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Oil Shale Retorting in a 150-Ton Batch-Type Pilot Plant

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7995

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Laramie Energy Research Center, Laramie, Wyo.

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CONTENTS

ILLUSTRATIONS

Shale bed temperatures during run 11 for--

ILLUSTRATIONS--Continued

TABLES

OIL SHALE RETORTING IN A 150-TON BATCH-TYPE PILOT PLANT

by

A. E. Harak,[1] L. Dockter,[1] A. Long,[2] and H. W. Sohns[3]

ABSTRACT

To determine the retorting characteristics of a column of mine-run, ungraded oil shale ranging in size from fines to 5-ton pieces, a 150-ton batch-type retort was designed and constructed at the Bureau of Mines Laramie Energy Research Center, Laramie, Wyo. The retort vessel is 45 feet high by 11½ feet inside diameter, and is supported in a 95-foot-high steel superstructure. Mine-run shale from the Bureau of Mines facility near Rifle, Colo., assaying about 25 gallons of oil per ton, was used as the test shale. To date, 11 runs have been completed, and the results of the last 10 of these are reported.

The effects of oxygen content of the retorting gas and the superficial gas velocity of the retorting gas on oil recovery from a column of mine-run oil shale were studied. In one run, the average particle size of the shale was substantially increased to determine its effect on oil yield. Oil recoveries ranged from a low of 39.3 to a high of 65.8 volume-percent of Fischer assay.

INTRODUCTION

Liquid fuel has been extracted from oil shale in various parts of the world since the early 19th century; however, at present only a few countries have viable oil shale industries. A number of companies were processing oil shale in the United States around 1860 (3),[4] but the discovery of petroleum in 1859 virtually ended the oil shale industry in this country. During the 1920's, the high price of petroleum revived the interest in oil shale, and several pilot plants were constructed, including two by the Bureau of Mines (4). Then, large discoveries of petroleum caused the price to decline, and oil shale activity was again halted.

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[2] Research chemist.

[3] Research supervisor.

[4] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

During World War II, the huge demand for liquid fuels prompted the Government to pass the Synthetic Liquid Fuels Act of April 5, 1944. After passage of this act, the Government resumed its efforts to develop a feasible process for producing shale oil. After about 11 years of operation, the Government terminated its demonstration-scale activities and limited its activities to smaller scale work.

When it became apparent in the middle 1960's that the ever-increasing demands for energy would soon reach a point that would require the development of all possible sources in order to stave off an energy crisis, interest in oil shale development again increased, and continues to do so.

A recent study by the Bureau of Mines (_7_) indicates that shale-oil production using current technology could be economically attractive at current crude oil prices. However, the methods and costs of environmental control associated with commercial-scale operations must still be established.

The sequence of operations that for many years has been the subject of most research and development on commercializing oil shale includes mining, crushing and screening, and retorting the oil shale to produce a crude shale oil, which is then refined to yield a range of products similar to those derived from petroleum. This sequence of operations, generally referred to as aboveground retorting, presents a number of environmental problems that must be solved before an industry using the aboveground technique can become operable. Perhaps the greatest problem is that of disposing of the large quantities of spent or retorted shale that would be produced by a commercial-scale operation. For example, an oil shale installation producing 1 million barrels of oil per day would process about 1-1/2 million tons of shale per day, resulting in a discharge of 1-1/3 million tons of spent shale. This shale would have a loose-packed volume of 1.2 million cubic yards, or a compacted volume of about 0.9 million cubic yards per day.

One way in which spent-shale handling could be eliminated is by retorting the shale in place, a technique commonly known as in situ retorting. A process using this technique would not only eliminate the need for disposing of the spent shale, but also the need for mining, transporting, crushing, and screening the raw shale. Although the associated savings would be offset to to some degree by others that are unique to in situ processing, the latter approach could have an economic, as well as an environmental, advantage over aboveground processing.

Before an in situ process can become operable, the shale must be fractured to provide passages for hot gases to pass through the shale to heat it to retorting temperatures. The success of an in situ retorting technique for recovering shale oil from a fractured mass of oil shale will depend largely upon (1) the permeability of the mass of fractured shale, (2) the average size of the shale pieces resulting from the fracturing, (3) the degree of control which can be maintained in the combustion front, and (4) the uniformity of the rate of advance of the combustion front.

To simulate in situ retorting conditions, an experimental aboveground retort with a capacity of about 10 tons of shale was put into operation by the Bureau of Mines at the Laramie Energy Research Center in January 1965. Results of the work with this retort have shown that oil yields as high as 80 percent of Fischer assay can be obtained when retorting mine-run oil shale in pieces as large as 20 inches square (1-2, 8). Other work has indicated that oil recovery is a function of the maximum particle size, as well as the operating variables such as air rate, recycle gas rate, and retorting temperature. Particle size also determined the quantity of residual carbon that is available for fuel for the combustion phase of the process, and needed because of the low permeability of oil shale. Air can contact only the carbon that is at or within about 4 inches of the surface of the shale pieces during the time they are in the combustion zone; thus, the amount of carbon available for combustion is determined largely by available surface area and, therefore, by the particle size of the shale mass.

It is predicted that most of the pieces of fractured oil shale under actual in situ processing conditions would have a maximum dimension in excess of 20 inches; consequently, a retort similar to the 10-ton retort, except in size, was constructed. This unit has a nominal capacity of 150 tons of shale and can readily handle pieces as large as 4-foot cubes (5-6). This report discusses the work that has been done with the 150-ton retort to study the effects of superficial gas velocity and the oxygen content of the retorting gas on oil yield. It also discusses some of the current work on the effect of shale-particle size on oil yield.

PILOT PLANT DESIGN

The nominally sized, 150-ton, batch-type, oil shale retort is shown in figure 1. The shell of the cylindrically shaped retort vessel is constructed of 3/8-inch-thick carbon steel, is 45 feet high, and has an outside diameter of 13 feet 3 inches. The vessel has a 10-inch-thick refractory lining, which consists of a 6-inch layer of firebrick backed up by 4 inches of insulating castable material. The resultant inside diameter is 11-1/2 feet. A 6-foot-diameter top opening is used for shale loading; a hinged grate at the bottom supports the shale bed. The grate can be lowered by a hydraulic mechanism to discharge spent shale from the vessel after a run. A 92-foot-high steel superstructure supports the retort vessel.

A cylindrically shaped, 3-ton-capacity, bottom-opening loading bucket and a 10-ton hoist, mounted on the top of the superstructure, are used to load oil shale into the retort. The bottom of this bucket is designed to open hydraulically to discharge the shale after it is lowered into the vessel. If large pieces of shale were to be included in the shale charge, they would be loaded individually.

A flow diagram of the retorting pilot plant is shown in figure 2. A natural gas burner mounted on the retort lid is used to initiate combustion of the shale bed. A positive-displacement blower is used to force air into the retort and propagate the retorting reaction downward through the shale bed. Liquid products (water and shale oil) are collected in a tank located below

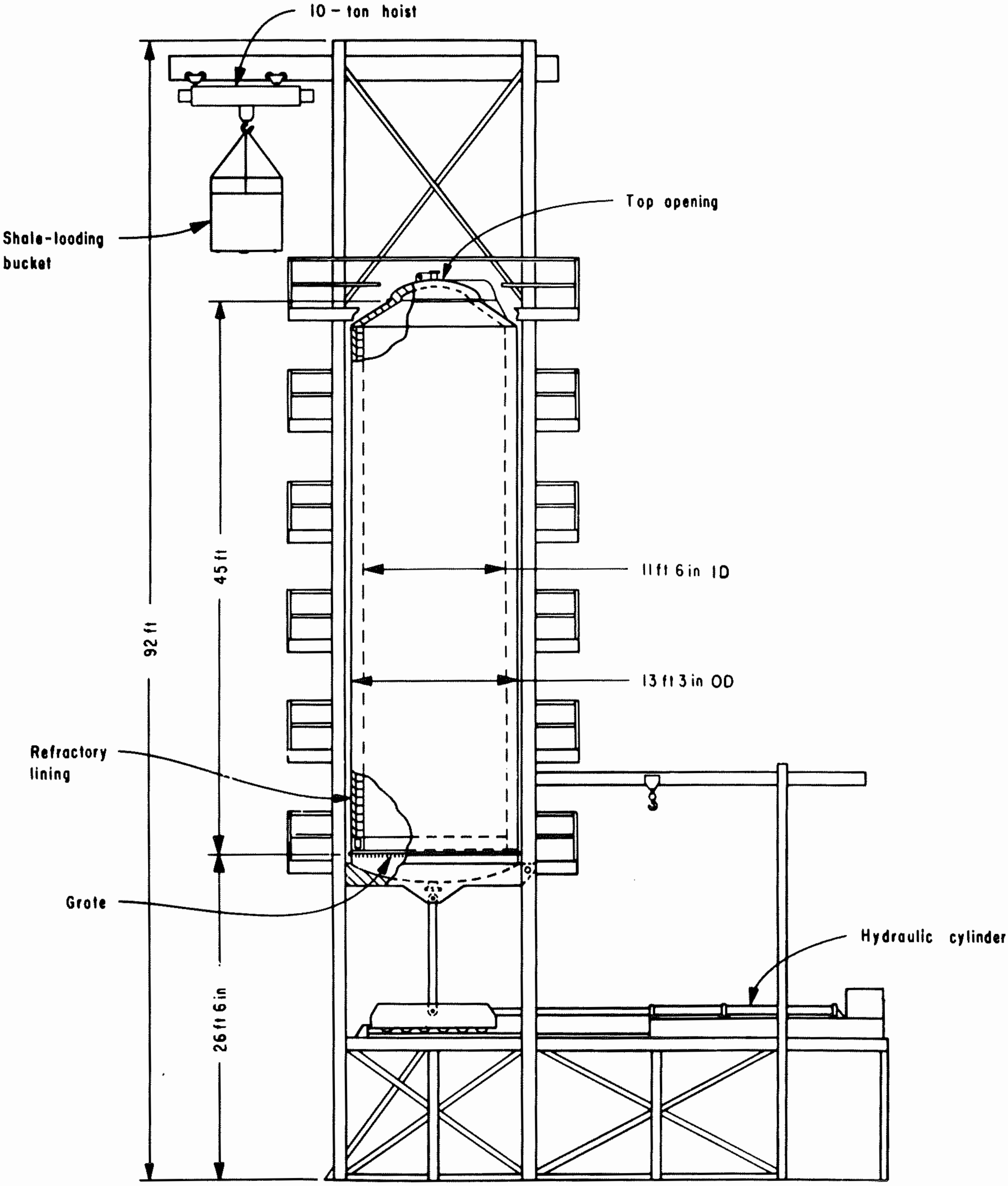
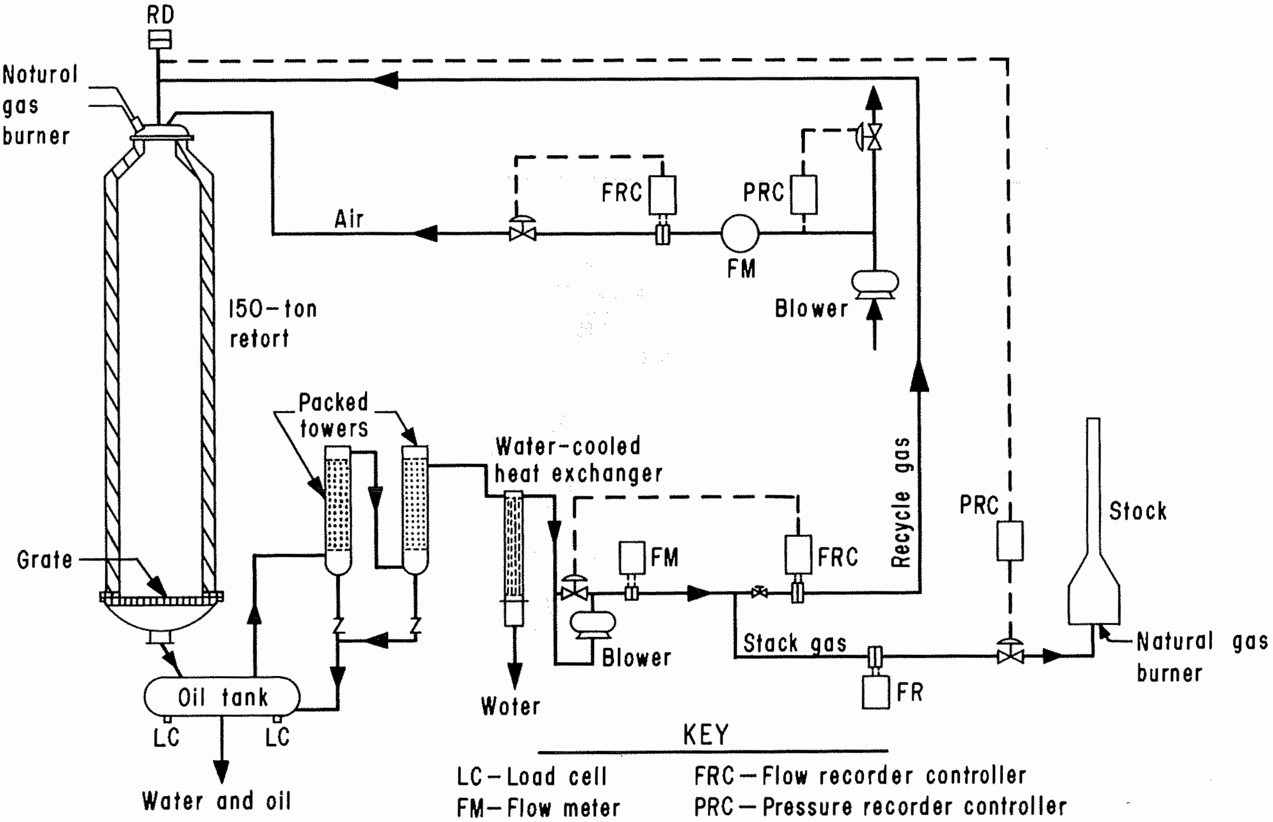


FIGURE 1. - 150-ton oil shale retort.

the retort vessel. This tank is mounted on four load cells to determine the quantity of liquid products generated.

Gaseous products from the collection tank, which contain some water and oil mist, are then passed through two packed towers in series and through a water-cooled heat exchanger to remove most of this entrained material. After



KEY

LC—Load cell
FM—Flow meter
FR—Flow recorder
FRC—Flow recorder controller
PRC—Pressure recorder controller
RD —Rupture disk

FIGURE 2. - Flow diagram of 150-ton retort.

passing through a positive-displacement blower to increase line pressure, the gas stream splits: Some can be recycled back into the retort to blend with air to lower the oxygen content of the retorting gas; the excess is vented to a stack. The waste-gas stack is equipped with a natural gas burner to oxidize combustible components in the gas stream.

