ENERGY EFFICIENCY OF THE GARRETT IN SITU OIL SHALE PROCESS

Chang Yul Cha and Donald E. Garrett

The economic analysis of return on investment and total capital cost usually provides the principal data for comparing various processes. However, the continuing energy crisis is leading to a new awareness of how much energy is used in producing usable energy from alternate solid fuels resources. An energy analysis can reveal the specific energy inputs at each step in the process. The analysis can include the direct energy used for fuel and to run machinery, as well as the energy required to make available each of the input materials, tracing them back to their primary sources. An energy analysis is necessary to determine the energy required for each alternative, and can furnish new insights that can be used to develop quantitative parameters for private and public decision-making regarding energy use and recovery of energy resources. To begin an energy analysis it is necessary to define the system and its boundary.

The Garrett process consists of two basic steps:

(1) forming the in situ retorts by mining approximately 15 percent of the shale deposit, and by blasting to expand the remaining rock to fill the entire volume, and
(2) retorting the expanded oil shale in place using underground combustion.

Based upon the results of three actual in situ test retorts, a mining plan, retorting sequence, gas and oil handling equipment, and auxiliary facilities for producing shale oil at 30,000 barrels per day have been developed, and operating and capital cost estimates have been made. The retort is assumed to be approximately 120 by 120 feet in horizontal cross section, and 300 feet high. The retorting is accomplished by blowing a mixture of air diluted with recycle gas to a controlled oxygen concentration. The gas velocity entering the retorts is also closely controlled. The following energy analysis will be based upon the results of this study.

Chang Yul Cha, Group Leader, Oil Shale, Garrett Research and Development Company, Inc.
Donald E. Garrett, President, Garrett Research and Development Company, Inc., 1855 Carrion Road, La Verne, California 91750.

ENERGY CONTENT OF OIL SHALE

One ton of rubblized oil shale is chosen as a basis for the energy calculations. The initial energy content of the oil shale can be evaluated from the elemental composition of its combustible constituents. A typical composition of the organic material in Colorado oil shale is shown in table 1 (Smith 1961).

TABLE 1.—*Organic composition of oil shale.*

(Mahogany Zone, Colorado)

Element	Weight %
Carbon	80.5
Hydrogen	10.3
Nitrogen	2.4
Sulfur	1.0
Oxygen	5.8

Since the Fischer assay is customarily used to measure oil shale grade, the concentration of kerogen may be approximately expressed in terms of its Fischer assay as follows (Cook 1974):

Concentration of kerogen = 11.21F lb/ton (1)
where F = gal/ton.

Using the heat of combustion for the elements shown in table 1, and the above equation, the energy content of kerogen has been calculated as:

Energy content of oil shale = 197,809F Btu/ton. (2)
This energy is distributed into various products by the thermal decomposition of kerogen approximately as follows:

Oil	139,287F
Combustible gases	29,707F
Residual carbon	28,815F
Total	197,809F

ENERGY INPUT

Conversion factors for the Btu requirements per dollar of equipment cost have been obtained from the 1967 Census of Manufacturer's data (Oregon Energy Study 1974), adjusted by the Wholesale Price Index for 1975:

	Btu per dollar of initial cost
Compressors, pumps, transmission lines	41,278
Mining and construction equipment	36,203
Concrete and steel for construction	40,000
Engines and turbines	33,776

With these conversion factors, the energy input at various steps in the Garrett in situ oil shale process has been calculated from operating and capital cost estimates for producing the shale oil at 30,000 barrels per day for 20 years. The energy for life-support of manpower and for transportation of products has been neglected as a minor item. The electric energy required for gas compression and pumping was multiplied by 2.89 in order to convert to the equivalent Btu for their primary fuel sources. A list of energy inputs by such calculations follows:

A. Initial installation
  (1) Mine equipment = 967 Btu/ton
  (2) Retorting equipment and piping = 4,022 Btu/ton
  Subtotal = 4,989 Btu/ton

B. Operation
  (1) Equipment replacement and continuing construction of retorts = 10,872 Btu/ton
  (2) Electrical energy for pumps and blowers in the mine = 11,253 Btu/ton
  (3) Diesel fuel used for drilling and blasting = 5,693 Btu/ton
  (4) Explosives = 1,495 Btu/ton
  (5) Electrical energy for pumping of liquid products = 107 Btu/ton
  (6) Electrical energy for gas compression required for retorting = 22,722 + 5154F Btu/ton
  (7) Initial heatup of retort = 14,600 Btu/ton
  Subtotal = 66,742 + 5154F Btu/ton
  Total energy input = 71,731 + 5154F Btu/ton (3)
  F = Fischer assay, gal/ton.

