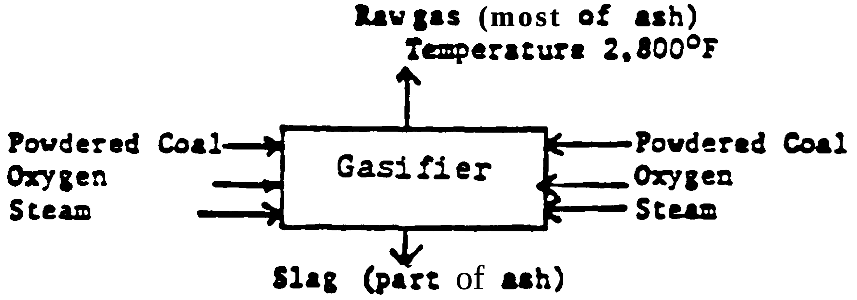
Figure 3.1: Basic Coal Gasification Processes



Fixed Bed Gasification e.g. Lurgi



Fluid Bed Gasification e.g. Winkler



Entrained Gasification e.g. Koppers-Totzek

SOURCE : Reference 31

Figure 3.2 (Reference No. 31) is a schematic diagram of coal gasification. It represents the whole coal gasification fuel cycle, including the production of low-, medium- or high-Btu gas. All of these gasification processes share a number of process steps. If high-Btu, pipeline-quality gas is desired, essentially all of the following process steps are required. In some cases, some of them may be omitted, depending on the type of coal being processed and the type of gas product desired. The process steps are as follows (Reference No. 25)..

1. Pretreatment of coal[2] (if sizing or caking are problems) .
2. Primary gasification of coal.
3. Secondary gasification of carbonaceous residue from primary gasifier.
4. Removal of CO_2, H_2S, and other acid gases.
5. shift conversion for adjustment of the carbon monoxide/hydrogen mole ratio to the desired 1:3.
6. Catalytic methanation of the carbon monoxide/hydrogen mixture to form methane.

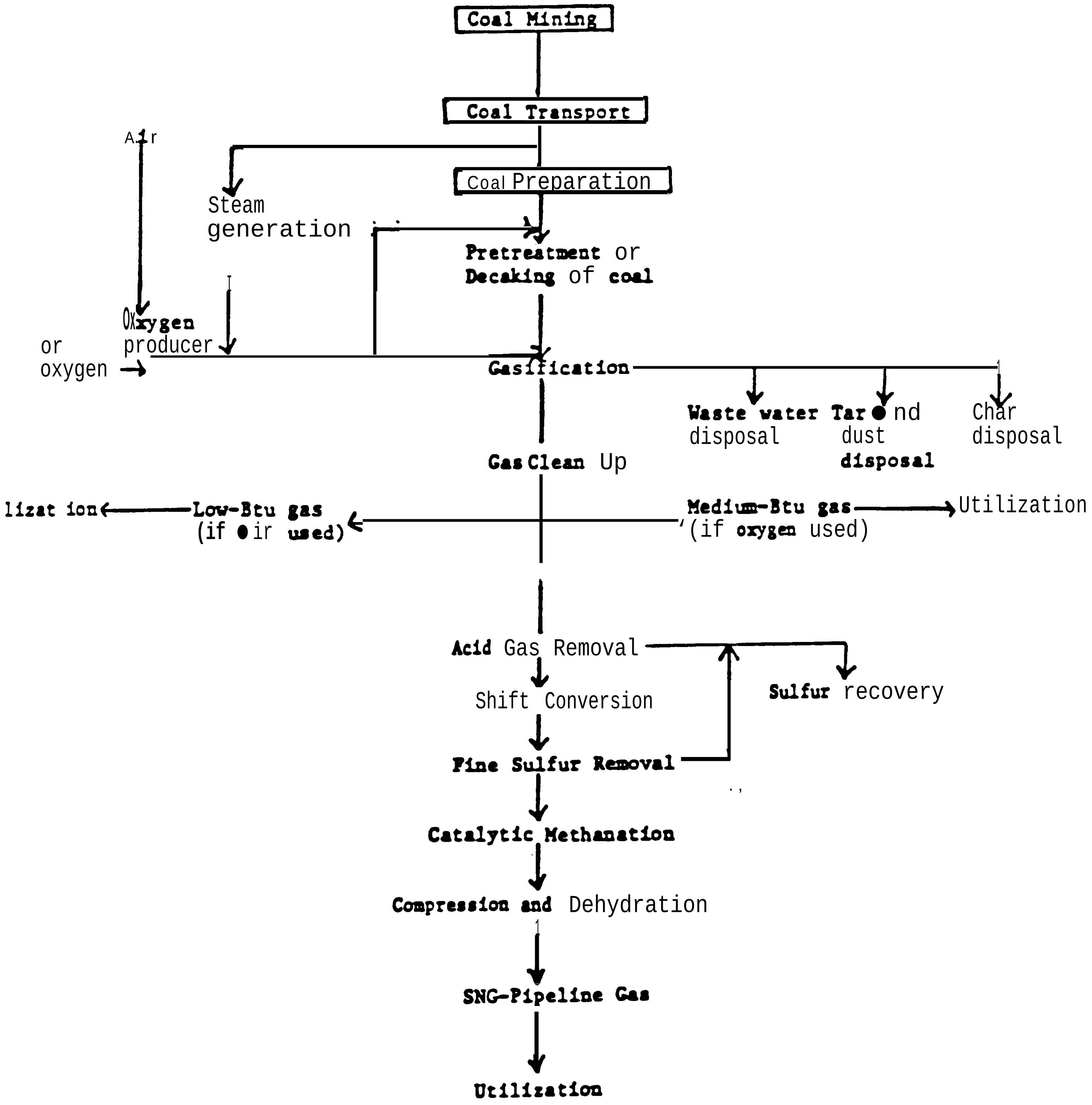
Pretreatment

The coal received at the plant must be further cleaned and crushed or ground before it can enter the gasifier. Extaneous materials such as shale, rocks, metal, etc. are removed by conventional cleaning methods . For fluidized or entrained gasification processes, the coal needs to be finely ground. Crushing and sizing may also be required for other processes. In the case of certain bituminous coals called caking coals, agglomeration of the material is observed when they are heated. Treatment is needed if they are to be gasified by fluidized or Moving bed processes, or even in fixed bed reaction. The caking characteristics are destroyed when the coal is heated to low temperatures in the presence of air or oxygen.

---

[2] Pretreatment of coal by partial oxidation with air or oxygen is not in general a cost-effective approach to destroying the caking characteristics of certain coals, such as Eastern bituminous coals, because of the loss of Btu values of the coal in producing CO_2 & H_2O. The caking problem is a serious problem in the processing of such coals and limits the applicability of current commercial gasifiers such as the dry-bottom Lurgi to Western Subbituminous coals and lignite.

Figure 3.2: Schematic Diagram of Coal Gasification



SOURCE: Reference 31

Primary Gasification

This is the heart of the process, and is basically a pyrolysis process of the raw coal. The coal feed is contacted with synthesis gas (carbon monoxide and hydrogen) . The coal is devolatized according to the following general reaction (Reference No. 25).

COAL + HEAT (Pyrolysis) + Methane, water, tars, phenols,
hydrogen sulfide, hydrogen,
carbon dioxide, char, etc.

The pressures used for gasification range from atmospheric pressure to 1000 psi. The heat required to maintain the endothermic gasification reaction is supplied from burning coal. Air or oxygen are also needed to support the combustion reaction. If air is used, the product is low Btu gas ranging from essentially a carbon monoxide/hydrogen mixture (Koppers-Totzek process) to mixtures containing various proportions of carbon monoxide, carbon dioxide, hydrogen, water, methane, hydrogen sulfide, nitrogen, and typical products of pyrolysis such as tar, oils, phenols, etc. If oxygen is used, medium Btu gas results.

The bulk of the original coal is transformed into a solid char. Certain coals are more “reactive” to gasification than others. Thus the type of coal being processed determines to a large “extent the amount of char produced, and the analysis of the gaseous products. The char is usually gasified by additional processing steps, or is marketed.

Secondary Gasification

Secondary gasification involves the gasification of char from the primary gasifier. This is usually done by reacting the hot char with water vapor to produce carbon monoxide and hydrogen.

If the desired final product is either low- or medium-Btu gas, secondary gasification is usually followed by scrubbing and cleaning. Carbon dioxide and sulfur compounds are partially removed, and the resulting gas is used directly. If high-Btu gas is desired, shift conversion and methanation are further required.

Shift Conversion

In most gasification processes, a shift reaction is employed prior to methanation. Its-purpose is to react a portion of the carbon monoxide with steam to form more hydrogen.

$$co + H_2O + CO_2 + H_2$$

By this exothermic reaction the ratio of carbon monoxide to hydrogen may be increased to 1:3 mole ratio needed to produce methane. Otherwise, deactivation of the catalyst used in the methanation takes place.

The catalytic shift conversion reaction is a well-known process, but it has not been applied on the large scale required for commercial coal gasification. For coal gas shifting, conventional iron-chromium catalysts may be used; however, the coal gas stream must be purified prior to shifting (Reference No. 25).

Methanation

If carbon monoxide and hydrogen are present in the mole ratio of 1:3, the coal gas can be reacted in the presence of a catalyst to produce methane. Group VII transition elements such as iron, cobalt, nickel, ruthenium, rhodium, palladium, osmium, iridium, and platinum have been found to be effective catalysts. The following exothermic reactions occur simultaneously within the methanation unit (Reference No. 25).

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$CO + H_2O \rightarrow CO_2 + {}'_2$$

$$2CO \rightarrow CO_2 + C$$

Special care must be taken to prevent deactivation of **the** catalyst by temperatures above 750°F. It can also be Poisoned by carbon deposition. These can be circumvented by ensuring that the mixture of carbon monoxide and hydrogen shall be fed to the methanator in the ratio of 1:3. Scrubbing of sulfur from the synthesis gas feed is employed to alleviate sulfur poisoning of the catalyst.

The final step to prepare high Btu gas for marketing is to remove water to specified levels. The product gas usually undergoes compression prior to storage *or* marketing.

3.3 Coal Liquefaction

303.1 General

Coal liquefaction processes are conversion processes in which liquids are the primary products. Some gases and solid char may also be produced.

There are two basic routes to coal liquefaction, namely direct and indirect liquefaction. In direct processes, slurried crushed coal is reacted directly with hydrogen at high temperature and pressure conditions to produce liquid hydrocarbons. In indirect liquefaction, coal is first gasified to produce a hydrogen-and carbon monoxide mixture. Further recombination with the aid of a catalyst produces liquid products.

Direct liquefaction is further broken down into three generic processes, namely: pyrolysis, solvent extraction, and catalytic liquefaction. The yields and physical properties of the produced liquid products depend directly on the reactor conditions and degree of hydrogenation.

Pyrolysis

In pyrolysis processes, coal is heated to temperatures above 750°F. It is converted into gases, liquids, and char. The latter accounts for more than 50 percent of the weight of the feed coal and requires hydrogenation. Some amount of solids remain in the raw gas and liquid products. They consist of unreacted coal and ash, and can be relatively easily removed from the gas stream. But the liquid requires filtration, distillation, or some other treatment to remove the solids.

Solvent Extraction

This process makes use of coal derived liquids known as “donor” solvents to increase the fraction of the coal that goes into solution. The “donor” solvents act as a source of hydrogen to the coal products, and are reacted together at temperatures up to 95O°F. Hydrogen may be supplied under pressure in the extraction step, or it may be used to hydrogenate the solvent prior to recycle. In some processes the unreacted coal is used to generate the necessary hydrogen. In other processes, the hydrogen is generated from by-product gases or from additional raw coal.

Catalytic Liquefaction

In this process, pulverized coal is mixed with 1-1.5 parts of recycle solvent. A suitable catalyst is used to add hydrogen. Most precesses of this type operate in the liquid phase with catalyst dispersed throughout or in a fixed bed. Some prccesses now in the development stage involve the injection of catalyst-impregnated coal into a stream of hot hydrogen at about 950° F for a very short time (Reference No. 25).

