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OIL-SHALE UTILIZATION AT MORGANTOWN, WV

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Morgantown Energy Technology Center
Morgantown, West Virginia

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OIL-SHALE UTILIZATION AT MORGANTOWN, WV

J.Y. Shang[1], J.E. Notestein[2], J.S. Mei[3],
R.R. Romanosky[4], J.A. King[5], and L.W. Zeng[6]

Introduction

The Morgantown Energy Technology Center (METC), United States Department of Energy (U.S. DOE), is the designated lead technology center for the areas of fluidized-bed combustion, coal gasification, gas cleanup, solids handling, and computer modeling. In pursuing the designated responsibility in fluidized-bed combustion, METC embarked on a comprehensive program of widening the fuel-supply base. Feasibility studies were conducted for various low-grade fuels and oil shales were among the fuels of interest to METC.

As the world energy supply initiated an economic strain in the petroleum-importing countries, means of recovering hydrocarbon fuels from oil shales gained increasing attention from the oil-shale-producing states. In response to requests from DOE Headquarters, METC has also conducted numerous feasibility studies in oil-shale utilization, combustion, and retorting for foreign countries. Oil shales from Israel and Morocco were test burned and retorted. As a result of METC's efforts, innovative designs for oil-shale combustion and retorting were developed. Some oil shales have a high limestone (calcium-carbonate) content and indiscriminate application of heat will result in calcining the limestone and consumption of a considerable amount of heat within the process without the benefit of high heat recovery. a pseudo two-staged fluidized-bed combustion design was proposed as an approach to mitigate this effect. The feasibility of burning the oil-shale volatiles without producing excessive calcination of the limestone was demonstrated in METC's FBC units.

One of the major criteria for achieving high-energy conversion efficiency in coal gasification as well as oil-shale retorting is the proximity of the heat-generating reaction, combustion, and heat-consuming reaction—gasification or retorting. In fact, this is why the moving-bed, counter-current gasifier or oil-shale retort has a slightly higher conversion efficiency than that of the conventional fluidized-bed reactors. However, owing to the vigorous inter-particle motion inside a fluidized bed, a high heat-transfer rate can be used to achieve good heat recovery between the hot spent shale and the cold fresh shale. A twin-bed fluidized-bed oil-shale retort/combustor was conceived and developed at METC, with a special feature of separating the products of retorting and/or gasification from the products of combustion.

Fully aware of the nation's need to develop high-risk and long-term research in eastern oil-shale and low-grade oil-shale utilization in general, the U.S. DOE/METC initiated an eastern oil-shale characterization program. In less than 3 months, METC produced shale oil from a selected eastern-U.S. oil shale with a Fischer assay of 8.0 gallons/ton. In view of the relatively low oil yield from this particular oil shale, efforts were directed to determine the process conditions which give the highest oil yield. A 2-inch-diameter electrically heated fluidized-

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bed retort was constructed, and "Celina" oil shale from Tennessee was selected to be used as a representative eastern oil shale. After more than 50 runs, the retorting data were analyzed and reviewed and the best oil-yield operating condition was determined. In addition, while conducting the oil-shale retorting experiments, a number of technical problems were identified, addressed, and overcome.

The oil-shale retorting study was supported by a competent and well-equipped technical staff that is capable of conducting conventional solid-fuel analyses, size distribution, surface-area measurement, electron microscopic analysis, low- and high-temperature ash analyses, differential thermal and thermogravimetrical analyses, etc.

The retorting process conditions, temperature, residence time, and rate of heating (size distribution) do affect the yield and composition of the shale oil retorted. Shale oil is produced from the thermal decomposition of oil-shale organics. Under the thermal-decomposition conditions, the organics in the oil-shale matrix are converted into char, gases, and liquid hydrocarbons. The manner under which the oil shale was retorted contributes to both the amount and composition of the shale oil produced.

Two-Inch-Diameter, Electrically Heated, Fluidized-Bed, Oil-Shale Retort

METC has designed and constructed a 2-inch-diameter electrically heated fluidized-bed retort (EHFBR) for use in this retorting study. This reactor allows accurate study of the effects of various precisely controlled, process/thermal conditions on shale oil yield and characteristics, recognizing that combustion effects will be evaluated later. The EHFBR is made of a 2-inch-diameter, 21-inch-long schule 160, 316 stainless-steel tube. The exterior of the EHFBR is wrapped with an electrical heating element which is capable of heating the EHFBR to 1200°F. Hot nitrogen, with a controlled temperature in the range of 700 to 1000°F, is fed into the bottom of the EHFBR below the distributor. The distributor is made of a perforated plate with an open area of 1.8 percent. The 37 .03-inch-diameter perforations are arranged in a triangular pitch of .26 inch and counter-sunk to control the plugging and weeping. The distributor pressure drop is maintained at 4 to 5 inches of water to assure flow stability and to prevent maldistribution. The expanded bed height is controlled to be 5 inches by the provision of an over-flow drain of 3/4-inch-diameter tube. This drain tube is branched downward to form an angle of 26 degrees with the major vertical axis of the EHFBR. The in-bed residence time is controlled by internal baffles which form a triangular truss with a main function of controlling bubble growth. Solids are delivered to the retort by a 1/4-inch-diameter screw feeder which receives crushed oil shale from a hopper and enters the EHFBR bed region at a pressure balance point (the pressure balance point is the point where the local pressure is equal to atmospheric pressure). The screw solid feeder has a feeding capacity of up to 250 gm/hour and the rate of feed is controlled by a variable-speed motor. The size of crushed oil shale utilized in the tests was 30 x 45 mesh. The cold minimum fluidization velocity was determined to be 0.3 ft/sec at room temperature. The operating fluidization velocity was in the range of 0.9 to 1.0 ft/sec.

The experimental configuration using this retort is shown in Figure 1. The gaseous products of retorting were passed through a glass-wool filter (GWF) which removed accompanying dust particles. An air-cooled condenser was used which collected about 20 percent of the heavy oil, and a subsequent water-cooled condenser collected about 30 percent of the light oil. A membrane "filtration" technique was then utilized to collect the remaining 50 percent of oil which was in the form of an oil "fog." The fog, or aerosol, was passed through a membrane filter with a pore size of 5 microns. The small pores force the aerosol droplets to coalesce into larger liquid drops which are then trapped and recovered after the membrane. The uncondensable gases are then passed through an activated carbon-packed bed, a glass-wool filter, and a vacuum-pump gas meter before being vented into an exhaust hood. The oils collected were weighed and an overall material balance was computed. Most of the material balances were accurate to within 95 percent, which is quite good for a lab-scale unit.

Retorting Test Activities

METC designed a series of experiments with the intention of determining controllable process variables which yield more oil and one with characteristics more compatible with conventional refineries. At present, the controllable process variables are the oil-shale feeding rate, the retorting temperature, and the oil-shale particle-size distribution. Determination of the product oil's compositions in terms of the fractions represented by saturated (paraffinics and naphthenic), unsaturated (olefinic), and aromatic hydrocarbons as well as a host of other pertinent oil feedstock properties is currently in progress. Reportedly, low retorting temperature favors the formation of paraffinic hydrocarbons, intermediate temperature favors olefinics, and high temperature favors aromatics. The rate of heating also affects the hydrocarbon composition. At a heating rate below 1°C/min, the retorting product is mostly paraffinic; at a rate between 1 and 100°C/min, the retorting products are mostly olefinic; if the heating rate is faster than 100°C/min, the retorting products are mostly aromatic. Of the three types of candidate oil-shale retorting processes (packed-bed, fluidized-bed, and entrained-bed), the fluidized-bed retorting process can easily achieve the heating rate of 100°C/min with a wide feedstock size distribution to achieve a desirably high aromatic hydrocarbon yield.