It can be seen that the energy required for gas compression is more than 50 percent of the total energy input, and, unless carefully controlled, can represent a significant loss.

ENERGY OUTPUT

Since the amount of residual carbon resulting from the thermal decomposition of kerogen is more than enough to supply the heat required for the retorting process, and a significant amount of sensible heat is contained in the processed (retorted) shale, both primary and secondary recoveries should be considered.

PRIMARY ENERGY RECOVERY

Shale oil and combustible gases are produced from retorting. Also experimental data from three in situ tests indicate that much of the residual carbon can be recovered by a water gas reaction either during primary recovery, or later as a secondary recovery.

Shale oil energy output $= 139{,}287F\eta$ Btu/ton

where η is the fractional oil yield with respect to Fischer assay. The oil yield is dependent upon the Fischer assay, the operating conditions, the shale particle size and size distribution. This oil yield as a function of Fischer assay for a given set of operating conditions and particle size distribution is shown in figure 1. These values have been calculated from the mathematical model of the Garrett in situ process. The calculated values showed reasonably good agreement with the experimental data.

An examination of experimental data from three in situ retorts indicates that approximately 19,225 Btu/ton of combustible gases can be recovered from the residual carbon by water gas reactions. The energy output in the form of gas is as follows:

Energy output $= 48{,}932F$ Btu/ton

then, total energy output from primary recovery is given by the equation:

$$139{,}287F\eta + 48{,}932F \text{ Btu/ton} \qquad (4)$$

Energy Loss During Primary Recovery

The energy losses during primary recovery is dependent upon operating conditions and therefore has been included in calculating energy output in terms of the oil yield. However, in order to see some insight to what factors contribute to this energy loss, the approximate estimates of the energy loss at a typical operating condition are given as follows:

(1) Heat loss in the off-gas $= 8{,}500 + 718F$ Btu/ton
(2) Heat loss in the liquid products $= 9{,}000 + 438F$ Btu/ton
(3) Heat loss in the uncondensed water $= 40{,}000 + 3{,}395F$ Btu/ton

