COMBINED MODIFIED IN SITU/ABOVEGROUND OIL SHALE PROCESSING DEVELOPMENT NEEDS

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ABSTRACT

An analysis of the sensitivity of commercial-scale oil shale economics to development risk factors has been completed. The study was performed using published data for the modified in situ, mining and surface retorting, and combined modified in situ/surface retorting processes. The results of this analysis show the need for development efforts in rock fragmentation and mining equipment, together with the need for commercial-scale demonstration modules for both modified in situ and above-ground processing. Numerical data leading to these results, and rationale for the projected development needs, are presented. It is concluded that development and commercialization efforts may be done concurrently, and must be, if an accelerated commercialization schedule is to be realized.

INTRODUCTION

Substantial information has been published describing the technology of obtaining oil from shale. The open literature details the basic approaches: modified in situ (MIS); mining and surface processing (MSP); combined modified in situ/surface processing (CMIS/SP), as well as operational alternatives within each approach: mine design, in situ retort configuration, choice of surface retort, ... Data are also available on the economics associated with specific unit operations (mining, retorting, ...) and, to a lesser extent, on overall system economics. Virtually no data have been presented that would permit a spectrum of processes and operational alternatives to be comparatively evaluated on a common basis.

The purpose of this study was to develop system economics data for commercial-scale modules; objectives were as follows:

(1) obtaining comparative economic performance data for a spectrum of system possibilities;
(2) developing the sensitivities of economics to the uncertainties in technology; and
(3) deriving development program priorities which would eliminate key technological risks that threaten commercial development at present.

The study was accomplished as follows: First, published technology assessments were reviewed to delineate recovery process options and unit operation alternatives, and to obtain performance data bases. This review defined system candidates that showed promise for accelerated commercialization, given technical R&D and economic assistance; revealed specific R&D needs; principal unknowns; and greatest uncertainties.

Next, a comprehensive analysis of system economics was performed. Published cost data bases were obtained and evaluated (and completed where necessary); major assumptions as to development scenario were synthesized. These inputs were used to perform baseline calculations and sensitivity testing. Discounted cash flow return on investment (DCFROI) analysis was used as the basic measure of effectiveness of a given system. Sensitivities tested related to both technical and public policy issues. The results of this step were a refined and narrowed set of system candidates, including quantified key leverage issues, and specification of preferred options for accelerated development analysis.

The third and final step was to analyze commercialization and R&D programs to assess an accelerated development objective. Developmental scenarios were identified and major assumptions were established; developmental scheduling was synthesized and subjected to critical path analysis. This work led to conclusions regarding the preferred process for accelerated development, the master development plan and schedules, and government/industry participations.

SUMMARY OF RESULTS

Technology Assessment

The MSP approach to oil shale has been well-discussed in the literature. Cameron Engineers (1976) has documented mining options and data bases for deep underground mines in the Mahogany zone. TOSCO (Whitcombe 1977; Lenhart 1968), PARAHO (U.S. Bur. Mines), and the USBM (Katell and Wellman 1974; 1971) have presented operating and cost data for surface retorts. The state of the industry in surface retorting technology is such that long-term reliability on a commercial-scale retort is the most substantial risk area. The state of the industry in the development of 50-100 kTPD* mines is such that considerable risk is associated with mining equipment cost, reliability, manpower intensity, speed, and availability.

Taken together, the above risk areas impact economic viability, resource utilization, manpower requirements, and project continuity.

A substantial volume of material has been published pertaining to MIS oil shale processing concerning the effect, the economics, and overall concept. Occidental Petroleum Corporation (Oxy) has published many articles on its work to date. Included are McCarthy and others (1976); McCarthy (1977); French (1976); and others. In addition, Oxy has been granted over 20 process patents in this area. Another MIS system is under development by Lawrence Livermore Laboratory, and is referred to as the RISE process (Lewis 1977).

In addition to the use of MIS, substantial effort has recently been devoted to the idea of a combined modified in situ/surface retorting (CMIS/SP) concept. Again, more than one concept has been presented. Grossman (1977) has presented a paper on the economics of CMIS/SP, based upon the Fenix and Scisson model of a combined module. McCarthy (1977) presented a paper on the effect upon resource recovery of the CMIS/SP process. Table 1 shows resource recovery data he presented, comparing percent recovery for different core holes in different locations in the Piceance Basin. Exact locations are given in McCarthy (1977).