In view of the low hydrogen content of the eastern oil shale and the low hydrogen-to-carbon ratio in the aromatic hydrocarbons, fluidized-bed retorting appears to be the logical means of eastern oil-shale retorting. To date, METC has conducted 60 retorting runs using the electrically heated fluidized-bed retort for a wide variety of oil shales. The ultimate and elemental analyses of these oil shales (Celina, Tennessee; Sunbury, Kentucky; Colorado; Morocco; and Israel) and Fischer assays are shown in Table 1 and their respective material balances for the retorting tests are shown in Table 2.

As mentioned above, METC selected the oil shale from Celina, Tennessee, as the basis for this study. Two controlling variables (retorting temperature and oil-shale feeding rate) were also adopted as the two main controlling, or independent, variables. The results of the variable study are summarized in Table 2. The temperature of retorting was varied from 700 to 1000°F; the oil-shale feeding rate was varied from 115 to 206 grams/hour.

The retorted-shale oil yield was plotted as a function of the retorting temperature and oil-shale feed rate. This is shown in Figure 2. In the contour plot, the data are divided into three groups with oil-yield ranges of 0.96 to 1.21, 1.73 to 2.00, and 2.51 to 2.77 weight-percent. A regression analysis was applied to correlate the shale oil yield as the function of retorting temperature and oil-shale feed rate. The regression analysis produced the following relationship:

$$Y = -24.813 + 0.0536T - 2.703 \times 10^{-5}\ T^2 + 0.0381\ F - 8.96 \times 10^{-5}\ F^2 - 1.799 \times 10^{-5}\ T \cdot F$$

where: Y is the shale yield in weight-percent; T is the retorting temperature in °F; and F is the oil-shale feed rate in grams/hour.

Based on the consideration of high throughput and maximum oil yield for reduced retort investment requirements, a retorting temperature of 950°F and a feeding rate of 180 grams/hour appear to be the logical retorting condition. Current efforts are directed at determining the effect of oil-shale size distribution on the oil yield and composition. We expected to receive the shale oil analyses including API gravity, ASTM distillation, paraffinic, olefinic, naphthenic, aromatic-hydrocarbon contents, and sulfur and nitrogen contents in time for this printing; however, they are not yet complete. A process parameter study will be conducted using the analytical results to determine the controlling variables and magnitude of the effect on the yield and composition of the shale oil.

Israeli oil shale was available and selected to study the effect of oil-shale size distribution on retorted-shale oil yield. In addition, Israeli oil shale has a very small average pore size with an approximate pore population of 10^8 pores per square centimeter, which is about one order of magnitude less than that of the Colorado oil shale. Four batches of the Israeli oil shales of size distribution 60 x 80, 30 x 45, 20 x 30, and 14 x 20 mesh with a respective average size of 0.21, 0.50, 0.72, and 1.13 millimeters were subjected to the retorting study in the 2-inch-diameter electrically heated fluidized-bed retort. The bed temperatures were 900°F. The fluidization velocity utilized was three times minimum fluidization velocity for each size, and the resulting average residence times were in the range of 42-47 minutes. It was found that oil yields were virtually all identical with a value of 75 percent of the Fischer assay. We therefore concluded that the shale oil yield is not a function of oil-shale particle distribution within the 0.21- to 1.13-mm range. Other oil shales from Sunbury, Kentucky; Piceance, Colorado; Morocco; and Israel were also test retorted at 900°F using varied feeding rates. Respective oil yields of 94.5 percent, 84.4 percent, 93.4 percent, and 76.9 percent of Fischer assay were obtained. No effort was made to recover the uncondensables and the accompanying water vapors. The representative oil-yield data are shown in Table 2.

The Fischer assay of fresh shales in terms of gallons per ton, ultimate analysis and heating values of the fresh and spent shales, and elementary analysis of the fresh shales are shown in Table 1. It is interesting to note that about half of the carbon is retained in the spent shale for Celina and Sunbury oil shales which have low calcium-carbonate contents and is reflected in the heating values of the spent shales.

The 6-Inch-Diameter Fluidized-Bed Combustor

The experimental facility and major dimensions of the 6-inch-diameter laboratory-scale fluidized-bed combustor (FBC) are shown schematically in Figure 3. This 6-inch-diameter FBC unit is a refractory-lined cylindrical vessel. The bed region is 16 inches tall. The expanded freeboard section, 8 inches in diameter, is 100 inches in height. The 6-inch FBC unit has a conical air-distributor plate which has an open area of 2.77 percent of the total distributor area. Fluidizing air from the plenum passes through sixty-four 1/8-inch-diameter nozzles arranged in three concentric circles. Solid fuel from the hopper is fed directly into the bed by a 1-inch-diameter, variable-speed metering screw with a water-cooled jacket. Limestone, when needed, is fed directly into the top of the expanded bed through a 3/4-inch screw feeder. Spent-bed material can be extracted from the combustor through a 3/4-inch-diameter drainpipe at the bottom of the conical distributor or removed through an overflow tube which penetrates the combustor side wall at an angle of 30° with the vertical axis of the combustor. The overflow pipe is typically set such that a bed level of 4-1/2 inches is maintained. The bed solids are discharged into a lockhopper which is periodically emptied. The products of combustion are passed through two cyclones connected in series. The flue gas is filtered through a porous metal filter for ultimate dust removal before its final release to the atmosphere.

Flue gases are continuously sampled for carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen oxides, oxygen, and hydrocarbons. The carbon-monoxide and carbon-dioxide levels are measured by non-dispersed infrared analyzers, sulfur dioxide by flame photometric analyzers, oxides of nitrogen by chemiluminescence analyzers, oxygen by thermomagnetic analyzers, and total hydrocarbon by flame ionization.

Combustion Test Activities

Colorado, Celina (Tennessee), Sunbury (Kentucky), Israeli, and Moroccan oil shales were selected for combustion in the 6-inch-diameter FBC unit. One may notice from Table 3 that oil shales from Colorado, Morocco, and Israel contain sufficient limestone to, at least theoretically, absorb the sulfur dioxide generated from the combustion of their inherent sulfur. METC's experience in the fluidized-bed combustion of these limestone-containing oil shales indicated that, in fact, they can be burned without the addition of limestone or other modifications and meet the existing U.S. environmental regulations. These data are presented in Table 3.

In view of the high limestone content in the oil shales from Colorado, Morocco, and Israel, a concept was developed to isolate the devolatilization of oil shale and the combustion of volatiles by effecting a pseudo two-staged fluidized-bed combustion process. The main theme of this design was to take advantage of the difference between the temperatures required for devolatilization and calcination in these oil shales to preclude unnecessary energy consumption by the calcination reaction. The fluidized bed at the lower part of the oil-shale burning boiler will have devolatilization as its main function. It is known that the fluidized bed is an excellent solid burner, primarily because the fluidized bed offers vigorous mixing between particles. However, the fluidized bed is a poor gas burner, primarily because of poor mass and heat transfer between the solid and gas phases for any bubbles rising through the bed. As a consequence, a gas bubble may pass through the fluidized bed without completing combustion. It is thus highly desirable to take advantage of the fluidized bed as a devolatilizer or retort and burn the volatiles (gas phase) in the freeboard region. Secondary air will be introduced over bed to burn the volatiles to achieve high combustion efficiency and yet maintain the freeboard temperation within the temperature "window" for pollutant-emission control. For sulfur retention under atmospheric pressure, the optimum temperature is 1550°F. The relaxation and reduction of nitrogen oxides to nitrogen and oxygen occur best in a temperature "window" of 1450 to 1550°F. The burnout of carbon monoxide occurs at a temperature above 1300°F. The key to pollutant-emission control is the maintenance of an adequate freeboard temperature high enough for the completion of sulfur retention, nitrogen-oxide relaxation and reduction, and burnup of combustibles (carbon monoxide and hydrocarbons) but low enough to preclude thermal NO_x formation.