Indirect Liquefaction

Two stage conversion of coal typifies indirect liquefaction processes. Coal is first reacted with steam and oxygen to produce a gas composed primarily of carbon monoxide and hydrogen. This gas stream is subsequently purified to remove sulfur, nitrogen, and ash. The product gas is then catalytically reacted to yield liquid hydrocarbon products.

Figure 3.3 (Reference No. 31) presents a schematic diagram of the basic liquefaction processes. Each of them produces several types of products and sane gas, which may be used within the plant.

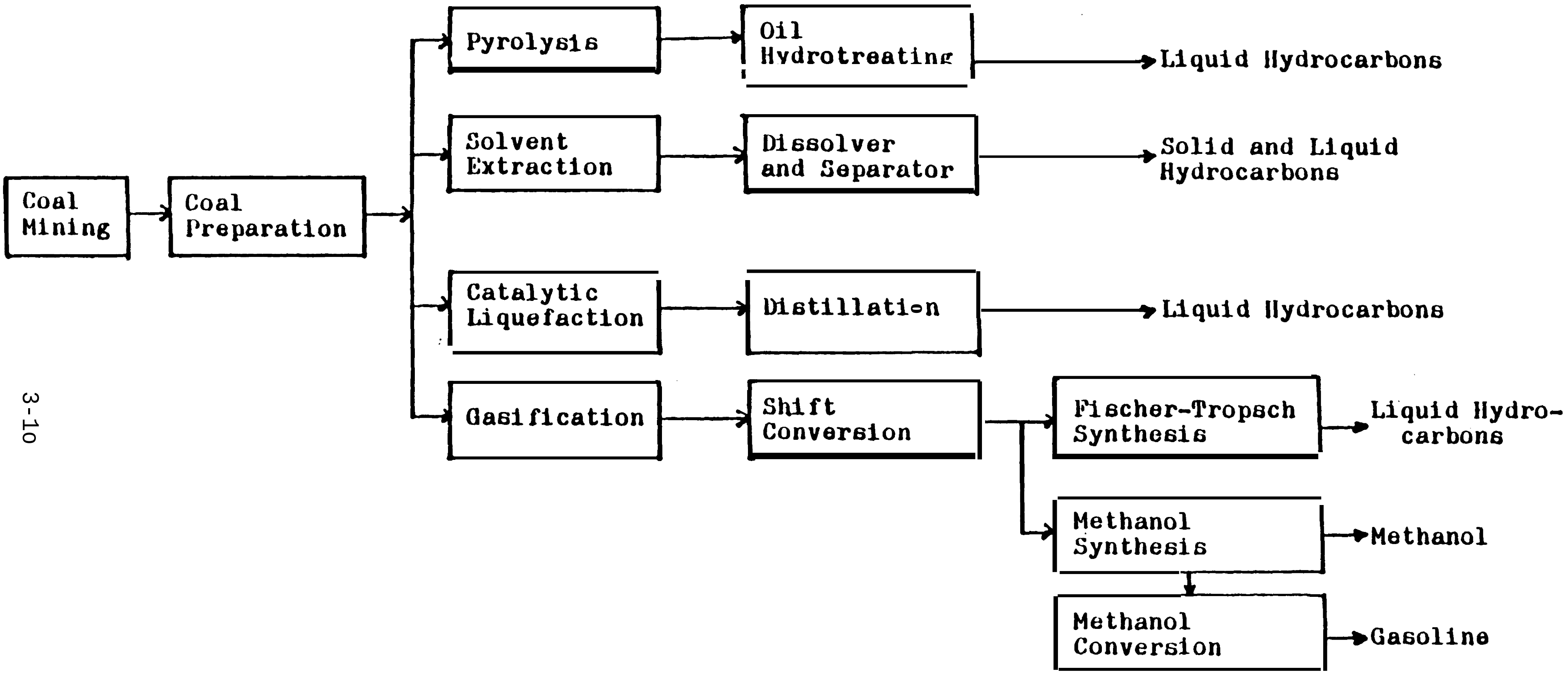
Removal of solids from coal liquids is a critical step in most of these liquefaction processes. Although there is currently a trend toward elimination of the solid-liquid separation step by the recovery of a solids-laden vacuum bottoms stream for gasification, most existing plant designs call for some type of physical/chemical solids removal systen.[3] The three processes receiving the most current interest are critical solvent deashing, antisolvent deashing, and pressure filtration (Reference No. 25).

Separation of ash and unreacted coal particulate from coal liquids is difficult because of the small size and large quantity of the solid particles, the snail density difference between solids and the liquid, and the high viscosity and melting point of the liquids. The Kerr McGee Corporation has been developing a separation technique which utilizes solvents such as benzene, toluene, xylene, pyridene, and cresols near their critical temperature and pressure, hence the term solvent deashing (Reference No-. 25).

---

[3] Solid\liquid separation is a critical step only in direct liquefaction process. Most modern coal hydroliquefaction processes in the pilot plant stage of development, such as SRCII , EDS , H-Coal (syncrude rode) do not require a solid/liquid separation stage.

Figure 3.3: Schematic Diagram of the Basic Liquefaction Processes*



* Only major products are shown. The last process represents indirect liquefaction.

SOURCE: Reference 31

3.3.2 Liquid Solvent Refined Coal (SRCII)

The SRCI process was developed to convert high-sulfur, high-ash coals to low-sulfur and ash solid fuels. The SRCII is the same kind of process, except the product is a liquid rather than a solid. This is achieved by adding more hydrogen through the followinq steps:

1. Recycling of a portion of the product slurry as solvent for the feed coal.
2. Higher residence time in dissolver.
3. Higher pressure.
4. Use, of vacuum distillation to separate solids from liquid, rather than the troublesome filtration step employed in SRCI .

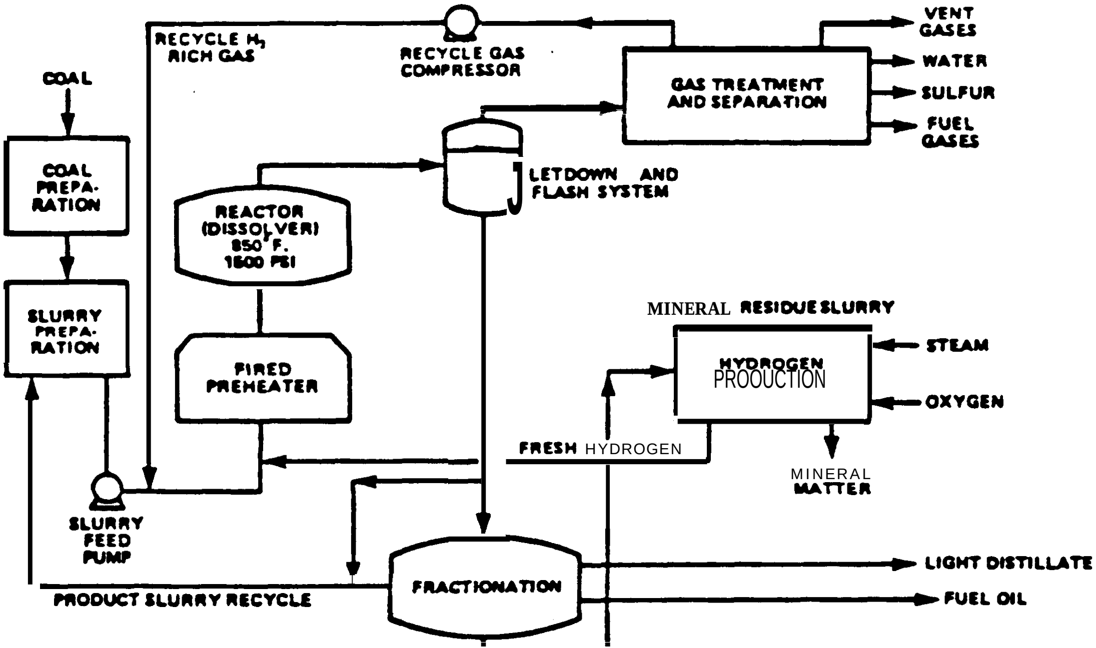
Figure 3.4 is a schematic diagram of the SRCII process (Reference No. 35) . Table 3.1 summarizes the components, resource requirements, and potential impacts of this process (Reference No. 17) . The feed coal is first pulverized to less than 1/8" size, dried and mixed with process derived solvent in a slurry mix tank (Reference No. 35) . Feed coal is limited to those containing certain trace mineral elements which may be required to act as catalysts for the breaking of solids to liquids in the liquefaction reaction[4] (Reference No. 291. However, in cases where the problem is concentration rather than the presence of specific trace elements, a recycle of residue may broaden the allowable coal feeds (Reference No. 29) . The coal slurry is then mixed with hydrogen generated by gasification of the vacuum bottoms from the liquefaction step and reacting with steam and oxygen in a gasifier-converter. The slurry is pumped through a preheater (700 to 750°F) and passed through a dissolver (2000 psi, 820 to 870°F) to dissolve about 90 percent of the coal (Reference No. 35) . The following additional reactions take Place in the dissolver (Reference No. 35) .

1. The coal is depolymerized and hydrogenated.
2. The solvent is hydrocracked to form lower molecular weight hydrocarbons, ranging from light oil to methane.
3. Much of the organic sulfur is removed in the form of hydrogen sulfide.

The sultry stream from the dissolver is split into two. One is recycled to provide solvent for coal slurry mixing. The other is fractionated to recover the primary

---

[4] **Opinions differ about the role of the trace minerals as catalysts.** The primary "catalyst" in the SRCII process may well be the pyritic mineral matter contained in the coal and not "trace mineral elements. "



SOURCE : Reference 35

Figure 3.4

A SCHEMATIC DIAGRAM OF THE SOLVENT REFINED COAL (SRC-II) PROCESS

TABLE 3.1

Solvent Refined Coal II *

ENERGY SYSTEM:

SIZE:
- 50,000 bbl/day(2)
- 0.335 x 10^{12} Btu/day(2)
- 90% plant availability(2)
- operates 329 days/year(2)
- 110.22 x 10^{12} Btu/year(2)
- 31,552 tons per day ROM coal(a)
- efficiency 64%(d)
- plant life 30 years(a)
- 6.7 x 10^6 Btu/bbl(2)

DESCRIPTION
- Coal is crushed to about 200 mesh and dried to three percent moisture and slurried with a solvent. A 70 to 85 percent hydrogen mixture is added. This mixture is first preheated, then hydrogenated in the reactor. The temperature is 425 to 495°C; pressure 68 to 136 atmospheres. Liquefaction produces a mixture of gases, vapor, liquids, and solids. The gases and vapors are separated from the liquids and solids and the vapors condensed. The liquid is separated from the solid by filtration (SRC II).