Location of some pertinent control instrumentation is also shown in figure 2. Air and recycle rates are regulated with pneumatic-flow recorder-controllers, and orifice plates are used as the primary measuring elements. Retort pressure is maintained at 3 psig using a pneumatic-pressure recorder-controller with the primary measuring element located at the top of the retort. Multipoint temperature recorders are used to monitor bed and process temperatures.

Fourteen heat-flux transducers are used to determine heat losses from the retort vessel. Two transducers are located on top of the vessel, two are on the bottom closure, and the rest are symmetrically spaced on the retort shell. The readout from these transducers is in British thermal units per square foot per hour.

The 150-ton oil shale retort (fig. 3) is located about 1 mile north of Laramie, Wyo. The retort is mounted inside a seven-floor steel superstructure.

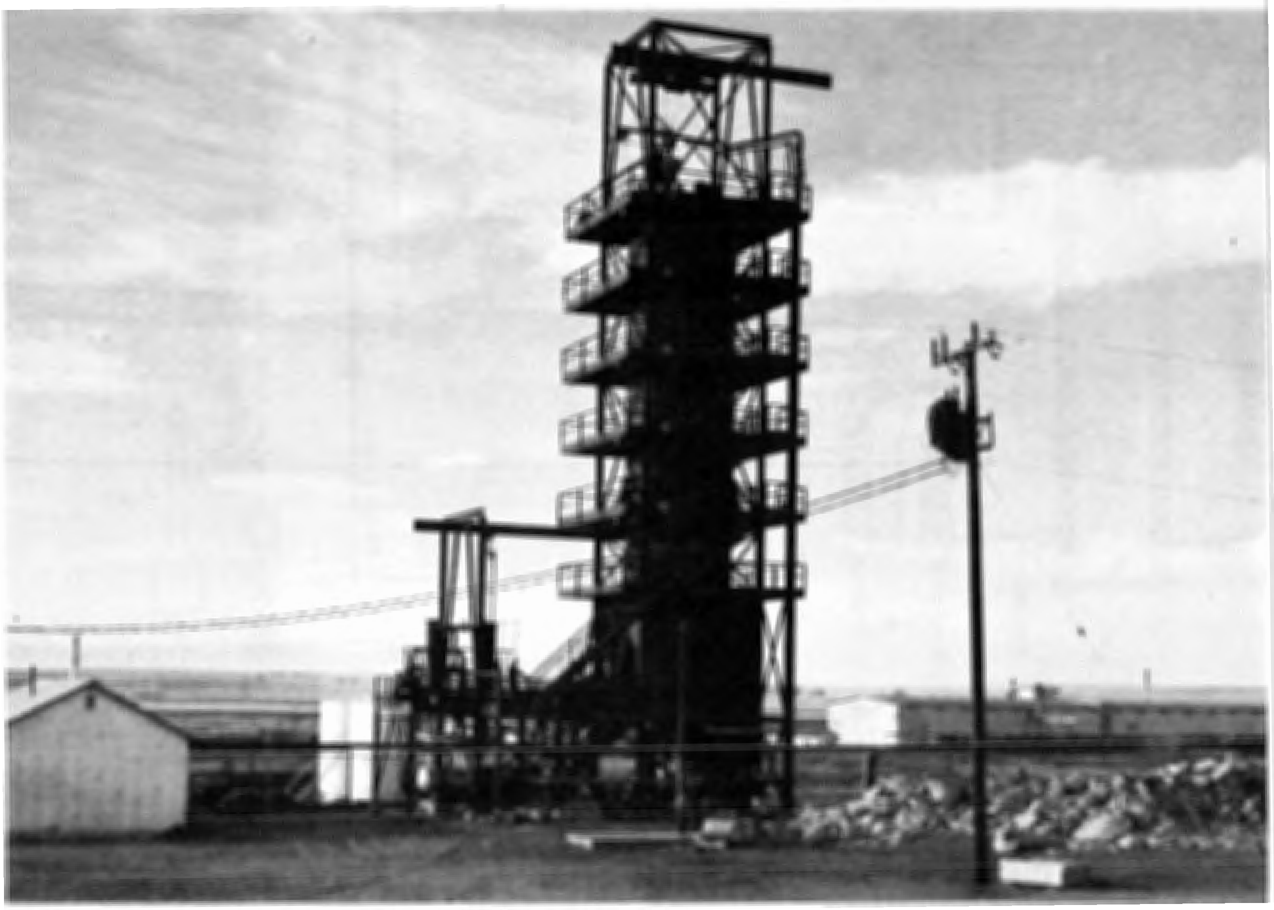


FIGURE 3. - Photograph of 150-ton retort.

Oil storage tanks and the instrument control room are located to the left of the retort.

EXPERIMENTAL PROCEDURE

The oil shale used for experimentation in the 150-ton retort was obtained from a stockpiled supply of mine-run shale located at the Bureau of Mines Anvil Points facility near Rifle, Colo. From each 250-ton shipment of shale, a 50-ton aliquot portion was withdrawn, crushed, and sampled for analysis. The rest of the shipment was used to load the retort. Fischer assays of the shale charges have ranged from 20.9 to 26.2 gallons of oil per ton.

Figure 4 shows the approximate size distribution for all but one of the shale charges used in the 150-ton retort. About 20 percent of the shale had a major dimension greater than 20 inches, about 40 percent was smaller than 4 inches, and about 12 percent was less than 1 inch in size. The curve was drawn from a combination of data obtained from screen analyses and photographic studies of the first shale charge. Screen analyses of the minus 1-inch size range (extrapolated section of the curve) were not made; however,

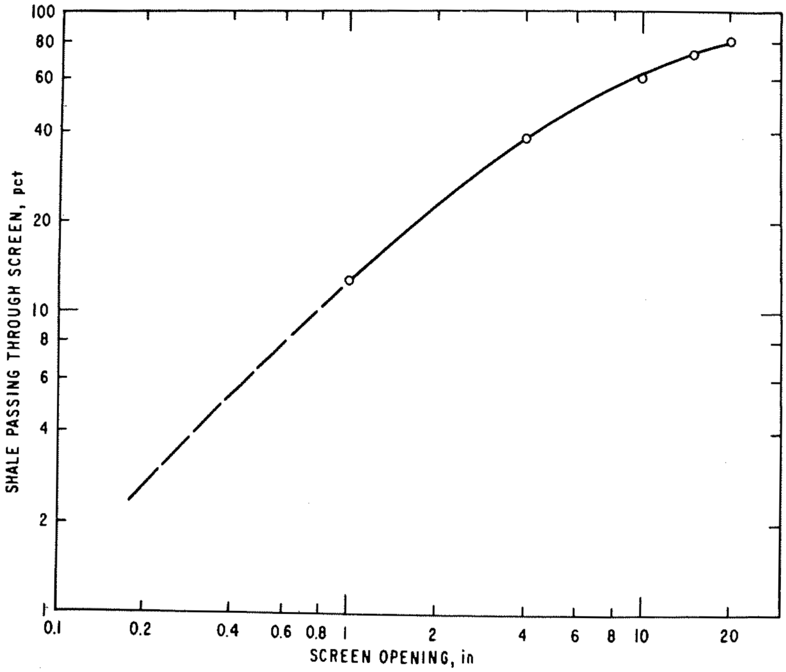


FIGURE 4. - Approximate size distribution for oil shale tested.

FIGURE 5. - Oil shale used in the 150-ton retort.

previous size distribution data of mine-run shale from the same mine show good correlation with the entire curve. Because subsequent shale charges were obtained from the same stockpiled supply, it is assumed that all have approximately the same size distribution. Run 11 had an appreciably different size distribution because larger pieces were intentionally segregated for this shale charge.

Figure 5 is a photograph of an oil shale charge before it was loaded into the retort. Some of the larger pieces weighed as much as 5 tons. Before the retort was loaded with oil shale, a 6-inch-thick layer of crushed rock, sized from 1½ to 3 inches, was placed on the grate. This was done to prevent an excessive amount of shale fines from falling through the 1-inch-wide grate openings during the loading operation, and to protect the grate from excessively high temperatures near the end of the run. As the retort was loaded, a man was periodically lowered into the vessel to level the shale bed and place thermocouples in position. At each 6-foot level of bed height, eight thermocouples were placed in a horizontal pattern as follows: Five thermocouples were placed around a 10-foot-diameter circle, two at opposite ends of the diameter of a 5-foot circle, and one in the center of the shale bed (shown in figs. B-1 through B-8 in appendix B). During some of the earlier runs, this procedure was repeated at 3-foot intervals. The shale charge for some of the runs included large blocks (up to 5 tons) of shale that had to be loaded individually. Thermocouples were placed inside these large pieces to indicate temperature behavior during the retorting operation.

When the retort was filled to a bed height of 43 feet, the top was closed, and the entire system was checked to make sure all equipment was operating satisfactorily. A run was started by igniting the shale at the top of the retort with a natural gas burner mounted through the retort lid. The burner was allowed to operate for 4 to 5 hours at a heat release rate of about 500,000 Btu/hr until the shale was well ignited, as evidenced by the first layer of thermocouples. The burner was then shut off and air, or air plus recycle gas, was forced downward through the shale bed at predetermined flow rates to sustain the retorting reaction. All flow rates to the retort were maintained constant throughout a run.

During a run, liquid products were periodically drained from the oil collection tank, sampled, and analyzed. The gaseous products from the retort that were not recycled were metered and flared in a stack-gas oxidizer. The stack-gas stream was sampled every 4 hours for analysis by gas chromatography.

Retorting was continued until the grate temperatures reached approximately 500° F, somewhat lower than the 600° F maximum design temperature. At that time, liquid production had already stopped and the oxygen content of the stack had begun to rise. The retort was then shut down and allowed to cool for approximately 3 to 4 weeks, or until the maximum shale temperature had dropped to below 200° F. The spent shale was then discharged from the retort and weighed. About one-fourth of the spent, discharged shale was crushed and sampled for analysis.

RESULTS AND DISCUSSION

A total of 11 oil shale retorting runs were completed in the nominally sized 150-ton retort between October 1969 and February 1973. Selected summary data for the last 10 runs are listed in table 1, and a more detailed summary table is presented in table A-1 in appendix A.

The results from the shakedown run (run 1), which was made to check equipment and familiarize personnel with operating procedures, have been published earlier and therefore are not included in this paper (6). The next eight runs (2-9) were part of a series to investigate the effects of retorting-gas oxygen content and superficial retorting-gas velocity on oil recovery. All other variables for these eight runs were maintained as constant as possible. Three levels of retorting-gas oxygen content (about 9, 15, and 21 volume-percent), and three levels of superficial gas velocity (about 1.25, 2.00, and 2.75 scfm/ft^2 of bed) were chosen and tested as the retorting parameters. The air and recycle-gas flow rates were set to operate as near as possible to these conditions. The actual values for retorting-gas oxygen content ranged from a low of 8.2 percent to a high of 21.0 percent; those for superficial gas velocity, from 1.19 to 2.85 scfm/ft^2 of bed for runs 2 through 9.

TABLE 1. - Selected summary data for 150-ton oil shale retort runs

	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11
Date test started...	3/23/70	6/24/70	2/16/71	4/19/71	8/4/71	10/27/71	1/18/72	4/26/72	8/21/72	2/6/73
Length of test...days..	12.25	52.00	6.83	11.28	7.93	18.15	4.30	21.18	22.53	10.53
Operating conditions:										
Oil shale charged...tons..	178.67	179.37	182.21	180.54	183.48	174.45	182.90	185.74	183.12	163.84
Fischer assay of shale...gal/ton..	25.4	24.7	25.5	26.2	20.9	22.4	22.3	24.0	23.8	24.4
Air rate...scfh..	8,100	2,340	12,590	7,430	11,030	4,890	17,780	4,730	4,250	8,240
Recycle gas rate...scfh..	4,000	5,000	0	0	5,410	12,140	0	2,930	910	4,420
Stack gas rate...scfh..	10,600	2,460	15,490	9,140	13,390	5,380	21,710	5,470	4,910	9,650
Oxygen content of retorting gas pct..	14.2	8.5	21.0	21.0	14.2	8.2	21.0	13.2	17.4	13.8
Max. retort diff. pressure in. H_2O..	0.6	0.4	1.0	0.5	1.0	0.6	1.2	0.6	0.4	0.4
Superficial gas velocity..scfm/ft^2..	1.94	1.24	2.02	1.19	2.63	2.73	2.85	1.23	0.83	2.03
Avg retorting advance rate...in/hr..	1.75	0.41	3.11	1.88	2.68	1.17	4.94	1.00	0.94	2.02
Avg max. bed temperature...° F..	1,240	850	1,410	1,380	1,360	1,230	1,510	1,260	1,220	1,090
Recovery:										
Oil (dry)...gal..	2,830	1,740	2,150	2,580	2,380	1,960	1,760	2,930	2,610	2,210
Oil (dry)...lb..	21,280	12,990	16,450	19,650	18,130	14,720	13,490	22,160	19,720	16,709
Oil...vol-pct of Fischer assay..	62.2	39.3	46.3	54.5	62.2	50.0	43.0	65.8	60.1	55.3
Water...lb..	16,030	21,540	17,510	12,300	11,250	14,670	10,590	13,990	17,490	22,250
Spent shale discharged...tons..	125.86	158.43	130.74	124.10	133.78	142.49	138.76	139.36	133.69	119.14
Stack gas composition, vol-pct:										
O_2...	0.5	3.1	0.5	0.8	0.2	3.1	0.3	0.7	0.8	0.4
N_2 + Ar...	67.3	79.6	65.4	64.6	66.2	73.2	65.8	69.5	68.6	68.8
CO...	2.3	0.9	3.4	2.9	2.6	1.2	3.3	1.3	1.3	1.5
CO_2...	28.7	15.4	29.0	30.0	29.9	21.9	28.7	27.9	28.3	28.3
CH_4...	0.7	0.7	0.9	0.9	0.6	0.3	0.7	0.3	0.5	0.5
C_2H_6...	0.4	0.3	0.7	0.6	0.4	0.2	0.7	0.3	0.3	0.4
Higher hydrocarbons...	0.2	0.2	0.2	0.1	0.1	0.1	0.4	0.1	0.2	0.2
Heating value...Btu/ft^3..	25.7	19.4	36.5	31.1	23.5	12.5	38.4	14.6	18.7	21.1
Oil properties:										
Gravity...° API..	25.2	26.4	22.6	23.3	23.1	25.6	22.0	24.3	24.5	24.3
Pour point...° F..	70	50	70	60	55	60	70	55	50	60
Nitrogen...wt-pct..	1.77	1.45	1.82	1.94	1.73	1.62	1.91	1.44	1.45	1.77
Sulfur...wt-pct..	0.76	1.10	0.87	0.81	0.86	1.04	0.92	0.98	1.19	0.83

After run 9, the results from all the completed runs were analyzed. A computer study suggested that a maximum oil-recovery value should be realized when using an oxygen content of 17 volume-percent in the retorting gas, and a superficial gas velocity of 0.87 scfm/ft^2 of bed as the operating conditions. These conditions were used for a subsequent run (run 10); however, contrary to the earlier prediction, the oil recovery was lower than that realized for some earlier tests.