A pseudo two-staged, combustion-concept, feasibility-verification test was conducted at METC to demonstrate the viability of achieving staged combustion in a fluidized-bed combustion unit without incurring excessive calcination. However, due to the poor insulation of the freeboard, a stable high freeboard temperature was difficult to maintain. Therefore, relatively high nitrogen-oxide emission levels were observed for high excess air in the fluidized-bed combustion of oil shales. However, this is felt to be an artifact of the test combustion design. Otherwise, the process did function and the concept is felt to be viable.

It is of great interest to point out that for the limestone-containing oil shales (Colorado, Israeli, and Moroccan), the sulfur-dioxide emissions were considerably below the EPA's sulfur-dioxide emission limit of 1.2 lb/million Btu. The inability to maintain favorable conditions for nitrogen-oxide reduction and relaxation, such as the maintenance of freeboard temperature, providing of reductants, etc., resulted in nitrogen-oxide emission levels on the order of 1.0 to 1.2 lb/million Btu. Current efforts at METC are addressing the nitrogen-oxide emissions from fluidized-bed combustion of oil shale. We believe that we have obtained some very encouraging results.

For eastern oil shales with high-sulfur content and low-limestone content, the addition of limestone to insure compliance with EPA's sulfur-dioxide emission standard may be required. Current research at METC is also addressing the sulfur-dioxide emission issue. It is expected that the sulfur-retention mechanics will be no different from the combustion of the high-sulfur bituminous coal. A calcium-to-sulfur molar ratio, Ca/S, of 3 to 4 may be required to lower the sulfur-dioxide emission so as to meet the EPA standard.

However, it should be pointed out that the high Ca/S ratio requirement could be attributed to the short sorbent residence time in the 6-inch-diameter bed. The small bed size requires constant withdrawal of spent-bed material. The high ash content of the eastern oil shale may also accelerate the process of spent-bed material withdrawal. Therefore, it is contemplated that a two-staged FBC may also be desirable as a means to insure complete combustion in the first stage and satisfactory sulfur retention in the second stage.

The combustion efficiencies for all the oil shales were on the order of 98 percent or higher. Only in two cases was the combustion of oil shales below 98 percent. Therefore, it is concluded that fluidized-bed combustion of oil shale is a viable energy-conversion process for oil shale.

Innovative Concepts of Oil-Shale Utilization

The cost of energy calls for efficient utilization of energy. METC has conceived and reduced to practice a number of innovative concepts for the efficient utilization of oil shales. It is indeed our pleasure to share this with the user public.

- ***Pseudo Two-Staged Combustion:*** As mentioned before, the fluidized bed, due to its inability to implement good mass transfer between the gas bubble phase and the surrounding emulsion phase, is a poor gas burner. However, because of the vigorous solid-solid mixing inside the bed, the fluidized bed is an excellent solid heater and combustor. Therefore, it is proposed that the combustion of oil shale take place in two stages, functionally separating devolatilization and combustion. This pseudo two-staged combustion calls for a fluidized-bed combustor with a high or a diverted freeboard such that the devolatilization in the fluidized bed and combustion in the freeboard can be isolated to avoid the excessive heat-consuming limestone-calcination reaction. A conceptual design of an FBC system for high-calcium carbonate-bearing oil shale is shown in Figure 4. The retorting process is consummated in the fluidized bed at the left. The retorting temperature is maintained by the heat released in the freeboard from the combustion of volatiles. Generally, the retorting process should be maintained sufficiently below the limestone calcination temperature. METC's in-house study has found that less than 50 percent calcination of Israeli oil-shale limestone could be maintained when the fluidized-bed temperature was maintained below 1300°F. This is depicted in Figure 5 which provides test data on carbonate decomposition as a function of bed temperature. A differential temperature analysis for an oil shale can also assist in pinpointing the most favored retorting temperatures.

The secondary air injected in the freeboard region would burn the combustibles from retorting to a satisfactory extent. The heat of combustion would be extracted from the flue gas by a waste-heat boiler which is located at the right side of the fluidized bed. Some of the heat of combustion in the freeboard would radiate down at the fluidized bed to keep the fluidized bed at a favorable retorting temperature. The waste-heat boiler volume also serves as a settling chamber where the fines are collected for disposal or as a heat source to assist at keeping the retorting fluidized-bed temperature at the most favored retorting conditions.

- ***Two-Staged Fluidized-Bed Combustion:*** This design physically separates the devolatilization combustion and sulfur retention. A conceptual design of this type FBC system for eastern oil shale is shown in Figure 6. In this approach, the retorting is conducted in a fluidized-bed retort with a slanted distributor to facilitate bed-material (spent-shale) movement. The heat of retorting is supplied by the partial combustion of oil shales. The spent shale passes through a waste-heat recovery fluidized bed, on the right, where the sensible heat of the spent shale is used to preheat the fluidizing and combustion air for the upper fluidized bed. Owing to the high inert content of the eastern oil shales, the sensible heat recovery from the large quantity of spent shale is an economical must.

The products of retorting and preheated air from the lower fluidized beds enter the upper fluidized bed, or the second stage, to complete combustion and pollutant-emission control. The gaseous retorting products, high in carbon-dioxide content, can enlarge the pore size of the calcium limestone such that the threefold increase of the molar volume of the sulfated limestone does not result in plugging the pore openings and reduction of calcium utilization. This design may be high in pressure drop, and shallow beds are preferred.

- ***Twin-Bed Retort/Combustor:*** In this approach, the sensible heat of the spent-bed material is utilized to supply the heat of oil-shale retorting. Figure 7 shows a conceptual design, and the principal feature of the twin-bed retort/combustor fluidized bed is a partition wall which separates the combustion and retorting compartments. Two in-bed passages and the design of the distributor plates keep the bed materials in the twin beds circulating properly. The circulation of bed materials is accomplished by use of a slanted distributor and/or slanted distributor nozzles. The freeboard regions of the combustion and retorting beds are separated so as to avoid contaminating the product gases from retorting with the products of combustion.

Raw oil shale is fed into the retort bed at a point where it is mixed with the hot spent-bed material from the combustion bed. The sensible heat of the spent-bed material heats the fresh oil shale to a temperature for oil-shale retorting. The gaseous retorting products pass through the freeboard region, leave the unit, and are transported to a hydrocarbon-recovery system for eventual hydrocarbon recovery. After the completion of retorting, the retorted oil shale flows into the combustion compartment for the burn off of the residual carbon. The gaseous products of combustion are directed to a flue-gas waste-heat recovery system for the generation of process steam. The hot-bed material, after some bleed off to control the total solid materials inventory in the bed, is recycled into the retort bed as a heat source.

The fluidizing gases in the combustion and retort beds can be different. For example, steam and/or easily recoverable inert gas (i.e., flue gas or carbon dioxide) can be used as fluidizing gas for the retorting bed. Air or oxygen can be used as the fluidizing gas for the combustion bed.