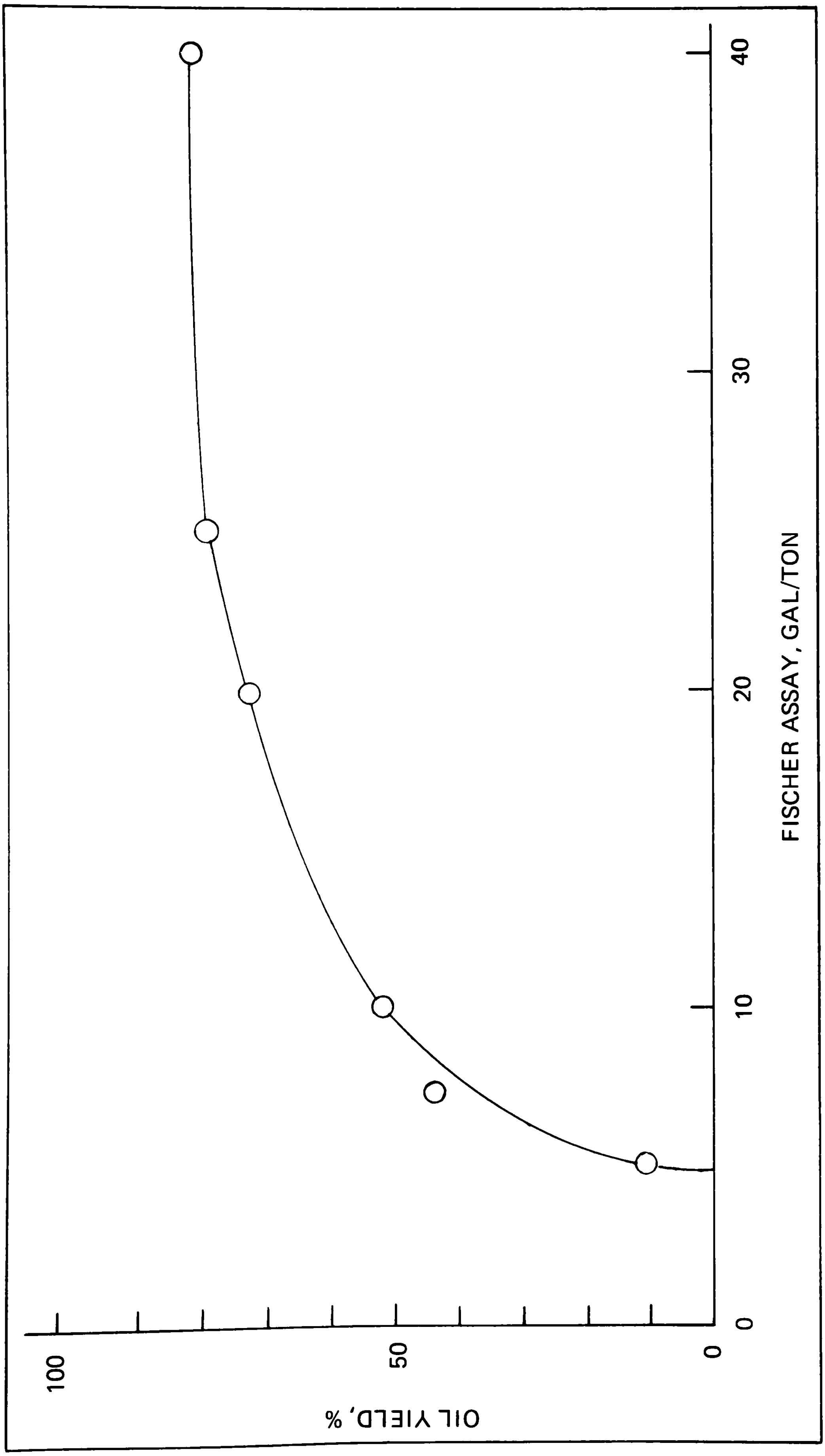

Figure 1.—Oil yield as a function of Fischer assay.

(4) Heat loss due to inorganic carbonates thermal decompositions = 197,000 Btu/ton

(5) Heat loss to the surroundings = 136,500 Btu/ton

These calculations assume that the initial oil shale temperature is 60°F and the inlet air temperature is 60°F. The gas leaves at 120°F while the oil and water products leave at 100°F. The inlet gas is assumed to be saturated with water.

As shown above, the energy loss due to thermal decomposition of inorganic carbonates is more than 40 percent of the total energy loss. Therefore, reducing the thermal decomposition of inorganic carbonates by reducing the retorting temperature can significantly decrease the energy loss.

SECONDARY ENERGY RECOVERY

Based upon theoretical calculations, approximately 14.3 percent of the residual carbon is available for secondary recovery when the Fischer assay of oil shale is greater than 10 gallons per ton. Assuming that the water gas reaction is used to recover the residual carbon, and 75 percent of residual carbon reacts with the water and oxygen, the energy output from residual carbon is 2318F Btu/ton. Run-2 data from Laramie Energy Research Center (Harak and others 1974) shows that the enthalpy of spent shale was on the average 343,100 Btu/ton. If we assume that 80 percent of this sensible heat can be recovered through air heat exchange or the water gas reaction, the total energy output from secondary recovery is

$$2{,}318F + 274{,}480 \text{ Btu/ton} \qquad (5)$$

NET ENERGY EFFICIENCY

The net energy output is obtained by subtracting the total energy input [eq. (3)] from the total energy output [eqs. (4) and (5)]. The results are as follows:

A. Net energy output by primary recovery

$$= 139{,}287F\eta + 43{,}778F - 71{,}731 \text{ Btu/ton} \qquad (6)$$

B. Net energy output by primary and secondary recovery

$$= 139{,}287F\eta + 46{,}096F + 202{,}749 \text{ Btu/ton} \qquad (7)$$

Net energy efficiency now can be obtained by dividing equation (6) or (7) by equation (2):

C. Net energy efficiency by primary recovery

$$\epsilon_1 = 0.70415\eta + 0.22131 - 0.36263/F \qquad (8)$$

D. Net energy efficiency by primary and secondary recovery

$$\epsilon_2 = 0.70415\eta + 0.23303 + 1.0250/F \qquad (9)$$

Energy efficiency as a function of the Fischer assay of oil shale is shown in figure 2. It should be pointed out that equations (7) to (9) are applicable when the Fischer assay of oil shale is greater than 10 gallons per ton.

