

# COMPUTER - BASED SUPPORT FOR ENHANCED OIL RECOVERY INVESTMENT DECISIONS\*

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## ABSTRACT

This paper reports on the development of a system dynamics model to enhance the economic decision-making processes involved in the identification, evaluation, and selection of chemical-based enhanced oil recovery projects. Model structure is described and an example illustrates usage of the model in project evaluation activities.

## Enhanced Oil Recovery

Enhanced Oil Recovery (EOR) refers to the fluid injection process technologies designed to recover the vast supplies of oil remaining in the world's known oil reservoirs. This oil is often called "tertiary oil" and remains in the ground after the conventional techniques of primary and secondary production have withdrawn all the oil they can. Together, these two conventional production stages recover only about one-third of all the oil in a given reservoir. The remainder stays locked in the porous underground rock formation. For example, the quantity of oil that awaits recovery is estimated at 300 billion barrels for the United States (Gary, 1978).

Most EOR recovery processes are employed rather late in the secondary--i.e., waterflood--production stage and therefore operate at relatively high water-saturation and low oil-saturation (Cronquist, 1976, pp. 531-555). The residual reservoir oil is contacted, reconnected, mobilized, banked up, and displaced to wells where it is then produced at economic water-to-oil ratios (WOR). To accomplish this task, the EOR process must have the capability of greatly reducing or eliminating the forces that cause oil to be trapped and retained in the reservoir. The problem is basically one of reducing or eliminating the oil-water interfacial tension forces (Taber, 1969, pp. 3-12) which lead to capillary trapping during immiscible displacement--e.g., during water encroachment. Three major approaches to EOR have been identified: steam injection, miscible processes, and chemical processes (Gary, 1978). This paper is concerned only with chemical processes.

The chemical process uses different types and combinations of chemicals to tap the oil. In the chemical "surfactant/polymer" or "micellar/polymer" methods, a detergent-like chemical is mixed with either water or oil and injected into the reservoir. The chemical lowers the interfacial tension between the oil and water locked in the rock. The oil is then free to move and coalesce into an oil bank. The oil bank flows to producing wells in front of the micellar slug which is then pushed in piston-link motion by polymer-thickened water. In these chemical processes, the chemical slugs are absorbed on the rock.

## Risk and Cost Considerations

Chemical EOR processes are among the best known exotic EOR methods and the most likely to produce significant amounts of oil in coming decades. However, the next generation

