MOBIL OIL CORPORATION
Research Department
Rifle, Colorado

Anvil Points Oil Shale Research Center

ECONOMIC ANALYSIS OF CRUDE SHALE OIL PRODUCTION USING THE GAS-COMBUSTION RETORT

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Gentlemen:

REPORT NO. 67.74 AP
ECONOMIC ANALYSIS OF CRUDE SHALE OIL PRODUCTION USING THE GAS-COMBUSTION RETORT

This is the last in a series of seven final summary reports covering specific research programs performed under the auspices of the Initial Program at Anvil Points. A single final report containing a summary of the most important findings and conclusions related to the entire Initial Program will also be issued.

The economic studies performed at Anvil Points and used for research guidance during the Initial Program are summarized herein. Because of the contractual constraints on the scope of the work, this analysis does not comprehensively treat a shale oil production complex. Refining, pipelining, water supply, land, research and development, and financing costs and depletion allowance have been excluded. However, the mining, crushing, retorting and off-site cost analyses are reasonably comprehensive and may be used as "building-blocks" for more complete proprietary studies.

A hypothetical 50,000 B/CD mining-crushing-retorting complex which processes 30 gallon per ton oil shale has been used as the basis. The oil shale deposit and outcrop cliff topography of Anvil Points were assumed. A complex comprising a two-level room-and-pillar mine, an underground two-stage crushing plant, and a Gas-Combustion Retort facility was analyzed. Calculated costs, including capital charges, were distributed as follows:

Mining	44%
Crushing	14%
Retorting	27%
Utility and Service Facilities	15%
	100%

A novel, relatively untested technique, based on subjective probability, was used to analyze the uncertainty of crude shale oil producing cost. Further application of this technique to economic analysis should prove worthwhile.

Yours truly,

R H Cramer

R. H. Cramer
Program Manager

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ECONOMIC ANALYSIS OF CRUDE SHALE OIL PRODUCTION USING THE GAS-COMBUSTION RETORT

INTRODUCTION

The former U. S. Bureau of Mines facility at Anvil Points, near Rifle, Colorado, was reactivated starting in May 1964 and was operated during 1965, 1966, and 1967. A research and development program was conducted to investigate the technical feasibility of room-and-pillar mining with explosives, crushing and Gas-Combustion Retorting techniques for oil shale. Mobil Oil Corporation acted as Project Manager for the cooperative industry group at Rifle which included Continental Oil Company, Humble Oil & Refining Company, Pan American Petroleum Corporation, Phillips Petroleum Company, and Sinclair Research, Inc. as Participating Parties. Costs of the Rifle operation were shared equally by the six participants. Each Participating Party was represented by personnel on the technical staff. The Colorado School of Mines Research Foundation, Inc. acted as lessor-of-record and supplied nontechnical personnel for administrative and logistic support.

The planned research program at Rifle consisted of two 18-month stages: Stage I, to determine retorting feasibility in small-scale pilot plant equipment and to provide information as to whether or not to continue the Rifle program; Stage II, to operate large-scale pilot plant equipment to develop information for scale-up to commercial-size retort elements and to conduct mining and crushing research. Because of technical difficulties with the retorting process, Stage I, which was initiated in May 1964, was extended by six months. These technical difficulties were resolved and Stage II commenced in April 1966. Experimental work was concluded in September 1967.

The final reporting from the Anvil Points project has been structured in pyramidal fashion. Reporting for three levels of interest has been implemented:

- General Management Summary - a single volume summary report covering the entire project.

- Technical Management Summary - seven reports, each summarizing work in a specific area, i.e., mining, crushing, retorting, mechanical models, mechanical engineering, analytical laboratory, and economics.

- Technical Detail - the mass of data transmissions, Monthly Progress Memoranda, Technical Memoranda, Weekly Newsletters, Technical Advisory Committee and Technical Observer presentations.

This is the Technical Management Summary report dealing with the economics of oil shale processing.

This study, which is based on the work carried out during the Initial Program at Anvil Points, is intended to summarize the economic analysis effort which has guided the research during the Initial Program and to provide a point of departure for comprehensive in-house economic evaluations of oil shale processing. A hypothetical mining-crushing-retorting complex designed to produce 50,000 B/CD of crude shale oil from 30 gallon per ton oil shale has been used as the basis for this study. Because refining, pipelining, and water development are beyond the scope of the work done in the Initial Program, these are not considered. These factors will have a profound effect on the economics of oil shale processing and must be considered in a more comprehensive analysis.

In considering a multifunctional complex such as this, the interaction of one portion of the complex with the remaining parts must be kept in mind. A danger of suboptimizing a component of the complex exists. For example, at fixed oil production, a decrease in retorting yield increases the quantity of shale that must be mined, and processed in the crushing plant. Also, at fixed oil production, if a particular combination of crushing and screening equipment increases the production of shale that will pass a 1/4-inch screen, mine and crushing plant production must be increased if it is assumed that minus 1/4-inch shale cannot be processed. A third interaction involves the mine and the crushing plant. A choice is available between crushing shale in the crushing plant or in fragmenting it in the mine with explosives. With all three of these interactions, the chosen alternative which is used in this study is either demonstrably optimum or judged to be so.

A preliminary study dealing with the economic optimum operating conditions for the Gas-Combustion Retort weighed heavily in planning the Initial Program of research (1), particularly the crushing and retorting portions. Two recent memoranda (2, 3) re-evaluated these conditions in light of all of the Initial Program experience. A preliminary evaluation of the cost of underground mining of oil shale was also made (4). These costs have been reviewed after the completion of the Initial Program mining research, and a cost analysis has been prepared (5). The Technical Management Summaries dealing with mining and crushing (7, 18) also discuss the cost of production in their respective plant areas. These three plant cost memoranda (2, 3, 5), plus an additional memorandum (6) which established a set of economic

(1) See references listed in Bibliography.

analysis guidelines and contained off-site facility, plant overhead and administrative expense estimates, have formed the groundwork upon which this report is based.

SUMMARY AND CONCLUSIONS

An analysis has been prepared to summarize the economic studies which have been used for research guidance during the Initial Program, and to provide a starting point for comprehensive proprietary economic evaluations of an oil shale processing venture. Four memoranda (2, 3, 5, 6) have been previously issued which deal in a more detailed fashion with the operating and capital costs of mining, crushing, retorting and their attendant utility and service facilities. Because of the limited scope of the Initial Program, significant parts of such a venture are not considered. These include refining, pipelining and water supply development.

A hypothetical 50,000 B/CD mining-crushing-retorting complex which processes 30 gallon per ton oil shale has been used as the basis for this economic analysis. This plant is assumed to be located in Colorado with the oil shale outcrop, cliff topography of Anvil Points. Two level, room and pillar mining is used. The shale is crushed underground using two single roll primary crushers and this product is stored underground in surge bins. These bins discharge to six standard cone secondary crushers which are also located underground. The secondary crusher product is fed to a screening plant located at the retorting plant elevation. This screening plant prepares three products, two of which are used as feed for the Gas-Combustion Retorts. These are 1/4- to 1-inch and 1- to 2 1/2-inch shale. The third fraction, which is 1/4 inch minus shale, is transferred to a fines processing facility adjacent to, but outside of the bounds of this hypothetical complex. The Gas-Combustion Retort feed fractions are processed in four retorting subplants, each of which include batteries of retort elements, recycle and air blowers as well as raw and spent shale handling systems. Spent shale handling is restricted to controlling its flow from the retorts. Spent shale disposal facilities are not within the bounds of the complex of this analysis, they are allowed for by estimating a spent shale disposal cost (3). The crude shale oil produced in this complex is not a finished product. Before it can be pipelined from the complex, some refining is required.

Much of the technology upon which this complex is based has been developed during the Initial Program carried out at Anvil Points. An implicit assumption which has been made in this analysis is that this Initial Program technology can be translated to commercial scale. This assumption is not completely justified, however. In the mining area, insufficient data were obtained for reliable design of shale pillars, and the extent of rib scaling, which is necessary during benching operations, was not clearly defined (7). In the retorting area, it has been concluded that additional work will be necessary before scale-up with 1/4- to 1-inch (or 1/4- to 2 1/2-inch) shale could be recommended. The reason for this lack of confidence is the operability problems that were experienced in Retort No. 3 with these two fractions (8).

The most significant yield loss in the Gas-Combustion Retort process is the loss of normally-liquid hydrocarbons as dilute vapor in the large volume of low pressure product gas (8). An economic analysis of this problem has indicated that the main deterrent to economical processing of retort gas is the low pressure at which it is available (10).

Within these constraints and with these reservations in mind, the investment in this complex has been projected. It is summarized in the following table:

	Total Fixed Capital Investment
Mining	$11,600,000
Crushing	15,100,000
Retorting	27,300,000
Utility and Service Facilities	15,600,000
	$69,600,000

As stated previously, refining and pipelining facilities and water supply development are excluded from this summary. Investment costs due to land acquisition, access road construction, utility access line construction, mine road construction, mine utility access line construction, site preparation and allocation of working capital have also been omitted. Labor and equipment costs used in this analysis are based on 1966 wages and prices, respectively. No escalation of either wages or prices has been assumed.

The most significant investment component is the retorting plant. The relatively low total investment compared to reported investments needed for oil shale processing, reflects the incomplete nature of this analysis rather than unusual economy of design. The individual component investments are probably most useful as building blocks in more comprehensive studies.

The operating cost and the cost of capital for each component part of the complex are tabulated below. (Cost of capital is defined as the cost due to capital recovery while earning a 10% discounted cash flow return on the investment, after taxes.)

Basis: 50,000 B/CD Crude Shale Oil	Mining, ¢/bbl	Crushing, ¢/bbl	Retorting, ¢/bbl	Utilities & Service Facilities, ¢/bbl	Total, ¢/bbl
Operating Cost	65.8(1)	11.2	21.6(2)	11.6(3)	110.2
Cost of Capital	20.2	17.1	31.5	18.0	86.8
Total	86.0	28.3	53.1	29.6	197.0

(1) Includes mine development cost
(2) Includes by-product disposal cost
(3) Includes plant overhead and administrative expense

These operating costs all include allowances for labor and supervision, operating and maintenance materials, utilities, insurance and property tax. Research and development charges, financing charges, depletion allowance credit, royalty charges and distribution and selling charges, where appropriate, are excluded from these operating costs.

The largest operating cost component by far is that due to mining - 60% of the operating cost. Labor and supervision, and operating materials including explosives, fuel and tires are the major factors in the high mine operating cost. The highest cost of capital component is retorting, which reflects the relatively high investment in that area. The highest total component in crude shale oil production cost is that due to mining. Forty-four percent of the total cost is due to this component.

The research strategy of increasing mine run yield in order to find the economic optimum operation for a crude shale oil production complex is effective because of the high mining component in the total production cost. Mine run yield, expressed as barrels of oil produced per ton of oil shale mined, may be increased by increasing retort yield, decreasing the fraction of shale mined that cannot be retorted, and increasing the richness of the shale. This last variable can only be varied in a very limited way because of increasing retort operability problems as the assay is increased and because of the distribution of shale richness in minable shale beds.

A novel, but relatively untested, technique has been used to evaluate the uncertainty in the estimate that 50,000 B/CD crude shale oil can be produced at 197.0 ¢/bbl. The method is based on a subjective probability analysis of the various cost items of the estimate. Using this method, a cumulative probability distribution of crude shale oil production cost can be developed. This distribution curve indicates that there is a 96% probability that crude shale oil production cost, within the constraints and qualifications of this report, will be equal to or less than 197.0 ¢/bbl.

DETAILED REPORT

A. General Economic Bases (1)

1. On-site Investment and Operating Expense

The mining-crushing-retorting complex, which is the subject of the economic analyses upon which this report is based, has been designed to produce 50,000 B/CD of crude shale oil from 30 gallon per ton oil shale. This plant has been assumed to be located in Colorado with the oil shale outcrop, cliff topography of Anvil Points. The elevations of the mine, the crushing, and the retorting plant areas are shown in Figure 1.

Refining, pipelining, and water development are beyond the scope of the work done in the Initial Program, therefore, these are not considered in this report. Because of the specific nature of land cost, access road construction, and site preparation (other than mine development), these have also been excluded. Company policies with regard to research and development cost, financing and provision of working capital vary widely and so they, also, have not been considered. Depletion allowance and royalty policies with regard to oil shale are not clearly established so these have been omitted from this investigation.