RATIO OF ENERGY OUTPUT TO ENERGY INPUT

The ratio of energy output to energy input from primary recovery can be obtained from equations (3) and (4):

$$\text{Ratio} = \frac{\text{Total energy output}}{\text{Total energy input}}$$

$$= \frac{139{,}287F\eta + 48{,}932F}{71{,}731 \quad + 5{,}154F} \qquad (10)$$

The ratios for the various Fischer assays of oil shale are calculated from equation (10) and plotted in figure 3.

As shown in figures 2 and 3, the energy efficiency and the ratio of energy output to energy input are dependent on both Fischer assay of oil shale and operating conditions. Net energy efficiency for the Garrett in situ oil shale process is from 55 to 80 percent for oil shale grades of 10 to 40 gallons per ton. The ratio of energy output to energy input is from 10 to 24 for oil shale grades of 10 to 40 gallons per ton. The energy analysis has revealed that the Garrett in situ oil shale process gives high energy efficiency. This energy efficiency can be increased by optimizing the process.

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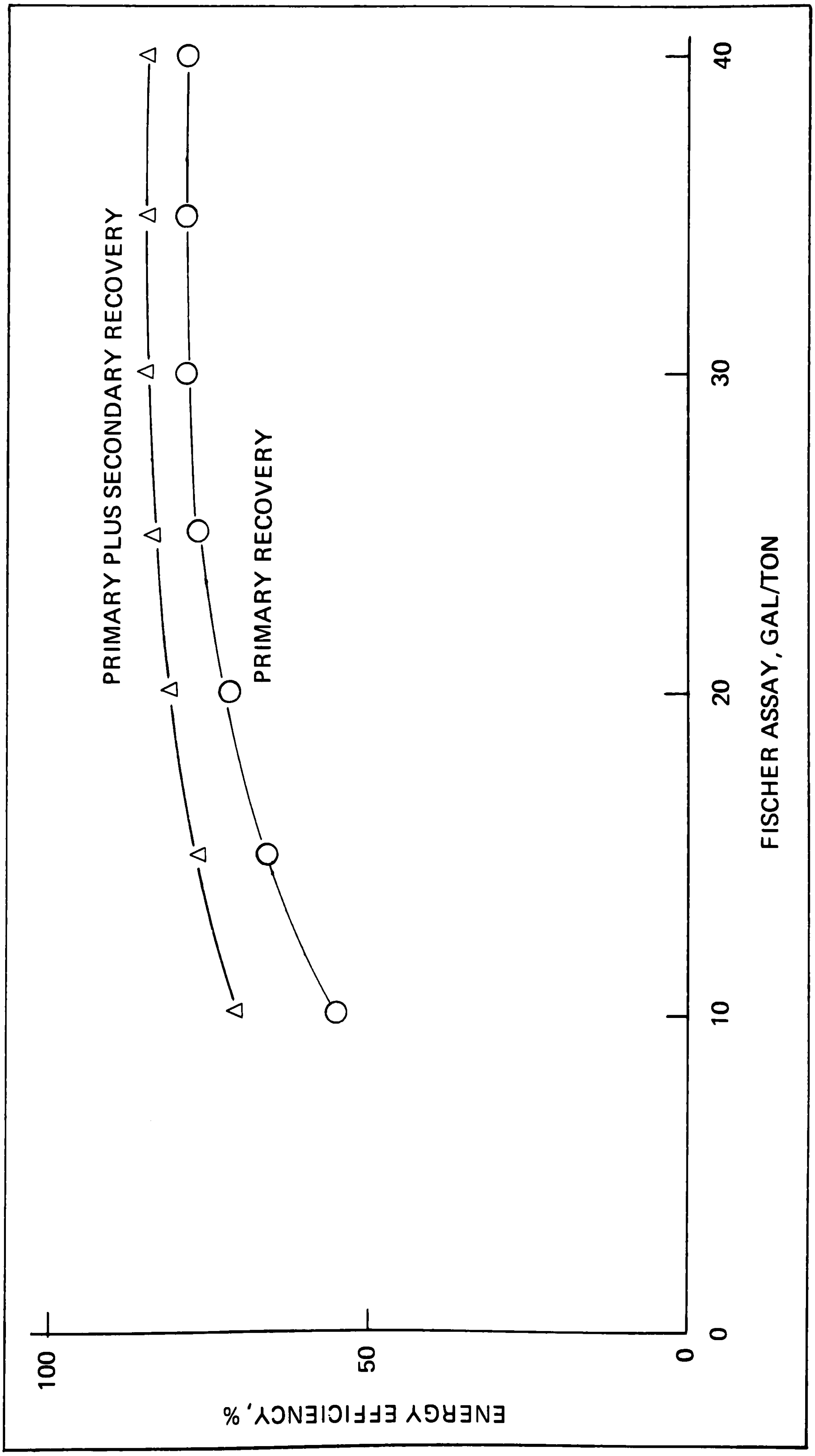

FIGURE 2.—Energy efficiency.