COMPONENTS
- crushers
- SRC reactor
- drying unit
- pre-heaters
- gas recovery plant
- filtering unit

ENVIRONMENTAL CONCERNS
- air emissions
- water pollution from runoff and leachates
- solid waste
- occupational hazards and health effects
- noise pollution
- odor

RESOURCES USED:
(Per 10^{12} Btu Produced)

FUEL(DAF)(c)	
coal:bituminous, plant input	60,919 tons
energy content	12,821 Btu/lb

COAL ANALYSIS(DAF)(a)	% by weight)
moisture	2.70
volatile matter	35.09
fixed carbon	51.70
sulfur	3.18
ash	7.13

LAND(c)	Acres
plant facilities	3.5
solid waste (per year)	0.21

WATER(c)	Acre-Ft.
cooling towers	64.5
plant use	11.0
steam	13.1
miscellaneous	0.9
total	89.5

COSTS	
construction	NA
operation	NA

PERSONNEL	
construction	NA
operation & maintenance	NA

RESIDUALS AND PRODUCTS:
(Per 10^{12} Btu Produced)

AIR POLLUTANTS(c)	Tons
particulates	1.6
SO_2	2 [illegible]
NO_x	30 [illegible]
hydrocarbons	[illegible]
CO	[illegible]
arsenic	1.8 x 10^{-6}
cadmium	1.7 x 10^{-4}
mercury	2.9 x 10^{-5}
zinc	1.3 x 10^{-3}
chromium	2.7 x 10^{-3}
nickel	5.9 x 10^{-4}
lead	6.2 x 10^{-4}
polynuclear organic material	1.5 x 10^{-9}

WATER POLLUTANTS
no direct discharge to any watercourse

SOLID WASTE(c)	Tons
dry ton equivalent	36,167(1)

ENERGY PRODUCT(2)	Equivalent Barrels
syncrude (SRC II) (energy content = 6.7 x 10^6 Btu/bbl)	149,256

*The data presented are based on a conceptual design of a commercial facility. The data will be updated when more current data become available. The data should not be used directly for comparison with other coal liquefaction processes.

(1)After coal preparation includes solid waste from mine burial and tailings pond.
(2)Representative values selected for analysis purposes.

SOURC
(a) Hittman Associates, Inc., Standards of Practice Manual for Solvent Refined Coal Liquefaction Process, 1978.
(b) Hittman Associates, Inc., Environmental Assessment of Coal Liquefaction, 1978.
(c) TRW, Characterizations and Data in the Area of Coal News Environmental Data Book, Volume IV, 1978.
(d) Flash and Pryor, Boiler Fuel and Building Blocks, 1978.

SOURCE: Reference 17

products which consist of naphtha, low sulfur fuel oil, and a vacuum residue which is separated from the solution in a filtration unit. The residue consists of heavy oil, ash and undissolved organic material from the coal (Reference No. 25).

The gases from the dissolver are treated to remove hydrogen sulfide and carbon dioxide. Liquid petroleum gases and pipeline gas are separated in a cryogenic separation unit. Unreacted hydrogen is recovered and recycled.

Recent developments have resulted in increased efficiency of the SRCII process. A combination of solid and liquid products are produced. A wide range of products can be obtained depending on the severity of recycling. Table 3.2 (Reference No. 25) shows the properties of a typical mix of products.

3.3.3. Exxon Donor Solvent (EDS)

The process is similar to SRCII, except that the major portion of the hydrogen supplied as part of the solvent is chemically combined rather than in the form of a free dissolved gas (Reference No. 29). A schematic diagram of the process is illustrated in Figure 35 (Reference No. 35). Crushed coal is liquefied in a reactor at 800-880°F and 1500 - 2000 psig (Reference No. 25). The reaction is non-catalytic, in the presence of molecular hydrogen and the hydrogen-donor solvent, which transfers hydrogen to the coal. The product from the liquefaction reactor is separated into two portions. One part is sent to the solvent hydrogenation unit to produce donor solvent. It is a catalytically hydrogenated recycle stream which is fractionated from the middle boiling range of the liquid product, and has a boiling range of 400 - 850°F (Reference No. 25). After hydrogenation, the solvent is mixed with fresh coal feed, heated in a furnace, and pumped into the liquefaction reactor.

The other portion from the product liquefaction reactor is a slurry. It is separated by distillation into gas, naphtha, middle distillate, and a bottom product that contains heavy liquid, untreated coal and mineral matter. The vacuum bottoms slurry is cooked to produce additional liquids.

The major advantages of the EDS process are:

1. High yields of low sulfur liquids are obtained from bituminous and sub-bituminous coals or lignites (Reference No. 25). A yield

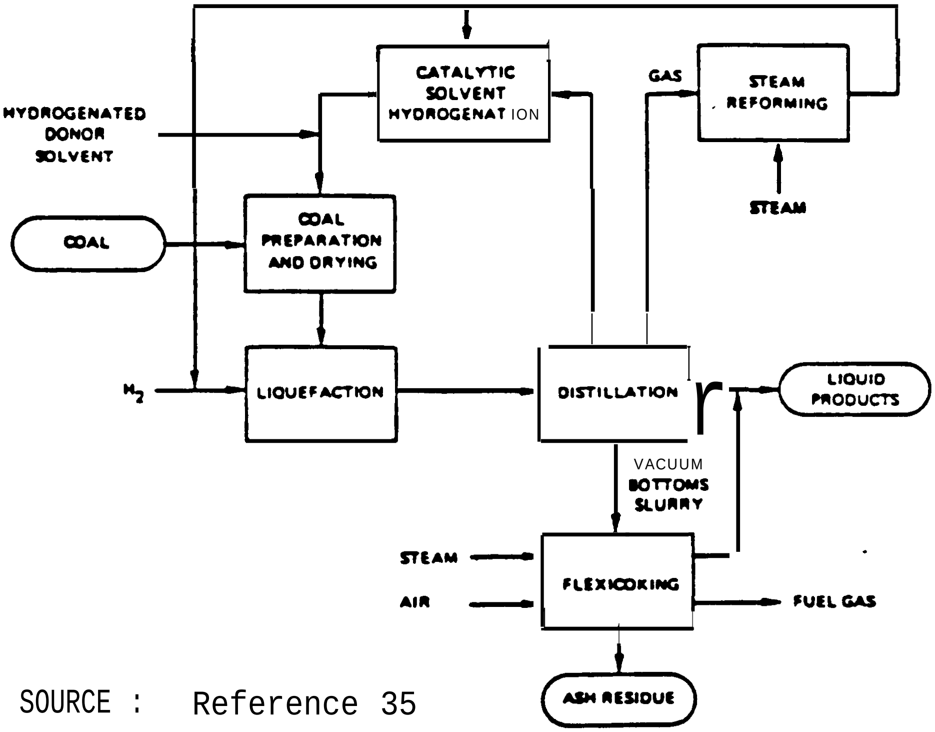
TABLE 3.2

TYPICAL PROPERTIES OF SRC FUELS USING RECYCLE SRC II PROCESS

	Solid Fuel	Distillate Fuel
Gravity: ‘API	-18.3	5.0
Approximate Boiling Range: ‘F	800+	400-800
Fusion Point: ‘F	350	
Flash Point: ‘F		168
Viscosity: SUS at 100°F		50
Sulfur*: Percent	0.8	0.3
Nitrogen*: Percent	2.0	0.9
Heating Value: Btu/lb.	16,000	17,300

* Assuming Western Kentucky coal feed with 4% Sulfur and 2% Nitrogen.

SOURCE: Reference 15



SOURCE : Reference 35

Figure 3.5
A Schematic Diagram of the
Donor Solvent Liquefaction Process

of 2.6 barrels of liquids per ton of dry coal is typical for an Illinois bituminous coal (Reference No. 25).

2. The only by-products of significance are ammonia and elemental sulfur (Reference No. 25).

3. There is wide flexibility in product distribution by varying liquefaction conditions or adjusting solvent properties (Reference No. 25).

The typical properties of the products from the EDS process are shown in Table 3.3 (Reference No. 25]. An estimated heat balance is qiven in Table 3.4 (Reference No. 35).

3.3.4 H-Coal

The H-coal process converts coal to hydrocarbon liquids by hydrogenation with a cobalt-molybdenum catalyst. An ebullated bed reactor is employed. The liquid products may range from a heavy boiler fuel to a synthetic crude product (Reference No. 25).

Figure 3.6 (Reference No. 35) is a schematic diagram of the H-coal process. Coal is first crushed to minus 60 mesh, dried, and then slurried with recycled oils at pressures of approximately 200 atmospheres (Reference No. 25) " Mixing of the slurry with compressed hydrogen follows, and the mixture is preheated. The material is pumped to the bottom of the ebullated bed reactor, with the-upward flow of slurry through the reactor maintaining the catalyst in a fluidized state (i.e. random motion) . The catalyst needs periodic additions of fresh catalyst and withdrawals of spent portions. Typical temperatures of the slurry entering the reactor are 650 - 700°F (Reference No. 25). The finely divided coal and ash particles flowing through the ebullating bed are removed with liquid and vapor products.

The reactor effluent is separated into recycle and net product streams. Conventional processing equipment is used. The liquid stream is distilled to produce a mixture of light distillate and a heavy distillate product. Gaseous products composed of hydrocarbon gas, hydrogen sulfide and ammonia are separated. A portion of the heavy distillate is recycled as the slurrying medium.

The operating conditions of the H-Coal process can be altered to produce various types of primary products. For

TABLE 3.3

DONOR SOLVENT PRODUCT ANALYSES

	Heavy Naphtha[1]		200°C+ Fuel Oil	
	Raw Liquid	Hydrotreated Liquid	Raw Liquid	Hydrotreated Liquid
Nominal Boiling Range, °C	70/200	70/200	200/540	200/540
Distillation, 15/5°C				
10 wt. %	106	92	247	239
50 wt. %	180	157	368	347
90 wt. %	199	182	433	412
Density (g/cm^3)	0.87	0.80	1.08	1.01
Elemental Analysis, Wt. %				
C	85.60	86.80	89.40	90.80
H	10.90	12.90	7.70	8.60
O	2.82	0.23	1.83	0.32
N	0.21	0.06	0.66	0.24
S	0.47	0.005	0.41	0.04
Higher Heating Value MJ/kg	42.6	44.9	39.8	42.1

[1] Excludes C_6/70°C naphtha cut

SOURCE: Reference 25

Table 3.4

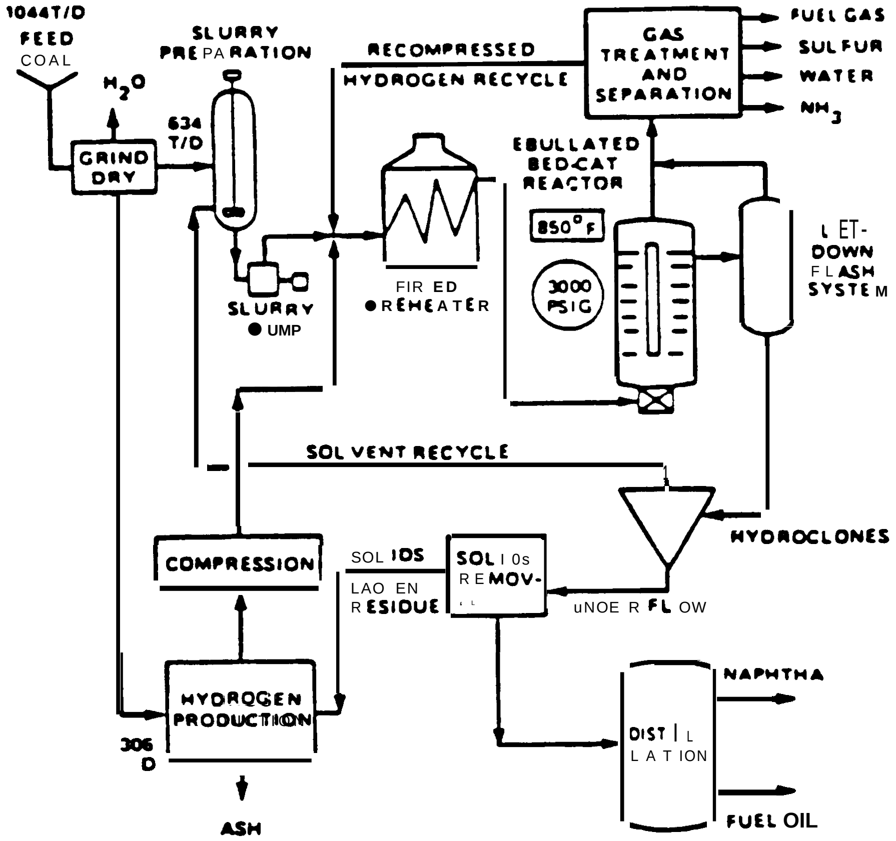
Estimated Heat Balance for a Commercial Scale EDS Plant

	Btu/day (10 Btu's)	Percent of Total Energy Input
System Products		
Liquids	323,071	61.72
Sulfur, ammonia	8,309	1.59
System Losses		
Ash, combustibles and sensible heat	26,082	5.13
Stack losses	20,039	3.83
Energy losses via water and air	136,853	26.14
Liquefaction and solvent hydrogenation (9.80%)		
Flexicoking (6.44%)		
Hydrogenation and recovery (6.72%)		
By-product recovery, offsites, and miscellaneous (3.18%)		
Other miscellaneous	8,309	1.59
Energy Input		
Coal (cleaned)*	488,761	93.37
Electrical power**	34,702	6.63

* Coal - Illinois No. 6; 10,574 Btu/lb as received prior to cleaning

** Power based on 8,500 Btu/kwh to generate

SOURCE: Reference 35



SOURCE : Reference 35

Figure 3.6

SCHEMATIC DIAGRAM OF THE H-COAL PROCESS

example, relatively high temperatures and high hydrogen partial. pressures are used to produce a synthetic crude products. Vacuum distillation is used to separate the solids from the liquid phase. If gas and oil are desired, lower temperatures and pressures are used (Reference No. 25) . Conversion and yield structure are determined by reactor conditions, catalyst replacement rate, and recycle slurry oil composition (Reference No. 29) .