As shown, core hole A, near the southern exposed edge of the basin, yields a 48 percent recovery for the CMIS/SP, with 39 percent recovery for MIS retorting and an added 19 percent recovery for surface processing. For a core hole located on Colorado "b" tract, recoveries are higher for the mineable upper Mahogany and R5 334-foot (100.2 m) section, with 53 percent recovery for the combined, 43 percent for modified in situ, and 15 percent for the surface process. In the center of the basin, where the thicker, richer shale lies, the recovery goes up accordingly. The ratio of resource recovery from a combined system versus a surface processing system is shown to be in the range of 2.1:1 to 4.1:1. Evaluation of the combined system shows about a 25 percent increase in resource recovery over a MIS-only concept. Thus, one of the big advantages of CMIS/SP is increased resource recovery. Assuming that only 25 gpt (110 l/metric ton), or higher, oil

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* k denotes thousands.

Table 1. Comparison of recovery from different processes.

	MINEABLE	SECTION	RECOVERY		RATIO		
CORE HOLE	HEIGHT	Bbl/ACRE	Bbl/ACRE	%	MIS/SP	COM/SP	COM/MIS
Core Hole A USBM RI-5321	220	327,318			2.12	2.61	1.23
Surface Process			60,672	19			
Modified In Situ			128,434	39			
Combination			158,060	48			
Colo. "b" Hole	334	612,980			2.87	3.53	1.23
Surface Process			91,794	15			
Modified In Situ			263,812	43			
Combination			323,664	53			
Sulfur Creek #10 USBM #7051	1,140	2,193,723			3.23	4.14	1.28
Surface Process			293,040	13			
Modified In Situ			948,000	43			
Combination			1,214,000	55			

MIS - Modified In Situ
SP - Surface Process
COM - Combination

shale can be economically retorted in surface processes, the combined systems have a higher resource recovery than open pit mining (Sun Co. 1976). This result is primarily because of the ability of MIS to economically retort shales having 15 gpt (66 l/metric ton) or higher oil shale content.

However, there is another significant - potentially best - reason for going to a CMIS/SP system: a thick, high grade (over 32 gpt; 140.8 l/metric ton) bed, rubblized in low void volume conditions within large-scale retorts, may, in fact, not work. This problem originates in the fact that large deformations can occur in rich oil shale when subjected to heat before retorting. These large deformations are termed "cold flow". Cold flow, if it occurs, is likely to cause plugging of large size retorts.

Oxy has not reported the occurrence of problems of this kind in their test retorts, but these have been located in the more variable grade basin-edge shales. Furthermore, it is unlikely that such a problem would exist in small-scale retorts, because there would be virtually no pressure transmitted through the rubble to the high grade seam. In addition, all tests have been run in the relatively lean edge of the basin material. It is true that in this area there is a rich seam. However, it is fairly thin and in this circumstance the problem may not exist. Lawrence Livermore Laboratory (Rothman 1977) has shown a reduction in permanent porosity from 43 to 8 percent under 300 psi (2.1 MPa) pressure in a simulation of this potential problem. For this reason, it is felt that mining within high grade material to provide surface retort feed would offer significant advantages, both economically and technically, for in situ processing of oil shale. However, it is fair to say there is a lot of work to be done in this area.

ECONOMICS

In order to understand potential development needs more clearly, one should first look at the technological and economic policy areas where the most significant economic impact can be made. In order to do that, it is necessary to develop an engineering estimate of recovery system capital and operating costs. The open literature offers data from which these different costs can be generated. For mining cost, refer to Cameron (1976); for costs on the TOSCO process, refer to Whitcombe (1977); Lenhart (1968); for PARAHO cost, U.S. Bureau of Mines (1975). These references served as the basis for our estimates for the capital costs for aboveground processing and the mining costs for MIS. The MIS costs, however, were taken from Ashland and Occidental (1977); TRW (1974).