The key to desirable performance is the keeping of a pressure equilibrium between these two separated beds to avoid contamination of the retorting products by the combustion products.

• ***Devolatilization Bed:*** The oil-shale devolation process takes place in a few seconds. The rate of devolatilization may subject the region near the feeder to a reducing environment. The presence of sulfur compounds can cause the formation of metal sulfides on the metal surfaces exposed to the reducing and corrosive environment. Subsequent instability in the location of the barrier of the reducing and corrosive environment may expose the metal surface to an alternating reducing and oxidation zone (AROZ). Owing to the very nature of the metal oxides and sulfides, catastrophic metal failures can occur under this condition. This conceptual design, depicted in Figure 8, utilizes a devolatilization sub-cell to allow substantial completion of the devolatilization process in a fluidized-bed sub-cell with virtually a constant reducing environment and few to no metal surfaces present. In addition to its designed function of devolatilization, the devolatilization sub-cell can also serve as a header for feeding devolatized oil shale into a number of fluidized-bed combustion cells. The devolatilization sub-cell is an integral part of the fluidized-bed combustor and receives heat from the adjacent combustion cell via conduction through the refractory partition and heat transfer from the overbed gases and reradiating ceiling. The devolatilization cell, as depicted in Figure 8, will have a low adiabatic refractory ceiling, which will also insure a freeboard temperature high enough to produce nitrogen-oxide reduction and relaxation. The volatiles generated are burned in the freeboard region and the devolatized oil shale, with considerable carbon content, is burned in the primary fluidized-bed combustion cell. Hot bed material overflows into a secondary combustion cell which achieves the final stage of combustion and recovers sensible heat from the hot spent-bed material to increase the overall efficiency of combustors. Immersed in-bed heat-transfer surfaces will cool the spent-bed material and preheat the fluidizing air for combustion.

Conclusion

Oil shale constitutes a major source of future fossil-energy supply in the form of direct combustion as well as retorting. Owing to the inherent high rates of heat and mass transfers inside the fluidized bed, the fluidized-bed combustor and retorting appear to be a desirable process technology for an effective and efficient means for oil-shale utilization. The fluidized-bed operation is a time-tested, process-proven, high-throughput, solid-processing operation which may contribute to the efficient utilization of oil-shale energy.

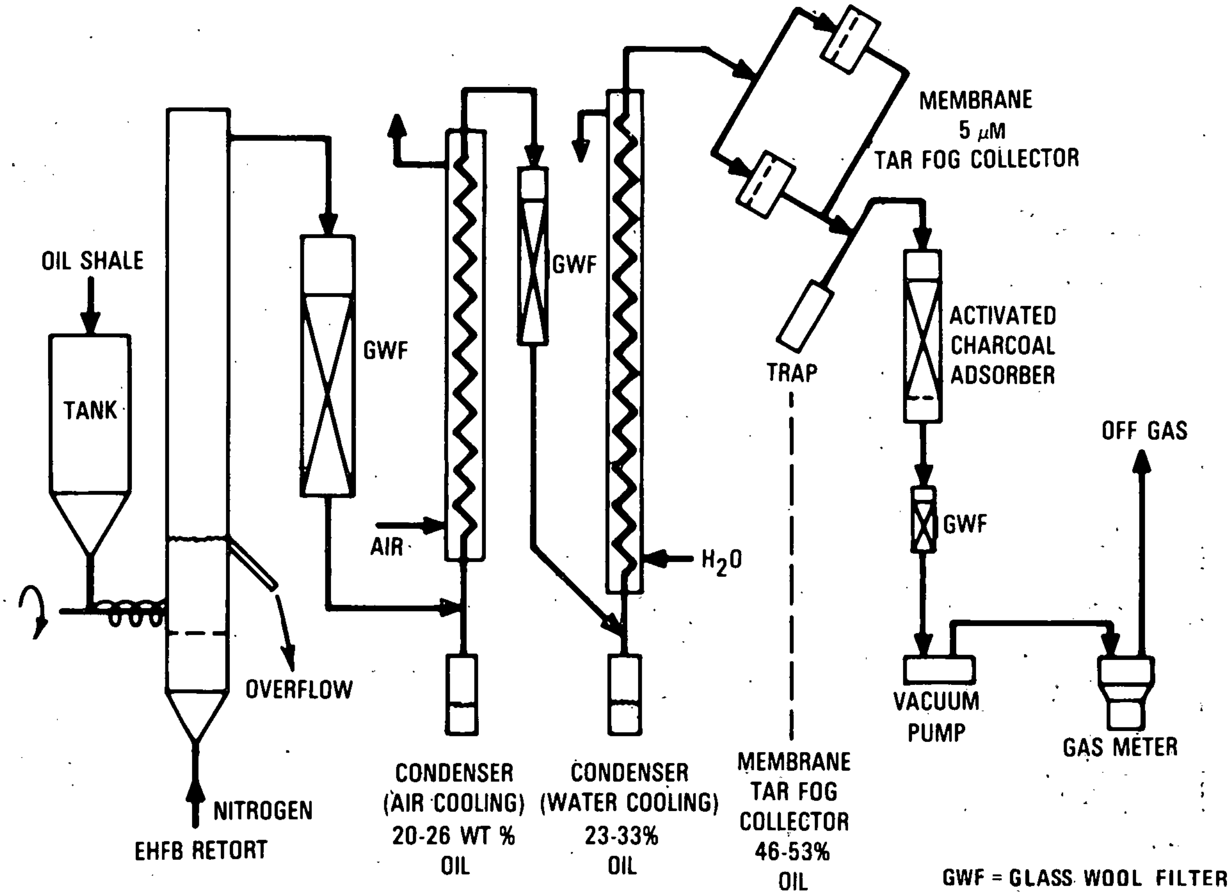

Figure 1. Two-Inch-Diameter, Electrically Heated, Fluidized-Bed Retorting System, Experimental Configuration