The size distribution of the shale charges for runs 2 through 10 are considered to be fairly constant, with an average particle size of approximately 6 inches. For run 11, this average particle size was increased to about 30 inches by including several larger shale pieces weighing as much as 4.4 tons, in the shale charge. To study the effect of larger shale sizes on oil recovery, operating conditions for run 11 were chosen to duplicate run 2. Comparison of oil recoveries for these two tests showed that larger size shale resulted in a somewhat lower oil recovery (55.3 volume-percent of Fischer assay for run 11, compared with 62.2 for run 2). Additional information on temperatures and retorting of large blocks of shale will be reported later in this paper.

Oil recoveries ranged from 39.3 to 65.8 volume-percent of Fischer assay; the highest value was recorded for run 9. The API gravity of the oil recovered ranged from 22.0 to 26.4, and the pour points ranged from a low of 50° F to a high of 70° F. The nitrogen and sulfur concentrations are somewhat higher than desirable for crude oil.

Retorting advance rates, average maximum bed temperatures, and stack-gas compositions are also listed in table 1. The retorting-advance rate, which is the rate at which the retorting zone passes down through the shale bed, is calculated by dividing the bed height by the run length. The average maximum bed temperature was determined by averaging the highest temperature indicated by each thermocouple in the shale bed.

Because the retort was loaded with random-size shale and no effort was made to pack the bed, a void volume of about 43 percent was present in each charge. This high void volume resulted in very little pressure drop down through the shale bed; the value never reached more than 1.2 inches of water during a run.

Table 2 shows the oil recoveries for runs 2 through 9, tabulated in a nine-square pattern, as functions of oxygen content of the retorting gas and the superficial gas velocity.

Although this nine-square pattern was not fully completed, some trends are indicated. Oil yield within the limits of the pattern probably will reach a maximum between 60 and 66 volume-percent of the Fischer assay; 15 volume-percent of oxygen in the retorting gas appears to be an optimum value. At high oxygen concentrations, yield seems to decrease with increasing superficial gas velocity, whereas at low oxygen concentrations, the opposite is indicated. At 15-percent oxygen content, superficial gas velocity seems to have little or no effect on yield.

TABLE 2. - Oil-recovery results, volume-percent of Fischer assay, 150-ton retort

Approximate superficial gas velocity, scfm/ft^2 of bed	Approximate oxygen content of retorting gas, volume-percent		
	9	15	21
1.25	39.3 (run 3)	65.8 (run 9)	54.5 (run 5)
2.00	([1])	62.2 (run 2)	46.3 (run 4)
2.75	50.0 (run 7)	62.2 (run 6)	43.0 (run 8)

[1] Due to the complexity and expense of these tests, it was considered unnecessary to complete the pattern, since data trends are indicated.

Stepwise linear regression analysis was used to derive an equation describing oil recovery as a function of retorting-gas oxygen content and superficial gas velocity. This equation and the family of curves representing it are presented in figure 6. The value of R^2, or the fraction of the total

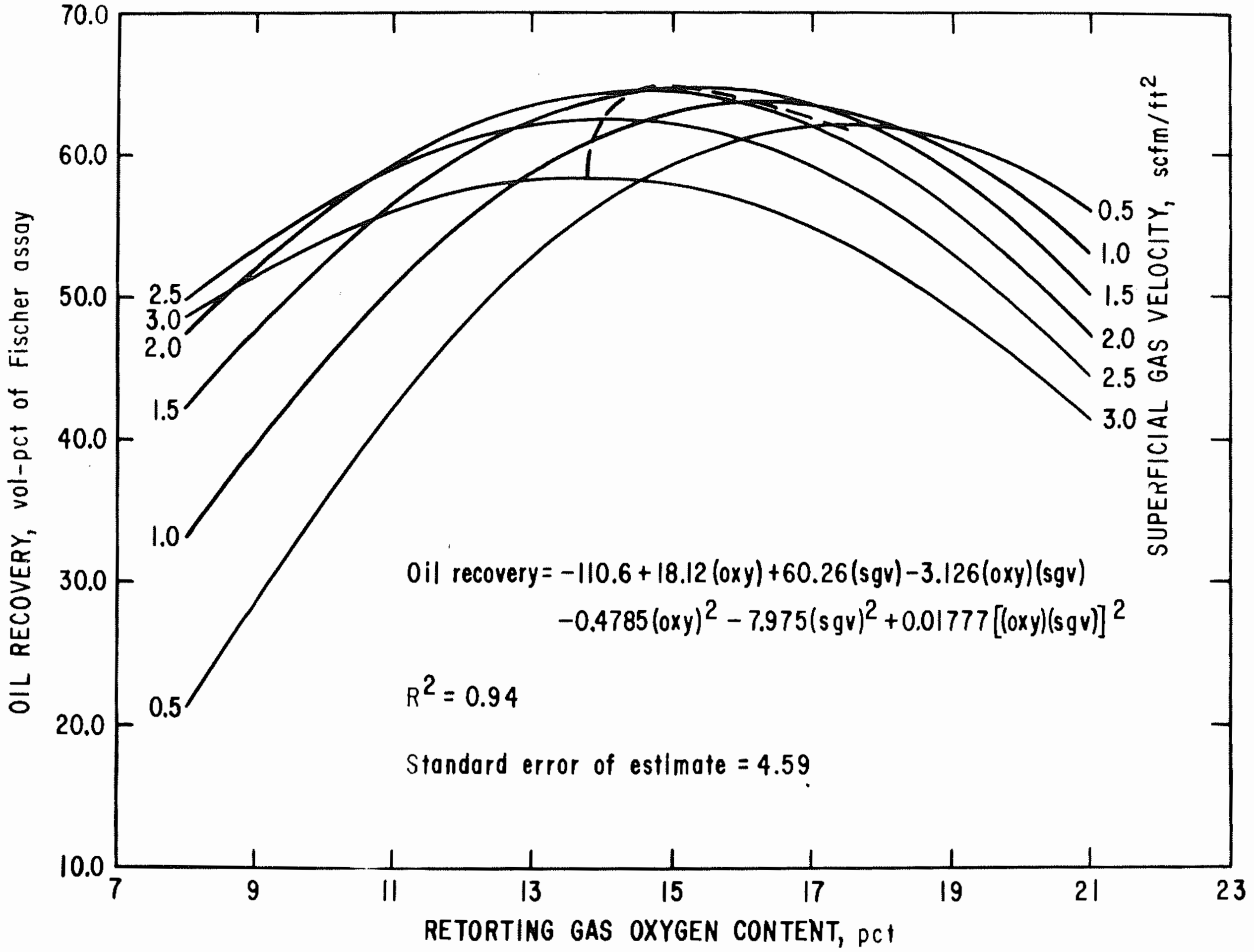


FIGURE 6. - Effects of superficial gas velocity and retorting-gas oxygen content on oil recovery.

variation in the predicted oil recovery which is accounted for by the regression equation, is 0.94. The standard error of the estimate, or the average or typical error, to be expected in the predicted value is 4.59. As shown in this figure, the oil recovery increases to a maximum at any superficial gas velocity, and then decreases as the oxygen content is increased. This maximum oil recovery is achieved at retorting-gas oxygen contents from about 14 to 18 percent, depending on the superficial gas velocity. Optimum oil recovery is obtained at an oxygen content of about 15 percent and a superficial gas velocity of about 1.5 scfm/ft^2. The dashed line of the figure connects the maximum oil recovery values of each curve.

A response surface for oil recovery as a function of retorting-gas oxygen content and superficial gas velocity was generated using the equation presented in figure 6. Five-percent oil-recovery contour intervals for this response surface are presented in figure 7 along with a maximum oil-recovery ridge. Also plotted on figure 7 are points indicating retorting conditions tested, and their respective oil recoveries. It should be noted that near-maximum oil recovery can be achieved over a large percentage of the range of the two retorting variables.

The rate at which the retorting zone passes down through the shale column in the retort is presented as a function of oxygen flux (standard cubic feet per minute of oxygen entering the retort per square foot of bed) in figure 8. As may be expected, the retorting advance rate increases as the oxygen flux is increased. The equation for this linear relationship is also presented in the figure.

In conjunction with the retorting advance rate, it is interesting to note the change in the temperature profile of the shale bed with time. To more clearly illustrate the temperature behavior inside a column of oil shale during retorting, the temperature histories for all 64 thermocouple points recorded during run 9 are shown in figures B-1 through B-6 of appendix B, and the temperature histories for all 104 thermocouple points recorded during run 11 are shown in figures C-2 through C-9 of appendix C. Run 9 was chosen because it produced the highest oil yield and because it is an excellent example of the shale-bed temperature behavior of all the runs. The temperature history for run 11 is presented because the shale-size distribution was deliberately altered, as will be discussed later in this report.

It should be realized that temperature behavior, as monitored by thermocouples embedded in a column of nonhomogeneous oil shale, is often difficult to explain. For example, a thermocouple between shale particles would be reading the temperature of a hot gas stream; another buried under a large block and shielded from high temperature would be presenting a temperature lag; still others near shale pieces that are extremely hot from oxygen reacting with residual carbon would be reading excessively high. These factors should be kept in mind when studying the temperature histories presented in figures B-1 through B-8 and later in figures C-2 through C-9.

Several other thermocouple-associated problems were also encountered and should be mentioned at this point. One of these problems occurred when the

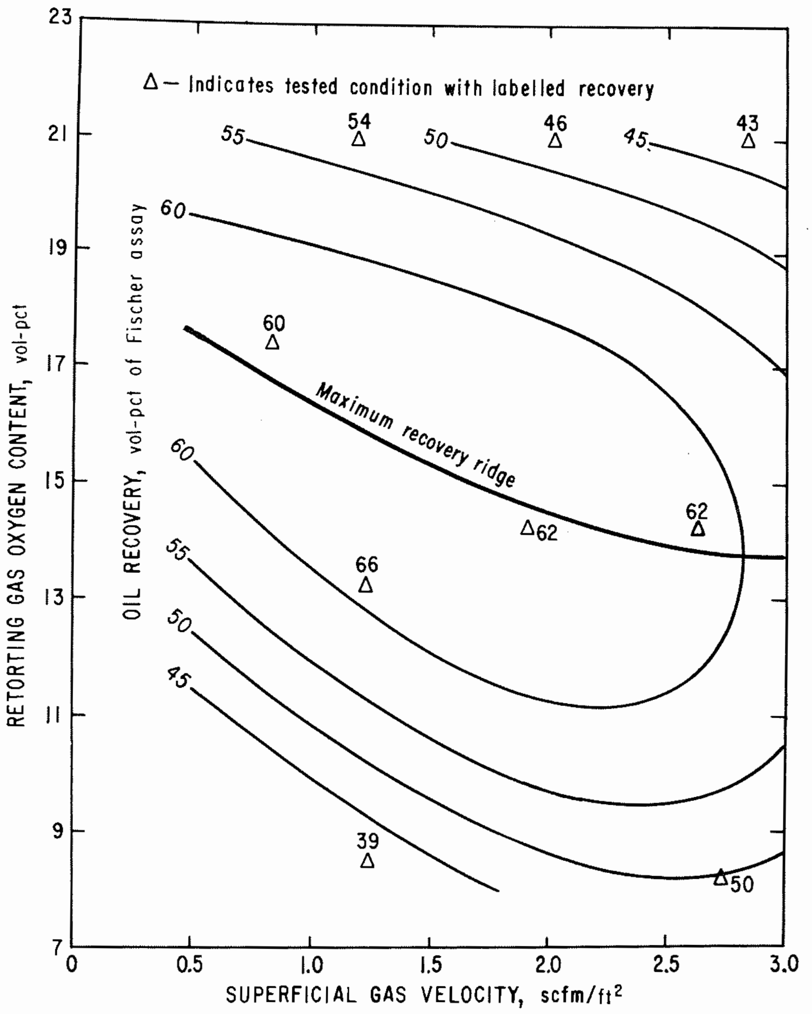


FIGURE 7. - Oil recovery contours for 150-ton retort.

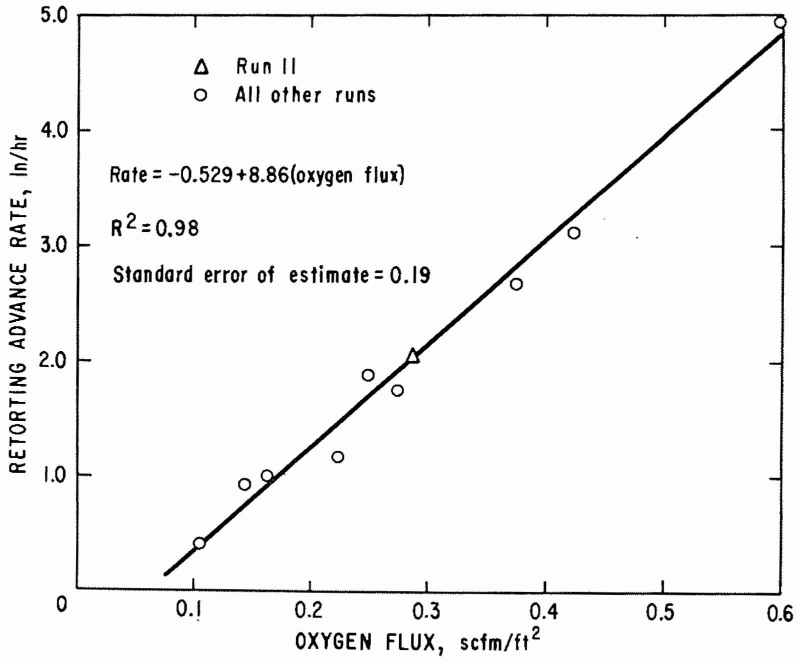


FIGURE 8. - Retorting advance rate versus oxygen flux for 150-ton retort.

thermocouples below the retorting zone were coated with the oil-water emulsion formed during retorting. In this soaked condition, the thermocouples produced completely spurious readings, probably caused by galvanic action. As the temperature rose, however, the thermocouples dried and once again produced reasonable readings. Another problem was produced by the mass of shale in the retort bearing down on the thermocouples. Any shifting or movement of the bed could cause thermocouple abrasion and shorting-out, or simply mechanical failure of the thermocouple wire. Other problems occurred at high temperatures when the thermocouples burned out or otherwise degraded, once again producing spurious readings. As a result, several of the temperature plots in the figures stop abruptly when a problem of the types mentioned caused a thermocouple to produce obviously erroneous readings.