As can be seen in Table 2, capital cost per daily barrel ranges from \$12,000 to \$13,000 for surface processing down to \$7,000 for the MIS and \$8,600 for the combined system. Operating costs are about \$4.40/barrel* for the surface and MIS processes, with about \$3.80/barrel for the combined system. The basic trade seems to be capital cost for operating cost. As will be shown, this is not a particularly good trade. However, in view of resource recovery and technical advantages, the CMIS/SP is judged the better process to go with.

In order to develop a comparative picture of process economics, capital and operating costs for each system were used in a DCFROI economic analysis computer program to determine the effect of different variables. These results are summarized in figures 1 through 5.

Table 2.

Process	Plant Capacity	Capital Cost \$/daily Bbl	Operating Costs \$/daily Bbl
TOSCO	50,000	13,260	4.44
Paraho	50,000	12,000	4.33
Occidental Modified In Situ	57,000	7,015	4.40
Combined TOSCO/Modified In Situ	83,000	8,615	3.80

First, in figure 1, we show the effect of variation in bonus bid payments. The base case which we use throughout assumes a \$50 million bonus bid. As shown in figure 1, the DCFROI versus the sales price in dollars/barrel relates to about 20 percent DCFROI for \$15/barrel for the base case. It is our contention that the technology has not yet been developed to the point where the risk involved in a 20 percent DCFROI would be worth the pursuit of a project of this magnitude.

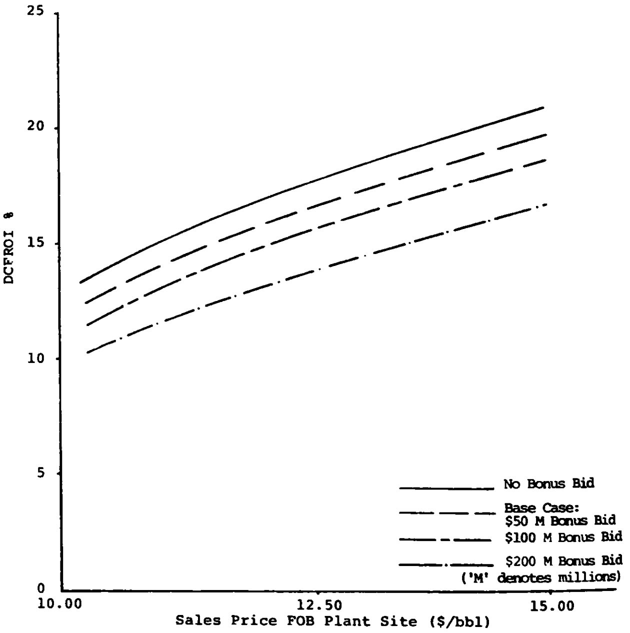

Figure 1. Economics of combined modified in situ/surface processing: effect of bonus bid.

In figure 2, we show why this technology development is so critical. In this figure, the effect of oil yield on the MIS process alone is presented. Oxy

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*1 barrel = .1598 m^3.

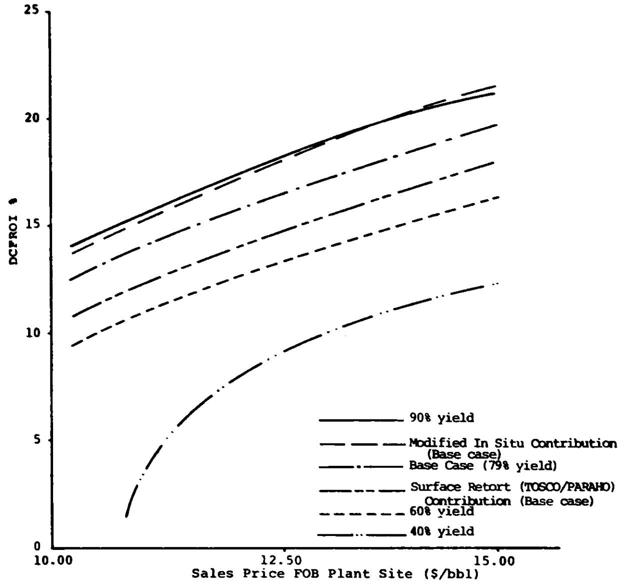

Figure 2. Economics of combined modified in situ/surface processing: effect of yield on the modified in situ portion of the system.

has reported (1977) a yield in excess of 60 percent for the MIS on a small-scale retort. However, if the yield were unexpectedly lower in a commercial-sized scale-up, say 40 percent rather than 60, the 40 percent yield would not present an acceptable DCFROI. However, if we look at a 60 percent yield on the combined system, the economics are quite similar to the above-ground processing.