Table 3.5 (Reference No. 25) summarizes the properties of both the fuel oil syncrude products from H-coal.

Table 3.6 (Reference No. 17) summarizes the components , resources and potential impacts from H-coal process. It requires between 14,000 and 20,000 standard cubic feet of hydrogen for each ton of coal produced. Hydrogen consumption depends on the type of product produced, with less hydrogen required during the production of residual oil (Reference No. 25) .

3.3.5 Fischer-Tropsch Process

A commercial plant using a modification of this process is currently operaing in South Africa (Reference No. 36) . This is the only commercial sized plant producing synfuels. Table 3.7 (Reference No. 35) is an overview of this plant.

In the Fischer-Tropsch process the coal is initially gasified (for description of gasification see section 3.2 of this report) . The synthesis gas is then converted to largely aliphatic hydrocarbons using an iron or cobalt catalyst.

Figure 3.7 (Reference No. 35) is a schematic diagram of the SASOL I plant, which utilizes the Fischer-Tropsch process. Thirteen high pressure gasifiers convert coal in the presence of steam and oxygen to medium Btu gas containing mainly carbon monoxide, tars and oils. The product gas is then cleaned of carbon dioxide, hydrogen sulfide, organic sulfur, ammonia, and phenols. The cleaned gas is then subjected to the catalytic Fischer-Tropsch reaction which produces a mixture of gases, liquid hydrocarbons, and an aqueous chemical mixture that must be further processed to set the desired plant output .

The cleaned gas from the Lurgi gasifiers is partitioned into two streams . One stream is reacted in a fixed bed catalytic reactor to produce straight chain and medium boiling oils, diesel oil, LPG, and some alcohols. Operating conditions are 450°F and 360 psig (Reference No. 35) . The other stream is combined with reformed product gas to increase the hydrogen to carbon ratio. It is reacted in a fluidized bed reactor

TABLE 3.5

PROPERTIES OF H-COAL DISTILLATES FROM ILLINOIS NO. 6 COAL LIQUIDS

Property	Fuel Oil <203°C distillate	Fuel Oil >203°C distillate	Syncrude <197°c distillate	Syncrude >1970C distillate
Specific gravity, 60°/60°F	0.864	0.979	0.838	1.025
Gravity, ‘API	32.3	13.0	37.4	6.6
Pour point, ASTM D-97, °F	<5	<5	<5	<5
Color, ASTM D-1500 or (BuMines description)	NPA6	Brownish black	NPA4-1/2	Brownish black
Kinematic viscosity @ 100°F, ASTM D-455, C_s	1.08	3.87	0.96	14.90
Saybolt viscosity, SUS, 100°F		39		77
Sulfur (Bomb) ASTM D-129, wt-pet	0.13	0.29	0.06	0.35
Nitrogen, Kjeldahl, Wt-pet	0.420	0.446	0.212	0.871
Carbon residue (Conradson) ASTM-524, Wt-pet	0	2.33	0	5.44

SOURCE: Reference 25

TABLE 3.6

H-Coal

ENERGY SYSTEM:

SIZE
- 50,000 bbl/day
- .32 x 10^{12} Btu/day
- 105.12 x 10^{12} Btu/year
- 90% plant availability
- operates 328.5 days/year
- efficiency 70%
- plant life 30 years

DESCRIPTION
- Coal is crushed to about 3/4 inches and then ground to minus 60 mesh and mixed with recycled oil. The slurry is then preheated and fed to the reactor and hydrogenated as it comes in contact with the ebullating bed of catalyst. Reaction temperature is about 350°C. Gases and vapors are then withdrawn from the top of the reactor and passed through condensers for product separation. The heavier product is withdrawn as a side-stream from the reactor and pumped to an atmosphere distillation unit.

COMPONENTS
- crushers
- drying unit
- hydrogen plant (gasifier)
- H-coal reactor
- gas recovery plant
- distillation unit

ENVIRONMENTAL CONCERNS
- ● ir emissions
- solid waste
- water pollution from runoff and leaching
- occupational hazards and health effects
- noise
- odor

RESOURCES USED:
(Per 10^{12} Btu Produced)

FUEL	
coal: bituminous	57,756 tons
energy content	11,900 Btu/lb

COAL ANALYSIS	**% (by weight)**
moisture	2.7
volatile matter	35.5
fixed carbon	51.7
sulfur	3.0
ash	7.1

LAND$^{(1)}$	**Acres**
plant facility	3.9
solid waste disposal	0.31

CONSUMPTIVE WATER USE	**Acre-Ft.**
process water	9.3
cooling water	101.6
waste water	7.8
potable	.3
other (utility, quench, etc)	2.8
Total	121.8

COSTS	**Dollars (1975)**
construction$^{(2)}$	6,200,000
operation	3,700,000

PERSONNEL	**Workers**
construction	NA
operation & maintenance	4.1

RESIDUALS AND PRODUCTS:
(Per 10^{12} Btu Produced)

AIR POLLUTANTS	**Tons**
particulates	6.6
SO_2	20.2
NO_x	40.9
hydrocarbons	0.6
co	NA
● rsenic	0.1
cadmium	1.1 x 10^{-2}
mercury	6.2 x 10^{-3}
● lbr	5.9 x 10^{-2}
chromium	0.1
● lch*l	3.3 x 10^{-3}
lead	1.1 x 10^{-2}
polynuclear ● SSMIC material	NA

WATER POLLUTANTS

no direct discharge into any water source

SOLID WASTE$^{(3)}$	**Tons**
dry ton equivalent	5,705

ENERGY PRODUCT	**Barrels**
liquid fuel	156,250
(energy content Btu/bbl)	6.4 x 10^6

*The data presented are based on a conceptual design of a commercial facility. The data will be updated when more current data become available. The data should not be used directly for comparison with other coal liquefaction processes.

(1) This represents land committed to use over the lifetime of the plant, divided by the annual output of the plant, expressed in trillion Btu., (405 acres ÷ 105.12 = 3.9 acres)
(2) This represents total cost of constructing the plant, divided by the annual output of the plant, expressed in trillion Btu. ($650 million ÷ 105.12 = $6.2 million).
(3) Does not include solid waste from mine burial and tailings pond.

SOURCES: Hittman Associates, Inc., Environmental Assessment of Coal Liquefaction, 1978.
TRW, Characterizations and Data in the Area of Coal Mese Environmental Data Book, Volume IV, 1978.
U.S. Energy Research and Development Administration, Synthetic Liquid Fuels Development: Assessment of Critical Factors, ERDA 76-129/2.
Fluor Engineers and Constructors, Inc., H-Coal, Commercial Evaluation FE-2002-12. March 1976.

SOURCE: Reference 17

TABLE 3.7

Overviews on SASOL I and SASOL II, based on reference 8, follow:

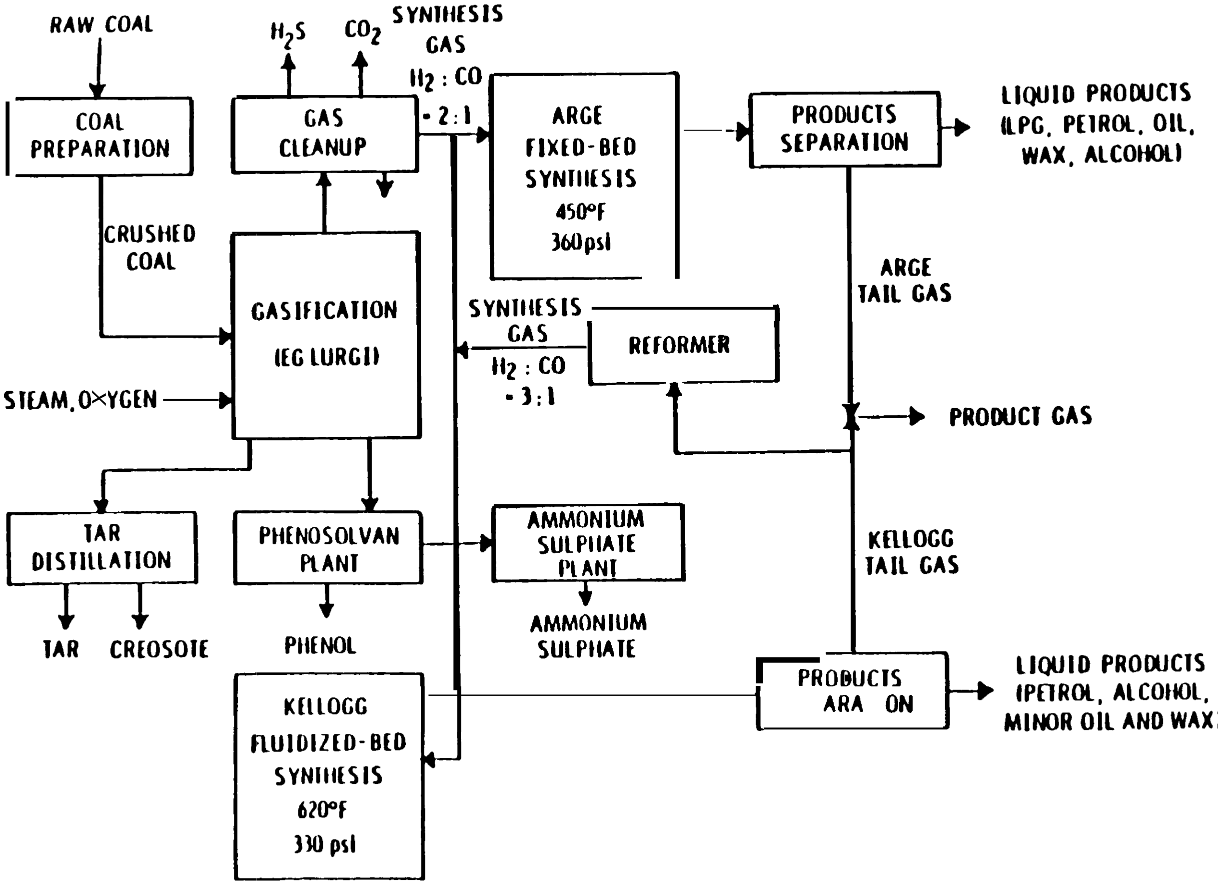
SASOL 1

LOCATION:	Sasolburg, South Africa
DESCRIPTION:	Gasification in Lurgi gasifiers Two Fischer-Tropsch synthesis units; 1) ARGE fixed-bed unit, temp. 230°C; press. 23 atm.; catalyst, pelleted precipitated iron. 2) Kellogg SYNTHOL process, hlgh-velocity entrained-flow reaction using a doubly promoted iron catalyst.
SIZE:	10,000 bpd
STATUS:	in commercial production since 1956
YEARS OPERATION:	24
COAL TYPE:	Subbituminous
MAJOR PRODUCTS:	Liquid fuels, chemicals, and fuel gas.