The investment estimation guidelines which have been used in these studies are summarized in Table 1. A 15-year project life, the "sum-of-the-years digits" depreciation method and no salvage value have been used as the bases for the equipment depreciation calculation. The equipment life has been assumed to be equal to the project life in the retorting and crushing parts of the complex. The mining equipment has been estimated to have an average life of about five years (5). Since mine development has been assumed to start before plant startup, there is an undepreciated portion of the mining investment at the end of the project. This undepreciated investment is assumed to be recovered. An investment schedule for the crushing, retorting, and off-site investments based on Anvil Points experience has been set forth. The estimated project development during this pre-production period is shown in Figure 2. Sixteen percent of the investment, excluding the mining investment, will occur in the first year of this period. In each of the three subsequent years, 28% of the investment, excluding the mining investment, will occur. The investment which is made according to this schedule is assumed to have a useful life equal to the project life. Since the mining equipment has an average life of five years, periodic re-investment in mining equipment occurs throughout the life of the project. Equipment cost estimates have been based on 1966 prices. No escalation of equipment costs from this base has been assumed.

FIGURE 1

MINING-CRUSHING-RETORTING COMPLEX FOR PRODUCTION OF CRUDE SHALE OIL

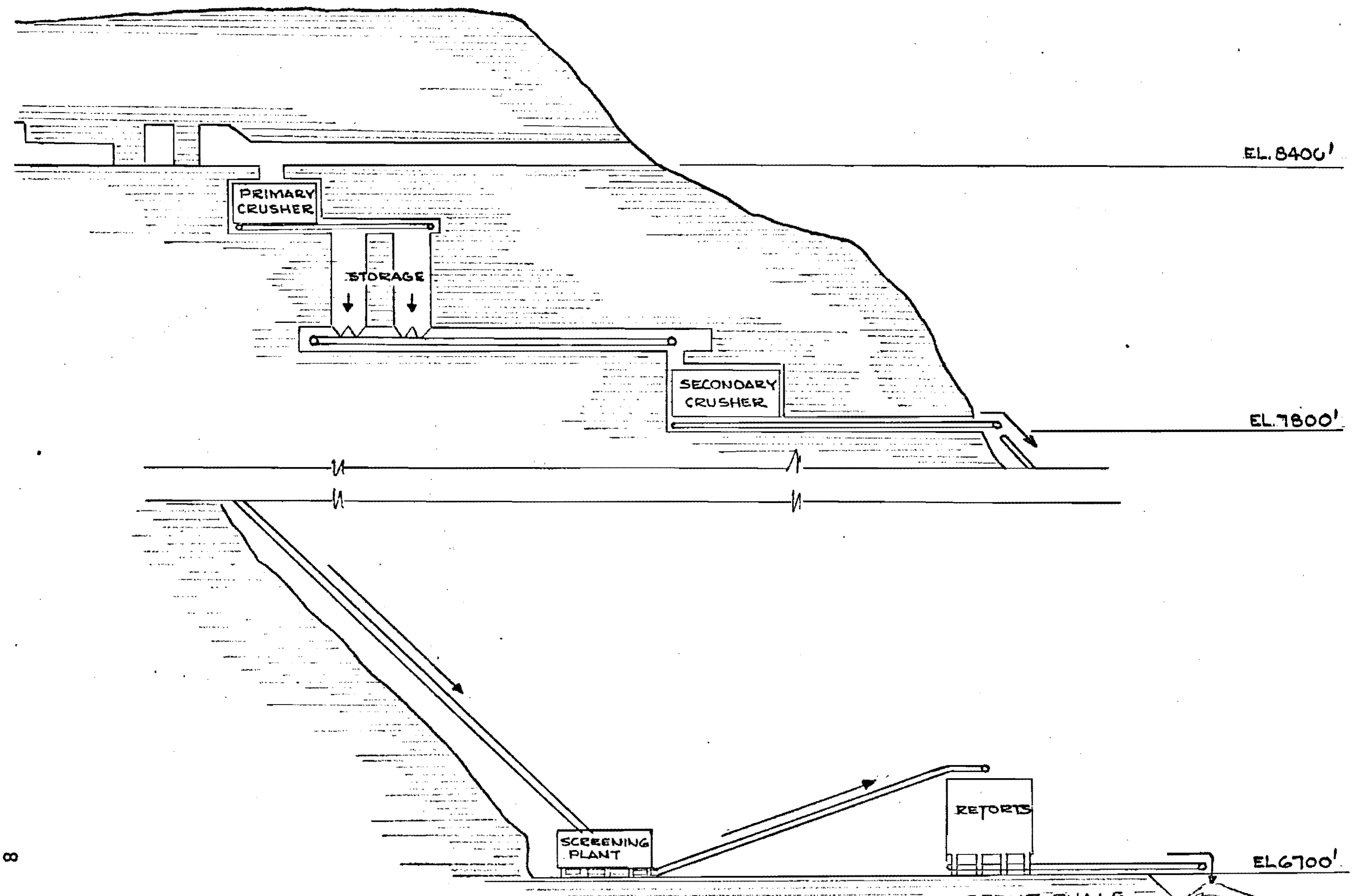

TABLE 1

GUIDELINES FOR INVESTMENT ESTIMATION

Direct Cost	Method of Estimation
Process Equipment a. Stationary Equipment b. Mobile Equipment	Detail of these estimates varies for each element of complex. See pertinent memorandum for description of technique used.
Mobile Equipment Erection Cost	1% of mobile equipment investment.
Off-Sites a. Utilities b. Services	See Table 3 for Off-Sites investment estimate.
(Each of these items are included as operating expenses during pre-production period.)	
1. Freight on equipment	$ .03/$ uninstalled equipment investment.
2. Colorado Sales and Use Tax on equipment	$ .03/$ uninstalled equipment investment.
Indirect Cost	
Engineering and Construction (Includes design services, field engineering, field offices and supervision, temporary construction overhead).	$ .25/$ stationary equipment investment.
Contractor's Fee	$ 07/$ stationary equipment investment.
Contingency	$ .15/$ total equipment investment.
Land Cost (including access roads)	Excluded from estimate.
Working Capital	Excluded from estimate.

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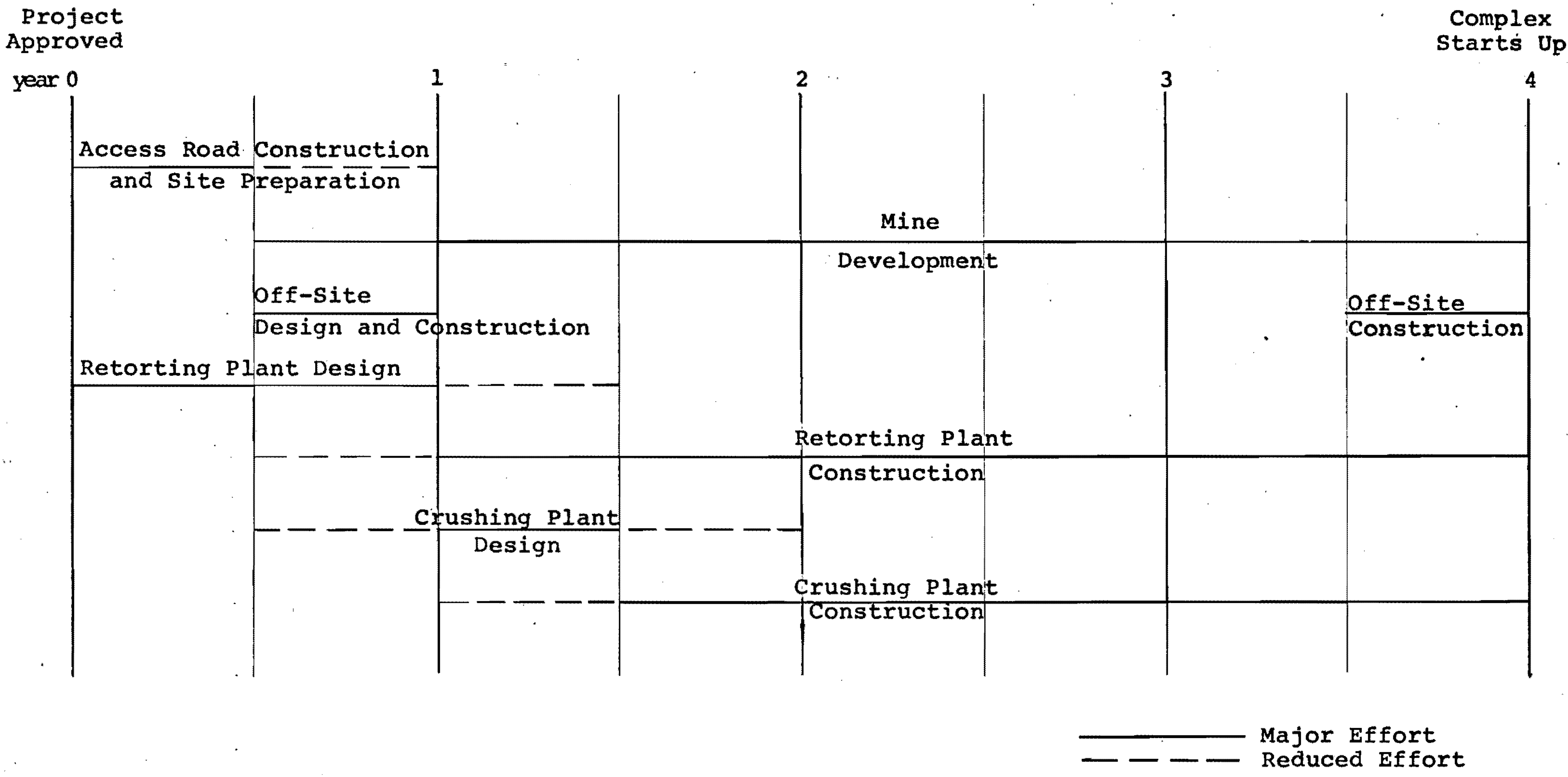
FIGURE 2

ESTIMATED PROJECT DEVELOPMENT DURING
PRE-PRODUCTION PERIOD



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A 10% rate of return, on a discounted cash-flow basis, has been assumed in calculating the overall price of crude shale oil.

A federal income tax of 50% and a Colorado state income tax of 5% have been considered in these analyses. An investment credit of 7% has been allowed on qualifying investments. Although this credit had been suspended in 1966, it was reinstated on March 9, 1967 and is considered to be a probable feature of the tax structure in the future.

The operating cost estimation guidelines are listed in Table 2. Labor costs are based on 1966 wage rates and no escalation of labor costs has been assumed.

2. Off-site Investment, Plant Overhead, and Administrative Expense

A separate cost estimate has been made for the utility and service facilities for the mining-crushing-retorting complex. This estimate prevents possible duplication or omissions that could occur if an off-site estimate were included with each of the on-site cost estimates, and should also improve the accuracy of the off-site cost estimate. Estimated investment for the off-site facilities is $15,700,000, while the total cost chargeable to these facilities is 29.6 ¢/bbl.

The revised cost estimates for mining and crushing were not complete when the off-site cost estimate was made. Consequently, these costs were based on earlier studies (4, 11) as well as the Allis-Chalmers flowsheet-type design for an 84,000 tons per calendar day crushing plant (12). Cost estimating was done by detailed estimates where the off-sites could be sufficiently defined, or as a percentage of the on-site cost where the off-site requirements could not be well defined.

The off-site facilities include all utility and service functions except utility lines into the plant and between the plant and the mine, and the road connecting the plant area and the mine. No storage and handling facilities are included.

The investment in utilities and services is detailed in Technical Memorandum No. 67-28 (6). The investment guidelines used have been described in Table 1. The direct investment in utility facilities is $4,700,000 and includes a 45,000 kva electrical system, a 30,000 lb/hr steam system and a 864,000 gallon per day water system. The direct investment in service facilities is $5,600,000. The total investment in these facilities is summarized in Table 3. The plant overhead and administrative expense were also directly estimated and are presented in Table 4. The guidelines used are described, in part, in Table 2 of this report.