Table 1. Properties of the Oil Shales

Type of Oil Shale/ Analysis Items		U.S. Oil Shale						Moroccan Oil Shale		Israeli Oil Shale	
		U.S. Oil Shale Celina, TN		Sunbury Oil Shale, KY		Colorado Oil Shale					
		Fresh	Spent	Fresh	Spent	Fresh	Spent	Fresh	Spent	Fresh	Spent
Gallon/Ton	Oil	8.0		16.4		23.0		17.7		13.6	
	Water	2.4		6.5		3.4		10.2		10.1	
Wt %	Oil	3.1		6.5		8.7		7.1		5.4	
	Water	1.0		2.7		1.4		4.2		4.2	
	Spent Shale	93.1		88.1		87.5		85.0		86.8	
	Gas + Loss	2.8		2.8		2.3		3.6		3.5	
Specific Gravity 60°/60°F		0.925		0.945		0.911		0.970		0.963	
Tend to Coke		None		None		Slight		None		None	
Moisture		0.45	0.25	0.93	0.48	0.21	0.14	4.34	0.32	4.14	0.56
Ash		79.37	85.68	75.45	86.79	67.77	79.04	62.77	75.56	64.24	70.92
Sulfur		6.98	6.38	1.98	1.81	0.45	0.53	1.83	1.18	3.07	1.97
Hydrogen		1.31	0.49	1.73	0.68	1.74	0.36	1.76	1.27	1.53	0.68
Total Carbon		11.49	7.73	15.86	8.39	16.53	7.82	18.34	7.52	15.22	6.71
Nitrogen		0.36	0.29	0.53		0.36	0.15	0.51	0.35	0.35	0.23
Oxygen		0.04		3.52	1.85	12.94	11.96	10.45	13.8	11.45	18.93
Silicon, SiO_2		60.74	61.04	67.34	66.29	47.58	47.02	40.62	40.64	23.49	24.33
Aluminum, Al_2O_3		13.76	13.76	15.99	15.59	10.07	9.83	11.28	11.29	9.67	9.69
Iron, Fe_2O_3		15.30	15.29	7.22	7.20	4.79	4.56	5.76	5.61	4.24	4.16
Calcium, CaO		0.83	0.89	0.57	0.55	20.87	19.70	27.08	27.04	51.92	51.65
Magnesium, MgO		1.52	1.55	1.68	1.36	8.39	7.99	6.43	6.07	0.75	1.31
Sodium, Na_2O		0.67	1.09	1.14	1.53	1.18	3.07	0.50	1.01	0.66	1.08
Potassium, K_2O		4.91	4.88	4.60	4.65	3.05	2.93	1.61	1.62	0.75	0.76
Phosphorus, P_2S_5		0.17	0.18	0.28	0.24	0.36	0.38	1.84	1.81	2.31	2.29
Titanium, TiO_2		0.88	0.86	0.92	0.91	0.44	0.45	0.68	0.69	0.42	0.46
Sulfur, SO_3		1.01	0.76	0.52	0.43	2.89	2.36	4.88	4.10	6.02	4.46
Heating Value, Btu/lb		2,617	1,699	3,120	1,558	2,296	310	2,543	1,010	1,669	486
Ash Fusion, °F		2,133 2,206 2,245						2,135 2,160 2,200		2,665 2,680 2,695	

Table 2. Oil-Yield Data Obtained in the 2-Inch-Diameter Fluidized-Bed Retort

Run No.	Type of Tested Oil Shale	Retorting Temperature °F	Feed Rate g/hr	Oil Yield From Tests wt %	Oil Yield From Tests gal/ton	Fischer Assay Oil Yield wt %	Fischer Assay Oil Yield gal/ton	Water + Gas + Loss	Mass Balance out/in %	Oil Yield of Fischer Assay wt %	Experimental Errors %
032	U.S. Oil Shale Celina, TN	700	115.7	1.16	3.02	3.1	8.0	3.8	93.4	37.4	- 2.8
025	U.S. Oil Shale Celina, TN	800	131.8	2.45	6.38	3.1	8.0	3.8	94.3	79.0	- 1.9
045	U.S. Oil Shale Celina, TN	900	130.6	2.77	7.22	3.1	8.0	3.8	99.3	89.4	+ 3.1
046	U.S. Oil Shale Celina, TN	1000	132.6	2.74	7.14	3.1	8.0	3.8	95.9	88.4	- 0.3
041	U.S. Oil Shale Celina, TN	700	167.2	1.07	2.79	3.1	8.0	3.8	94.0	34.5	- 2.2
033	U.S. Oil Shale Celina, TN	800	153.2	2.29	5.97	3.1	8.0	3.8	99.3	73.9	+ 3.1
039	U.S. Oil Shale Celina, TN	900	165.8	2.61	6.80	3.1	8.0	3.8	96.5	84.2	+ 0.3
040	U.S. Oil Shale Celina, TN	1000	162.5	2.71	7.06	3.1	8.0	3.8	97.3	87.2	+ 1.1
044	U.S. Oil Shale Celina, TN	700	199.0	1.05	2.74	3.1	8.0	3.8	94.8	33.9	- 1.4
043	U.S. Oil Shale Celina, TN	800	179.0	2.09	5.45	3.1	8.0	3.8	97.7	67.4	+ 1.5
042	U.S. Oil Shale Celina, TN	900	206.4	2.14	5.58	3.1	8.0	3.8	94.7	69.0	- 1.5
036	U.S. Oil Shale Celina, TN	1000	190.5	2.31	6.02	3.1	8.0	3.8	93.0	74.5	- 3.2
053	Sunbury Oil Shale, KY	900	182.6	6.14	16.00	6.5	16.4	5.5	93.5	94.5	- 1.0
052	Colorado Oil Shale	900	120.6	7.34	19.12	8.7	23.0	3.7	96.5	84.4	+ 0.2
057	Moroccan Oil Shale	900	153.2	6.63	17.27	7.1	17.7	7.8	86.9	93.4	- 5.3
058	Israeli Oil Shale	900	162.7	4.15	10.81	5.4	13.6	7.7	87.7	76.9	- 4.6

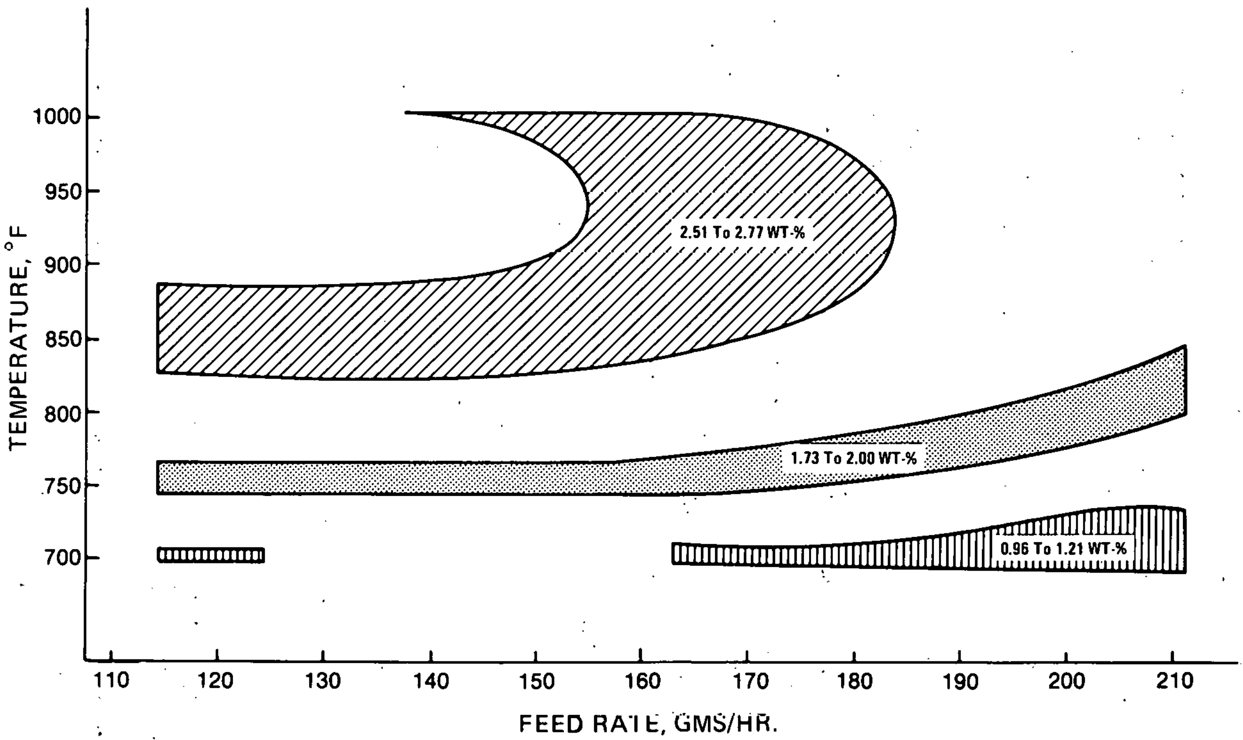

Figure 2. Contour Plot of Oil Yield as a Function of Feed Rate and Retorting Temperature