SASOL II

LOCATION:	Secunda, South Africa
DESCRIPTION:	Gasification in Lurgi gasifiers, Fischer-Tropsch synthesis unit using the Kellogg SYNTHOL process
SIZE:	Nominal 40,000 bpd
STATUS:	Anticipate ready for commissioning in 1980
COAL TYPE:	Subbituminous
MAJOR PRODUCTS:	Liquid fuels (gasoline is the major product).

SOURCE: Reference 35



SOURCE: Reference 35

Figure 3.7

Fischer-Tropsch Synthesis

at 620%′ and 330 psig, (Reference No. 35). The main products are gasoline, fuel oil fractions, and various chemical products. The gasoline has a lower octane rating than the one derived from petroleum crude. The products produced do not fit well into existing markets. However, Mobil Oil Corporation has developed catalysts that improve the quantity and quality of gasoline (Reference No. **29**).

3.3.6 Methanol Process

The production of methanol from synthesis gas is a specialized application of the Fischer-Tropsch reaction. Whereas the F-T process produces liquid fuels and chemical products, the Mobil methanol process produces gasolines . The schematic outline of this process is given in Figures 3.8 and 3.9 (Reference No. 35) . Table 3.8 ‘(Reference No. 35) presents a comparison of the thermal efficiencies of the Fischer-Tropsch and the Mobil methanol-to-gasoline process.

In the Mobil methanol liquefaction process, synthesis gas is produced from coal by any of the mediun-Btu coal-gasification processes. The synthesis gas is converted to methanol by a number of catalytic processes . The reaction is exothermic. The yield of methanol is optimized by using high pressures and low temperatures, optim um type and shape of catalysts, and of recycling of the unreacted gases.

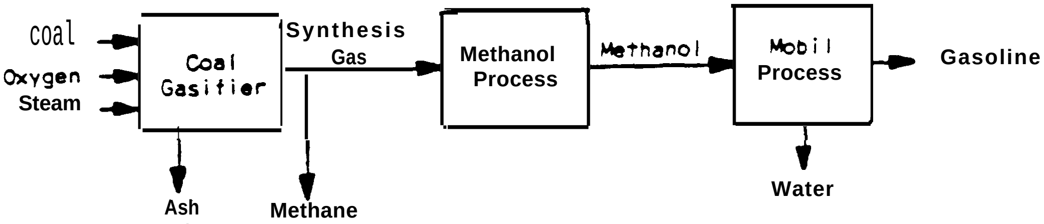
The conversion of methanol to gasoline is a separate catalytic conversion process. The Mobil conversion process dehydrates methanol, then rearranges the carbon and hydrogen atoms. The zeolite catalysts employed in the process (called ZSM-5 class catalysts) have a unique channe The pore openings are of the right size to limit the size of the product molecules that can pass through then. the conversion proceeds to conventional high quality gasoline Reference No. 25) .

Table 3.9 (Reference NO. 25) summarizes the overall material and energy balances of the methanol-to-gasoline conversion process.

Table 3.9 (Reference No. 25) shows typical product yields produced from methanol by this conversion process.

---

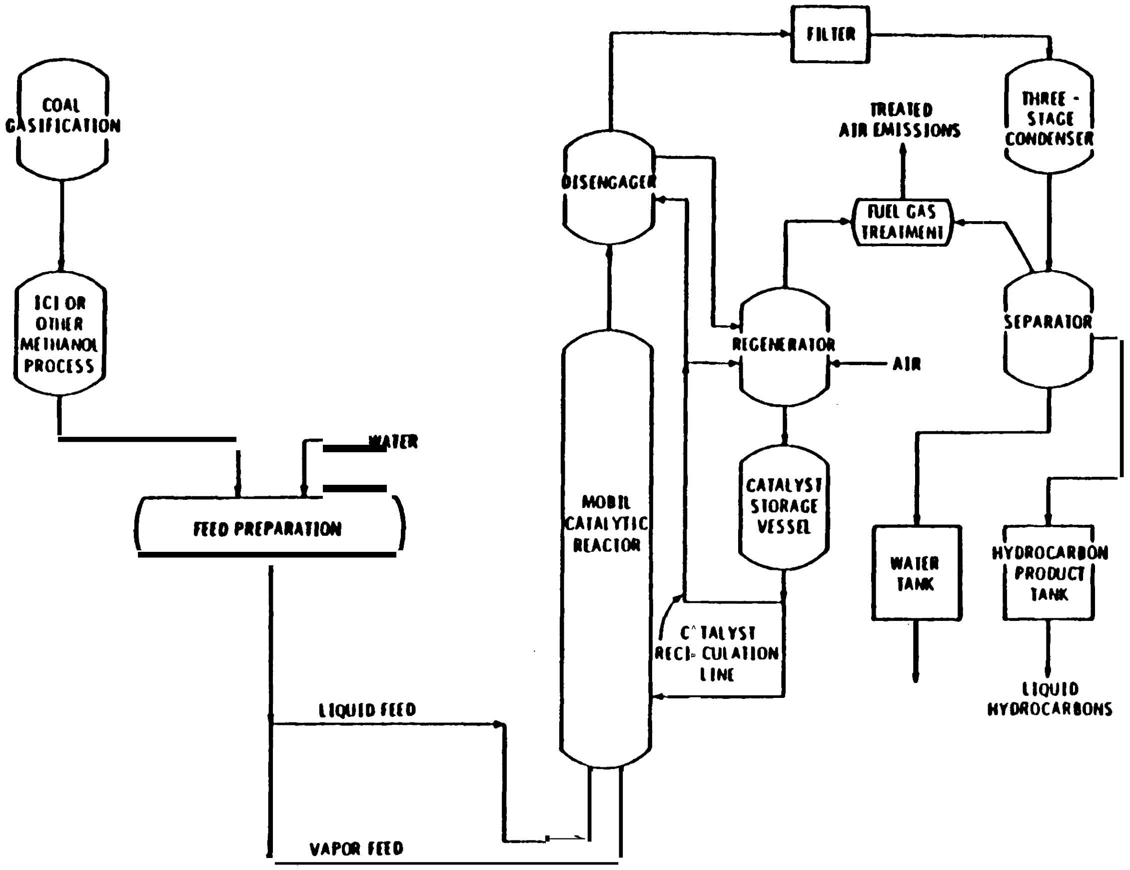
[5] Even though no commercial demonstration plants of the “indirect” coal-methanol-gasoline process has been built as of this date, this route is considered by many authorities to be a very promising way to get gasoline from coal. There are several proposed studies and plants under instruction in the U.S. using this process (see Appendix chart) . Also, New Zealand Liquid Fuels Trust Board (Report No. LF 5502, 10/31/79) has a large Mobil-M gasoline plant under construction (expected to become operational by 1983-5) .



SOURCE: Reference 3S

Figure 3.8

Synthesized Gasoline From Coal



SOURCE: Reference 35

Figure 3.9

Mobil Catalytic Process

Table 3.8

Thermal Efficiencies

	Methanol-to-Gasoline[7]		Fischer-Tropsch[7]	
	Btu/hour (1C^{6} Btu)	Percent of Input	Btu/hour (106 Btu)	Percent of Input
Input				
coal	**19,383**		19,708	
Coal Fines (excess)	**(872)**		—	
Methanol	·		3	
Total Input	18,511		19,711	
output				
SNG	6,067	32.8	7,243	36.8
C3 LPG	247	1.3	176	0.9
C_4LPG	385	2.1	26	0.1
10 RVP Gasoline	4,689	25.3	2,842	14.4
Diesel Fuel			514	2.6
Heavy Fuel Oil			147	0.7
subtotal	11,388	61.5	10 ,948	55.5
Alcohols			290	1.5
sulfur	19	0.1	19	0.1
Ammonia	83	**0.5**	83	0.4
Power	18	0.1	11	0.1
Total Output	11,508	62.2	11,351	57.6

[6] Thermal efficiencies are highly dependent on product mix.

[7] The indirect liquefaction processes shown here may be Considered as gasification processes for SNG, with the major coproduct being galosine, e.g. , for the "Fischer-Tropsch process" shown, the yield of SNG is 1.45 BOE/ton of coal, with a gasoline yield of 0.58 BOE/ton of coal. It is thus not representative of the SASOL-II process which emphasizes the production of liquid fuels.

[8] Direct thermal equivalent value (therma1 efficiencies are highly dependent on product mix (see Section 7. 5) .

SOURCE : Reference 35

TABLE 3.9

METHANOL-TO-GASOLINE BALANCES

	Methanol →	Hydrocarbons +	Water
Material Balance	100 tons	44 tons	45 tons
Energy Balance:	100 Btu	95 Btu	0 Btu

YIELDS FROM METHANOL

Average Bed Temperature, °F	775°F
Pressure, psig	25
Space Velocity (WHSV)	1.0
Yields, wt % of charge	
Methanol + Ether	0.2
Hydrocarbons	43.5
Water	56.0
co, CO_2	0.1
Coke, Other	0.2
	100.0
Hydrocarbon products, wt %	
Light gas	5.6
Propane	5.9
Propylene	5.0
i-Butane	14.5
n-Butane	1.7
Butenes	7.3
C_5 + Gasoline	60.0
	100.0
Gasoline (including alkylates), wt, % (96 RON, 9 RVP)	88.0
LP Gas, wt %	6.4
Fuel Gas, wt %	5.6
	100.0

SOURCE: Reference 25

3.4 Oil Shale Retorting

3.4.1. General

Oil shale resources vary widely in their oil yields. High grade shale is normally defined as a deposit that averages 30 or more gallons of oil per ton of shale. Low grade shale averages 10 to 30 gallons per ton[8] (Reference No. 7) . Several factors determine whether or not an oil shale deposit is recoverable. These include oil yield (usually equal or above 20 gallons per ton) , zone thickness, overburden thickness, the presence of other materials in the shale, availability of needed resources such as water and services, and location relative to markets.

There are two major routes for converting oil shale to liquid or gaseous fuels. They are:

1. Conventional mining followed by surface retorting (heating) , and
2. In situ (in place) retorting

In addition, there is modified in situ. In this process, the permeability (i.e., void volume) of oil shale deposits is increased in order to enhance the in situ retorting by removing some of the shale. The methods of rein@ or increasing the permeability of the oil shale deposits are explained in reference 8.

3.4.2. Surface Retorting

In surface retorting of oil shale, the heating takes place above ground. The shale is crushed to the right size, and fed into a retorting vessel. Heating the shale to between 800°F and 1000°'F removes abut 75 percent of the kerogen from the shale (Reference No. 8) . Different retorting precesses apply heat to the shale in different ways. Gas or non combustible solids such as sand or ceramic balls can be used as heat carriers. The vapor produced during the heat@ is condensed to form crude shale oil. It can be further upgraded and refined to produce more marketable products.

As a generic surface retorting process, TOSCO II is described. Its schematic diagram is given in Figure 3.10 (Reference No. 8).