Each of the eight figures presented in appendix B for run 9 shows the temperature history of eight thermocouples located as shown within the drawing. The thermocouple layers are illustrated as ellipses for clarity; however, they lie horizontally in the shale bed. Their locations are drawn to scale relative to distances from the outer wall and the top of the shale bed. For example, figure B-1 shows the first layer of thermocouples 1½ feet below the top of the shale bed. The second level, as indicated in figure B-2, is 6 feet below the first, and each subsequent level is 6 feet lower. Numbered temperature plots correspond to the numbered thermocouple locations in the drawing.

The temperature histories presented in figures B-1 through B-8 for run 9 portray phenomena that occur in essentially all tests performed with the 150-ton retort. The temperature at each level in the retort increases slowly, then goes through a very sharp temperature increase as the combustion front arrives. The temperature evens out at some maximum value, and then decreases slowly as the combustion front moves down the retort. This temperature history is repeated in succession at each level as the combustion zone moves down through the shale bed. Although at any one level there may be some spread in the time at which the various thermocouples show the sharp temperature increase, in nearly every instance the thermocouple at one level will increase to a maximum before any thermocouple in the next lower level registers a sharp temperature increase. This phenomenon indicates that very little flow channeling occurs.

Although severe gas channeling does not seem to occur, the combustion zone seems to tilt occasionally, as is evidenced in figures B-4 through B-8. Referring specifically to level 5 (fig. B-5), thermocouples 1, 5, and 6, located on the left side of the retort as pictured, lagged about 1 day behind and did not achieve as high a maximum temperature as the other thermocouples in the level. The angle of the combustion-zone tilt increased as the zone passed down through the retort, until at level 8 the temperature on the left side of the retort lagged about 2½ days behind the temperatures in the rest of that level. After the maximum temperature period was completed, the side of the shale bed that heated the earliest also cooled down much quicker than the side that heated later. This indicates possibly higher gas flows in the side that heated earlier. Although the exact cause for this tilt is still unknown, a pocket of unusually fine shale could tend to retard the gas flow or, conversely, a pocket of coarse shale could cause increased gas flow.

As mentioned earlier in this report, run 11 was a special test using a shale charge containing many large blocks of shale. The purpose of this test was to determine whether a concentration of large blocks would seriously affect the retorting process, and if so, how. Figure C-1 of appendix C is a diagram of the shale charge in the retort for run 11 presenting thermocouple locations, and the location and size of instrumented oil shale blocks, in the shale bed. As can be seen in this figure, a major portion of the shale in the lower three-quarters of the retort consisted of shale blocks weighing over 1 ton. Approximately the lower quarter of the shale charge consisted of large, instrumented blocks surrounded by mine-run shale. The middle half of the shale charge contained instrumented blocks surrounded by shale with a bottom size of 10 inches, while the top quarter contained mine-run shale to insure proper ignition of the shale bed.

Figure 9 is a photograph of a 7,500-pound block of shale similar to those loaded in run 11, but actually retorted in run 2. The thermocouple bundle used to measure internal block temperatures can be seen on top of the block. Shale blocks such as the one in figure 9 were retorted in runs 1-4, as well as in run 11. Temperature histories for the blocks in runs 2 and 3 were

FIGURE 9. - Oil shale block retorted during run 2.

presented in a previous report (5) and therefore will not be discussed here. Temperature histories for the thermocouples in run 11 are presented in figures C-2 through C-9 of appendix C. The numbers in the legends and on the curves in these figures refer to the thermocouple locations as presented in figure C-1.

The temperature histories for run 11 are quite similar to those of run 9 presented earlier, in that there is an intial slow warmup period followed by rapid heatup to maximum temperature, and then a gradual cooling period. The combustion zone also presents a fairly uniform front; most temperatures at any specified level achieved maximum values before the temperatures in the next lower level started rising sharply. There was, however, some channeling around the large blocks as illustrated by the temperature history shown in figure C-4 for block C, located as shown in figure C-1. The temperatures at thermocouple locations 33 and 34 in the left half of block C rose simultaneously with the temperatures at points 29 and 30 in the shale bed above the block, whereas the temperature at points 35 and 36 in the right half of the block rose to a maximum a little later. The temperatures at points 38 and 39, located in the shale bed about halfway between blocks C and D, increased to a maximum still later.

An interesting phenomenon is seen in figure C-5 during the cooling period for the locations presented. Block E, which contained thermocouples 45 through 48, was located in the shale bed above block F, which contained thermocouples 49 through 52. Block E heated to maximum temperature earlier than block F, as would be expected; however, block F, which achieved a higher maximum temperature, cooled off at a faster rate, and was actually cooler than block E for most of the cooling period. Furthermore, thermocouples 54 through 56, which were located in the shale bed below blocks E and F, achieved maximum temperature at almost the same time as block F, but cooled down at a much slower rate than either of the two blocks. Anomalies such as these occur frequently, and many theories could be proposed to explain them; however, the important aspect concerning these anomalies is that their existence does not seem to greatly influence the ultimate oil recovery.

Material balances are presented in table 3 for the tests performed. Closure on the balance is fairly good, with a maximum weight gain of 3.2 percent in test 3 and a maximum weight loss of 3.2 percent in test 5. Average deviation from complete closure is 1.2 percent. All mass flows occurring during the ignition period are included in the material balance calculations.

Energy balances over the retort vessel for the tests performed are presented in table 4. The energy-balance calculations cover the time period between the start of ignition and shutdown. For these energy balances, all heating values used are gross, and the reference temperature is 77° F. Spent shale enthalpies were calculated using average bed temperatures in the retort at shutdown. Energy loss to the atmosphere was calculated by integrating the curve for retort heat-loss rate versus time, obtained using the heat-flux transducers described under "Pilot Plant Design" for the duration of the test. Energy lost to carbonate decomposition was calculated using the difference in mineral carbonate between the feed and spent shale, assuming an endothermic heat of reaction of 57,000 Btu/lb-mole.

TABLE 3. - Material balances for oil shale tests in 150-ton retort

	Run 2		Run 3		Run 4		Run 5		Run 6	
	Lb	Pct	Lb	Pct	Lb	Pct	Lb	Pct	Lb	Pct
MATERIAL IN										
Oil shale............	357,340	66.1	358,740	61.4	364,420	69.8	361,080	70.0	366,960	69.4
Natural gas..........	70	-	80	-	80	-	130	-	150	-
Air (wet)............	182,900	33.9	225,640	38.6	157,660	30.2	154,950	30.0	161,600	30.6
Total in........	540,310	100.0	584,460	100.0	522,160	100.0	516,160	100.0	528,710	100.0
MATERIAL OUT										
Spent shale..........	251,710	45.5	316,870	52.5	261,490	50.7	248,200	49.7	267,560	50.9
Shale oil (dry).......	21,280	3.9	12,990	2.1	16,450	3.2	19,650	3.9	18,130	3.4
Stack gas (dry).......	257,200	46.5	247,060	41.0	218,430	42.4	215,180	43.1	220,730	41.9
Water:										
In oil.............	16,030	-	21,540	-	17,510	-	12,300	-	11,250	-
In stack gas........	6,520	-	4,930	-	6,210	-	4,390	-	8,820	-
Total water......	22,550	4.1	26,470	4.4	23,720	4.6	16,690	3.3	20,070	3.8
Total out........	552,740	100.0	603,390	100.0	520,090	100.0	499,720	100.0	526,490	100.0
Gain/loss out pct..	-	2.3	-	3.2	-	-0.4	-	-3.2	-	-0.4

	Run 7		Run 8		Run 9		Run 10		Run 11	
	Lb	Pct	Lb	Pct	Lb	Pct	Lb	Pct	Lb	Pct
MATERIAL IN										
Oil shale............	348,900	67.7	365,790	72.4	371,480	66.5	366,240	66.6	327,680	67.0
Natural gas..........	150	-	150	-	120	-	320	0.1	160	-
Air (wet)............	166,220	32.3	139,700	27.6	187,140	33.5	183,350	33.3	160,910	33.0
Total in........	515,270	100.0	505,640	100.0	558,740	100.0	549,910	100.0	488,750	100.0
MATERIAL OUT										
Spent shale..........	284,980	55.0	277,530	55.4	278,720	49.7	267,380	48.6	238,290	48.2
Shale oil (dry).......	14,720	2.8	13,490	2.7	22,170	4.0	19,720	3.6	16,710	3.4
Stack gas (dry).......	199,500	38.5	192,060	38.3	242,100	43.2	241,730	43.9	212,810	43.0
Water:										
In oil.............	14,670	-	10,590	-	13,990	-	17,490	-	22,250	-
In stack gas........	4,310	-	7,400	-	3,400	-	3,800	-	4,460	-
Total water......	18,980	3.7	17,990	3.6	17,390	3.1	21,290	3.9	26,710	5.4
Total out........	518,180	100.0	501,070	100.0	560,380	100.0	550,120	100.0	494,520	100.0
Gain/loss out pct..	-	0.6	-	-0.9	-	0.3	-	0.0	-	1.2

TABLE 4. - Energy balances for oil shale tests in 150-ton retort, Btu per ton of raw shale, except as indicated[1]

	Run 2	Run 3	Run 4	Run 5	Run 6
ENERGY ENTERING RETORT					
Enthalpy of raw shale	-60,000	-30,000	-20,000	-10,000	-10,000
Enthalpy of air	-11,600	-600	-8,700	-5,600	-3,600
Enthalpy of recycle gas	-4,100	2,200	0	0	1,400
Heating value of raw shale	4,540,000	4,580,000	4,480,000	4,500,000	4,100,000
Heating value of recycle gas	160,300	628,700	0	0	125,300
Heating value of ignition gas	9,200	10,700	10,100	17,900	20,200
Total energy in	4,633,800	5,191,000	4,461,400	4,502,300	4,233,300
ENERGY LEAVING RETORT					
Enthalpy of spent shale	155,000	141,300	272,700	158,100	262,500
Enthalpy of exit gas	19,900	34,700	12,000	9,100	14,700
Heat of vaporization, uncondensed water	109,600	135,300	73,600	53,400	94,700
Enthalpy of oil	2,300	1,100	1,700	1,600	1,700
Enthalpy of condensed water	0	0	800	1,100	2,300
Heating value of spent shale	169,100	635,900	409,000	192,500	364,600
Heating value of oil	2,217,700	1,361,800	1,671,600	2,012,000	1,830,800
Heating value of exit gas	512,700	894,600	496,000	407,000	416,300
Energy into water coil	16,200	283,800	6,000	6,700	6,700
Energy transferred to atmosphere	452,000	1,719,400	(2)	553,800	705,700
Carbonate decomposition	331,500	52,900	296,900	357,300	296,700
Total energy out	3,986,000	5,260,800	3,240,300	3,752,600	3,996,700
Total unaccountable energy loss	647,800	-69,800	1,221,100	749,700	236,600
Unaccountable energy loss..pct	14.0	-1.3	27.4	16.7	5.6
	Run 7	Run 8	Run 9	Run 10	Run 11
ENERGY ENTERING RETORT					
Enthalpy of raw shale	-20,000	-20,000	-16,000	-8,000	-40,000
Enthalpy of air	-7,300	-5,000	-9,000	-4,100	-12,300
Enthalpy of recycle gas	-6,900	0	-4,200	-600	-5,500
Heating value of raw shale	4,420,000	4,540,000	4,660,000	4,060,000	4,540,000
Heating value of recycle gas	348,900	0	106,400	47,100	139,200
Heating value of ignition gas	21,000	19,600	15,800	41,500	23,400
Total energy in	4,755,700	4,534,600	4,753,000	4,135,900	4,644,800
ENERGY LEAVING RETORT					
Enthalpy of spent shale	343,100	273,100	120,000	204,400	261,700
Enthalpy of exit gas	62,300	10,600	10,600	11,800	18,600
Heat of vaporization, uncondensed water	101,000	70,000	68,700	72,500	114,700
Enthalpy of oil	2,800	1,400	1,200	1,600	1,900
Enthalpy of condensed water	0	900	400	1,100	1,200
Heating value of spent shale	702,400	257,900	150,100	8,800	596,100
Heating value of oil	1,567,700	1,344,100	2,198,900	1,993,400	1,877,800
Heating value of exit gas	492,700	421,500	293,500	293,300	406,600
Energy into water coil	26,800	5,300	19,900	24,900	15,000
Energy transferred to atmosphere	486,600	210,000	680,000	700,500	462,600
Carbonate decomposition	243,200	266,200	255,100	316,300	454,800
Total energy out	4,028,600	2,861,000	3,798,400	3,628,600	4,211,000
Total unaccountable energy loss	727,100	1,673,600	954,600	507,300	433,800
Unaccountable energy loss..pct	15.3	36.9	20.1	12.3	9.3

[1] All heating values are gross. Reference temperature is 77° F. Standard cubic feet taken at 60° F, 1 atm.

[2] Data not available.

The total energy into the retort ranged from a low of 4.1 million Btu/ton of raw shale charged, to a high of 5.2 million. Closure on the energy balances was poor, ranging from a high of 36.9 percent to a low of -1.3 percent of the energy entering the retort. Except for run 4, where part of the unaccountable energy loss was caused by the lack of data used to calculate atmospheric heat losses, no reasonable explanation could be found for these high energy losses.

Because the unaccountable energy loss in some runs was much higher than desirable (amounting to about 12 gallons per ton of raw shale in run 8, for example), a thorough study of each energy balance component was made. Each value was cross-checked in various ways to establish its accuracy. For example, the energy transferred to atmosphere together with run length, average maximum bed temperature, and the retort surface area, were used to calculate an overall heat-transfer coefficient, which compared quite well with one calculated using the refractory lining in the retort. All values were found to be reasonable. All attempts to correlate the unaccountable energy loss to process variables also failed; that is, a cursory comparison of tests 3 and 8 indicates that the unaccountable energy loss increases with retorting rate and bed temperature. However, this relationship is not substantiated by the other tests. Process-flow errors of the magnitude necessary to explain the lost energy can be discounted by the good closure on the material balances. It would seem that the high unaccountable energy loss must be caused by an unfortunate accumulation of small errors.

CONCLUSIONS

Random-sized oil shale assaying about 25 gallons of oil per ton was successfully retorted in the 150-ton aboveground retort, and oil yields as high as 65 volume-percent of Fischer assay were realized.

In a large-scale in situ retorting operation, similar oil yields can be expected if surface area, particle size of the fractured shale, and operating conditions approximate those used in the 150-ton retort.