TABLE 2

GUIDELINES FOR OPERATING COST ESTIMATION

Direct Production Costs	Method of Estimation	
Maintenance Labor	$3.25/man hour (1)	No. of men directly estimated
Mining Labor	$3.25/man hour (2)	
Operating Labor	$3.00/man hour (1)	
Underground differential	$0.05/$ direct wage	
Maintenance Supervision	$9000/man year	No. of men directly estimated
Mining Supervision	$9000/man year	
Operating Supervision	$8000/man year	
Benefits	$ .30/$ of labor base wages plus supervisory salaries	
Raw Materials	None	
Maintenance Materials	$ .03/$ of equipment investment/y	
Operating and Miscellaneous Materials	Directly estimated	
Utilities	Directly estimated	
Royalties	Excluded	
Fixed Charges		
Rent	None	
Insurance and Property Taxes	$ .015/$ equipment investment/yr	
Depreciation	Sum of years digits for 15 year project life	
Depletion	Excluded	
Plant Overhead (includes medical, safety, protection, cafeteria, laboratories, storage facilities, general plant and payroll overhead, engineering services)	Directly estimated (See Table 4)	
Administrative Expenses (includes executive salaries, clerical wages, office supplies, communications)	Directly estimated (See Table 4)	
Distribution and Selling Expenses	None (since product is unfinished	
Research and Development Charges	Excluded	
Financing Charges	Excluded	

(1) CHEMICAL WEEK, pp. 95 - 118, October 29, 1966.

(2) Private Communication, Kennecott Copper Corporation, Bingham Canyon, Uta

TABLE 3

INVESTMENT IN UTILITY AND SERVICE FACILITIES

Direct Costs, M$	
Utilities	$ 4,700
Services	5,600
Freight to Site(1)	200
Colorado Sales Tax(1)	200
Indirect Costs, M$	
Engineering and Construction	2,700
Contractor's Fee	700
Fixed Capital Investment, M$	14,100
Contingency	1,500
Total Fixed Capital Investment, M$	15,600
Depreciable Investment	15,200
Cost of Capital, ¢/bbl(2)	17.9

(1) The Colorado Sales and Use Tax and freight are 3% of the material cost of equipment. It has been assumed that 60% of the utilities and service equipment investment is due to material cost.

(2) Cost of capital is defined as the cost of recovering the capital invested and earning a 10% discounted cash-flow return on the investment, after income taxes. In Technical Memorandum No. 67-28 (1), it was shown that within the general investment guidelines stated, the cost of capital was 1.184 ¢/bbl of crude shale oil/$1,000,000 of depreciable investment.

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TABLE 4

PLANT OVERHEAD AND ADMINISTRATIVE EXPENSE

Direct Operating Cost, $/CD	
Plant Overhead	
Wages(1)	1659
Salaries(2)	1667
Materials	499
	3825
Administrative Expense	
Wages(1)	399
Salaries(2)	556
Materials	143
	1098
Utility Cost for Off-Site Facilities	258
Fixed Cost, $/CD	
Insurance and Property Tax	625
Total Operating Cost for Off-Site Facilities,	
$/CD	5806
¢/bbl	11.7
Cost of Capital	
$/bbl	17.9
Total Plant Overhead and Administrative Expense, ¢/bbl	29.6

(1) Including overtime and benefits.

(2) Including benefits.

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The total cost for utilities and services investment, plant overhead, and administrative expense is also summarized in Table 4.

B. Mining Cost

1. Process Basis

The level of production that was used in carrying out the mining cost estimate (5) was 84,000 T/CD of 30 gallon per ton oil shale. This is not exactly consistent with the 50,000 B/CD crude shale oil basis used for the entire complex. The factor method has been used to adjust the mining cost estimate, in a minor way, so that it is consistent with the 50,000 B/CD crude shale oil basis (13). An exponent of 0.8 was used in this adjustment because of the labor-intensive nature of mining costs (1).

The mine layout and development costs were based upon a hypothetical ore body, 76 feet thick with a Fischer Assay averaging 30 gallons per ton. A bed thickness of 76 feet was selected to conform with the 76 foot room height mined at Anvil Points during the Initial Program. It was also assumed that access to the mine can be gained through an adit in a cliff face typical of the Anvil Points terrain. In any subsequent studies carried out by individual companies, a considerable degree of adjustment will have to be made to orient the study toward specific ore bodies in specific locations.

It was assumed that the actual mining will be carried out in two steps. The first one was to mine out the upper 41 feet of the Mahogany Ledge using a heading operation. The second step was to mine out the lower level, 35 feet thick, by means of a benching operation. Unfortunately, due to rib spalling problems encountered during the benching operation at Anvil Points, it was not possible to complete the entire mining research program originally laid out. As a result, there were two major unknowns in this mining cost study (5).

- Insufficient data were obtained for reliable design of shale pillars. For the purpose of the mining cost study it was assumed that 40 foot thick rib pillars between 60 foot wide rooms were adequate. However even this had not been demonstrated conclusively. The extent of the spalling problems on pillar corners at Anvil Points indicates that pillars should be rib rather than square, keeping the number of corners to a minimum. The restriction to 40 foot wide rib pillars reduces the overall extraction ratio to 51%. Further pillar research and blasting research would be necessary before this extraction ratio could be improved upon.

- The second unknown was the amount of rib scaling which was required during benching operations. The equipment and manpower assumed to be necessary for scaling, in the mining cost study, was an absolute minimum. It may well be, that in a full scale operating mine, the scaling will become an unmanageable problem.

A number of other low-cost mining methods, in addition to the room-and-pillar method, have been considered at various times by other investigators. These include block caving (14) and open-pit mining (15), but none are considered to be as practical for the particular topography considered as room-and-pillar mining. Even in applying this method, a variety of schemes can be envisaged. It would require an inordinate length of time to consider all the various permutations and combinations of mining systems. Therefore, this economic analysis has been confined to one set of conditions using only one set of mining procedures. It may be considered that this mining method approaches the optimum for the conditions and procedures selected for study. It is a highly mechanized method which makes good use of modern earth-moving technology.

2. Other Economic Bases

Mining costs have been calculated so that they are generally consistent with the economic guidelines outlined in Tables 1 and 2. Specific exceptions, however, are mine development, equipment life, investment credit and maintenance materials.

a. Mine Development

This expense is a unique mining cost and is not directly comparable to any of the conventional process investment or operating costs.

It has been estimated that $1,500,000 of on-site equipment will be required four years before production starts. This will be used for mine development. The cost of mine development is estimated at $847,000 per year for each year prior to the start of production. The development charges have been deducted from expenses in the last full year of production because there will be a reduced amount of haulageway development to be done in that year.

b. Equipment Life

An average equipment life of five years has been estimated for the mining investment (5). This is in contrast with the assumption that the equipment life is equal to the project life which is assumed in the cost analyses for other parts of the complex. This short equipment life reflects the severity of mobile equipment service.

c. Investment Credit

Because of the short equipment life, only 33 1/3% of the investment may be considered for the 7% investment credit (5).

d. Maintenance Materials

The maintenance material cost developed in Technical Memorandum No. 67-38 has been used in this report. Although the method of calculating maintenance materials used in that memorandum appears to be different from that recommended in the "Guidelines for Operating Cost Estimates" (Table 2), it is approximately equivalent. This equivalance includes the additional cost for drill maintenance of $400/CD.

3. Mining Investment

The mine has two types of equipment. These are stationary equipment, which is quite comparable to conventional process equipment, and mobile equipment, which includes specialized mining equipment and more conventional automotive equipment. Most of the equipment falls into the mobile category. In Table 5, an approximate analysis of the distribution of mining investment is presented. This analysis is based on the maximum depreciable investment attributable to mining during the project life. (Because of the phased manner in which mining investment is made, the depreciable mining investment used in this analysis is slightly lower than the "total cost of on-site investment capital" used in Table 1 of Technical Memorandum No. 67-38 (5).) This is a more precise method of estimating the capital required to start the mining venture. It has been derived from the mining cost calculation previously presented (16).

4. Mining Operating Cost

The operating costs of an 84,000 T/CD mine are presented in Table 6. This summary indicates that at this level of production, the total mining cost is 51.7 ¢/T. The largest items in the direct production costs are labor, supervision, and materials. Utility expense and cost of capital are relatively minor components of mining cost.

C. Crushing Cost

1. Process Basis

The level of production that was used in carrying out the commercial crushing plant cost estimate (2) was 84,000 T/CD of 30 gallon per ton oil shale. This, again, is not exactly consistent with the 50,000 B/CD crude shale oil basis used for

TABLE 5

MINING EQUIPMENT INVESTMENT[1]

Direct Costs, M$	
Stationary Equipment (Installed)	33
Mobile Equipment (Erected)	9,554
Colorado Sales and Use Tax[2]	284
Freight[2]	284
Indirect Costs, M$	
Engineering and Construction	8
Contractor's Fee	2
Fixed Capital Investment, M$	10,165
Contingency	1,424
Total Fixed Capital Investment, M$	11,589
Depreciable Investment, M$	11,021
Cost of Capital, ¢/T	12.1

[1] The average equipment life for mining equipment is five years.

[2] The Colorado Sales and Use Tax and freight are 3% of the material cost of equipment. It has been assumed that 60% of the stationary equipment investment and all of the mobile equipment cost is due to material cost.

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TABLE 6

MINING COST SUMMARY
(84,000 T/CD Basis)

Direct Production Costs, $/CD		
Labor(1)		
Operating	8,250	
Maintenance	5,545	
Supervision		
Operating	904	
Maintenance	603	
Materials		
Operating and Miscellaneous(2)	12,754	
Maintenance	3,074	
Utilities	564	
Fixed Cost, $/CD		
Insurance and Property Taxes	437	
Operating Cost, $/CD	32,131	
¢/T		38.3
Mine Development Cost, ¢/T		1.3
Cost of Capital, ¢/T		12.1
Total Mining Cost, ¢/T		51.7

(1) Including benefits (no overtime assumed for labor; extra men hired).

(2) Includes explosives, fuel and tires and other operating supplies.

the entire complex. The factor method has also been used to adjust the crushing cost estimate so that it is consistent with the 50,000 B/CD crude shale oil basis. An exponent of 0.6 was used in this adjustment because of the capital-intensive nature of crushing cost (1).

The plant upon which the crushing cost estimate is based, was assumed to be equipped with tooth-type single roll primary crushers. In an earlier study (11), gyratory primary crushers were considered. Tooth-type single roll crushers are preferred at this time, however, because their performance has been demonstrated with mine run shale (17) and there is some question about the ability of gyratory crushers to crush the largest pieces of mine run shale (18).

The secondary crushers in this plant were assumed to be cone crushers. This type of crusher was chosen from three designs on the result of a secondary crusher optimization study (2). The three types considered were the standard cone crusher, the single-cage disintegrator, and the double roll crusher. This study (2) showed that the cone crusher appears best on a cost per ton of plus 1/4-inch product basis, followed by the single-cage disintegrator and double roll crusher, respectively. The disintegrator compared quite favorably to the cone crusher, and is better than the cone crusher when compared on a cost per ton of feed basis. Both the wear and capacity data for the cone crusher have been established by long-term crushing of oil shale. These data have only been estimated for the disintegrator. The largest standard cone crusher currently made has a slightly greater new feed capacity than the largest disintegrator when both are run in closed circuit to produce similar products. This means that a cone crusher plant would always have a slightly greater safety factor, and certain size plants would require an additional disintegrator. More flexibility is available with a cone crusher because it can be operated in open circuit, while a single-cage disintegrator would not produce an acceptable product in open circuit operation. These factors all favor the cone crusher unless further test work establishes higher capacity and a lower wear rate for the disintegrator.

Tooth-type double roll crushers do not appear to be attractive even for an optimistic wear rate of half that measured at Anvil Points. The reason for this is that application of hardfacing, one weld rod at a time, requires a high amount of downtime and maintenance labor. This results in extra crushing lines being required and a high maintenance cost.

This optimization study is heavily dependent on the quality of the wear maintenance data; therefore, the question arises - how reasonable are the data? Below are listed the absolute metal wear rates per ton crushed that have been used in this study:

Standard cone crusher	0.008 lb/ton
Single-cage disintegrator	0.013 lb/ton
Tooth-type double roll crusher	0.012 lb/ton

The wear rates are close and in good agreement. A slightly lower wear rate would be expected for a cone crusher relative to the impact crushers because the relatively flat surfaces of the cone crusher liners have an easier duty than the impact areas of the other crushers. Wear rates for the cone and double roll crushers have been determined by long-term crushing of shale, while the disintegrator wear rate is judged to be a reasonable estimate.