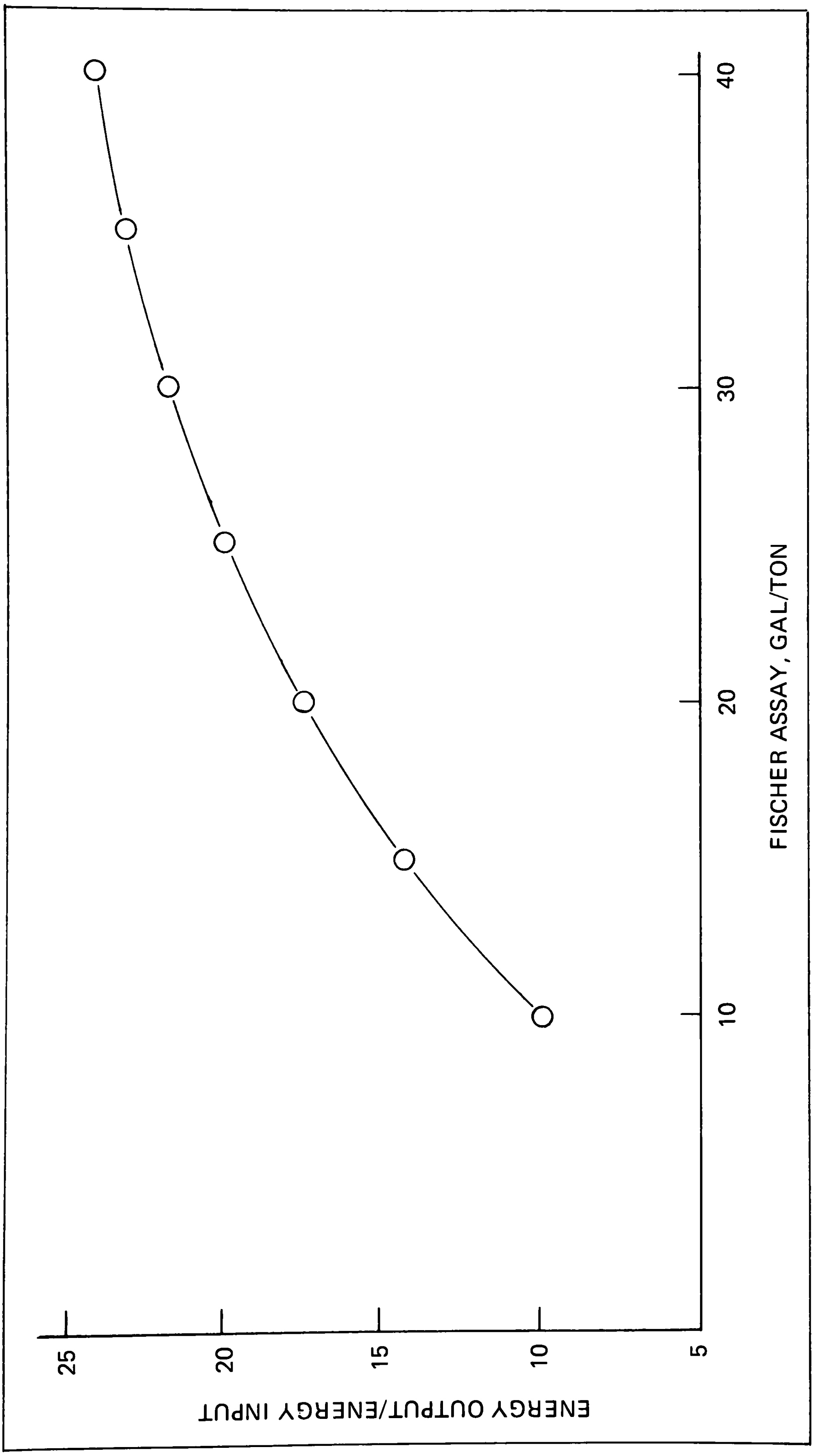

FIGURE 3.—Ratio of energy output to energy input (primary recovery).