When comparing the oil-yield results of run 11, where several large shale blocks were included in the charge, with run 2, where a much smaller shale-particle size was used, a difference of only about 7 volume-percent of Fischer assay was observed. In addition to this relatively low difference in oil recovery, the very fact that shale charges containing several large shale blocks can be retorted in a reasonable length of time is encouraging.

The pressure drop across a 43-foot column of oil shale with a void volume of about 40 percent is negligible. However, in a larger scale in situ retorting situation, where the shale bed is much thicker and the void volume considerably less than the above values, higher pressure differentials could become a major factor.

The temperature history of run 9, as shown in figures B-1 through B-8, indicates a slight tilt in the retorting front as it passed downward through the shale bed. This phenomena was also observed during some other runs; however, the tilting was not severe enough to cause operational problems due to gas flow channeling.

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APPENDIX A.--TABULATION OF DATA

TABLE A-1. - Data from oil shale tests in 150-ton retort

	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11
Date	3/23/70	6/24/70	2/16/71	4/19/71	8/4/71	10/27/71	1/18/72	4/26/72	8/21/72	2/6/73
Length of run, days	12.25	52.00	6.83	11.28	7.93	18.15	4.30	21.18	22.53	10.53
Operating conditions:										
Shale charge, tons	178.67	179.37	182.21	180.54	183.48	174.45	182.90	185.74	183.12	163.84
Retort pressure, psig	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Time burner on, hr	3.0	4.0	5.0	5.0	5.2	5.5	4.1	4.4	12.1	6.3
Burner heat release rate, Btu/hr	633,000	475,000	362,000	635,000	136,000	653,000	854,000	660,000	618,000	594,000
Air rate (dry), scfh	8,100	2,340	12,590	7,430	11,030	4,890	17,780	4,730	4,250	8,240
Air rate (dry), scf/ton shale	13,300	16,310	11,300	11,190	11,430	12,440	9,960	13,130	13,010	12,840
Avg air temperature into retort, ° F	30	75	35	50	60	45	50	40	60	25
Recycle gas rate (dry), scfh	4,000	5,420	0	0	5,410	12,140	0	2,930	910	4,420
Recycle gas rate (dry), scf/ton shale	6,400	37,680	0	0	5,450	29,920	0	7,940	2,640	6,640
Avg recycle gas temperature into retort, ° F	45	80	-	-	90	65	-	50	65	35
Oxygen content of retorting gas, pct	14.2	8.5	21.0	21.0	14.2	8.2	21.0	13.2	17.4	13.8
Superficial gas velocity, scfm/ft^2 bed	1.94	1.24	2.02	1.19	2.63	2.73	2.85	1.23	0.83	2.03
Stack gas rate (dry), scfh	10,600	2,460	15,490	9,140	13,390	5,380	21,710	5,470	4,910	9,650
Stack gas rate (dry), scf/ton shale	16,700	17,110	13,900	13,770	13,880	13,690	12,160	15,190	15,010	15,030
Avg off gas temperature, ° F	120	110	120	110	115	150	120	100	110	120
Gas produced in retort (dry), scfh	2,500	120	2,900	1,710	2,360	490	3,930	740	660	1,410
Gas produced in retort (dry), scf/ton shale	3,400	830	2,600	2,580	2,450	1,250	2,200	2,060	2,000	2,190
Max. retort diff. pressure, in. H_2O	0.6	0.4	1.0	0.5	1.0	0.6	1.2	0.6	0.4	0.4
Avg barometric pressure, in.Hg	22.93	23.22	22.81	22.85	23.24	22.86	22.70	22.87	22.97	22.78
Avg ambient temperature, ° F	26	69	22	38	65	34	37	43	56	14
Avg retorting advance rate, in/hr	1.75	0.41	3.11	1.88	2.68	1.17	4.94	1.00	0.94	2.02
Avg max. bed temperature, ° F	1,240	850	1,410	1,380	1,360	1,230	1,510	1,260	1,220	1,090
Shale feed properties:										
Fischer assay, gal/ton	25.4	24.7	25.5	26.2	20.9	22.4	22.3	24.0	23.8	24.4
Oil content, wt-pct	9.6	9.5	9.8	9.9	8.0	8.6	8.5	9.1	9.1	9.3
Water content, gal/ton	2.9	2.6	3.1	2.8	4.7	4.7	5.9	3.7	4.0	4.0
Size range, in	0-48	0-48	0-48	0-20	0-20	0-20	0-20	0-20	0-20	0-60
Void space in retort, pct	42.0	41.0	40.2	40.4	41.8	43.9	41.1	39.6	40.5	46.6
Hydrogen, wt-pct	1.66	1.69	1.66	1.64	1.56	1.63	1.66	1.74	1.61	1.74
Mineral carbon, wt-pct	4.78	4.71	4.86	4.78	4.51	4.54	4.56	4.74	4.63	4.80
Organic carbon, wt-pct	11.04	11.17	10.86	11.10	10.12	10.80	10.98	11.56	10.80	11.56
Carbon dioxide, wt-pct	17.52	17.26	17.81	17.51	16.52	16.64	16.70	17.38	16.97	17.60
Mineral carbonate, wt-pct	23.90	23.54	24.28	23.88	22.53	22.69	22.80	23.70	23.14	24.00
Total carbon, wt-pct	15.82	15.88	15.72	15.88	14.63	15.34	15.54	16.30	15.43	16.36
Ash, wt-pct	68.73	68.79	68.80	68.60	70.60	68.88	69.54	67.83	69.44	68.26
Nitrogen, wt-pct	0.38	0.37	0.40	0.37	0.26	0.29	0.26	0.38	0.33	0.36
Sulfur, wt-pct	0.57	0.58	0.57	0.58	0.60	0.63	0.66	0.64	0.60	0.58
Gross heating value, Btu/lb	2,270	2,290	2,240	2,250	2,050	2,210	2,270	2,330	2,030	2,270

TABLE A-1. - Data from oil shale tests in 150-ton retort--Continued

	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11
Liquid recovery:										
Oil-water emulsion...lb..	37,310	34,530	33,960	31,950	29,380	29,390	24,080	36,150	37,210	38,960
Water in oil...lb..	16,030	21,540	17,510	12,300	11,250	14,670	10,590	13,990	17,490	22,250
Avg water in oil...pct..	43.0	62.4	51.6	38.5	38.3	49.9	44.0	38.7	47.0	57.1
Oil recovery...gal..	2,830	1,740	2,150	2,580	2,380	1,960	1,760	2,930	2,610	2,210
Oil recovery...gal/ton of shale feed..	15.8	9.7	11.8	14.3	13.0	11.2	9.6	15.8	14.3	13.5
Oil recovery...vol-pct of Fischer assay..	62.2	39.3	46.3	54.5	62.2	50.0	43.0	65.8	60.1	55.3
Oil properties:										
Distillation, vol-pct:										
IBP-392° F at 760 mm Hg...	5.7	6.0	5.3	5.9	4.7	6.3	7.6	7.1	9.0	7.3
302°-392° F at 40 mm Hg...	25.8	27.2	21.3	19.1	13.9	21.4	24.1	24.3	22.3	26.2
392°-572° F at 40 mm Hg...	42.4	40.9	37.6	38.5	45.9	43.0	36.1	44.1	46.9	42.6
Residuum...	26.1	25.9	29.5	33.4	34.2	27.1	31.1	25.1	21.6	21.1
Specific gravity...60°/60° F..	0.90	0.90	0.92	0.91	0.92	0.90	0.92	0.91	0.91	0.91
Gravity...° API..	25.2	26.4	22.6	23.3	23.1	25.6	22.0	24.3	24.5	24.3
Pour point...° F..	70	50	70	60	55	60	70	55	50	60
Viscosity...SUS at 100° F..	79	64	88	84	84	71	89	73	69	72
Hydrogen...wt-pct..	11.76	12.11	11.71	11.66	11.67	11.86	11.38	12.55	11.80	11.66
Nitrogen...wt-pct..	1.77	1.45	1.82	1.94	1.73	1.62	1.91	1.44	1.45	1.77
Sulfur...wt-pct..	0.76	1.10	0.87	0.81	0.86	1.04	0.92	0.98	1.19	0.83
Carbon...wt-pct..	84.58	84.63	84.58	84.40	84.30	84.10	84.35	84.30	84.02	84.48
Ash...wt-pct..	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Gross heating value...Btu/lb..	18,660	18,810	18,510	18,480	18,520	18,650	18,230	18,400	18,450	18,390
Stack gas properties (dry basis):										
O_2...vol-pct..	0.5	3.1	0.5	0.8	0.2	3.1	0.3	0.7	0.8	0.4
N_2 + Ar...vol-pct..	67.3	79.6	65.4	64.6	66.2	73.2	65.8	69.5	68.6	68.8
CO...vol-pct..	2.3	0.9	3.4	2.9	2.6	1.2	3.3	1.3	1.3	1.5
CO_2...vol-pct..	28.7	15.4	29.0	30.0	29.9	21.9	28.7	27.9	28.3	28.3
CH_4...vol-pct..	0.7	0.7	0.9	0.9	0.6	0.3	0.7	0.3	0.5	0.5
C_2's...vol-pct..	0.4	0.3	0.7	0.6	0.4	0.2	0.7	0.3	0.3	0.4
Higher hydrocarbons...vol-pct..	0.2	0.2	0.2	0.1	0.1	0.1	0.4	0.1	0.2	0.2
Heating value...Btu/ft^3..	25.7	19.4	36.5	31.1	23.5	12.5	38.4	14.6	18.7	21.1
Specific gravity, air = 1...	1.13	1.06	1.13	1.14	1.13	1.09	1.13	1.13	1.15	1.11
Spent shale properties:										
Shale discharged...tons..	125.86	158.43	130.74	124.10	133.78	142.49	138.76	139.36	133.69	119.14
Fischer assay...gal/ton..	0.0	0.4	0.6	0.2	0.5	2.6	0.1	0.0	0.0	1.6
Oil content...wt-pct..	0.0	0.2	0.2	0.1	0.2	1.0	0.4	0.0	0.0	0.6
Water content...wt-pct..	0.3	1.7	0.6	0.6	0.3	0.3	0.4	0.4	1.3	0.4
Hydrogen...wt-pct..	0.14	0.43	0.23	0.16	0.19	0.32	0.24	0.27	0.20	0.32
Mineral carbon...wt-pct..	1.83	4.70	2.41	1.48	1.90	2.42	2.31	3.00	1.77	2.42
Organic carbon...wt-pct..	1.24	3.10	2.35	1.32	2.08	3.02	1.89	1.99	1.38	3.28
Carbon dioxide...wt-pct..	6.71	17.23	8.85	5.41	6.95	8.88	8.47	10.04	6.52	8.87
Mineral carbonate...wt-pct..	9.15	23.50	12.07	7.58	9.47	12.01	11.56	14.98	8.89	12.09
Total carbon...wt-pct..	3.07	7.80	4.76	2.80	3.97	5.44	4.21	4.99	3.15	5.70
Ash...wt-pct..	91.91	78.24	88.65	93.17	91.11	87.72	89.44	86.72	91.23	87.41
Nitrogen...wt-pct..	0.10	0.19	0.12	0.06	0.11	0.15	0.07	0.11	0.45	0.13
Sulfur...wt-pct..	0.56	0.51	0.55	0.55	0.60	0.60	0.57	0.48	0.64	0.61
Gross heating value...Btu/lb..	115	355	280	140	250	430	170	100	5	410

APPENDIX B.--SUPPLEMENTARY ILLUSTRATIONS--RUN 9

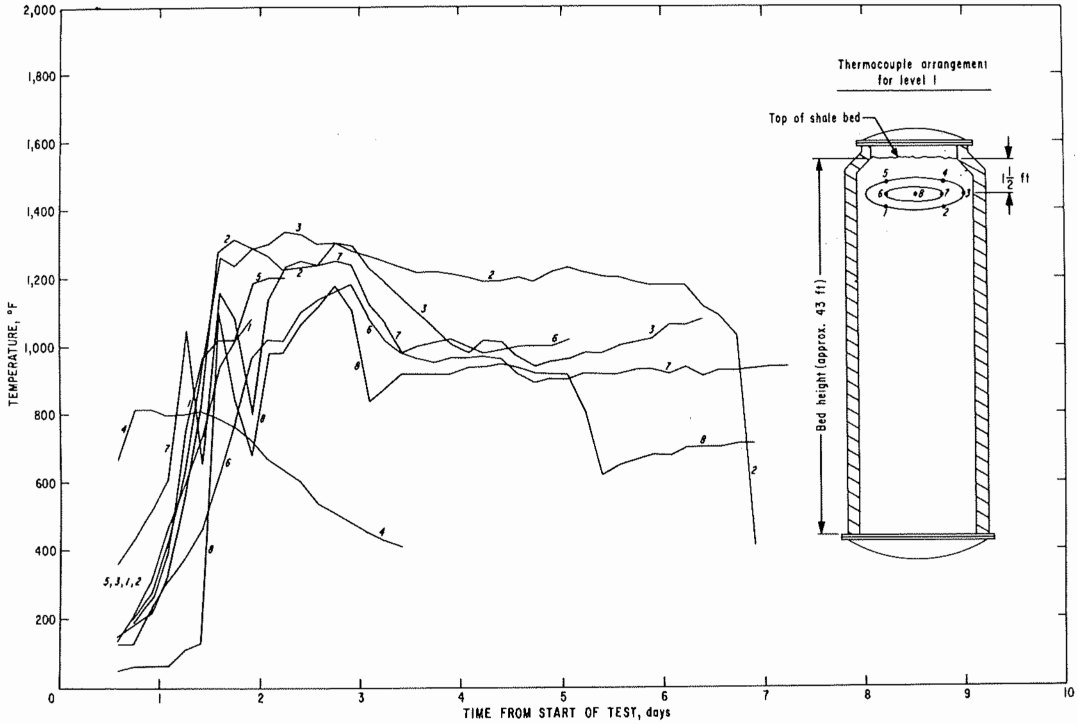

FIGURE B-1. - Thermocouple arrangement and temperature history of level 1, run 9, 150-ton retort.