In this plant, mine run shale was brought to the underground primary crushing station in 80-ton, side-dump trucks for the six hours of every shift that blasting was not occurring in the mine. It was then screened on a grizzly with a 6-inch spacing, and the grizzly oversize was crushed in either of two tooth-type single roll crushers. Primary crusher product and grizzly undersize were recombined and conveyed to underground storage bins. Underground storage was provided because it is more economical than surface storage (2). This type of storage is believed to be technically feasible. The major purpose of these bins was to provide surge volume, since all equipment downstream of the bins operates on a 24-hour per day basis.

Primary crusher product was withdrawn from the bins and conveyed to the underground secondary crushing station. Here six standard cone crushers - five operating plus one spare - were assumed to reduce plus 2 1/2-inch material in a closed circuit operation. The final product was put on conveyor belts to be transported to the cliff face and downhill to the retort level. A screening plant at retort level produced the three required fractions. All single deck screens, sized for 95% screening efficiency, were used to prepare the final products.

No final product storage was used to avoid segregation and breakage problems. Instead spare capacity was used to insure retort feed supply. Total bin storage capacity was one day's supply to take care of any primary crusher station breakdowns or any problem in the mine. Two bins were used so that either bin could be repaired without affecting production. A total of twelve bin drawoff points were installed, and any four of these were capable of supplying the required throughput. The secondary crushing station was designed to operate at about two-thirds of capacity. Parallel 72-inch conveyor belts were used between underground storage and the secondary crushing plant, and the secondary crushing plant and the final screening plant. Each 72-inch conveyor belt was designed to carry the required throughput. Three spare screening lines were included in the final screening plant to allow feeder and screen maintenance without interrupting production. The primary purpose of the spare capacity described above was to provide the required production rate in the face of the continuous maintenance that would be required with a moderately abrasive material such as oil shale rather than for emergencies. Such continuous maintenance would include periodic replacement of conveyor belting, crusher wearing surfaces, screen decks, chutes handling shale at high velocities, etc.

Since size distributions for the mine run product and the primary and secondary crusher products are available, a product size distribution for this commercial crushing plant can be estimated. Figure 3 shows the probable size distribution of minus 2 1/2-inch crusher product. This size has been judged to be optimum for the Gas-Combustion Retort (1).

2. Other Economic Bases

Crushing costs have been estimated in general accordance with the economic guidelines given in Tables 1 and 2. Two particularly significant items in this cost are maintenance materials and power costs.

Maintenance materials are an exception to the general economic bases. Because of the high usage of hardfacing material in this part of the plant, it has been added to the 3% of investment per year that has usually been estimated for regular maintenance material. It has been assumed that primary crusher weld rod usage would be one-half of that used for the Anvil Points double roll crusher (19).

Crusher power has been estimated to be 0.5 hp-hr of energy required per ton of finished product. For other equipment, the Allis-Chalmers estimate (12) has been increased by 25% to account for lighting, shop usage, etc. It has been assumed that the downhill conveyors would be retarded by generating electricity. The power recovery has been assumed to be 75% of the potential energy loss of the rock.

3. Crushing Investment

The investment in crushing plant equipment is described in Table 7. The major items of equipment are the crushers themselves and the shale conveying equipment for carrying the shale from the mine to the retort level.

4. Crushing Operating Cost

The operating cost of an 84,000 T/CD crushing plant equipped with single roll primary crushers and cone secondary crushers is presented in Table 8. This summary indicates

FIGURE 3

PROBABLE SIZE DISTRIBUTION OF MINUS 2 1/2 INCH CRUSHER PRODUCT (18)

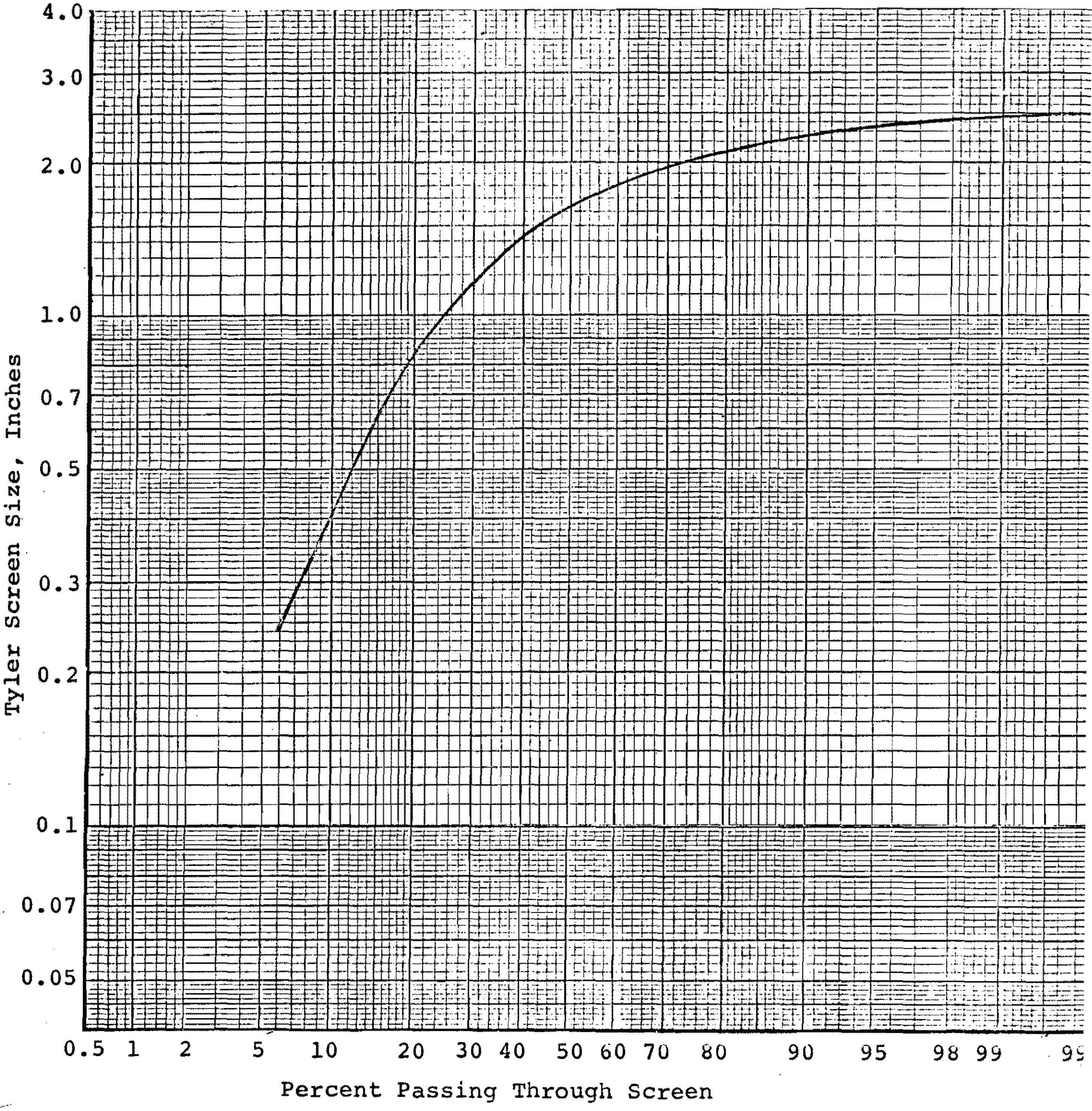

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TABLE 7

CRUSHING INVESTMENT

Direct Costs, M$	
Stationary equipment (Installed)	9,900
Colorado Sales and Use Tax (1)	260
Freight(1)	260
Indirect Costs, M$	
Engineering and Construction	2,480
Contractor's Fee	690
Fixed Capital Investment, M$	13,590
Contingency	1,480
Total Fixed Capital Investment, M$	15,070
Depreciable Investment, M$	14,550
Cost of Capital, ¢/T	10.3

(1) The Colorado Sales and Use Tax and freight are 3% of the material cost of equipment. It has been assumed that 60% of the stationary equipment investment is due to material cost.

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TABLE 8

CRUSHING COST SUMMARY
(84,000 T/CD Basis)

Direct Production Costs, $/CD	
Labor	
Operating(1)	1,351
Maintenance(1)	1,213
Supervision	
Operating(2)	114
Maintenance(2)	128
Materials	
Operating and Miscellaneous (3)	1,815
Maintenance	
Utilities(4)	420
Fixed Cost, $/CD	
Insurance and Property Taxes	588
Operating Cost, $/CD	5,629
¢/T	6.7
Cost of Capital, ¢/T	10.3
Total Crushing Cost, ¢/T	17.0

(1) Includes wages, benefits, overtime and underground differential where appropriate.

(2) Includes salaries and benefits.

(3) Includes complex hardfacing material plus an expenditure of 3% of investment per year.

(4) Cost of net utility usage. Some electrical power is generated from the shale movement from the mine to the retort level.

that at the 84,000 T/CD level of production, crushing cost is 17.0 ¢/T. The major items of cost, are labor, materials, and capital investment. Power recovery from the shale handling operation has been used to reduce utility costs.

D. Retorting Cost

1. Process Basis

It is desirable to design and operate the Gas-Combustion Retort at high shale rates in order to minimize investment in retort cross-sectional area. (Shale rate is defined as the shale mass velocity expressed in pounds per hour per square feet of retort cross-sectional area.) When shale rate is increased, retorting yield is reduced. This is due to a reduced shale residence time at temperatures at which retorting can take place. This, in turn, is due, primarily, to a reduced maximum operable gas rate and, secondarily, to the increased shale rate. If retorting yield is reduced and if a constant oil production basis is to be maintained, more shale must be mined and crushed, thus increasing mining and crushing costs per barrel of oil produced. Yields can be increased by reducing raw shale size but this increases crushing costs and fines produced. The optimum conditions to design and operate a commercial retort are not obvious because of these interactions which affect mine run yield (barrels of oil produced per ton of shale mined) and production costs.

A preliminary evaluation of the economic optimum operating conditions of the Gas-Combustion Retort (1) was carried out prior to and during the early stages of development of the Retort No. 3 program. The variables investigated were:

- Maximum size of crusher product
- Minimum number of retort feed size fractions
- Optimum shale rate
- Optimum air and recycle gas rates

Retort No. 2 data were screened for reliability and analyzed to define the process interactions. A computer program was developed to calculate the overall cost to produce 50,000 barrels per day of raw shale oil based on correlations developed from Retort No. 2 data and our best cost information. An IBM 1620 computer located at Mesa College in Grand Junction, Colorado was used to make the calculations (20).

This study indicated that the economic maximum size of the crusher product was 2 to 2 1/2 inches. Throughout the Retort No. 3 program, 2 1/2 inches was assumed to be the maximum size of the crusher product that would be used as retort feed in a commercial oil shale processing complex.

A two size-fraction retort shale feed was found to be more economically attractive than a single size-fraction feed. In the Retort No. 3 program, the two size-fraction feed consisted of 1/4- to 1-inch and 1- to 2 1/2-inch fractions. The single fraction feed had a 1/4- to 2 1/2-inch range. The conclusion that two size-fraction feed was more economical than a single size-fraction feed was confirmed with Retort No. 3 data.

This analysis also showed that the retorts should be designed and operated at the highest shale rate consistent with good operability. This was estimated to be 500 lb/(hr)(ft^2) based on Retort No. 2 experience. No significant difference between costs for operation at 400 and 500 lb/(hr)(ft^2) was observed with 1- to 2 1/2-inch shale. A preliminary economic screening of Retort No. 3 data confirmed this conclusion. It was not possible to operate with 1/4- to 1-inch shale at 500 lb/(hr)(ft^2) in Retort No. 3; but, satisfactory operation was achieved at 300 lb/(hr)(ft^2).