If one uses a 79 percent yield (the base case) - computed yield based on the data given in the Detailed Development Plan of Ashland and Oxy (1977) - then a significant increase in DCFROI is experienced. If a yield of 90 percent is achieved - as reported by Lawrence Livermore Laboratory for test programs in their pilot unit retorts - the DCFROI increases substantially more. Therefore, the major technical uncertainty to be resolved for the combined system and for the MIS system is: whether or not yields of 60 percent and greater are possible in large-scale retorts? In Oxy's Retort 5, only a 20 percent yield was reportedly achieved (1977); this yield would represent an unacceptable value as far as commercialization is concerned.

In order to improve the yield, and to assure repeatability, it seems essential that the basic phenomena of rock breakage, blasting patterns, and related process variables be more fully understood and that validated predictive models be developed. These observations lead to the conclusion that an extensive rock fragmentation research program is absolutely essential to furthering either the MIS or the combined system.

Figure 3 shows the effect on the economics of both capital cost and operating cost. As shown in this example, an increase in capital cost causes a significant decrease of the DCFROI. For example,

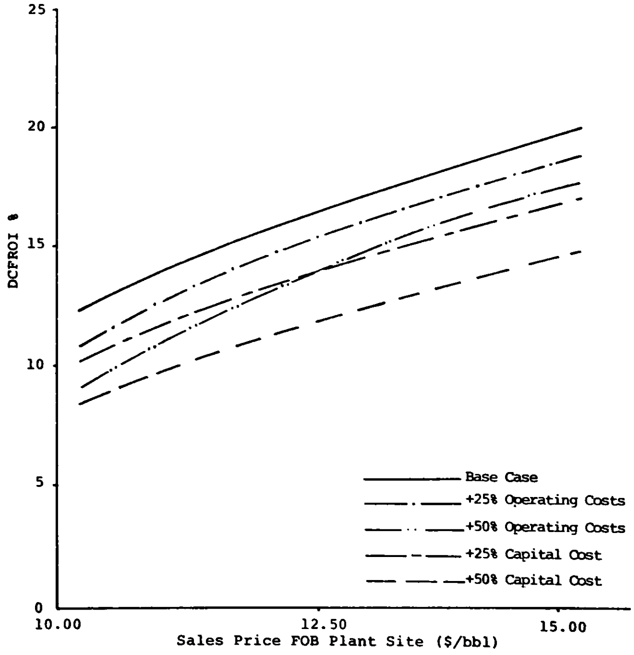

Figure 3. Economics of combined modified in situ/surface processing: effect of capital and operation costs; 10 percent interest on government loan portion.

at $15/barrel, the DCFROI goes from 20 percent down to 17 percent with a 25 percent capital cost increase; with a 50 percent increase in capital cost, the DCFROI goes down to about 15 percent. Therefore, it is necessary to tie down capital cost for the combined system. Table 2 shows that capital cost intensity for the above-ground processing part is higher than that for the MIS. Therefore, this increasing capital cost demands that a full-scale or sufficiently large-scale surface retort module be demonstrated so that the cost can be projected effectively. At the same time, it is equally important that full-scale modules of the MIS be tested. This matter will be more completely dealt with later.

In the same manner as capital cost, operating costs have a depressing effect upon DCFROI, although not as significant as capital cost. For example, a 50 percent increase in operating costs only lowers the DCFROI from 20 percent to 17½ percent at $15/barrel. This result shows why lowering operating cost and raising the capital cost will cause a net depressing effect upon DCFROI. Referring back to figure 2, we note that MIS processing, evaluated by using the numbers published in Ashland and Occidental (1977); TRW (1974), gives a decrease of about 1 to 1½ points in DCFROI for the combined system. Since operating costs are basically controlled by mining costs, this can be lowered by optimizing the mine plan, and by developing mining equipment, required for greatest efficiency and effectiveness for these types of mine plans. It is our conclusion, therefore, that a mining equipment development program is required.