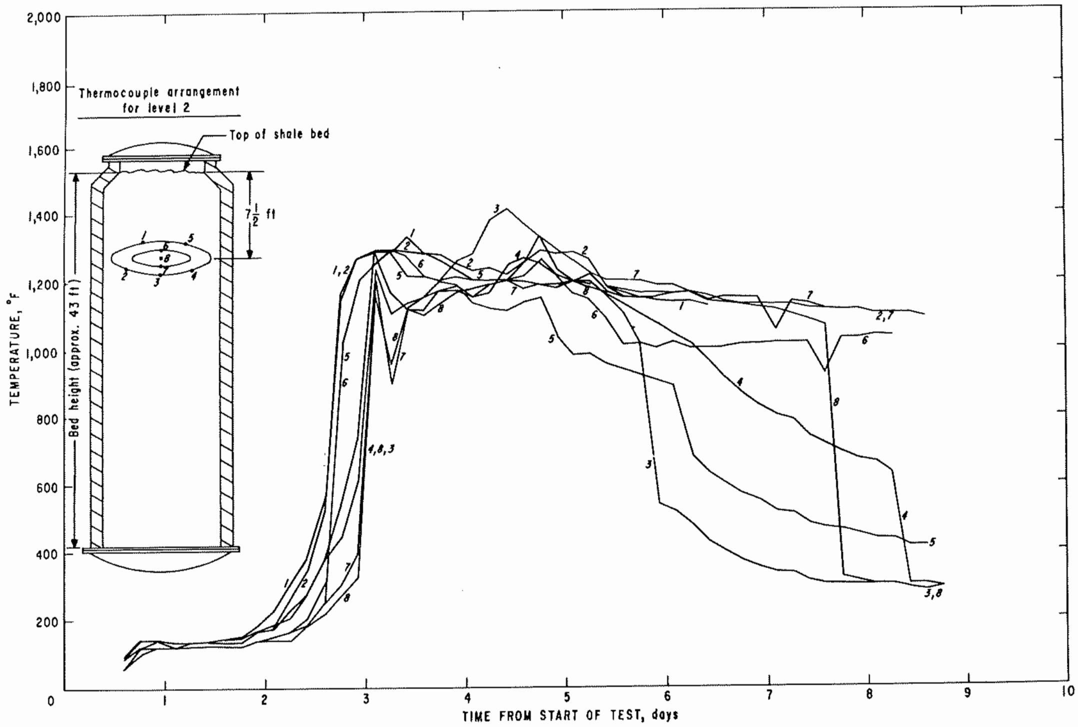

FIGURE B-2. - Thermocouple arrangement and temperature history of level 2, run 9, 150-ton retort.

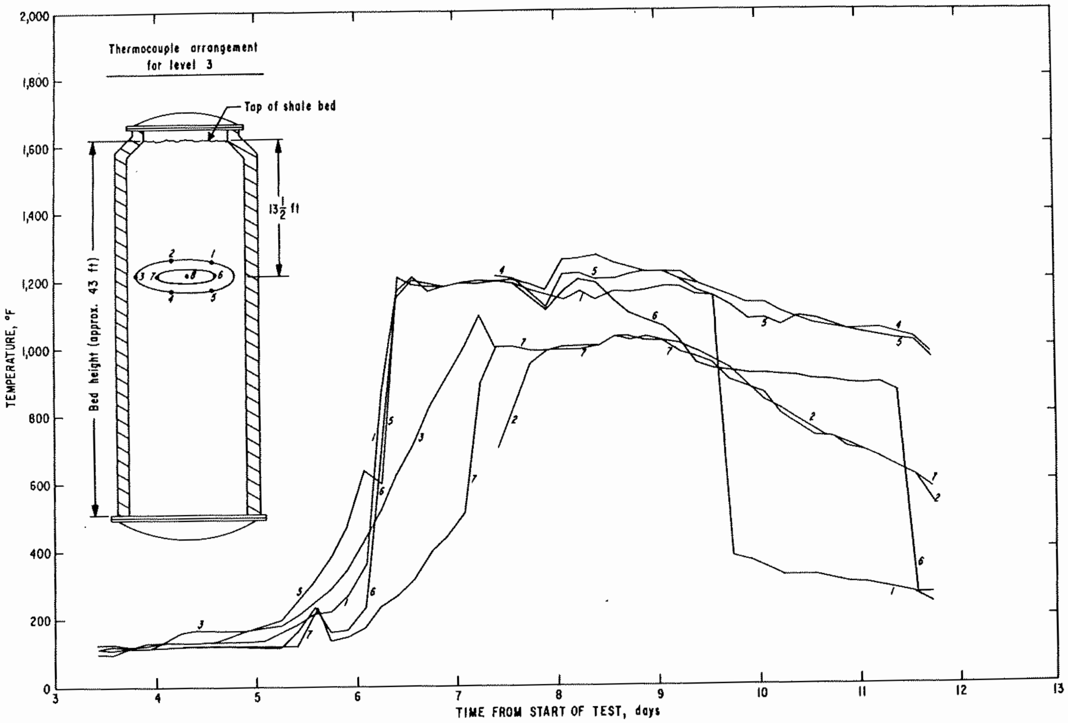

FIGURE B-3. - Thermocouple arrangement and temperature history of level 3, run 9, 150-ton retort.

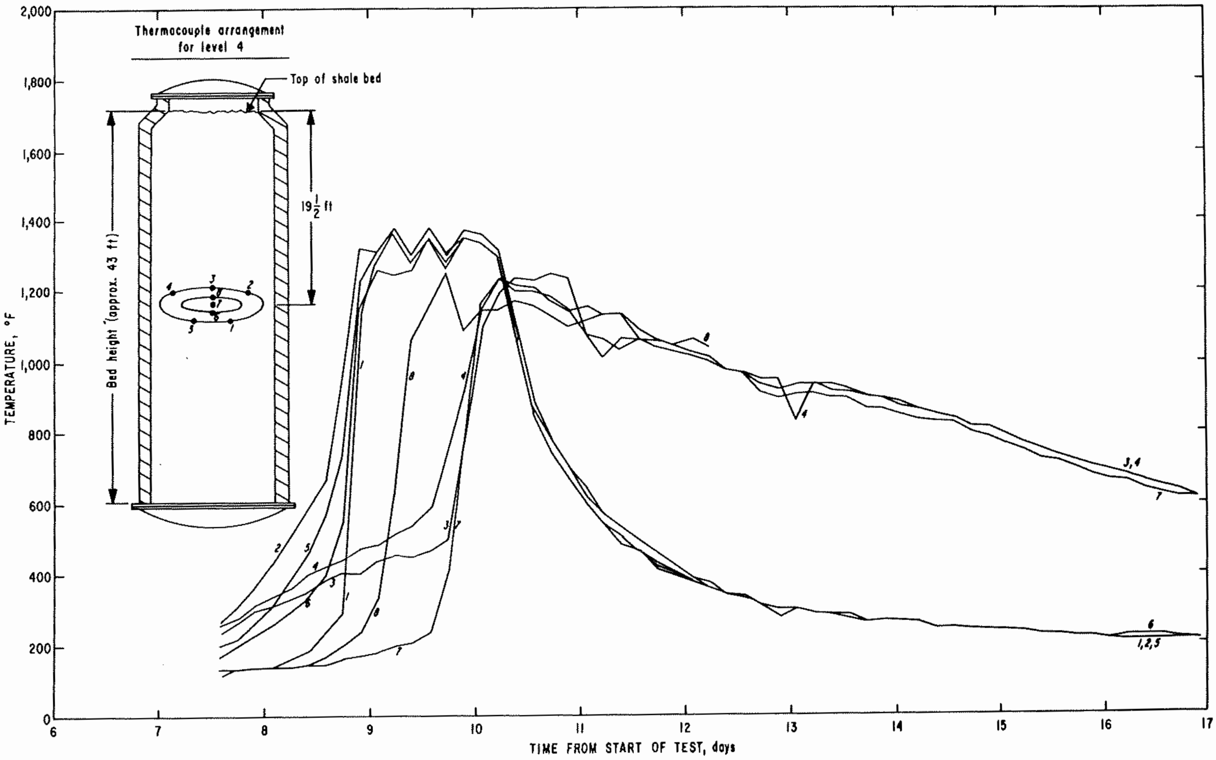

FIGURE B-4. - Thermocouple arrangement and temperature history of level 4, run 9, 150-ton retort.

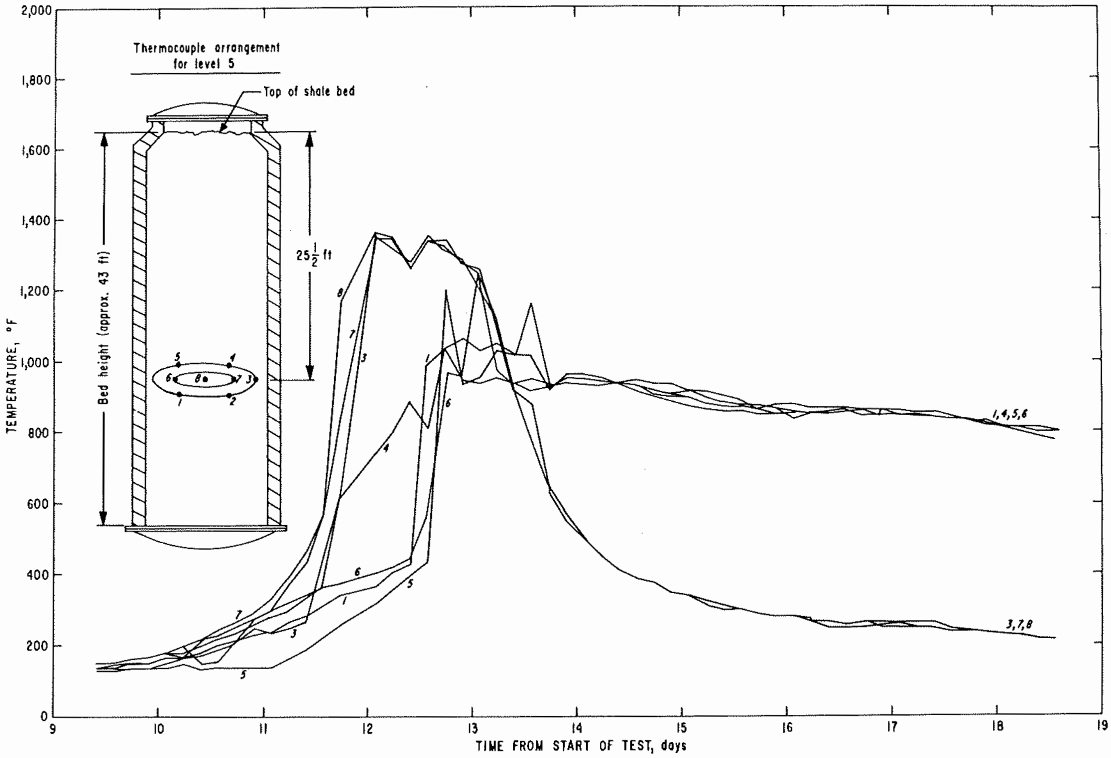

FIGURE B-5. - Thermocouple arrangement and temperature history of level 5, run 9, 150-ton retort.

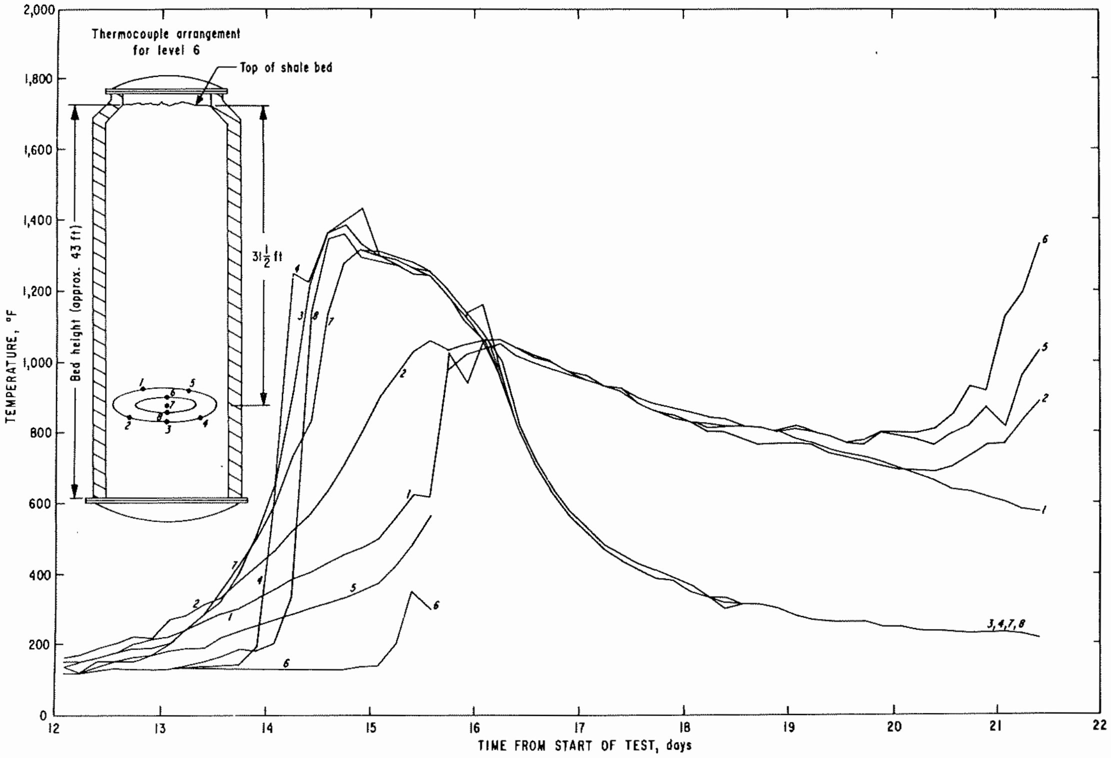

FIGURE B-6. - Thermocouple arrangement and temperature history of level 6, run 9, 150-ton retort.

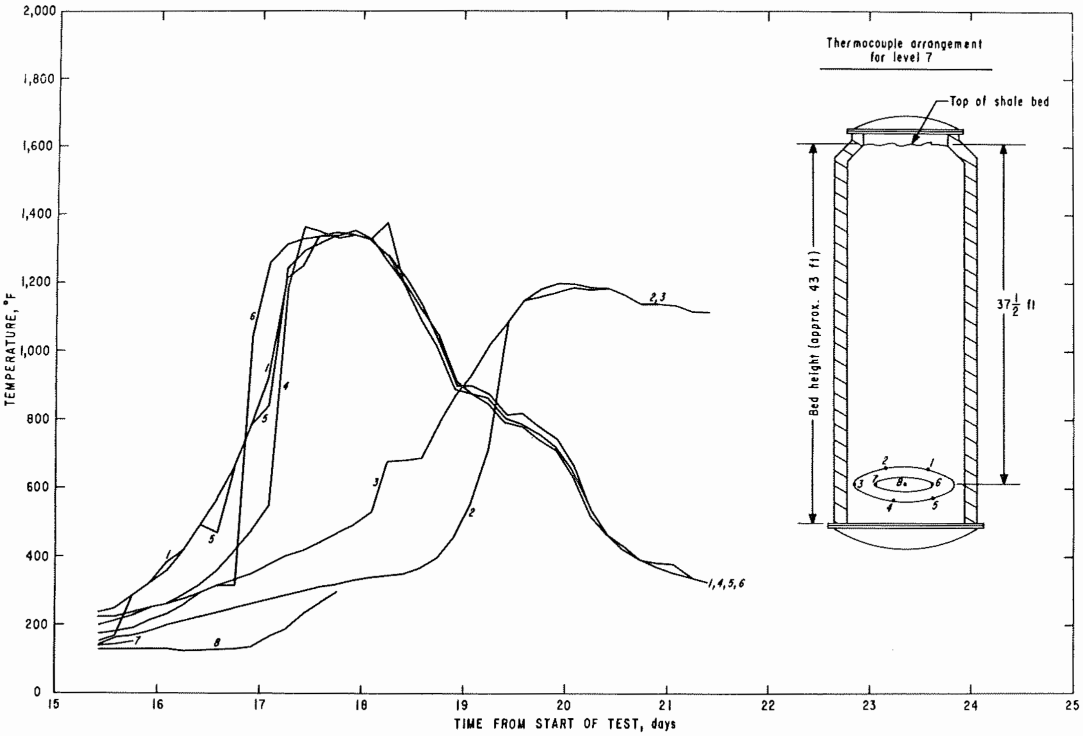

FIGURE B-7. - Thermocouple arrangement and temperature history of level 7, run 9, 150-ton retort.