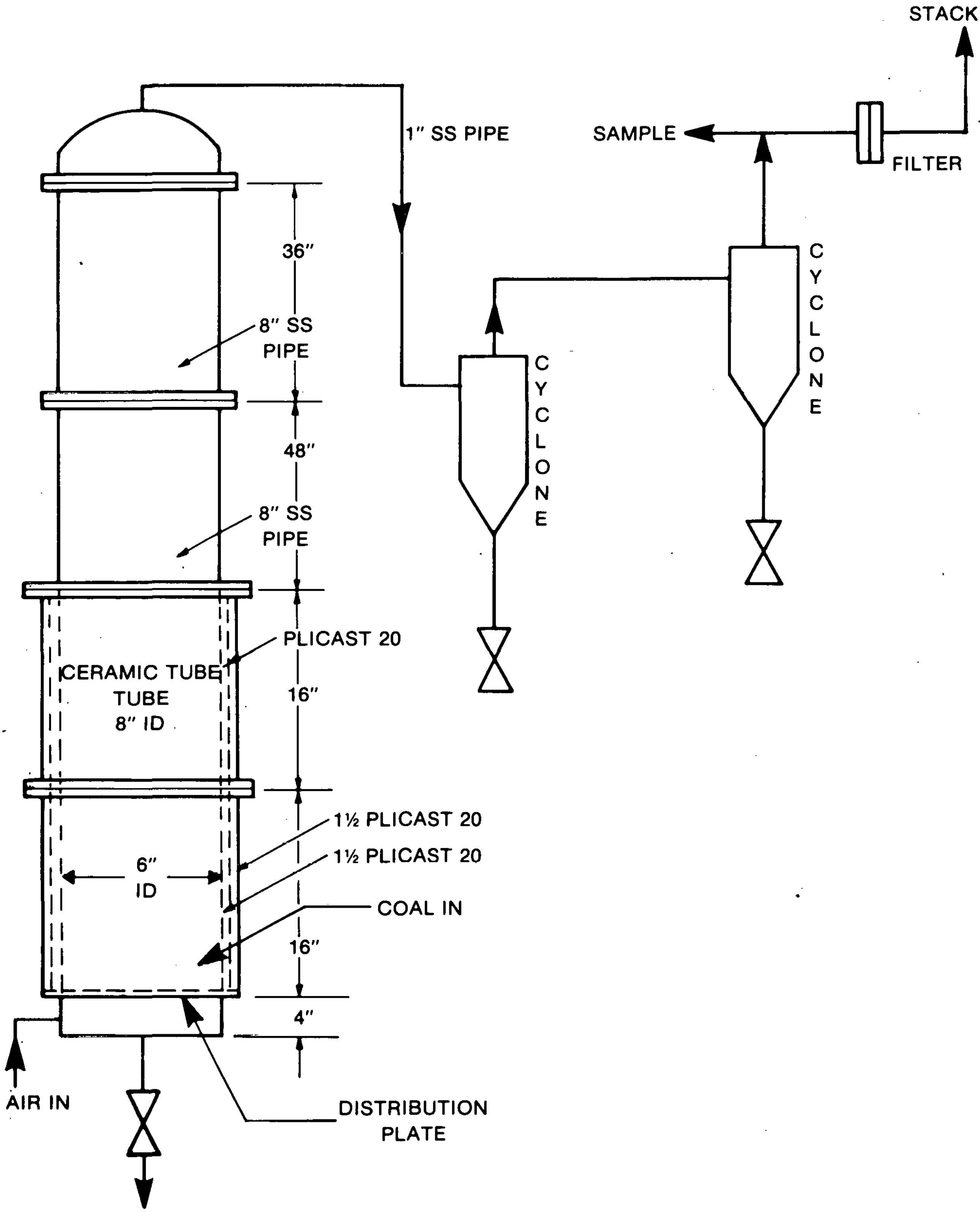

Figure 3. Six-Inch-Diameter Fluidized-Bed Combustor, Schematic Diagram

Table 3. Typical Experimental Results of Fluidized-Bed Combustion of Oil Shales

PROCESS VARIABLES \ TYPE OF OIL SHALE	COLORADO OIL SHALE	TENNESSEE OIL SHALE	KENTUCKY OIL SHALE	ISRAELI OIL SHALE	MOROCCAN OIL SHALE
OPERATING CONDITIONS					
BED TEMPERATURE (°F)	1550	1530	1600	1300	1450
SUPERFICIAL VELOCITY (ft/sec)	3.68	2.10	2.18	2.68	3.96
STATIC BED DEPTHS (in)	6	6	6	6	4
EXCESS AIR (%)	33.50	53.39	58.76	44.20	40.0
EXPERIMENTAL RESULTS					
COMBUSTION EFFICIENCY (%)	99.54	98.37	99.39	99.86	97.91
SO_2 EMISSION ($lb/10^6$ Btu)	0.37	24.32	8.80	0.26	0.29
NO_x EMISSION ($lb/10^6$ Btu)	0.53	1.67	1.20	1.00	1.00