An evaluation of retorting costs after the completion of the Retort No. 3 program has been completed (3). This study was intended to establish retorting costs with the assumed retort operation based upon Retort No. 3 results. In this study, five cases were considered. The base case for this study was the design basis for a Mobil engineering study (21) which was used as a guide for the equipment investment in the other four cases. The yields in these cases have all been adjusted to 30 gallons per ton assay and to the probable size distributions that are estimated for commercial retort feed, to put them on a common basis. These yields are not directly comparable to those reported in Technical Management Summary 67.71 AP (8) because of these adjustments. These cases are:

Case 1. - Base case

230 lb/(hr)(ft^2) operation with 1/4- to 3-inch shale and 90% yield

Case 2. - Best U. S. Bureau of Mines Retort No. 3 Operation

300 lb/(hr)(ft^2) operation with 1/4- to 3-inch shale and 81.3% adjusted yield

Case 3. - Initial Program Retort No. 3 Operations

500 lb/(hr)(ft^2) operation with 1/4- to 2 1/2-inch shale and 82.3% adjusted yield

Case 4. - Initial Program Retort No. 3 Operation

300 lb/(hr)(ft^2) operation with 1/4- to 1-inch shale and 89.4% adjusted yield, and 400 lb/(hr)(ft^2) operation with 1- to 2 1/2-inch shale and 87.3% adjusted yield

Case 5. - Initial Program Retort No. 2 Operation

500 lb/(hr)(ft^2) operation with 1/4- to 1-inch shale and 91.6% adjusted yield, and 400 lb/(hr)(ft^2) operation with 1- to 2 1/2-inch shale and 88.4% adjusted yield

Cases 4 and 5, in which a two size-fraction retort feed was fed to Retorts No. 3 and No. 2, respectively, had the lowest total production costs of the five cases. Case 4 was 1.2 ¢/bbl lower in cost than Case 3. Case 4 was not as low in cost as Case 5, but because of the larger scale of operation in Retort No. 3, it is judged to be more significant.

In this analysis, the implicit assumption has been made that Initial Program technology can be translated to commercial scale. This assumption is not completely justified, however. It has been concluded that additional work will be necessary before scale-up with 1/4- to 1-inch (or 1/4- to 2 1/2-inch) shale could be recommended. The reason for this lack of confidence is the operability problems that were experienced in Retort No. 3 with these two fractions. With each of these fractions, increasing difficulties with operability were experienced as the retort cross section was increased (8). Clinkers, which are closely associated with the operability problems, are judged to be caused, ultimately, by localized liquid accumulations in the shale bed (22). As retort cross section increases, the likelihood of such singularities occurring increases (8).

The retorting costs that are used in this report are based on Case 4. They represent what might be expected at the 50,000 B/CD level of production of crude shale oil from 30 gallon per ton oil shale if 1/4- to 1-inch and 1- to 2 1/2-inch shale fractions were processed.

The yield used in this analysis was obtained by adjusting the measured yields of the runs indicated in Table 9 for size distribution and assay using an adaptation of the yield regression analysis recently reported (8). The equation used was:

TABLE 9

RETORTING COST PROCESS BASES

Raw Shale Properties			
Nominal Size Range, Inch	1/4 to 1		1 to 2 1/2
Da, Inch	0.53		1.51
Dv, Inch	0.65		1.76
Weight Fraction of Crusher Product in Nominal Size Range	0.173		0.785
Fischer Assay, gal/T		30	
Retort Operating Conditions			
Raw Shale Rate, lb/(hr)(ft^2)	300		400
Gas Rates, SCF/T			
Recycle	13,000		14,500
Dilution	1.600		--
Air	5,200		4,600
Bed Height, Feet			
Above Air Distributor	5.5		12.5
Below Air Distributor	6		7
Feed and Product Rates			
Crusher Product, T/CD		83,320	
Retort Feed, T/CD		79,810	
Retort Feed, T/SD(1)	15,980		72,700
Oil Yield, vol % FA(2)	89.4		87.3
Vent Gas, MSCF/CD		582	
Fines, T/CD		3,510	
Spent Shale, T/CD		62,800	
Reference Nos. Run	C1051 1 to 3		C1027 1 to 4

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$$Ya = Ye - (34.74 - 2.20\ R)\ (Dv_a - Dv_e) - 3.93\left(\frac{Dv}{Da_a} - \frac{Dv}{Da_e}\right) + 0.283\ (A_a - Ae)$$

Where: Y = Volume % Fischer Assay yield
R = Recycle gas rate, MSCF/ton raw shale
Dv = Weight mean shale diameter, inches
Da = Surface mean shale diameter, inches
A = Fischer Assay, gallon per ton

Subscript: a = Adjusted variable
e = Experimental variable

The size distributions used for adjusting yields are given in Figures 4 and 5. These are contiguous 1/4- to 1-inch and 1- to 2 1/2-inch retort feed fractions. The crusher product screen analysis from which the retort feed screen analyses were derived has been presented in Figure 3.

The process details for the retorting cost element of the overall cost of oil shale processing are given in Table 9.

The retorting plant in which this process has been assumed to be carried out consists of a number of subplants. The size and number of these subplants that are used depends on shale throughput, shale mass velocity, and structural limitations imposed by the subplant design. The design of each of these subplants is partially based on a study by Mobil in which an engineering study of a plant for Case 1, the base case, was completed.

These subplants consist of a battery of retort elements equipped with a raw shale feed system, a spent shale drawoff system, a recovery system consisting of a battery of electrostatic precipitators, and a gas circulation system consisting of a battery of blowers. The duct work, piping, and insulation cost and the instrumentation and electrical system costs have been estimated for each of these subplants. No provision for separating product oil from product water has been provided. The disposal of the raw shale fines, vent gas and spent shale fines are considered separately.

2. Other Economic Bases

The investment and operating costs of retorting have been developed so that they are consistent with the guidelines outlined in Tables 1 and 2.

FIGURE 4

PROBABLE SHALE SIZE DISTRIBUTION OF 1/4 TO 1 INCH RETORT FEED (3)

Surface mean particle diameter, Da = 0.53 Inch
Weight mean particle diameter, Dv = 0.65 Inch

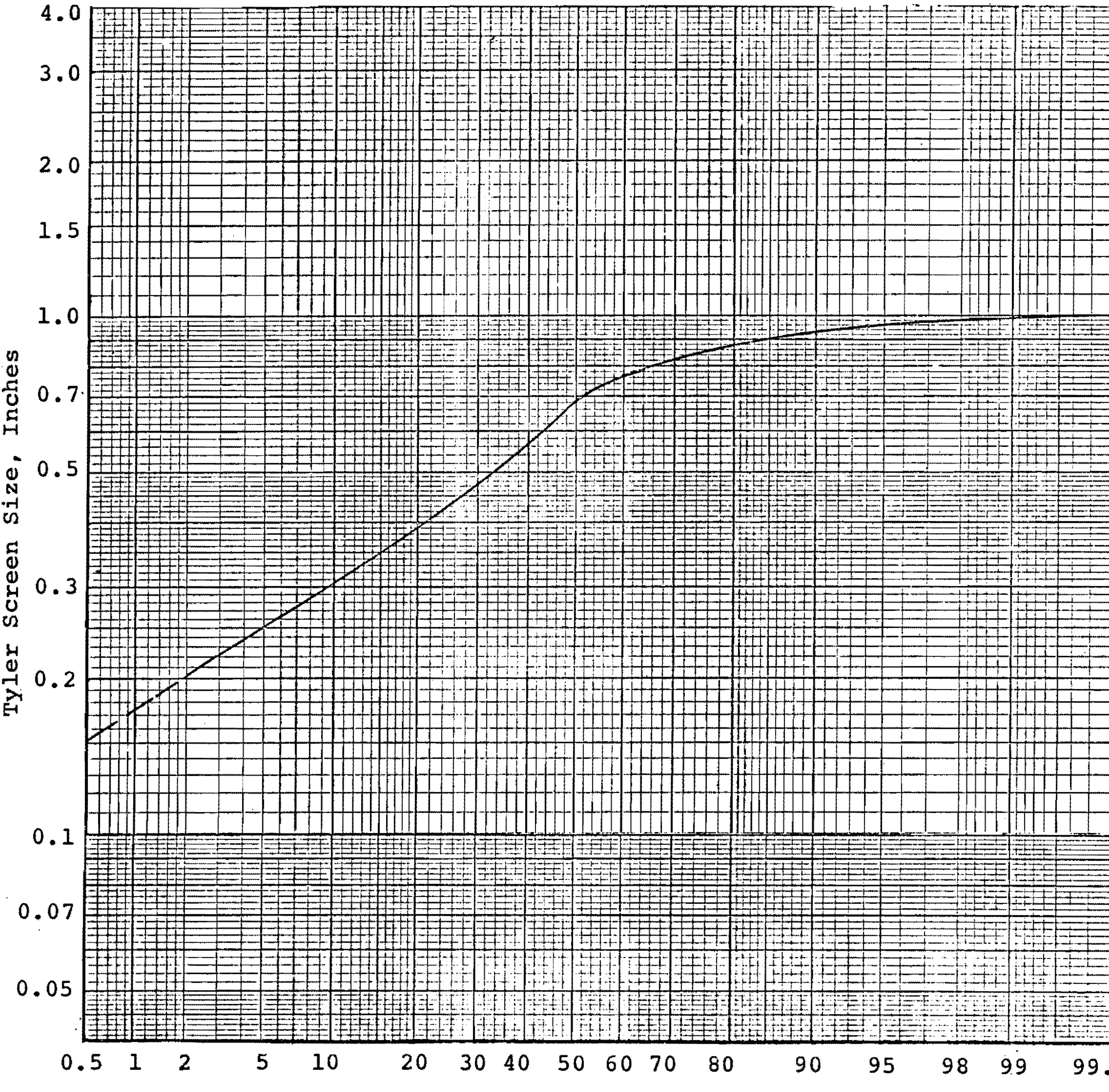

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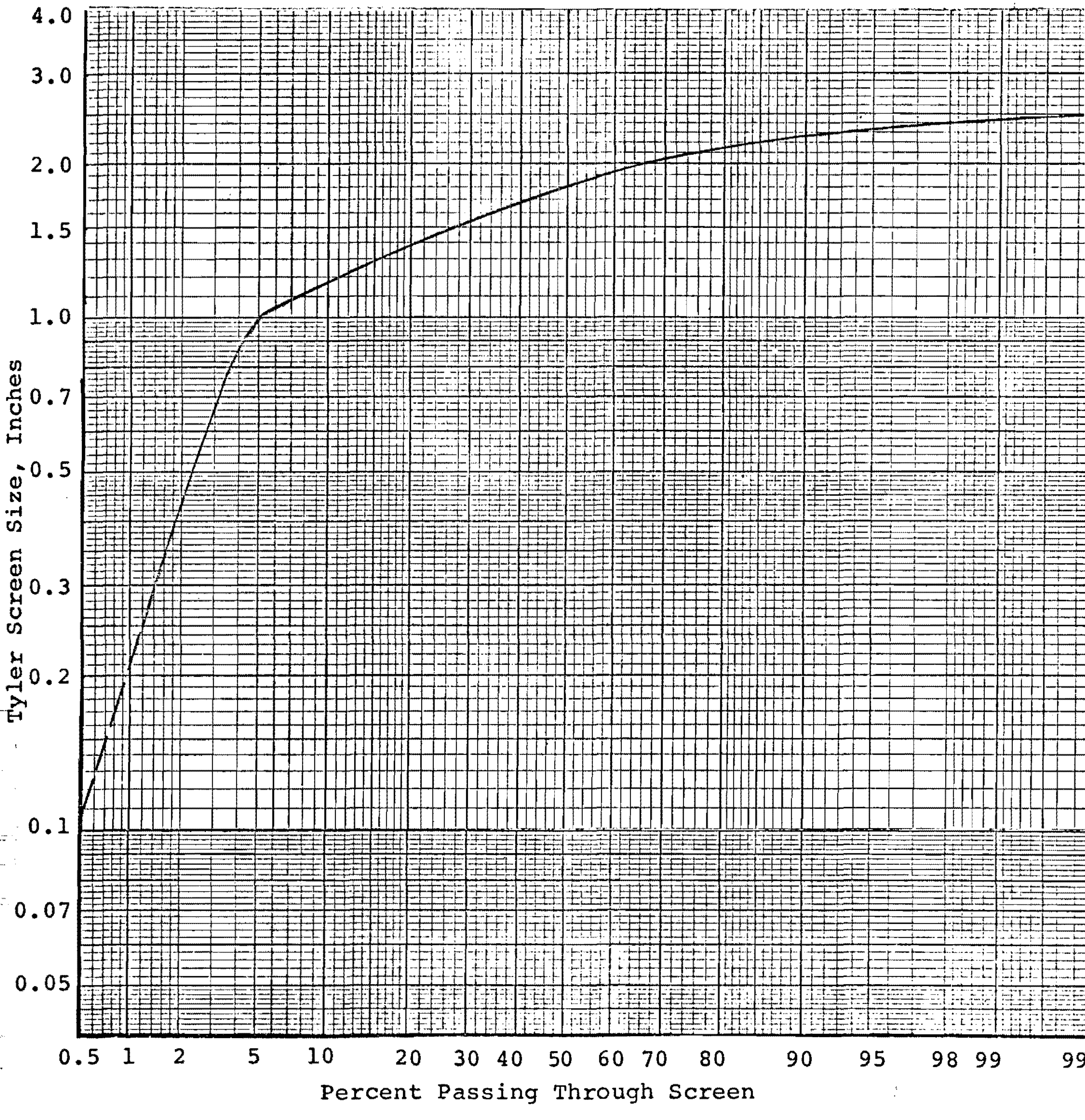
FIGURE 5

PROBABLE SHALE SIZE DISTRIBUTION OF 1 TO 2 1/2 INCH RETORT FEED (3)

Surface mean particle diameter, Da = 1.51 Inch
Weight mean particle diameter, Dv = 1.76 Inch



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3. Retorting Investment

The investment in retorting equipment is outlined in Table 10. More than half of the depreciable investment is in retort, vessels, supporting structure, and foundations.