Figure 4 shows the effect upon the DCFROI of delays in development schedule. One-year and three-year delays with 10 percent annual inflation have been evaluated and, at $15/barrel, the DCFROI drops from 20 to 13 percent with the three-year delay. Therefore, it is necessary not only to do the research programs, but to do them in a timely manner so that commercialization can proceed expeditiously. This same effect would result from time-consuming environmental or regulatory delays.

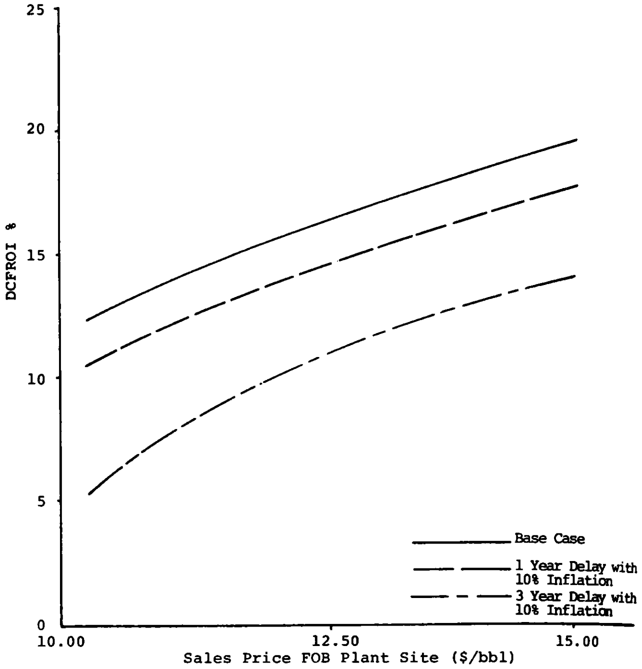

Figure 4. Economics of combined modified in situ/surface processing: effect of time delay.

In figure 5, we have explored the significant incentives which the federal government could provide to help spur development of the CMIS/SP oil shale concept. We have analyzed the effect of a government loan, using 25 and 50 percent debt-equity ratios, with a 10 percent interest rate on the loan, and including $1, $2, and $3/barrel tax credits. These calculations do not look at a total corporate tax structure, nor do they consider the overall benefit to a corporation from these tax credits, as the tax credits were assumed for this project only. In our model, as the tax credit goes up, no further benefit occurs once all the tax paid has been eliminated by the credit. So for a corporation, the benefits shown here are very conservative. The credit per barrel is

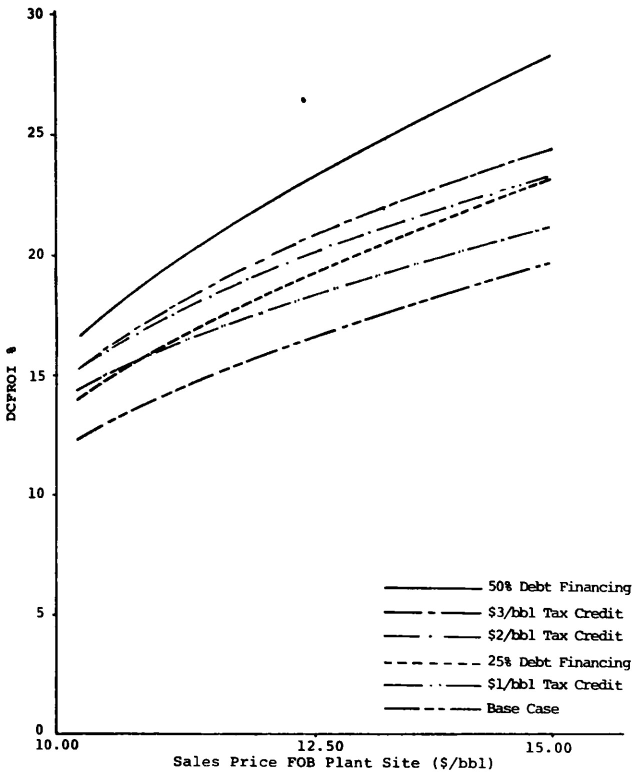

Figure 5. Economics of combined modified in situ/surface processing: effect of government incentives.

probably in the correct range. The $3/barrel is conservative. We would expect the DCFROI at $15/barrel with $3/barrel tax credit to be 25 percent or better for the combined system assuming the program is moving ahead according to plan.