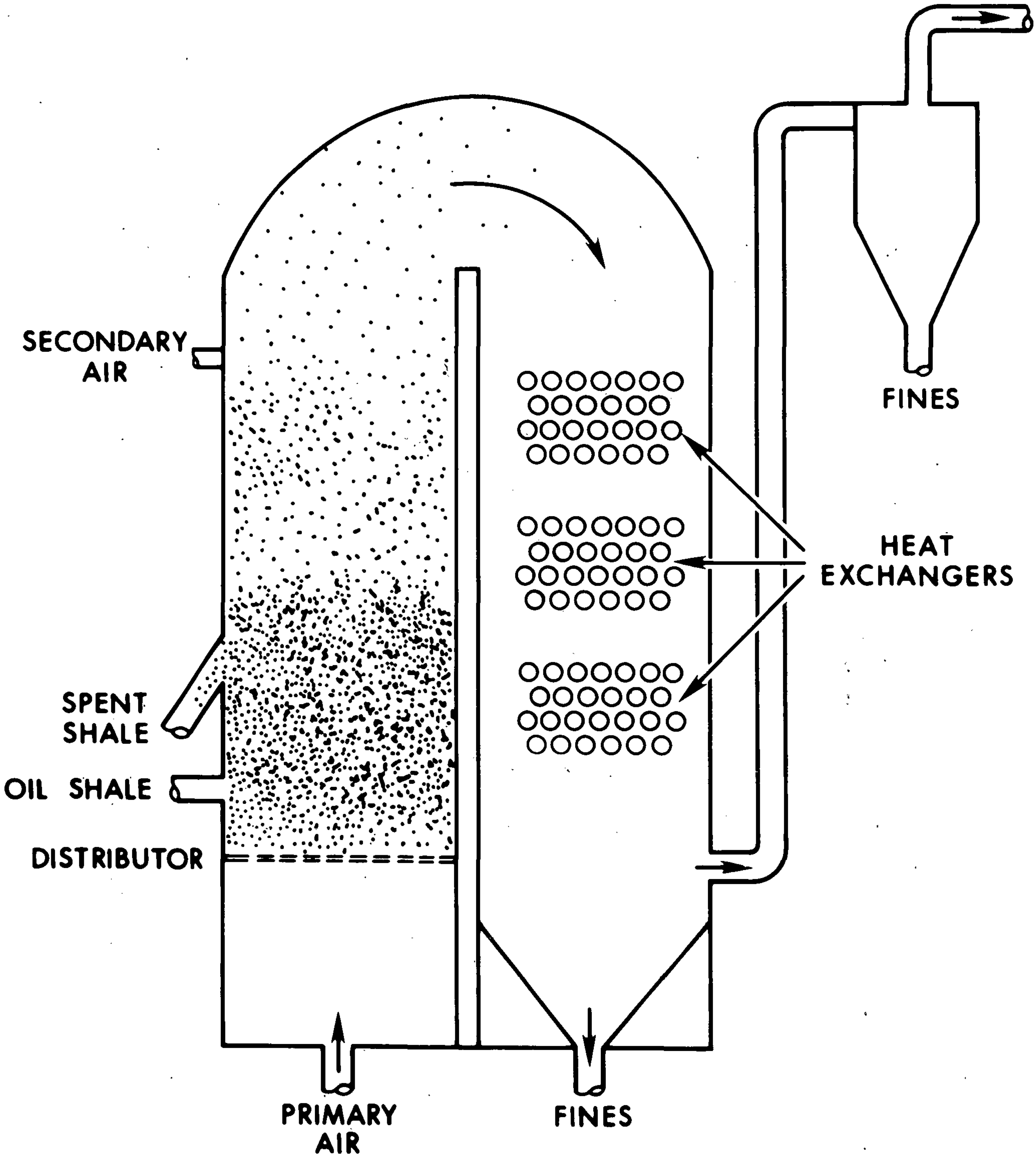

Figure 4. Conceptual Design of an FBC System for High-Calcium Carbonate-Bearing Oil Shale