In estimating the retort investment, the method used has been to estimate the number of retorting subplants and the bed cross-sectional area for each size fraction to be processed. For the process situation considered in this report, one subplant was used for retorting 1/4- to 1-inch shale and three subplants were used for 1- to 2 1/2-inch shale. The investment per retort element battery was then made with a suitable adjustment in cost for total bed height. The details of the calculation are presented in Technical Memorandum No. 67-39 (3).

4. Retorting Operating Cost

Retorting operating cost is summarized in Table 11. For purposes of this report, by-product disposal cost is separated from retort operating cost, but it will be considered in a separate section of this report. The major operating expense item is utility cost. This is only exceeded by the cost of capital. At the 50,000 B/CD rate, the retorting cost (ex by-product disposal) is 58.4 ¢/bbl.

E. By-Product Disposal Cost

The technology involved in disposing of the by-products of a retorting plant, which are raw shale fines, vent gas and spent shale, is either so poorly defined or is so dependent on factors such as plant location and marketability of the by-product that it is difficult to evaluate the effect of these factors on shale oil cost. To aid in this evaluation for various particular technological, location and market situations, these disposal costs have been separated from the cost of retorting, and are considered as separate costs incurred during disposal of these materials outside of the battery limits of the retorting plant.

In the case of raw shale fines, the most pessimistic situation that has been considered is the case in which the fines have no market value and are disposed of with spent shale. The most optimistic situation envisions that all of the raw shale fines are transferred to a fines processing facility at a transfer price approximately equal to the incremental cost of mining and crushing an additional ton of raw shale.

This cost is estimated by summing the operations cost of mining and crushing developed in this project. In Figure 6, a plot of raw shale fines disposal cost is presented as a function of the percent of the raw shale fines sold at 45¢ per ton. In light

TABLE 10

RETORTING INVESTMENT

Direct Costs, M$	
Stationary Equipment (Installed)	18,100
Colorado Sales and Use Tax(1)	330
Freight(1)	330
Indirect Costs, M$	
Engineering and Construction	4,520
Contractor's Fee	1,270
Fixed Capital Investment, M$	24,550
Contingency, M$	2,720
Total Fixed Capital Investment, M$	27,270
Depreciable Investment	26,610
Cost of Capital, ¢/bbl	31.5

(1) The Colorado Sales and Use Tax and freight are 3% of the material cost of equipment. It has been assumed that 60% of the stationary equipment investment is due to material cost.

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TABLE 11

RETORTING COST SUMMARY
(50,000 B/CD Basis)

Direct Production Costs, $/CD	
Labor(1)	
Operating	658
Maintenance	699
Supervision(2)	
Operating	114
Maintenance	160
Materials	
Operating and Miscellaneous	729
Maintenance	2,188
Utilities	7,815
Fixed Costs, $/CD	
Insurance and Property Taxes	1,094
Operating Costs,	
$/CD	13,457
¢/bbl	26.9
Cost of Capital, ¢/bbl	31.5
Total Retorting Cost(3), ¢/bbl	58.4

(1) Including benefits and overtime.

(2) Including benefits.

(3) Excluding by-product disposal cost.

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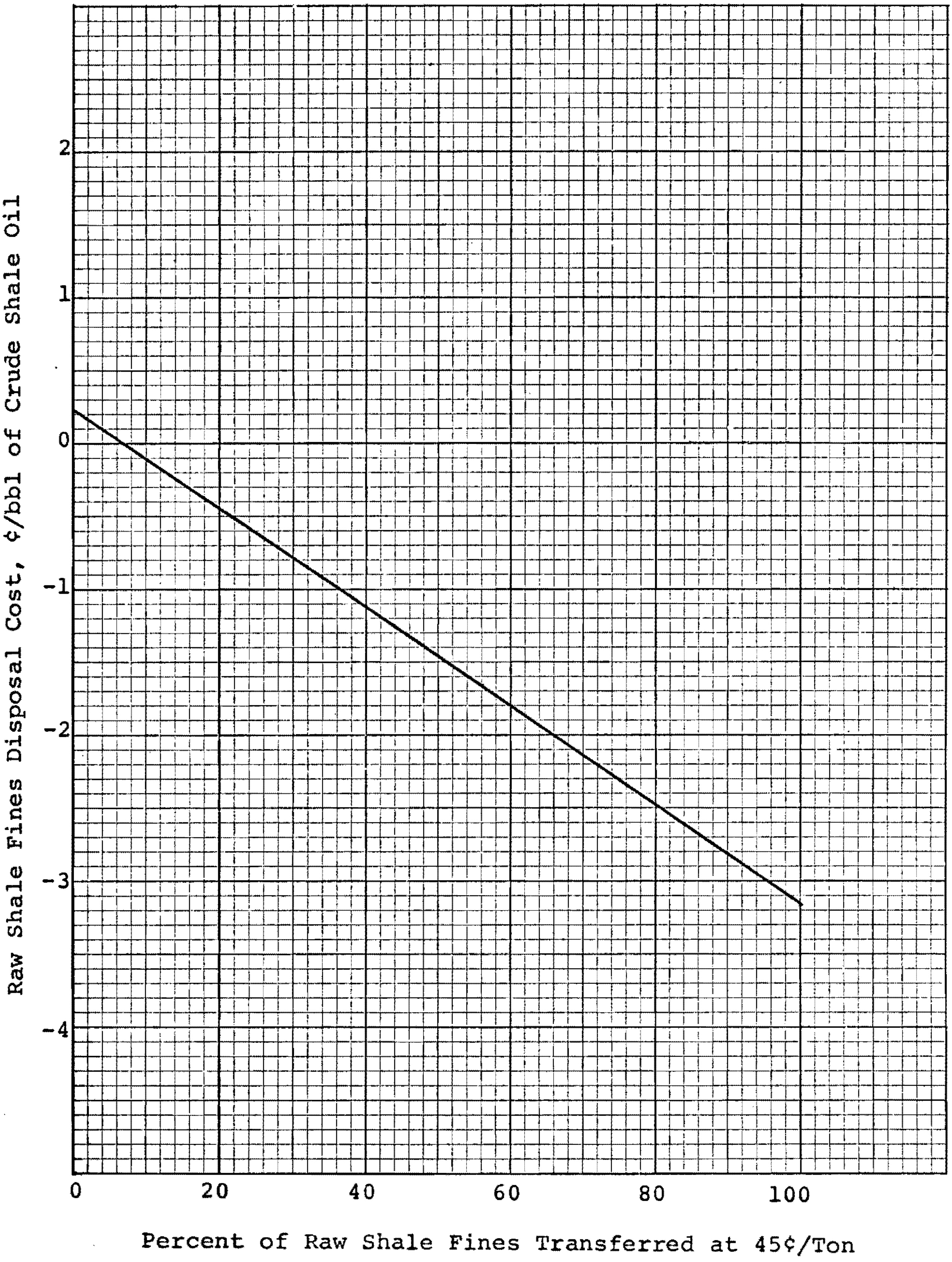
FIGURE 6

EFFECT OF RAW SHALE FINES DISPOSAL COST ON BY-PRODUCT DISPOSAL COST



of the recently reported success of TOSCO's operation, it is felt that the most probable situation is that all of the fines can be processed.

The vent gas disposal is handled in a similar manner. The pessimistic situation in this case is that the vent gas must be flared. The primary charge for flaring is the power cost of compressing air for the flare. A 1:1 air and vent gas mole ratio has been assumed. Optimistically, all of the gas can be sold at some discount from the price of natural gas. Natural gas can be purchased in this area for about 30¢ per million standard cubic feet. Because of the uncertainty of these projections, and because the joint action by a second party is required to use vent gas profitably, it has been assumed that half of the gas could be sold at this price. This quantity of gas is about the quantity needed to operate a power plant the size of the Public Service Company of Colorado installation at Cameo, Colorado. Vent gas disposal cost as a function of percent of vent gas sold at 16¢/MSCF is shown in Figure 7.

Spent shale disposal cost is very sensitive to plant location. Because of the hypothetical nature of the enterprise studied in this analysis, it is difficult to define this cost. No value of spent shale was assumed and a range of disposal costs was considered ranging from 0 to 6¢ per ton. In calculating by-product disposal cost, it has been assumed that it costs 3¢ per ton to dispose of 68,000 T/CD of spent shale. For cases which produced different amounts of spent shale than 68,000 T/CD, the cost of disposal was scaled using a 0.6 power. The cost of spent shale disposal in cents per barrel as a function of spent shale disposal cost in cents per ton is presented in Figure 8. By-product disposal cost is summarized in Table 12.

F. Economics of Naphtha Recovery

The most significant yield loss in the Gas-Combustion Retorting process is due to unrecoverable, normally liquid, hydrocarbons in a very dilute low pressure, gaseous state in the recycle and vent gas (8). An economic analysis of the recovery of this naphtha from the vent gas has been completed. The overall conclusion is that it is uneconomic (10).