DEVELOPMENT NEEDS

As explained above, development needs can be categorized as follows:

1. Rock fragmentation
2. Mining equipment development
3. Full-scale module development for both the modified in situ portion and the surface retort portion.

These development needs can be estimated by gross numbers, as will be discussed below.

Figure 6 shows a schedule for development program needs. We have concluded that commercialization can and must be initiated at the same time as the research program is being developed. A two-year rock fragmentation program, estimated to cost somewhere between $5 and $6 million, is required. The parallel program for mining equipment development is to develop continuous miners, multihead drill jumbos, material handling systems, specialized blasting systems, and other items specialized for this kind of mining. This is anticipated to take about 5 years and cost in the neighborhood of $30 million. In order to test the rock fragmentation program, small-scale retorts would be developed (not necessarily retorted); this will take about a year and a half and cost another $5 million. Large-scale retorts would be built singly at first; then, as clusters. This is estimated to take about 2-1/2 years for the single retort, with an additional 1-3/4 years for the clusters. It is anticipated that this program would cost in the neighborhood of $100 million. Co-development of a surface retort module, which we estimate to cost in the neighborhood of $100 million, is shown as program item Number 6. This line shows that the engineering and construction is a 1½-year program with a three-year retort operation. It is believed that a three-year retort operation is the minimum time required to develop maintenance and reliability data for such a system. Since the combined system would not be available for operation until the fifth year, it is believed that operation of the surface retort should not start until the fifth year, with engineering starting after a year and a half into the rock fragmentation and mining equipment development program.

As shown in line 7, engineering and environmental support studies will be required for the entire program (these are estimated to cost about $30 million). Thus, it is estimated that a $300 to $400-million program is needed, over a time period of no less than 7 years, before commercialization of oil shale by combined modified in situ surface processing can become a reality.