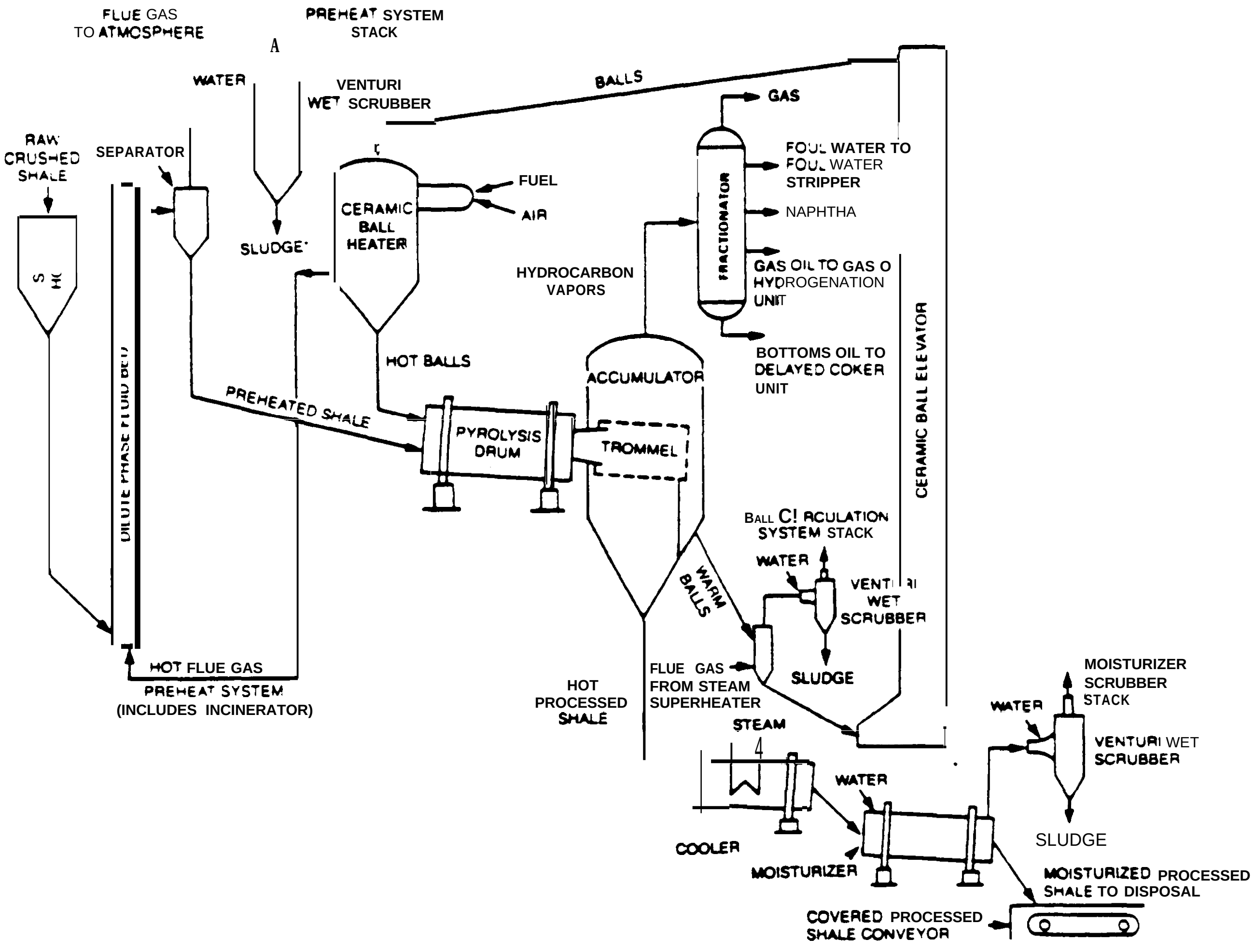
---

[9] Shale deposits yielding less than 10 gallons of oil per ton are normally omitted from USGS resource estimates.

Raw oil shale is crushed to 1/2 inch and preheated to 500° F. It is mixed with hot ceramic balls 3/4 inch in diameter and at 1200°F in a retorting Pyrolysis drum (Reference No. 25) . About two tons of balls mix with every ton of shale. The oil shale is heated to 900°F, releasing hydrocarbon vapors from the kerogen. The spent shale and the balls pass to the sealed accumulator vessel, in which the balls are separated from the shale by a heavy duty rotating cylinder with numerous holes. The balls are lifted by a bucket elevator to the gas fired ball heater, which heats the balls to 1270°F by direct contact heat exchanger. The spent shale goes through

FIGURE 3.10

The TOSCO II Oil Shale Retorting System



SOURCE *Oil Shale Retorting Technology* prepared for OTA by Cameron Engineers, Inc .1978

e j b &a

a special heat exchanger which cools the shale for disposal and produces steam for plant use. Then the spent shale is quenched with water and moisturized to 14 percent, a level proper for disposal.

Hot flue gas from the ball heater is used to lift raw shale to a point at which it can subsequently flow by gravity into the pyrolysis drum. The flue gas also heats the raw shale to approximately 500°F.

Table 3.10 (Reference No. 25) summarizes the basic material balance for a TOSCO II retort module.

TABLE 3.10

BASIC MATERIAL BALANCE FOR A TOSCO II RETORT MODULE

Oil Shale	
Feed rate, TPSD	10,700
Fischer Assay, GPT	20
Pipelineable Shale Oil Product	
production rate, BPSD	4,500
Properties	
Gravity, *API	28.6
Viscosity (SSU @ 30°F)	800
Pour Point, ‘F	30

Table 3.11 (Reference No. 35) summarizes the energy balance for a plant producing 47,000 barrels per day. Table 3.12 (Reference No. 17) summarizes the components, resource requirements and potential impacts of surface oil shale retorting.

Table 3.11

Estimated Energy Balance For a TOSCO II Plant producing 47,000 BPSD* Upgraded Shale Oil From 35 Gallons Per Ton Oil Shale

	Btu/hour (lo Btu's)	Percent of Total Energy Input
Product Output		
Product oil	10.30	58.00
LPG	0.70	3.94
Diesel fuel	0.11	0.62
System Losses		
Spent shale and moisture	1.78	10.02
Residual carbon (coke)	0.93	5.24
Ammonia	0.11	0.62
Sulfur	0.06	0.34
Cooling water	1.07	6.02
Water evaporation on shale	0.25	1.41
Losses (including flue gas heat)	2.45	13.79
Energy Input	17.76	100.0
Raw shale	17.00	95.72
Steam	0.53	2.98
Electrical energy	0.23	1.30

* BPSD = barrels per stream day

SOURCE: Reference 35

TABLE 3.12 TOSCO II Oil Shale Retorting

ENERGY SYSTEM:

SIZE
- 50,000 bbls/day of crude shale oil
- 16.43 x 10^6 barrels of oil/year
- .29 x 10^{12} Btu/day
- 5.8 x 10^6 Btu/barrel
- operates 328.5 days/year
- total annual output 95.27 x 10^{12} Btu
- plant life 30 years
- plant efficiency (thermal) 6[illegible] %

DESCRIPTION
- Heated ceramic balls are fed into a horizontal rotating cylindrical retort and mixed with crushed shale (1/2 inch diameter). Pyrolysis occurs at 900°F. Shale oil steam and gases are emitted from one end of the retort and are collected and fed into a fractionator for product recovery. The ceramic balls are recycled to a vertical ball heater where reheating for further use occurs.

COMPONENTS
- horizontal cylindrical retort
- fractionator and coker
- naphtha hydrofiner
- gas oil hydrofiner
- hydrogen plant
- by-product recovery

ENVIRONMENTAL CONCERNS
- air quality deteriortation
- health effects due to hydrocarbons
- modifications to biological environment
- deterioration of water quality due to leachates and runoff
- solid waste disposal
- socio-economic problems due to high influx of personnel in previously sparsely populated areas

RESOURCES USED:
(Per 10^{12} Btu Produced)

FUEL(b)	
raw shale	230,000 tons
oil content	35 gallons/tons

COMPOSITION(e)	(by weight)
oil	11.8
water	1.4
spent shale	84.9
gas	2.0

LAND(1)	Acres
retorting, upgrading and offsite facilities	3.36
expansion, water containment and greenbelt	3.42

WATER(b)	Acre-Feet
cooling towers	15.8
waste heat boilers	14.5
water treatment plant	0.4
processed shale	21.3
dust control on shale ash	3.9
moisture evaporator	7.9
dust scrubbers	10.4
revegetation	1.1
fire and drinking	2.4
total	77.7

COSTS(2)	Dollars (1978)
construction	
manpower	1,640,000
materials	671,000
equipment	1,655,000
other cost	337,000
total	4,303,000
operation & maintenanc	NA

PERSONNEL	Workers
construction	2.1
operation & maintenance	11.5

RESIDUALS AND PRODUCTS:
(Per 10^{12} Produced)

AIR POLLUTANTS(b)	Tons
particulates	19.6
SO_2	11.4
NO	63.3
hydrocarbons	11.2
CO	2.3

WATER POLLUTANTS
assume zero direct discharge to any water-course

SOLID WASTE(b)	Tons
spent shale	190,000

ENERGY PRODUCT(b)	Barrels
refined shale oil	172,400 barrels
heat content	5.8 x 10^6 Btu/barrel

(1) Land use value represents land committed to use for the facility, divided by annual production, measured in trillion Btu.
(2) Costs are total costs for plant construction, divided by annual output, measured in trillion Btu.

SOURCES: (a) Environmental Protection Agency, Monitoring Environmental Impacts of the Coal and Oil Shale Industries, 600/7-77-015, February 1977.
(b) University of Denver, Denver Research Institute. An Engineering Analysis Report on the TOSCO II Shale Process, March 1977.
(c) University of Oklahoma, Energy Alternatives: A Comparative Analysis, 1975.
(d) Bechtel Corporation, Energy Supply Planning Model, 1978.
(e) Cameron Engineers Incorporated, Synthetic Fuels Handbook, 1975.

SOURCE: Reference 17

3.4.3 Modified In Situ Retorting

Occidental modified in situ oil shale retorting process is selected as representative. It involves the mining out of about 10 to 25 percent of the shale deposit. This mined portion would presumably be retorted by one of the surface retorting processes, or if its oil content is too low, will be treated as waste (Reference No. 37).

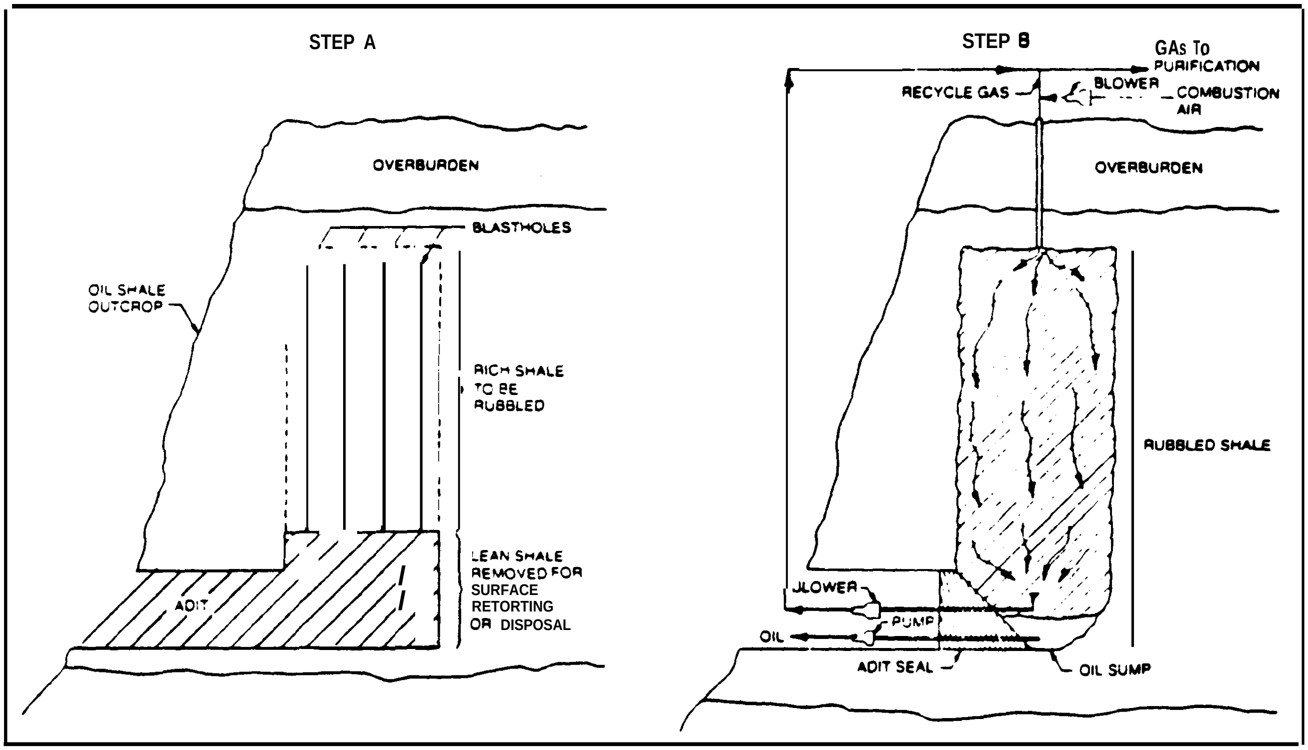
Figure 3.11 (Reference No. 8) represents in schematic form a generic modified in situ oil shale retorting process. ‘Figure 3.12 (Reference No. 37) is a more detailed description of the Occidental modified in situ retorting process. As observed in Figure 3.12 , in steps A or the pre-detonation phase, drifts (chambers) are excavated at the top and bottom of the shale deposit, which is about 300 feet-thick. An interconnecting shaft is dug to connect the drifts. Rooms with a volume of about 15 to 20 percent of the eventual volume of the planned chamber are then mined. Shot holes are drilled to allow blasting of the shale oil to produce the desired fragmentation.