Several conventional methods of hydrocarbon recovery from gases were screened to determine if any offered sufficient economic incentive to justify recovering part or all of the 2.5 lb/MSCFDG present in retort gas. Gas compression was found to be excessively expensive ($70 per barrel) for the amount of hydrocarbon recovered. Even isobaric cooling by indirect heat exchange with air resulted in a minimum oil cost of about $7 per barrel. The use of activated carbon as an adsorbent for the recovery of the hydrocarbon material was investigated and ruled out as a result of large carbon requirements. Absorption of the

FIGURE 7

EFFECT OF VENT GAS DISPOSAL COST
ON BY-PRODUCT DISPOSAL COST

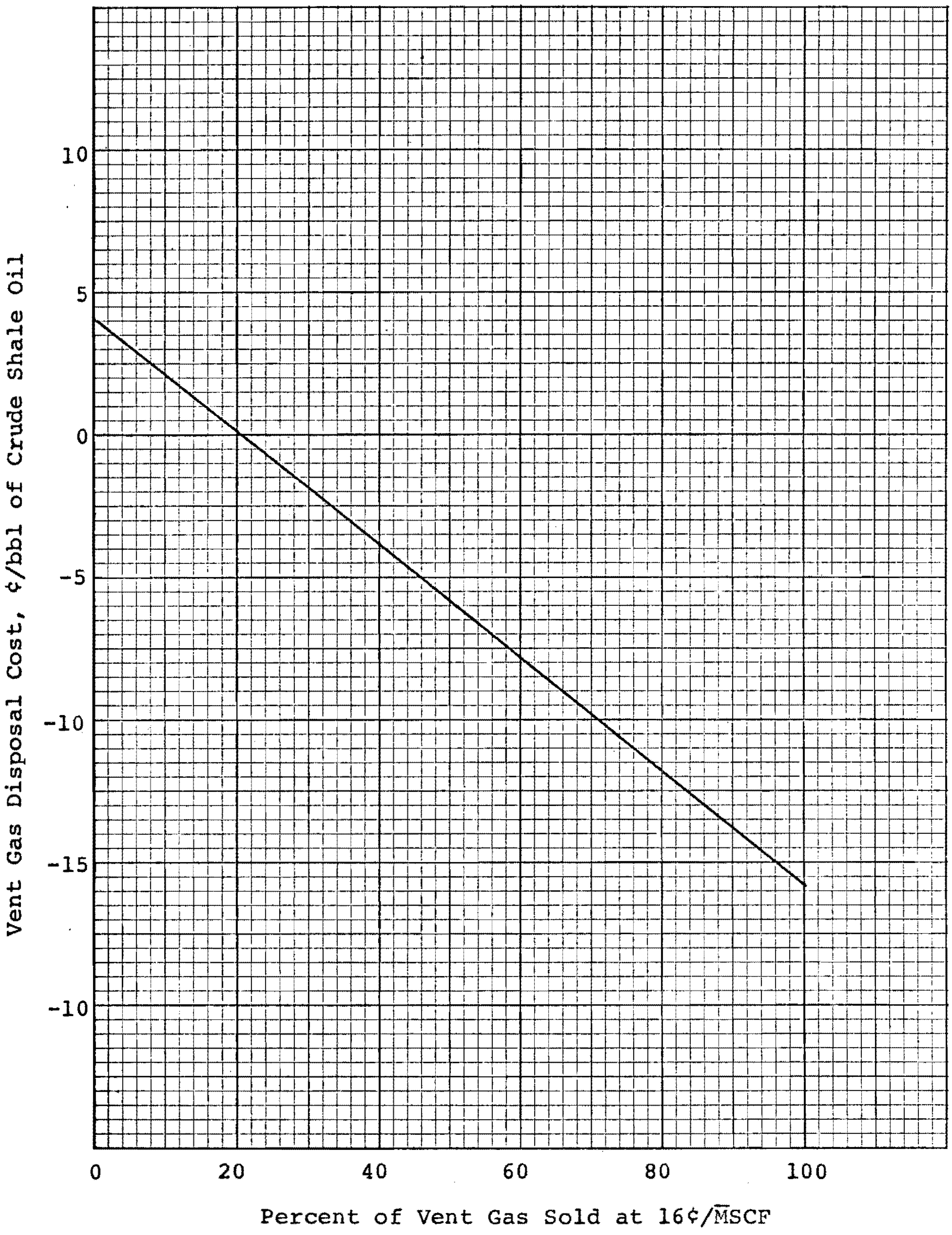


FIGURE 8

EFFECT OF SPENT SHALE DISPOSAL COST ON BY-PRODUCT DISPOSAL COST

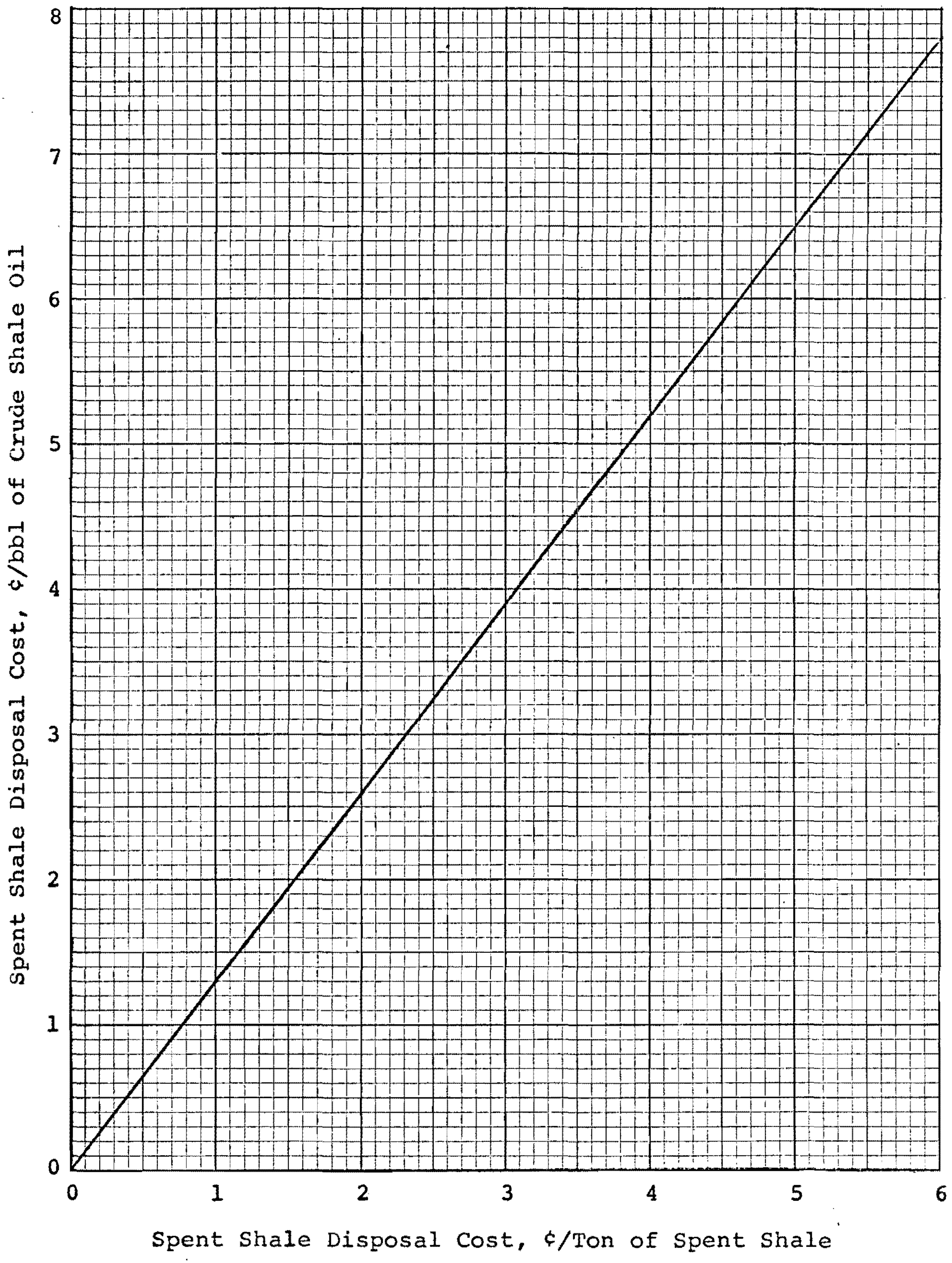


TABLE 12

BY-PRODUCT DISPOSAL COST
(50,000 B/CD Basis)

By-Product Disposal Cost, $/CD (Most Probable Value)		
Raw Shale Fines		-1580
Vent Gas		-2983
Spent Shale		1925
	Total, $/CD	-2638
	¢/bbl	- 5.3

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material with lean oil does not appear promising as a result of the lean oil requirement of 25 to 50 barrels lean oil per barrel oil recovered.

The main deterrent to economical processing of retort gas is the low pressure, about 12 psia, at which it is available.

G. Interaction of Mining, Crushing and Retorting Cost; Their Effects on Optimum Plant Design

The level of production assumed for the mining and crushing cost estimates is slightly higher than the level assumed for the retorting estimate. These costs have been placed on a consistent basis by scaling the mining costs by the 0.8 power and the crushing costs by the 0.6 power as described previously. The summarized production cost estimate is presented in Table 13. This cost is incomplete, as it stands, and the situation described by these estimates is hypothetical, but it is useful as a guide for further research. One item which has been excluded from this estimate that would lower production cost is depletion allowance. An interaction between retorting and refining that would permit some integration of these facilities might also lower this cost. Excluded items which would add to this cost include financing charges, land cost, water development cost, research and development charges, refining and pipelining operating and capital costs, and storage and handling facilities costs.

In order that the likelihood of achieving this production cost could be evaluated, the technique of subjective probability analysis has been applied. This technique involves specifying that each economic variable (labor cost, utility cost, etc.) can assume any value throughout the project life. Certain values would, of course, be more probable than others. With this concept, that certain values of the economic variable have a greater chance of occurring, one can then determine what the chances will be for obtaining certain ranges of an economic criterion such as total crude shale oil production cost.

To set up a statistical investment analysis, one must predict the probability distribution curve for each of the variables. This entails relating the probability that a variable will have a value equal to, or less than, some level, to the level of the variable. For example, the probability distribution of labor cost would be a plot of labor cost versus the probability that labor cost would have a value equal to or less than some level.

If this distribution curve is normal, it is easy to establish the mean and the standard deviation of the distribution. In general, the distribution is not normal. A recent article (9)

TABLE 13

CRUDE SHALE OIL PRODUCTION COST ESTIMATE SUMMARY
Basis: 50,000 B/CD of Crude Shale Oil
(All costs are expressed in $/CD)

	Mining		Crushing		Retorting		By-Product	Off-site	Total	
bor										
Operating	8,173		1,338		658				10,169	
Maintenance	5,494		1,203		699				7,396	
Total		13,667		2,541		1,357		2,064		19,629 (1)
pervision										
Operating	895		113		114				1,122	
Maintenance	597		126		160				883	
Total		1,492		239		274		2,229		4,234 (1)
terials										
Operating	12,636		--		729				13,365	
Maintenance	3,045		--		2,188				5,233	
Total		15,681		1,798		2,917		642		21,038
ilities		558		416		7,815		259		9,048
surance & Property Tax		433		583		1,094		627		2,737
tal Operating Cost		31,831		5,577		13,457		5,821		56,686
-Product Disposal Cost		--		--		--	-2,638	--		-2,638
ne Development Cost		1,082		--		--		--		1,082
st of Capital		10,070		8,573		15,750	--	8,974		43,367
tal Production Cost		42,983		14,150		29,207	-2,638	14,795		98,497
¢/bbl		86.0		28.3		58.4	-5.3	29.6		197.0
¢/Ton RS Thru G-C Retorts		53.9		17.7		36.6	-3.4	18.5		123.3
¢/Ton RS Mined		51.7		17.0		35.1	-3.2	17.8		118.4

)Off-site labor and supervision are not subdivided into operating and maintenance categories; therefore, the labor and supervision subtotals are not equal to the sum of operating and maintenance components.

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describes a method for "normalizing" the distribution in the general case so that the mean and the variance of the distribution can be established. (The variance is the square of the standard deviation.)

The mean of a cost variable in an analysis such as this can be stated in the following form:

$$m[Z] = S[Z]m[X]$$

Its variance is

$$v[Z] = (S[Z])^2 \, v[X]$$

Where m[Z] = Mean value of cost variable Z
S[Z] = Estimated single value of Z
m[X] = Mean value of dimensionless random variable X
v[Z] = Variance of cost variable Z
v[X] = Variance of dimensionless random variable X

To find the mean and variance of cost variable Z it is only necessary to know an estimated single value of Z and the mean and variance of X. If X is not normally distributed, a simple normalizing transform can be written such that

$$g\,(X) = \log\,(X + \alpha)$$

If this transform is used it can be shown that (9):

$$m[X] = \epsilon \, \exp\left[\frac{1}{2}\left(\ln \frac{\epsilon}{\lambda}\right)^2\right] - \alpha$$

and

$$v[X] = (m[X] + \alpha)^2 \left(\exp\left[\left(\ln \frac{\epsilon}{\lambda}\right)^2\right] - 1\right)$$

Where ϵ = Mean of normalized distribution of random dimensionless variable X.
λ = Standard deviation of normalized distribution of random dimensionless variable X.

These equations are applied by finding, by trial and error, the value of α that results in a linear plot of X on a logarithmic probability grid. ϵ is the value of X at 50% probability and λ is the value of X at 84.13% probability. When the mean and variance of X are known mean and variances for cost variable Z can be simply calculated. (The nomemclature used in this development is non-standard; however, it is consistent with that used in the reference article (9). This was done to facilitate further study of the reference.)

The first and most logical question is whether an individual can truly specify the distribution curve on an economic variable with little or no previous statistics on the variable. The answer is definitely no. Certainly no mathematical measure is any better than the estimates on which it is based. However, the more background information available on the variable in question, particularly about how it is affected by factors from outside and within the project, the closer one can come to predicting the "true" distribution. Development of such probability distributions must be classified as an art that requires experience and good judgment.