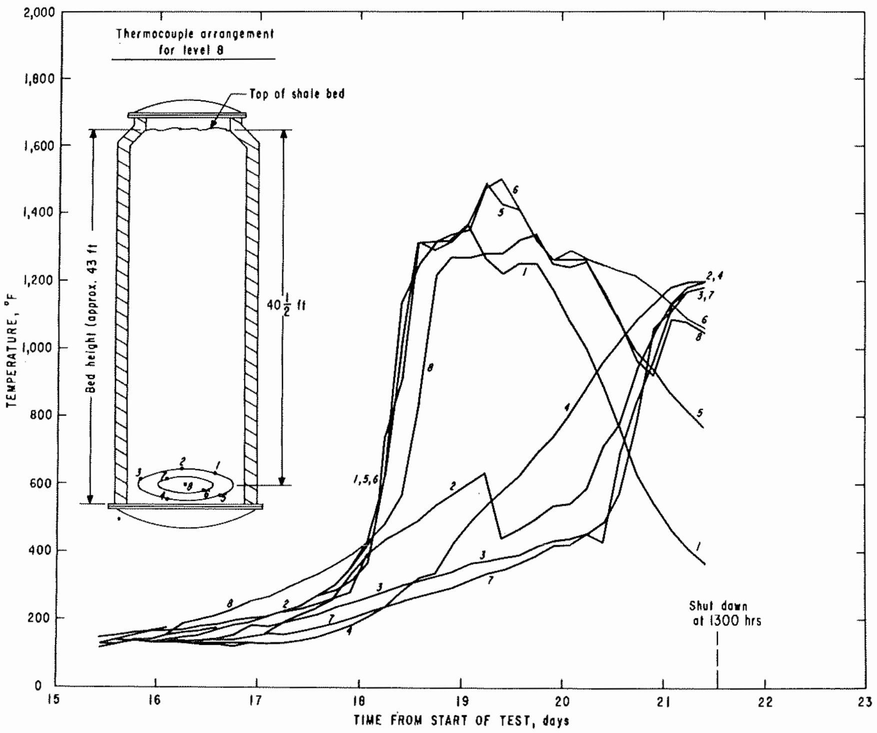

FIGURE B-8. - Thermocouple arrangement and temperature history of level 8, run 9, 150-ton retort.

APPENDIX C.--SUPPLEMENTARY ILLUSTRATIONS--RUN 11

KEY

Block letter	Size (feet)	Weight (tons)
A	1x2½x2½	1.1
B	1x2½x2½	0.9
C	1x2½x3	1.0
D	1x3x4½	2.2
E	1x3x4	2.0
F	1½x2½x4	1.4
G	1x4½x6	1.8
H	1x2x3	2.1
I	2½x5x6	2.5
J	2½x5x8	4.4
K	2½x4½x9	3.2
L	2½x4x5½	1.9
M	1x5x7	1.8
N	1½x3x5	1.4

NOTE.- Average particle size for entire charge calculated to be approximately 30 in.

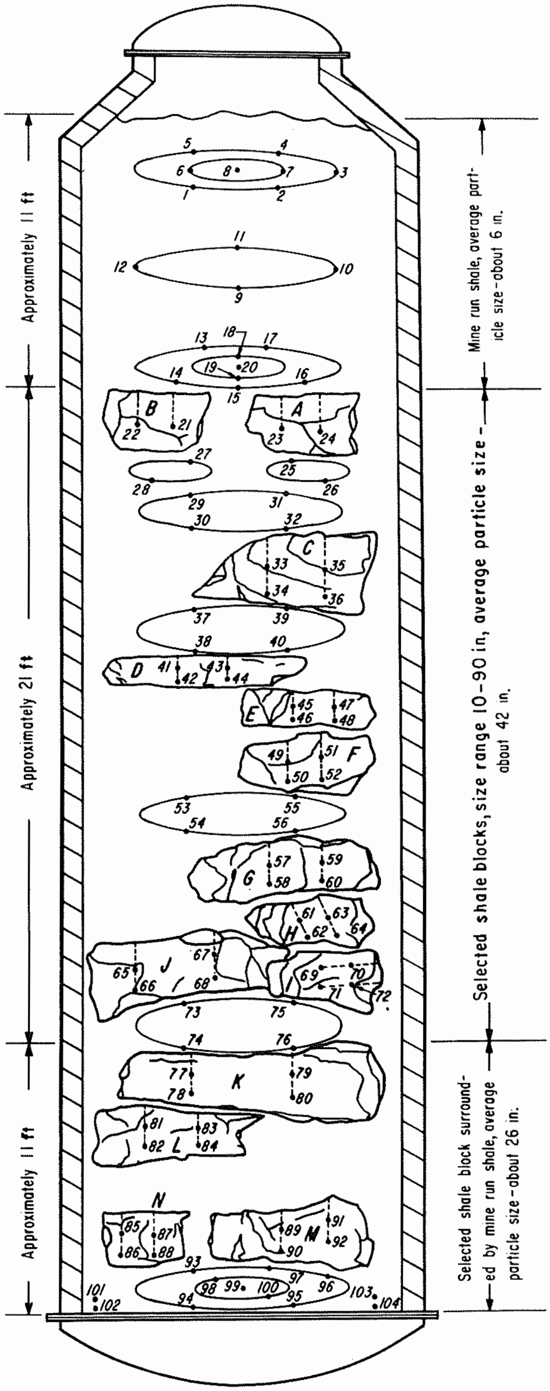

FIGURE C-1. - Large shale block locations, thermocouple arrangement, and shale particle-size distribution used for run 11.

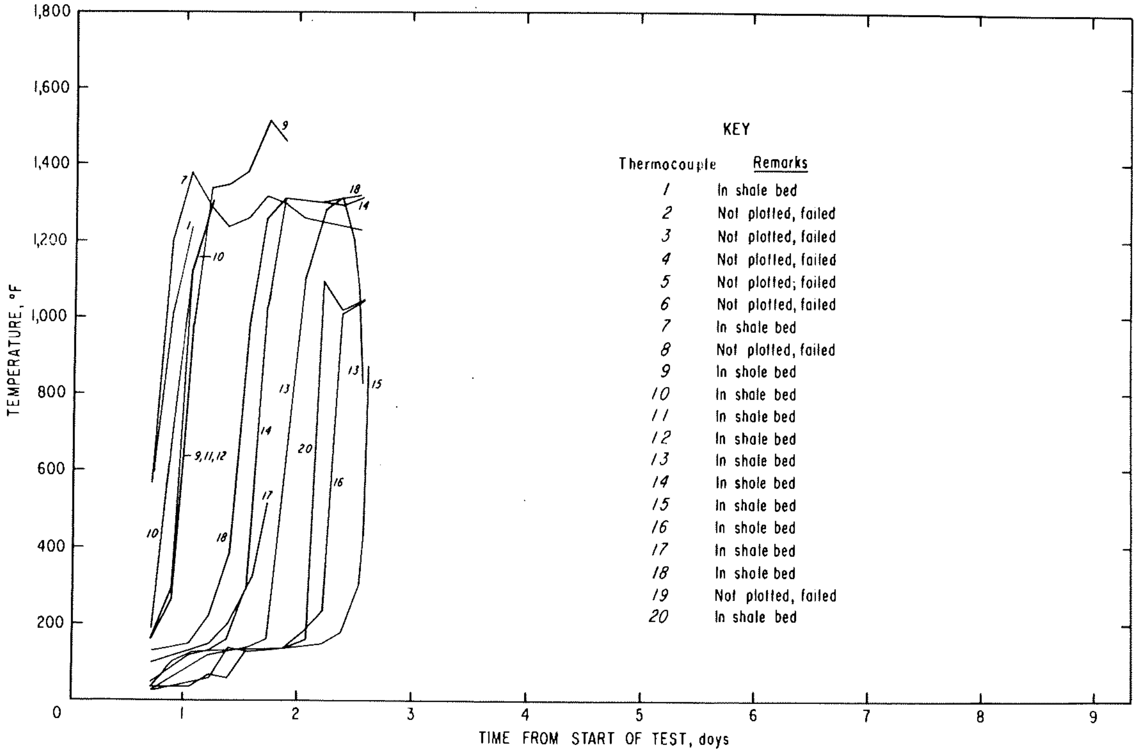

FIGURE C-2. - Shale bed temperatures during run 11 for thermocouples 1-20.

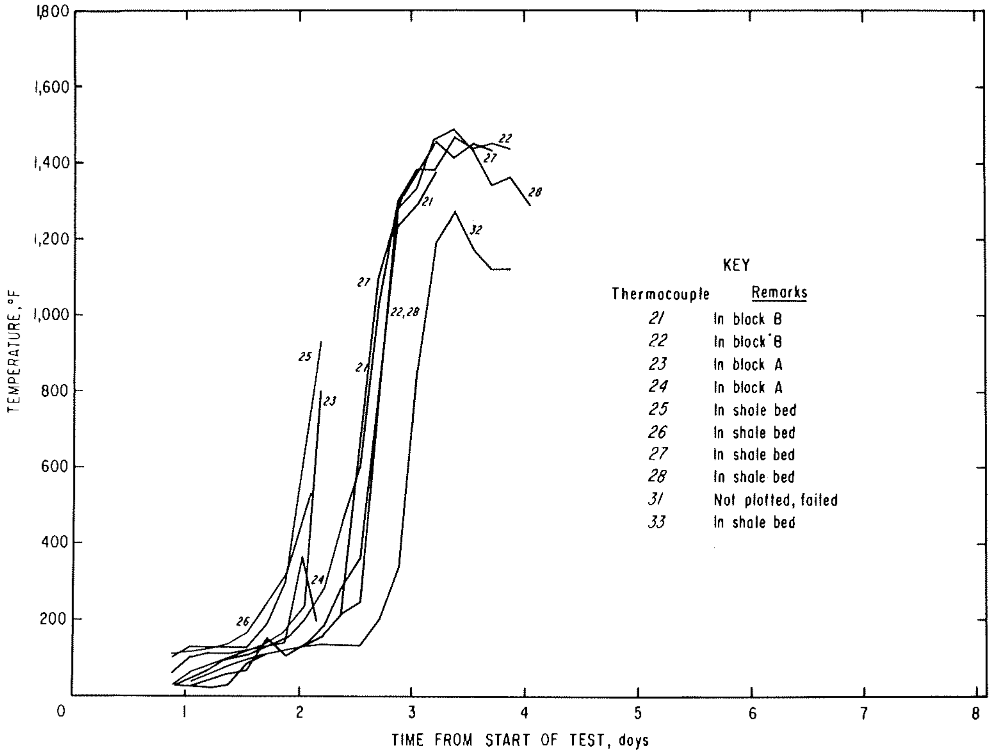

FIGURE C-3. - Shale bed temperatures during run 11 for thermocouples 21-33.

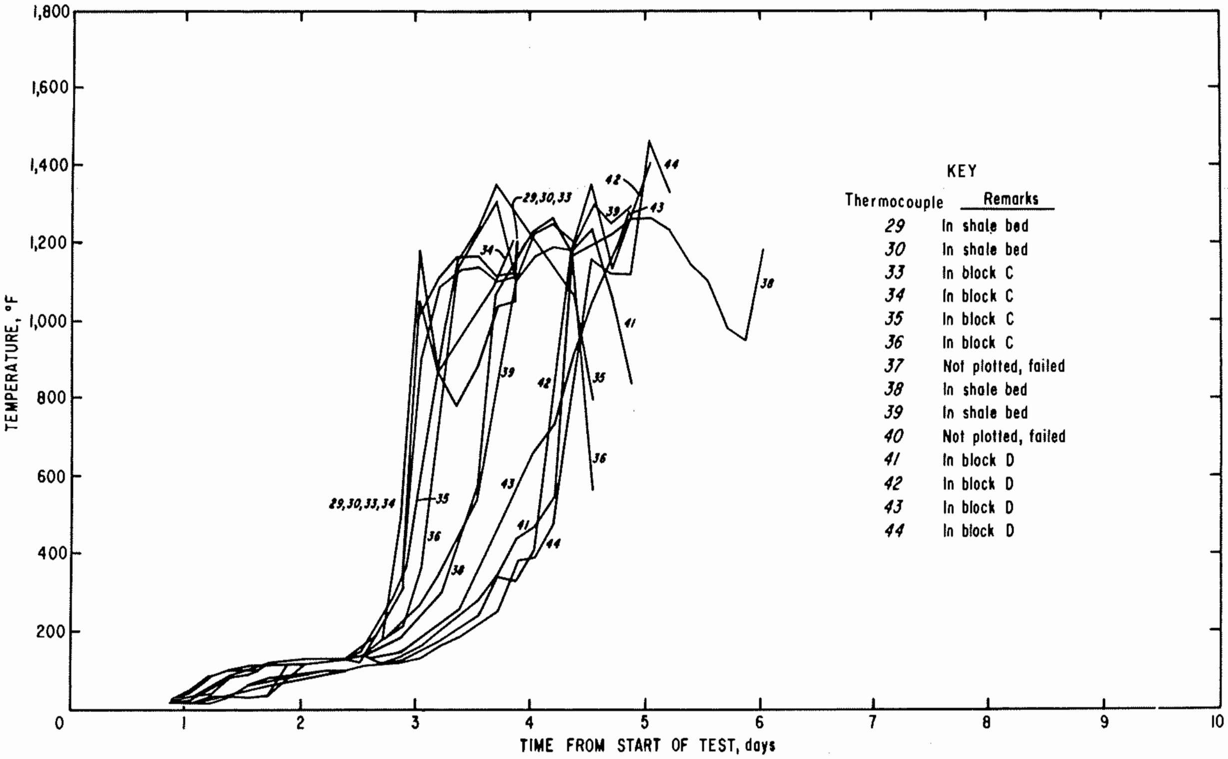

FIGURE C-4. - Shale bed temperatures during run 11 for thermocouples 29-44.