In the burn phase, the explosives in the shot holes are detonated. A rubble-filled chamber is created which can function as a batch retort. The percentage of void space and the particle size distribution of the rubble are a function of the explosive loading. Connections are made to air/gas recycle and air supply compressors. An outside heat source (e.g., off gas or oil from other retorts) is used for heating the rubble at the top of the retort. Oil shale and hydrocarbon gases are produced which move downward. Residual carbon is left on the spent shale.

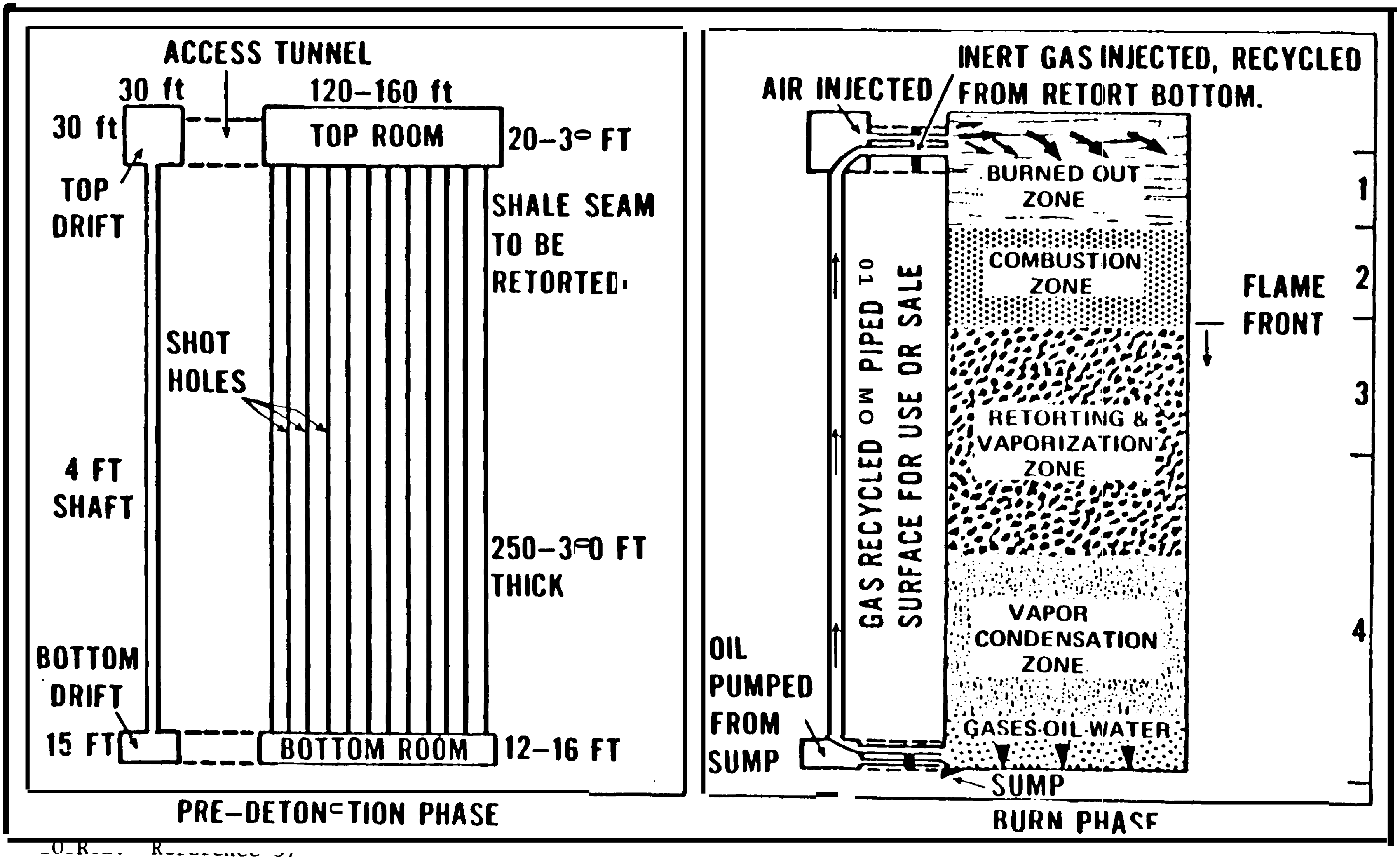
The retorting reaction is terminated after a predetermined amount of the rubble has been retorted by halting the external heating supply. The residual carbon is utilized to continue the combustion process, which now does not need external heating. The flame front moves downwards, preceded by the liquid and gaseous products retorted from the shale by the hot, oxygen-deficient combusion gases. The liquid hydrocarbons collect in a sump, from which they are pumped to the surface. The gaseous by-products are used partially, with steam, as a recycle stream to control the oxygen content of the inlet gas. The four distinct zones that develop during the retorting are shown in Figure 3.11 .

Table 3.13 (Reference No. 17) summarizes the components, resource requirements, and potential impacts of modified in situ retorting.

Figure 3.11: **Modified in Situ Retorting**



SOURCE: T. A. Sladek, "Recent Trends in Oil Shale—Part 2: Mining and Shale Oil Extraction Processes," *Mineral Industries Bulletin*, vol. 18, No. 1, January 1975, p. 18.



[illegible]

Figure 3.12: Occidental Modified In Situ Retorting

TABLE 3 13

Modified In-Situ Shale Retorting (Occidental)

ENERGY SYSTEM:

SIZE
- 34,200 tons of raw shale mined/day(d)
- 102,600 tons of raw shale retorted in-situ/day(c)
- shale oil content 25 gallons/ton(d)
- ○ 50,000 bbl/day
- ○ .29 x 10^{12} Btu/day
- ○ 95.3 x 10^{12} Btu/year
- ○ operates 328.5 days/year
- ○ plant life 30 years
- ○ thermal efficiency 61% overall(d)

DESCRIPTION
- In modified in-situ approximately 15-20% of the deposit is mined using conventional mining techniques in the ground and fractured using either chemical, hydraulic, or electric means. Prior to fracturing of the deposit, parallel wells (productions and injection) are drilled on two opposing sides of the deposit. A retorting fluid (hot steam or gas) is injected within the formation. After ignition, retorting takes place and the oil mist, gas and steam produced are forced to the surface through the production wells. Liquid gathered at the base of the combustion zone is later pumped out. The products are refined using techniques similar to surface refining.

COMPONENTS
- underground retort created from blasting procedure
- fractionator and coker
- naphtha hydrofiner
- gas oil hydrofiner
- hydrogen plant
- by-product

ENVIRONMENTAL CONCERNS
- air quality deterioration
- health effects due to hydrocarbons
- modifications to biological environment
- deterioration of water quality due to leachates and runoff
- solid waste disposal
- socio-economic problems due to high influx of personnel in previously sparsely populated areas

RESOURCES USED:
(Per 10^{12} Btu Produced)

FUEL(c,d)	
mined shale	117,900 tons
unmined shale	353,800 tons
oil content	25 gallons/ton
COMPOSITION(a)	(by weight)
organic material	NA
water	NA
inorganic material	NA
spent shale	NA
LAND(c)	Acres
permanent disposal	207-310/Year
surface facilities	345
active well area	862/Year
WATER(c)	Acre-Ft.
retorting and upgrading	(22.2)*
power generation	24.6
revegetation	0.9
steam injection	28.9
miscellaneous	4.4
total	36.6
COSTS(b)	Dollars (1978)
construction	13,400,000
operation & maintenance	NA
PERSONNEL(b)	Workers
construction	30.6
operation & maintenance	NA

RESIDUALS AND PRODUCTS:
(Per 10^{12} Btu Produced)

AIR POLLUTANTS(d,e)	Tons
particulates	39.6
SO_2	6.21
NO_x	33.7
hydrocarbons	0.51
CO	10.0

WATER POLLUTANTS
There is assumed a zero direct discharge of effluent into any water course.

SOLID WASTE(d)	Tons
spent shale	99,000
ENERGY PRODUCT	Barrels
refined shale oil	172,400

*Approximately one barrel of water/barrel of oil is produced during retorting by the release of interstitial water and the combustion of hydrocarbons.

SOURCES:
(a) Cameron Engineers, Incorporated, Synthetic Fuels Handbook, 1975.
(b) MESS Data Group, Environmental Characterizations for Energy Technologies and End Uses, Revision b, 1978.
(c) Department of Energy, Draft Environmental Impact Statement for the (updated) Prototype Oil Shale Leasing Program, 1979.
(d) Environmental Protection Agency, A Preliminary Assessment of the Environmental Impacts from Oil Shale Development, 600/7-77-060, July 1977.
(e) Ashland Oil, Inc., Lessee & Occidental Oil Shale , Inc., Modifications to Detailed Developmental Plan, Oil Shale Tract C-b, February, 1977.

SOURCE: Reference 17

3.5 comparison of the Various Synfuel Systems With Respect to Resource Requirements[10]

In order to estimate the resource requirements of the coal and oil shale fuel cycles we need first to assess their energy utilization efficiencies. These are summarized in Table 3.14.

The resource requirements of coal and oil shale energy systems per 10^6 Btu of product delivered to end user are given in Tables 3.15 and 3.16. Tables 3.17 and 3.18 convert these requirements to energy systems producing 50,000 barrels of oil equivalent per day.

Manpower requirements for operating and maintenance labor of coal conversion plants are given in Reference 29.

They are:

Plant operators	
Operating supervisors	
Maintenance labor	
Maintenance labor supervisors	30
Administration	30
Total	355

These manpower requirements are for a basic (ESCOE) coal conversion plant that consumes 25,000 tons of coal per day with 22.4 million Btu/ton and produces 50,000 bbl/day liquids output.

Very considerable variations exist in the literature in respect to manpower requirements for the other phases of the fuel cycle. They depend on such variables as methods of mining, location of mine, kind of transportation system and extent of beneficiation. A table indicating the ranges of variables is given in the footnote in respect to the conversion plants.

---

[10] Limitations of Data Sources: Evaluations carried out in this report are often subject to great uncertainties because:

(1) The information available is only of preliminary nature. There are no full scale operating synfuel plants in the U.S. (subject to U.S. siting considerations), so that data needs to be extrapolated from pilot plants with many uncertainties of scale and dissimilarities associated with the extrapolation, as well as specific siting and feedstock characteristics discussed below.

---

[10] (cent'd)

(2) There are variations among sources which are often due to different assumptions or local influences. Changes in design account for some differences as the technology changes and the environmental regulations change. Many of the assumptions are not stated - or even referenced. Budget and time limitations, however, nessitate the need to use exist& data bases, rather than the development of new data.