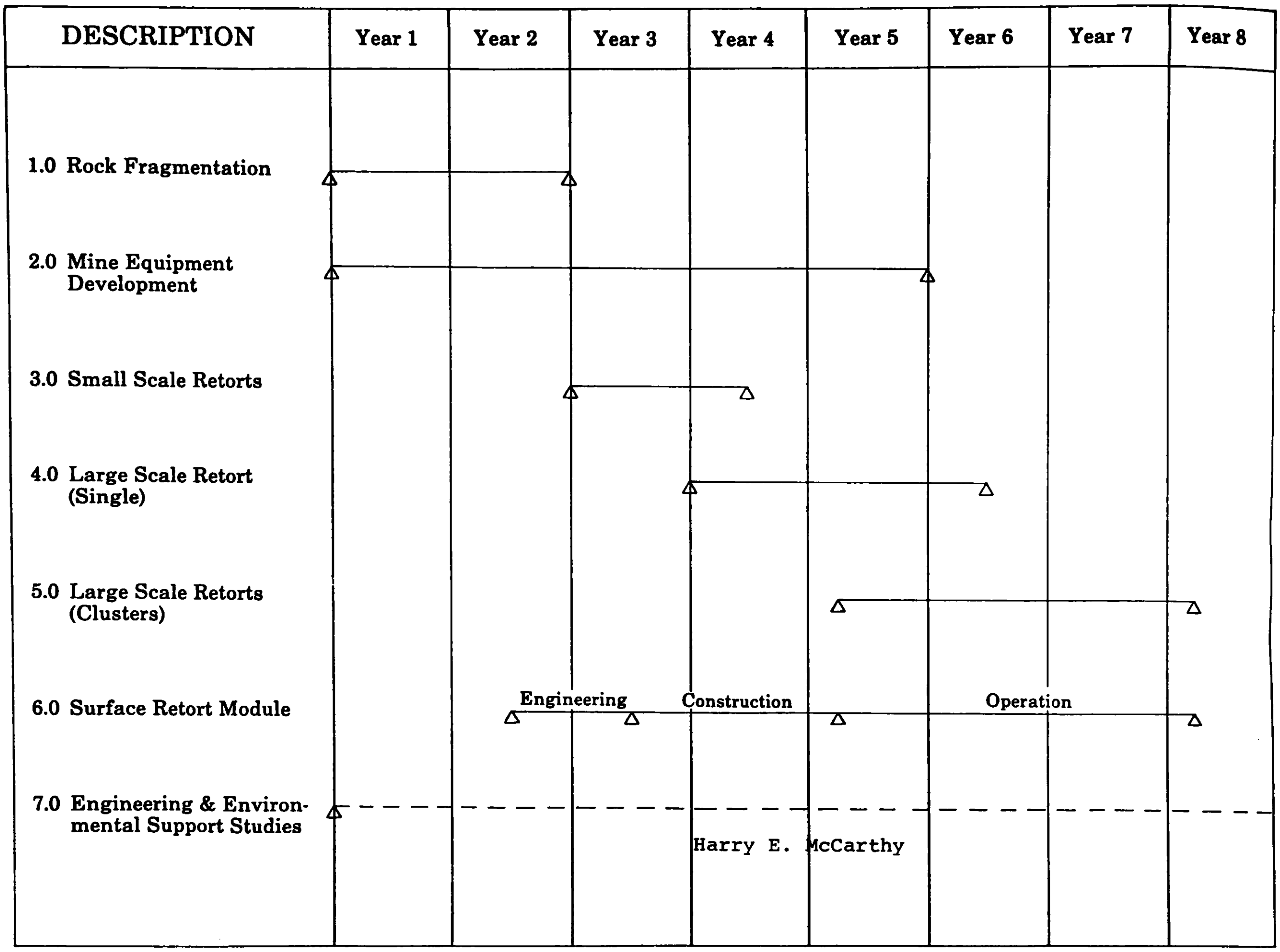

Figure 6. Schedule: development program needs.

Within this 7-year program, it is possible that by starting at the end of the third year, the mining being done for the full-scale modules and full-scale retorts could be done in a commercial mode; that is, this mining could constitute the beginning of a commercial system. It is also possible to start commercialization construction in about year three. The design, therefore, could be started at the end of year one. It would seem to be possible, therefore, to do the engineering for a commercial facility in parallel with development work at the end of year three, and to start committing for deliveries of equipment with the idea in mind that, at the end of year 5½ when a single, large-scale retort has been completed successfully, and when some operational experience for a single retort module is completed, a decision could be made to go full-scale while completing the first modules. Thus, the first modules could be part of the commercialization plan. It would then be possible to have a commercial plant up and running by the end of year eight. The size of this commercial plant could be anything from 50,000 barrels/day to 300,000 barrels/day

(7,990-47,940 m^3/d).

It is our belief that a large-scale 200,000 (31,960 m^3) to 300,000 barrels/day system is required to spur development work to the point at which a 2-million barrel/day (319,600 m^3/d) facility could be available in the last part of this century. To achieve these goals, we see an urgency to begin the described development program for the combined system and to move ahead diligently with commercialization. To do this, it is evident that federal government incentives, as shown in figure 5, or something similar, are going to be required. For industry to take on the risks of commercial-scale development, before all the development work is complete, would not seem to be in the cards, even with a DCFROI as high as 25 percent.

CONCLUSION

The foregoing results have clarified certain of the economic issues associated with commercialization of the three oil shale recovery processes, and have shown the relatively favored position of combined, modified in situ/surface processing. Sensitivities have been obtained which show the effects upon economics of key technical risk areas and of federal government economic policy. The authors recommend the following:

(1) a development program consisting of rock fragmentation, mining equipment, and full-scale operational demonstration of both surface and in situ retorts;

(2) the development of a federal economic incentive package that would result in stimulation of the oil shale industry by providing adequate safeguard against risk; and,

(3) a parallel development - commercialization program to achieve production of 50,000 to 300,000 bbl/day (7,990-47,940 m^3/d) within eight years.

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