This method has been applied to drilling decisions by oil and gas operators (23) and to a hypothetical chemical venture (9) in recent studies. In the following discussion, this method will be applied to this hypothetical oil shale venture. A number of constraints have been observed in the analysis up to this point; two additional ones that have been implied, but which should be kept in mind in evaluating the results of this subjective probability analysis are that a market exists for 50,000 B/CD of crude shale oil and that this quantity of product can be sold at the total production cost which covers expenses, pays taxes, recovers capital investment and pays a 10% discounted cash flow return on investment, after taxes. By making this assumption, the most difficult aspect of this type of an analysis is avoided, that is, market projection.

The total production cost of crude shale oil may be broken down into four component parts; these are, operating costs, by-product disposal cost, mine development cost and cost of capital. These components are further subdivided into twelve economic variables. The subjective probability distributions for these economic variables are summarized in Table 14.

Before discussing the subjective probability levels that have been chosen, it may be desirable to philosophize about the nature of the cost estimates that have been made. Generally, each investment and operating cost was estimated conservatively. Any reasonable need for spare capacity was provided in the investment and if high operating expenditure could be anticipated in an area, a conservative (high) estimate of the expense item was made. A 15% contingency was added to the investment and a 30% benefit factor was used in calculating labor and supervisory costs. The oil industry average benefit factor is 25 to 26% so this represents a 4 to 5% contingency in labor cost. Material expenditures are closely related to investment expenditures so they also may be considered to have an implicit contingency in the stated expense. Since this conservatism is judged to exist, it is reflected in the subjective probabilities which have been assigned.

The first of these component costs, operating cost, is subdivided into five variables. Labor cost, the first of these,

TABLE 14

SUBJECTIVE PROBABILITY DISTRIBUTION FOR PRODUCTION COST COMPONENTS

Operating Costs	X	P	X	P	X	P
Labor	0.5	2	1.0	90	1.2	98
Supervision	0.9	5	1.0	75	1.2	95
Materials	0.9	20	1.0	90	1.2	95
Utilities	0.9	5	1.0	75	1.2	95
Insurance & Property Tax	0.8	5	1.0	90	1.2	95
By-Product Disposal Cost						
Vent Gas	-1.7	10	-1.0	50	-0.5	98
Spent Shale	0.67	5	1.0	50	2.0	95
Raw Shale Fines	-1.5	25	-1.0	50	-0.5	90
Mine Development Cost	0.5	20	1.0	90	1.9	98
Cost of Capital						
Mine	0.9	20	1.0	90	1.2	95
Crusher	0.9	20	1.0	90	1.2	95
Retort	0.8	5	1.0	90	1.2	95
Off-sites	0.9	20	1.0	90	1.2	95

X is defined as a random-valued dimensionless factor such that $Z = SX$ Where Z is any variable in cost analysis, i.e. labor, etc. and S is the estimated single value of that variable.

P is defined as the probability of having a value of X which is less than or equal to the given value, % (mathematically, probabilities should be stated as decimal fractions, but percent probabilities have an attractive familiarity).

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is most strongly influenced by the size of the mine labor force. (The mine labor force is 70% of this cost.) The mining cost study is based on equipment and labor requirements for a mine which is developed to an extent that would exist seven years after the start of the project (5). During the early years of the project, less equipment and manpower would be needed. On the other hand, during these early years, a significant development in technology may be anticipated. This will probably lower labor requirements. This line of reasoning is reflected in the subjective probabilities chosen. Supervision is more closely related to function of a labor force rather than its size. As technology becomes more complex, generally, supervisory requirements do not decrease. The maintenance requirements which are anticipated in this plant may require more supervision than has been provided. Material requirements are closely related to mining cost and particularly mining investment. Both operating and maintenance material requirements are high in the mine. Some small improvement in mining material requirements is likely as technology improves during the early years of the project. It is unlikely that material requirements will increase much from the estimated level of expenditure in this area. Utility requirements should be reasonably well estimated and little change is anticipated. These costs are also closely related to function and a significant development in technology is not anticipated. Insurance and property taxes are assumed to be 1.5% of investment per year and the investment in the retorting plant is highest of the four plant areas, therefore, the probability distribution for insurance and property taxes is assumed to be the same as that for retorting investment.

The second cost component, by-product disposal cost, is subdivided into three categories. This is probably the most poorly defined area of this estimate. The reasons for this have been discussed in a previous section of this report. The negative values of $\underline{X}$ that are tabulated for vent gas and raw shale fines disposal reflect the fact that it is anticipated that these costs will actually be credits, which will be added to the other cost components in calculating the total production cost of crude shale oil. In all three cases, the estimated value is assigned a 50% probability. The upper and lower points on these distributions were developed after reviewing Figures 6, 7, and 8.

The mine development cost is the third cost component of total production cost. This cost is small so it can not add much to the uncertainty of the total production cost, therefore, the probability distribution was broadly and very approximately defined.

The final cost component of total production cost is the cost of capital. This, in turn, is subdivided into four categories. In all of these categories, the probability distributions which are prepared, really reflect investment rather than cost of capital. These variables are closely related provided that income tax, investment credit, depreciation guidelines, sales tax and freight charges do not change independently of investment. This assumption is made in this analysis. The first of these categories deals with mining cost of capital. The estimated mining investment contains an allowance of 40 to 50% for spares and contingencies so it is probable at the 90% level that it will not be exceeded. If an increased contingency of about 20% is allowed, it is felt to be 95% probable that the cost will not be exceeded. On the other hand, if the contingency is reduced by about 10%, it is felt that it is 20% probable that the cost will not be exceeded. The probability distribution for off-sites assumed for crushing and off-site investment. In the first instance, it is fortuitous; an additional primary and secondary crusher could be purchased by increasing the cost of capital by 20%. The off-site investment is closely related to the size of the labor force. The labor force size is predominantly mining personnel and this in turn is closely related to mining investment, therefore, the same probability distribution for off-sites cost of capital is the same as that for mining cost of capital. The cost of capital for retorting is estimated to have about a 25% contingency implicit in its value, so the subjective probability that the cost of capital will be equal to or less than the estimate has been fixed at 90%. By tightening the design, the cost of capital might be reduced to eight-tenths or less of the estimate. It is conjectured that there is a 5% probability of this occurring. It is felt to be probable at the 95% level that the cost of capital is equal to or less than 1.2 times the estimate.

The expected level and variance for each of these cost items has been derived from normalized distribution curves (9). These are tabulated in Table 15.

The algebraic summation of these cost items may be expected to be normally distributed (9, 24), because of the Central Limit Theorem. The variance of this distribution is the sum of the variances of the individual cost items. The expected level of production cost is 179.7 ¢/bbl. The standard deviation is 10.1 ¢/bbl. (The standard deviation is the square root of the variance.) These two data define the normal distribution of total production cost, since the normal distribution is a straight line on arithmetic probability paper. By plotting the expected level at 50% and the expected level plus the standard deviation at 84.13%, such a line is defined. Such a plot is presented in Figure 9.

This figure indicates that there is only a 1% probability of total production cost being less than 156 ¢/bbl with present technology. There is a 96% probability that the total production cost of crude shale oil will be equal to or less than the estimated level of 197.0 ¢/bbl. Finally, there is a 95% probability

TABLE 15

COMPARISON OF ESTIMATED PRODUCTION COST AND EXPECTED PRODUCTION COST FROM SUBJECTIVE PROBABILITY ANALYSIS

	Estimated $/CD	Expected $/CD		Variance ($/CD)^2
Operating Costs				
Labor	19,629	15,462		11.42×10^6
Supervision	4,234	4,178		0.09×10^6
Materials	21,038	20,281		3.81×10^6
Utilities	9,048	8,930		0.41×10^6
Insurance and Property Tax	2,737	2,472		0.06×10^6
By-Product Disposal Cost	-2,638	-3,027		5.73×10^6
Mine Development Cost	1,082	692		0.04×10^6
Cost of Capital	43,367	30,837		4.06×10^6
Total Production Cost	98,497	89,825	Total	25.62×10^6
¢/bbl	197.0	179.7		
Standard Deviation, s, ¢/bbl	--	10.1		

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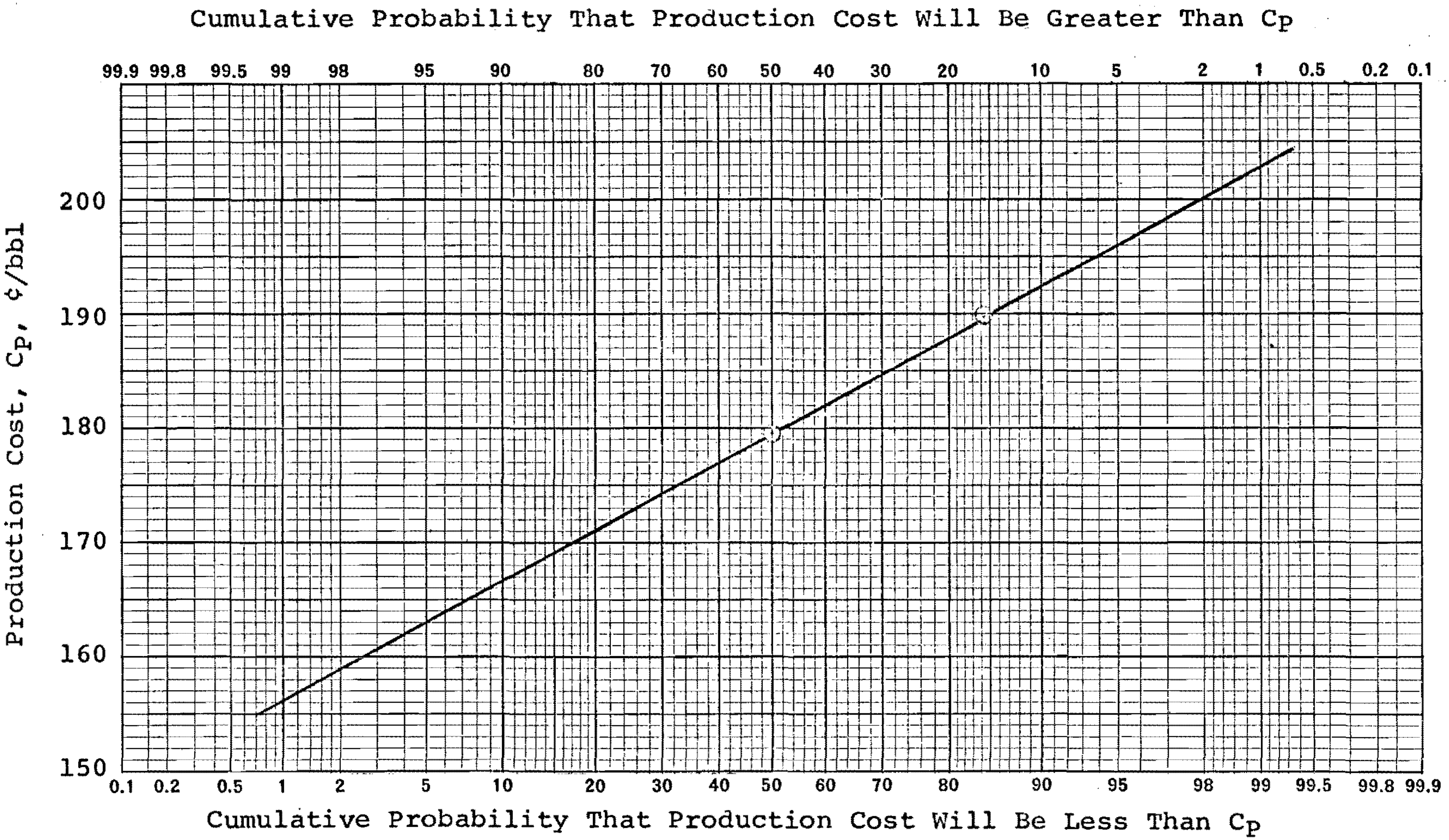
FIGURE 9

CUMULATIVE PROBABILITY DISTRIBUTION OF TOTAL PRODUCTION COST OF CRUDE SHALE OIL



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that the cost will be equal to or greater than 163 ¢/bbl but equal to or less than 196 ¢/bbl.

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