Even estimating the range of uncertainties is often a value judgement process , unless more extensive on-site interviewing with site and process specific sources of information are developed.

Table 3. 4 Resource Utilization Efficiencies of Generic Synthetic Fuel Energy Systems

(In Percent)

	1 Coal Gasification Medium-Btu	2 High-Btu	3 Coal Liquefaction Direct	4 Indirect	5 Oil Shale Retorting Surface	6 Modified in Situ
Beneficiation[a]	96.4-97.3	96.4-97.3	96.4-97.3	96.4-97.3	96.4-97.3	100
Transportation to Conversion Plant[b]	98.5	98.5	98.5	98.5	99.5	100
Conversion to Fuel[c]	83	59	64-70	48-57	67	61
Upgrading and Refining[d]	N.A.[e]	N.A.[e]	75-95[f]	95-100[f]	77[g]	77[g]
Distribution to End User	96.9[h]	97.1[i]	98.8[j]	98.8[j]	98.8[j]	98.8[j]
Overall Energy Efficiencies	76.4-79.2	54.4-54.9	45.0-63.0	42.8-54.0	48.9-49.3	46.4

SOURCE: E. J. Bentz & Associates

Notes for Table 3.14

a. Estimates of losses of coal and oil shale from beneficiation (in terms of Btu's) vary broadly among authors, depending on the assumed degree of upgrading and the kind of coal or oil shale used. Estimates vary from 0% (Reference 37a) ; 2.7-3.6% (Reference 7) ; and 12.5% for intensive beneficiation (Reference No. 17) .

b. Average value of losses are 1.5% (time from Reference No. 7) . In the case of oil shale, where distances are shorter, 0 .5% is assumed.

c. The @et efficiencies (rather than the process efficiencies) were used. The efficiencies for coal conversion processes are derived from Roger and Hill. (Reference 29) . In the case of H-Coal, the syncrude efficiency was used. In the case of oil shale retorting processes, the efficiencyes are derived from DOE (Reference No. 17) .

d. Data on efficiencies of upgrading and refining syncrudes is very limited and unreliable (see Section 1.7) .

e. N.A. means not applicable.

f. Overall yields for SRC II of finished fuels range between 83 and 98 liquid volume percent of SRC II syncrude, depending on the product slate and how refinery fuel and hydrogen plant feed are supplied. An average of the net product yields ranging between 88 and 91 was assumed (Reference No. 22) . However, these values apparently do not include coal use for the production of hydrogen needs for the upgrading process. If coal-derived hydrogen is to be used (as against hydrogen from nuclear fission or from biosynthesis) , then the upgrading and refining efficiencies for coal conversion products become 75 percent. However, in some cases it may be expected that all of the hydrogen and energy required for the Upgrading/refining process would be obtained from residuals, higher boiler fractions, and methane produced in the process or plant refinery(which may include the use of Petroleum derived vacuum . In the case of indirect liquefaction Processes, all the needed hydrogen is accounted for in the gasifier, and higher upgrading efficiencies can be achieved, depending on product slate .

g. Derived from Reference 26a. However, MIS oil is easier to upgrade, so that higher efficiency may be in order.

h. Derived from Reference 17.

i. Derived from Reference 7.

j. Derived from Reference 7 and 10.

Table 3.15 Fossil Carbon Consumption of Generic Synthetic Fuel Energy Systems (In 10^{-3} ton of fossil carbon/10^6 Btu fuel delivered to end user)

	1 Coal Gasification	2	3 Coal Liquefaction	4	5 Oil Shale Retorting	6
	Medium-Btu	High-Btu	Direct	Indirect	Surface	Modified in Situ
Beneficiation	1.2-1.6	1.7-2.2	2.0-2.7	2.1-2.8	0.9-1.2	⊙
Transportation to Conversion Plant	0.7	0.9	1.1	1.2	0.2	⊙
Conversion to Fuel	0.7	25.1	22.2-26.7	33.5-40.5	11.4	18.7
Upgrading and Refining	-	-	3.7-18.5	0-3.9	7.9	11.0
Distribution to End User	1.4	1.8	0.9	0.9	0.4	0.6
Overall Consumption	9.1-10.3	27.6-27.9	27.4-40.7	35.8-44.≤	17.5-17.6	25.7

SOURCE: E. J. Bentz & Associates

Notes to Table 3.15

a This table summnarizes the consumption of fossil carbon contained in the feedstocks or products during the various phases of the various synfuel cycles.

b The numbers in the table are based on the following assumptions:

(i) The resource utilization efficiencies are those developed in Table 3.14.

(ii) The carbon content of bitumimous coal averages 87.8%, lignites - 72. 5% and sub-bituminous~ reals - 73. 5%. The carbon content of the kerogen (i. e., crude shale oil) averages 80. 5%. (Ref. 26b) . For convenience, an average figure of 80% for the carbon content of coals and kerogen is used.

(iii)The loss in fossil carbon is directly proportional to the loss in coal or kerogen.

(iv) The Btu content of a ton of coal is 24x10^6 Btu and of ton crude shale oil is 36x10^6 Btu.

c A sample calculation for medium Btu coal gasification is as follows:

A ton of feedstock bituminous coal has 24x.10^6 Btu, of which 18. 34x10^6 to 19. Olx10^6 Btu is delivered to the end users (74.4 to 79. 2% overall energy efficiency - see Table 3.14) . Since a ton of feedstock coal. has 80% fossil carbon content, and 20.8% to 23.6% of it is consumed during the medium Btu coal gasification fuel cycle, (see Table 3.14) , the total fossil carbon consumption o the cycle is between 0.1664-0.1888 tons per 18.34x10 to 19. Olx10^7 Btu delivered to end users. This translated to 0.009 to 0.010 tons of fossil carbon per 10^6 Btu.

Table 3.16 Water Consumption of Synthetic Fuel Energy Systems (Generic (In gallons per 10^6 Btu product delivered to end user)

	1 Coal Gasification Medium-Btu	2 High-Btu	3 Coal Liquefaction Direct	4 Indirect	5 Oil Shale Retorting Surface	6 Modified in Situ
Mining[a,b]	0.6-0.9	0.6-0.9	0.6-0.9	0.6-0.9	0.7-1.1	0.7-1.1
Beneficiation[c]	1.2	1.2	1.2	1.2	0	0
Transportation to Conversion Plant	0	0	0	0	0	0
Conversion Fuel[d]	13-24	13-24	7-26	13-26	9-32	9-13
Upgrading and Refining[e]	0	0	–	–	24	24
Distribution to End User	0	0	0	0	0	0

SOURCE: E. J. Bentz & Associates

Notes to Table 3.16

a The water required for mining and preparation of the coal or shale and for the disposal of ash or spent shale is a function of location, mainly through the amount of material that must be mined or disposed; and the degree of attested surface reclamation. Assuminq 2/3 of coal is surface-mined and 1/3 is undergroundd mined, water consumption for surface mining ranges between 0.55 and 0.98 gallons per 10^b Btu of product, and for underground mining - 0.75 gallons per 10^6 Btu of Product (Reference No. 17) .

b Assume 2/3 of oil shale is surface mined and 1/3 is underqround mined. Water consumption or both kinds of operations range between 0.7 and 1.1 gallons per 10^6 Btu of product (Reference No. 17).

c Consumption of 1.2 gallons of water 10^6 Btu Of product is assuned for beneficiation of coal (Reference No. 17) and none for shale oil.

d Consumption of water for the conversion of feedstock to fuels depends principally on the overall plant conversion efficiency, degree of water recycling, and the water content of the coal or shale. Consumption figures range from 13-24 gallons per 106 Btu of product for coal gasification; 7-26 for direct coal liquefaction; 13-26 for indirect coal liquefaction; 9-32 for surface shale retorting; and 9-13 for modified in situ shale retorting (Derived from References 17, 37b,c) .

e Water consumption for upgrading and refining is not available in the literature. The estimates presented for shale oil upgrading are based on private conversation with Mr. Bobby Hall and Ray Young of the American Petroleum Institute 3/81. For shale oil - 100 gallons per barrel are needed to make the raw shale oil suitable for pumping, and 40 more gallons per barrel to convert it to transportation fuels. Polling of a large number of oil companies and API experts did not result in water consumption estimates for upgrading of coal liquids (name1y: Robert Howell, Bonner and Moore, Fred Wilson Texaco, Patton, Nanny, Hall and Young of API - 3/81) .

Table 3.17* Annual Feedstock Requirements for Generic Synthetic Fuel Energy Systems Producing 50,000 bbl Oil Equivalent per Day to End User (In millions of tons or barrels of oil)

	Coal Gasification		Coal Liquefaction		Oil Shale Retorting	
	Medium-Btu	High-Btu	Direct	Indirect	Surface	Modified in Situ
Mining^5	5.6-5.8	8.0-8.1	7.0-9.8	8.2-10.3	62.2-62.7	N.A.^{7}
Beneficiation^5	5.4-5.6	7.8	6.8-9.4	7.9-9.9	60.5-60.6	N.A.^{7}
Transportation to Conversion Plant^5	5.3-5.5	7.7	6.7-9.3	7.8-9.8	60.2-60.3	N.A.^{7}
Conversion to Fuel^6	18.9	18.8	19.4-24.6	18.5-19.4	24.0	24.0
Upgrading and Refining^6	18.8	18.8	18.5	18.5	18.5	18.5
Distribution to End User^6	18.3	18.3	18.3	18.3	18.3	18.3

* These are the quantities of coal, shale or equivalent oil leaving the indicated phase of the fuel cycle.

SOURCE: E. J. Bentz & Associates

Notes to Table 3.17

1. Same assumptions and references as those in Table 3.14.
2. Oil has energy content of 5.8 x 10^6 Btu/barrel.
3. Coal has energy content of 24 x 10^6 Btu/ton.
4. Oil shale has energy content of 3.45 x 10^6 Btu/ton (based on 25 gallons of oil per ton) .
5. Tons of coal or shale.
6. Barrels of oil equivalent.
7. N.A. is not applicable.

Table 3.18* Annual Water Consumption of Generic Synthetic Fuel Energy Systems Producing 50,000 bbl Oil Equivalent per Day to End User (In million gallons per year)

	Coal Gasification		Coal Liquefaction		Oil Shale Retorting	
	Medium-Btu	High-Btu	Direct	Indirect	Surface	Modified in Situ
Mining	64-95	64-95	64-95	64-95	74-120	74-120
Beneficiation	130	130	130	130	0	0
Transportation to Conversion Plant	0	0	0	0	0	0
Conversion to Fuel	1400-2500	1400-2500	740-2800	1400-2800	950-3400	950-1400
Upgrading and refining	0	0			2500	2500
Distribution to End User	0	0	0	0	0	0

* Sam assumptions and references as in Table 3.16.

SOURCE: E. J. Bentz &Associates

Table 1 Footnote to Chapter 3: Manpower Requirements of Generic Synfuel Plants Producing 50,000 Barrels of Oil Equivalent per Day

	1 Coal Gasification	2 Coal Liquefaction	3 Oil Shale Retorting	4
	Medium-Btu-High-Btu	Direct & Indirect	Surface	Modified in Situ
Peak Construction (men)	1,500-4,800[a]	2,200-8,000[b]	330[d]	4,900[d]
Construction (man-years)	3,400 - 10,800[a]	7,500-25,000[b]	1100[d]	16,000[d]
Operation and Maintenance (men)	320-500[a]	355-3800[c]	1200[d]	-

[a] DOE, 1980, Comparative Assessment of Health ahd Safety Impacts of Coal Use. DOE/EV 0069.

[b] The lower value is derived from DOE/EV 0069; the upper value - from Reference 34.

[c] The lower value is derived from Reference 29 ; the upper value - from Reference 34.

[d] Derived from Reference 17 and assuming 5 year construction of plant peaking at 30% of [illegible] man-years labor requirements (Reference 34).

SOURCE: E. J. Bentz & Associates