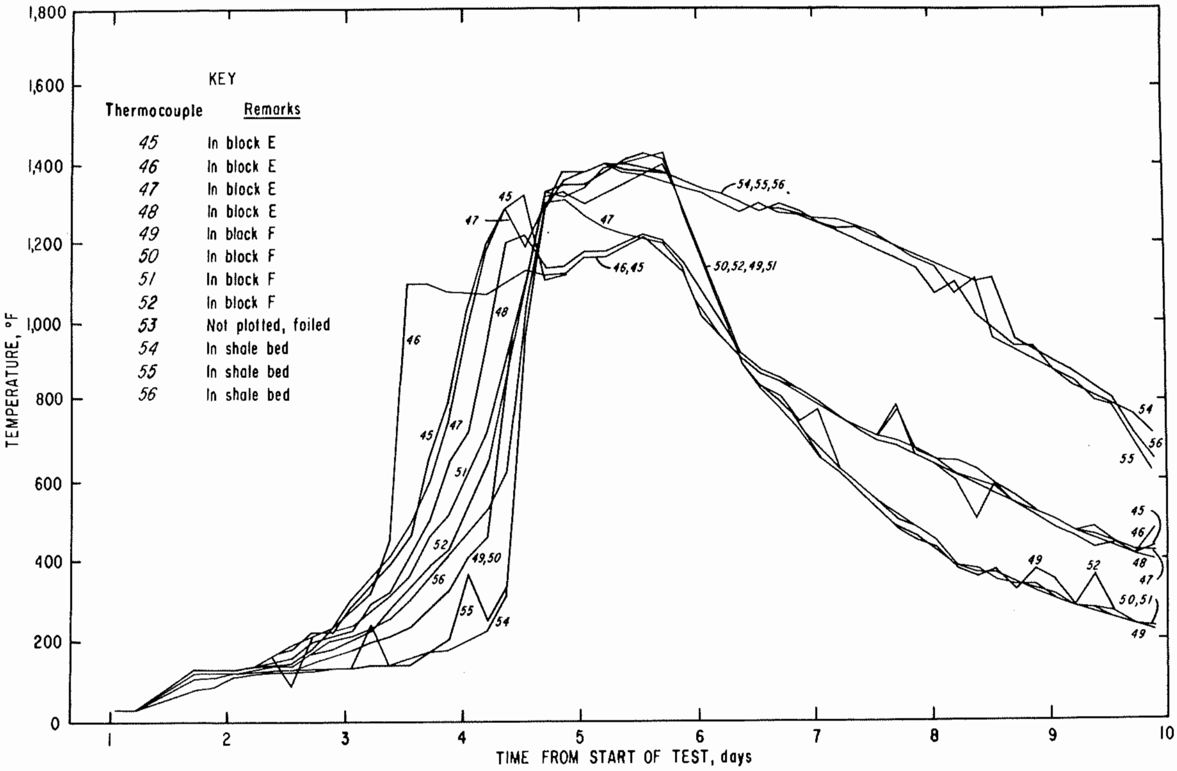

FIGURE C-5. - Shale bed temperatures during run 11 for thermocouples 45-56.

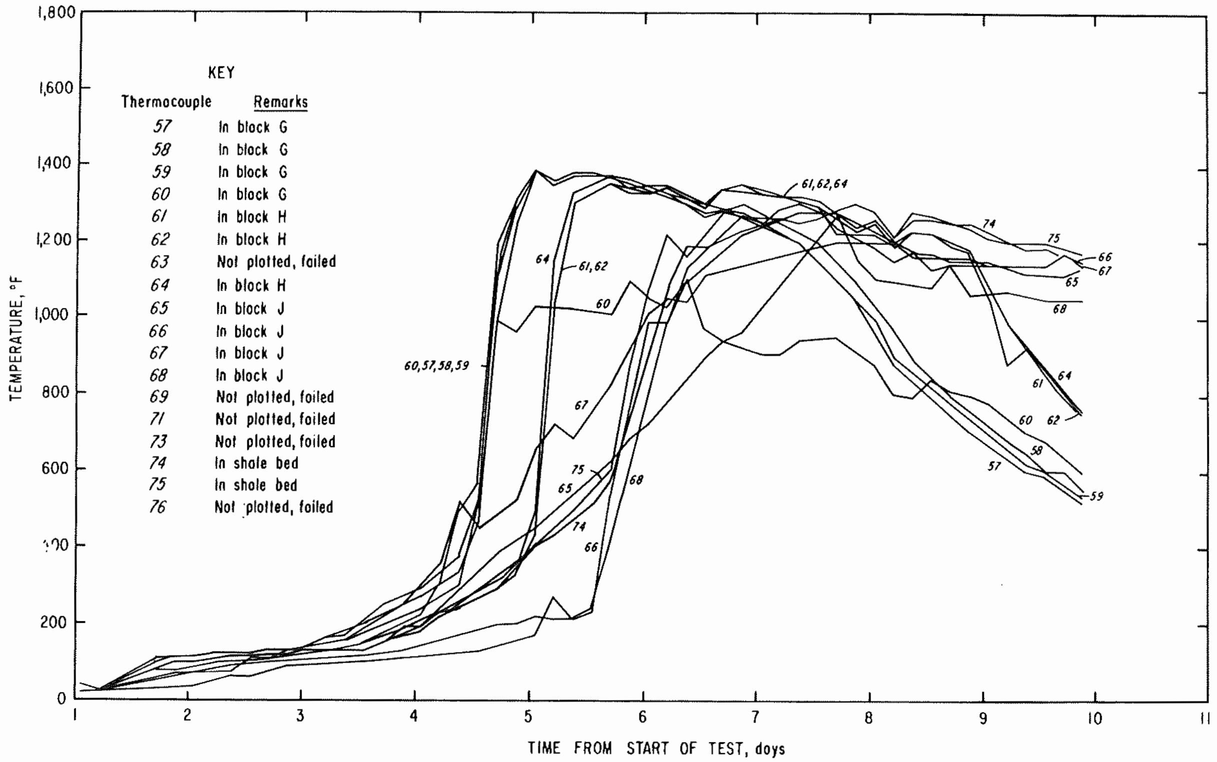

FIGURE C-6. - Shale bed temperatures during run 11 for thermocouples 57-69, 71, 73-76.

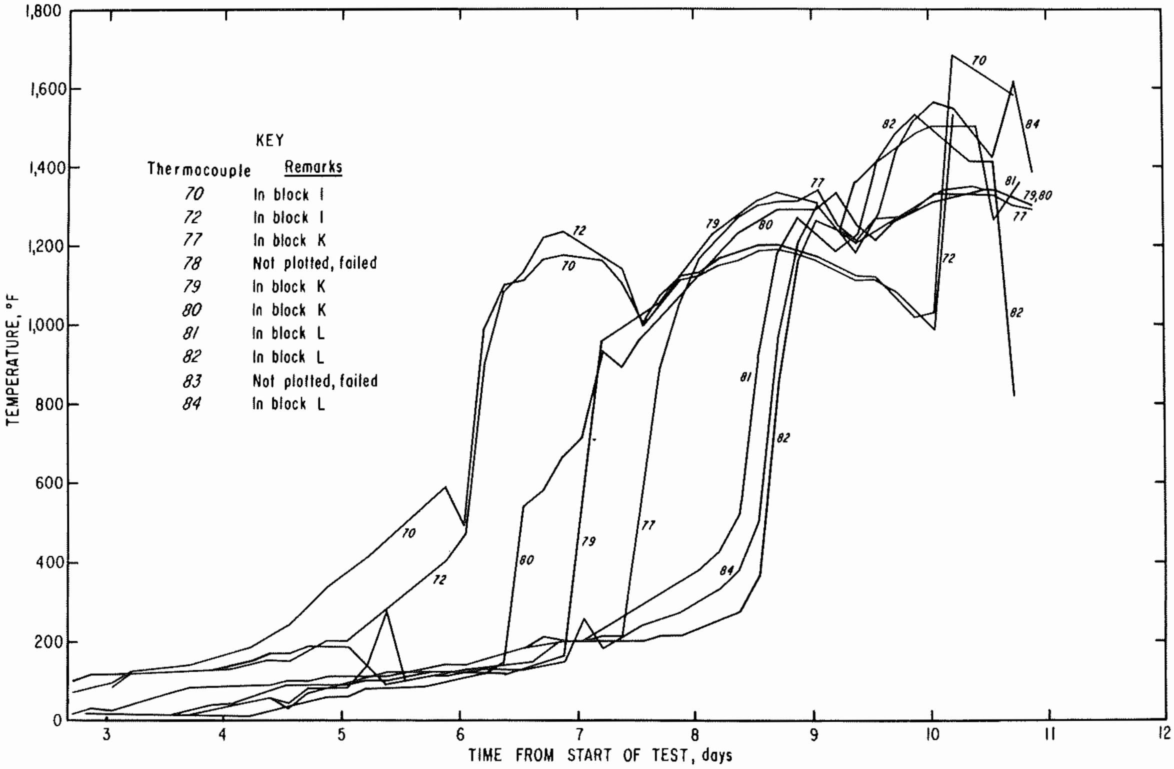

FIGURE C-7. - Shale bed temperatures during run 11 for thermocouples 70, 72, 78-84.

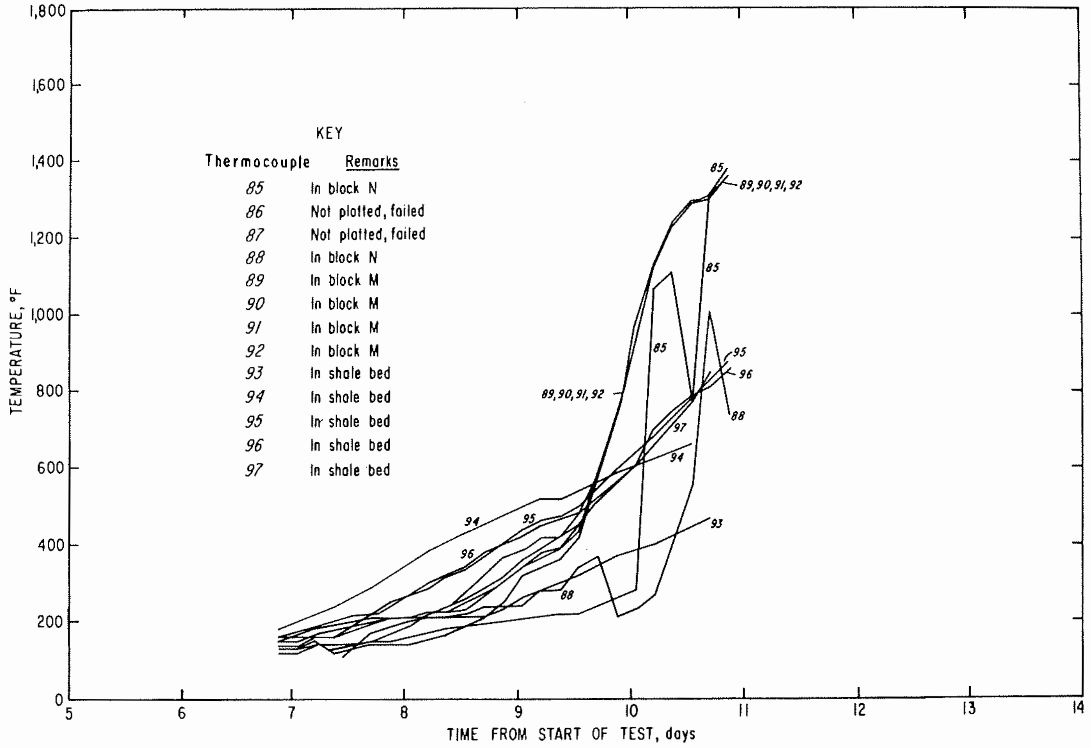

FIGURE C-8. - Shale bed temperatures during run 11 for thermocouples 85-97.

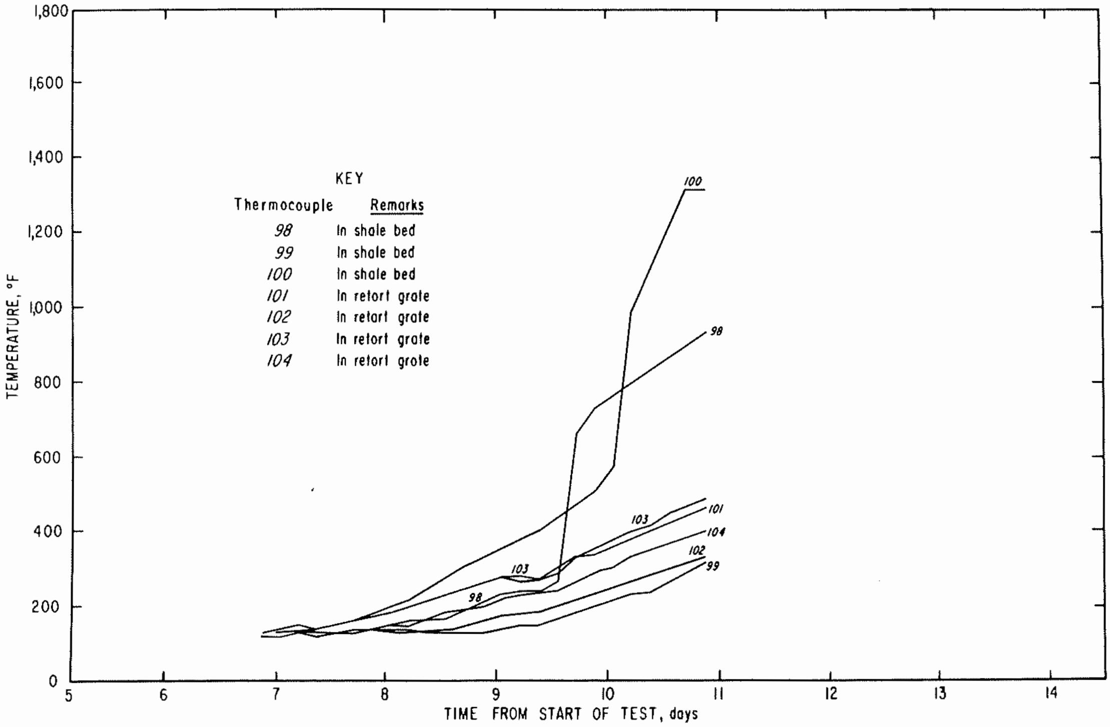

FIGURE C-9. - Shale bed temperatures during run 11 for thermocouples 98-104.