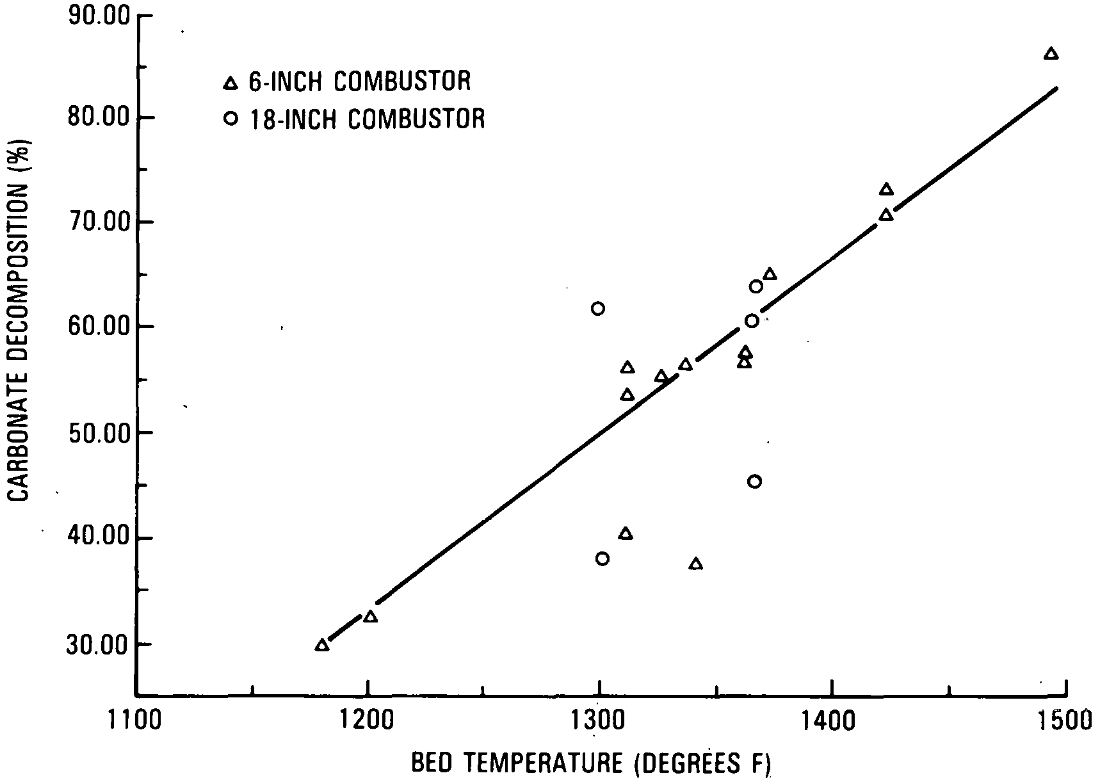

Figure 5. Carbonate Decomposition as a Function of Bed Temperature

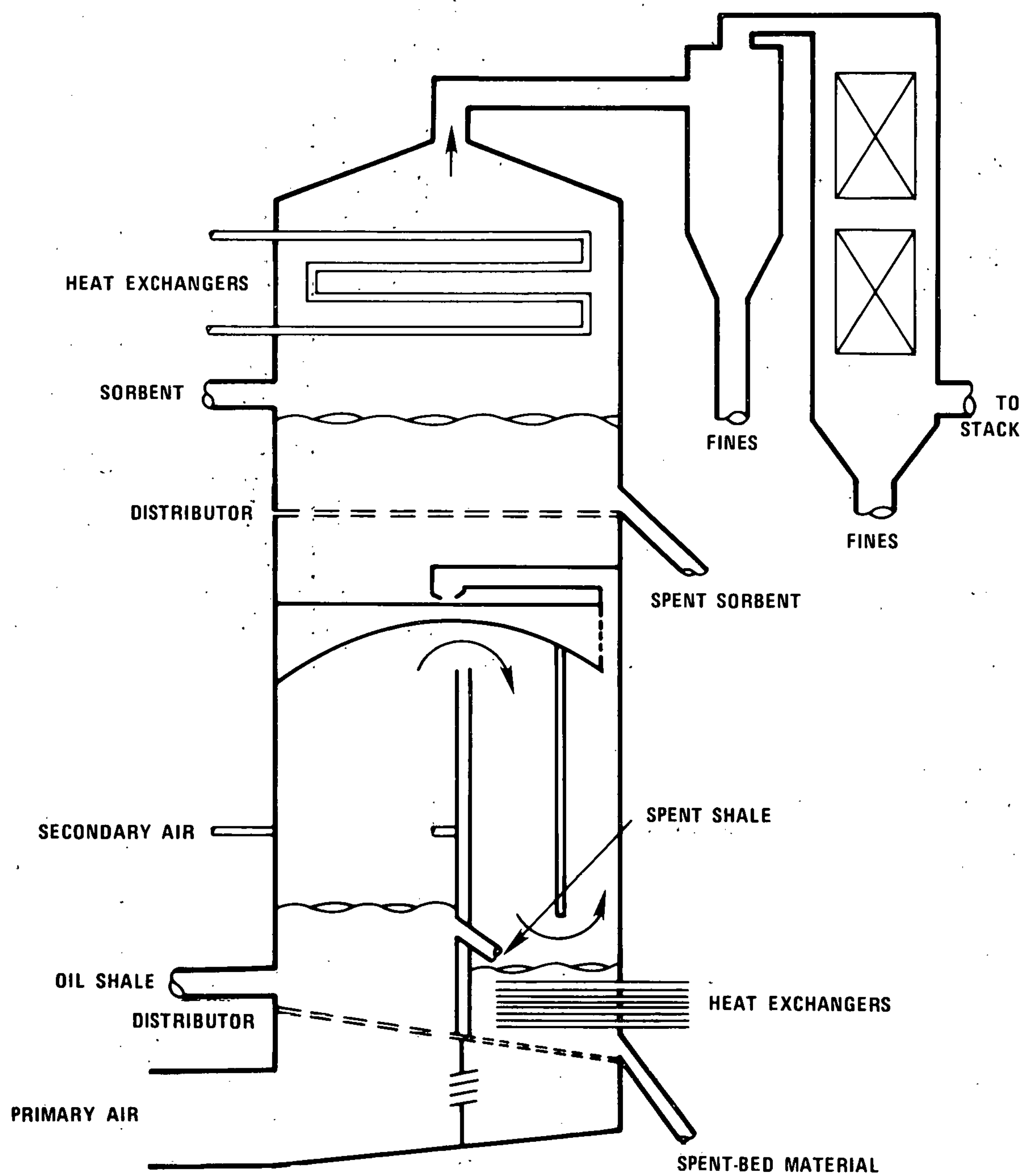

Figure 6. Conceptional Design of a Two-Staged FBC System for Eastern Oil Shale

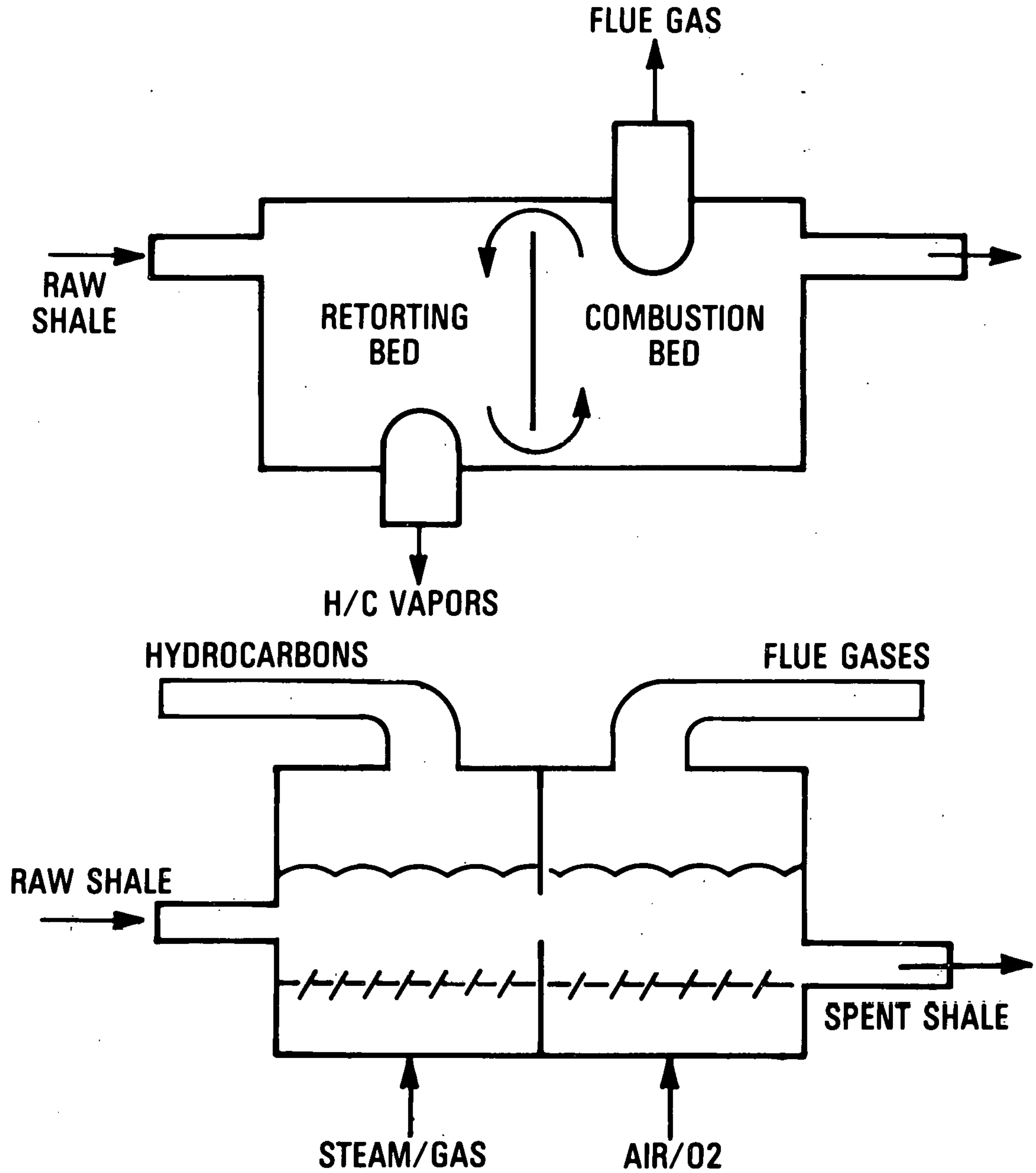

Figure 7. Twin-Bed Retort/Combustor

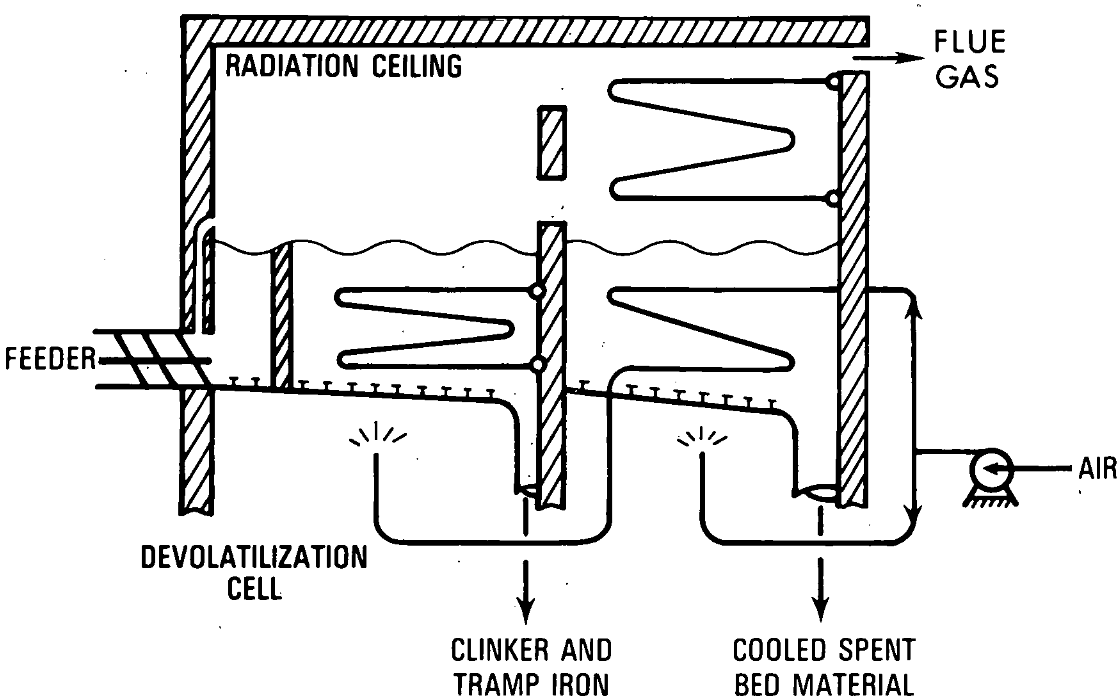

Figure 8. Use of a Devolatilization Cell

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