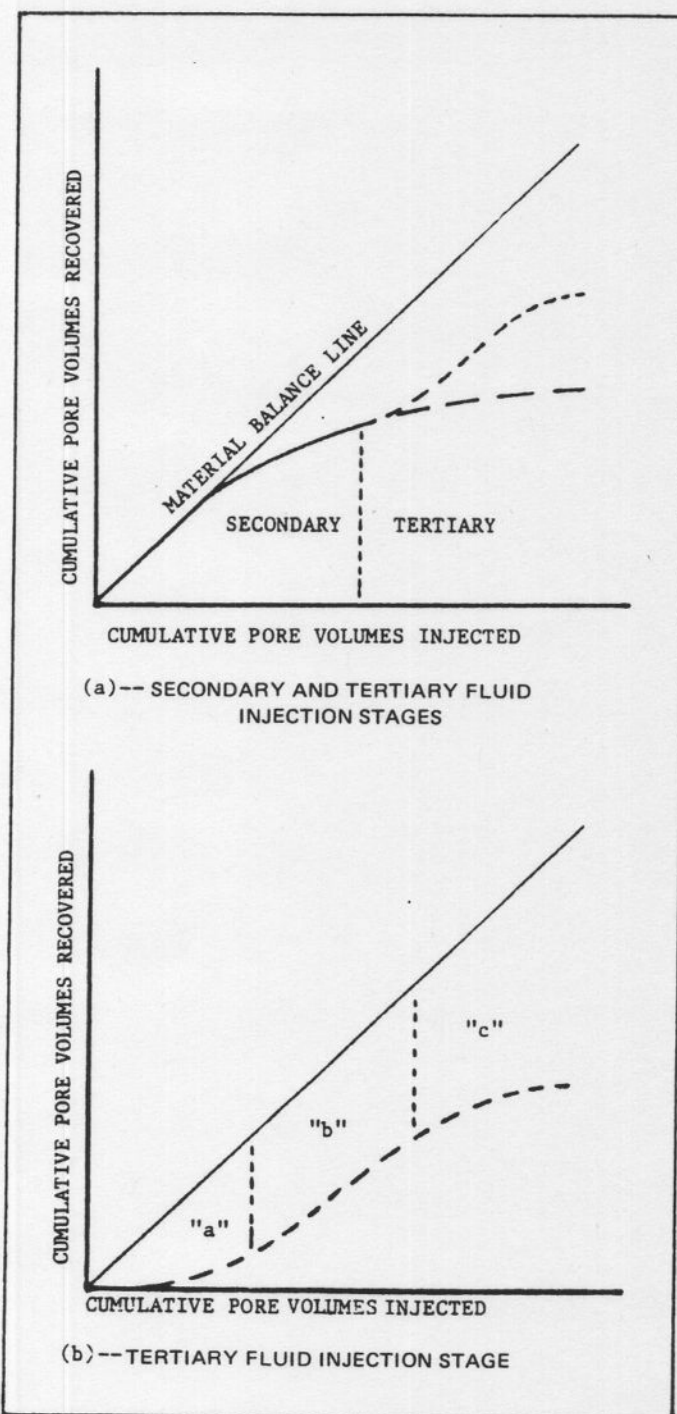


Figure 1

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of chemical EOR projects will require extremely high front-end costs. It has been estimated that the front-end chemical costs for an EOR chemical project producing three million barrels of oil could range between \$15 to \$30 million (Gary, 1978). And these chemicals are pumped into the ground anywhere from one to two years prior to any oil production from the project.

Other economic aspects of EOR are a direct consequence of the reservoir mechanics of these processes. After the expense of installing or modifying existing facilities, the EOR process is started by injecting a slug of expensive material to reconnect and mobilize the residual oil. This investment is followed by a period of high WOR production with little (if any) income during a phase in which wells must be operated and water lifted and disposed. Tertiary oil when finally produced is produced along with substantial amounts of water. Thus artificial lift costs must be borne throughout the project's life. In addition, the technology for EOR is embryonic. Performance predictions therefore carry a high degree of uncertainty. Analyses of low and high performance field test cases show that a small reduction in the process recovery performance can lead to a large reduction in the actual oil produced. Risk of failure is high.

In addition to the above economic uncertainties there also

exists reservoir anatomy uncertainties (Cronquist, 1976, pp. 531-555). Thus the investment of corporate funds in EOR projects becomes a high risk decision. This paper reports on a chemical-based EOR project evaluation simulation model that has been developed over a three-year period to support EOR project investment decision processes by providing sets of reservoir production and financial data that reflect the inherent risk and uncertainty of a specific project. The model structure is designed around a process transfer concept so future applications can be easily made to steam injection and miscible EOR processes.

### Modeling Methodology

Two stages can be identified in injection-recovery processes: "secondary" and "tertiary". These stages are shown in Figure 1<sup>a</sup> in terms of a curve that relates the dependent variable cumulative pore volumes recovered to the independent variable cumulative pore volumes injected. Second stage processes include fluid injection processes designed to supplement natural reservoir energy. Use of the term tertiary includes fluid injection processes designed to recover oil potentially remaining after water flood, whether or not the water flood was primary or secondary (Cronquist, 1976). Figure 1<sup>b</sup> demonstrates how the axes of the Figure 1<sup>a</sup> curve may be shifted so the tertiary portion of the curve passes through the origin. Cumulative volumes injected and recovered now become those

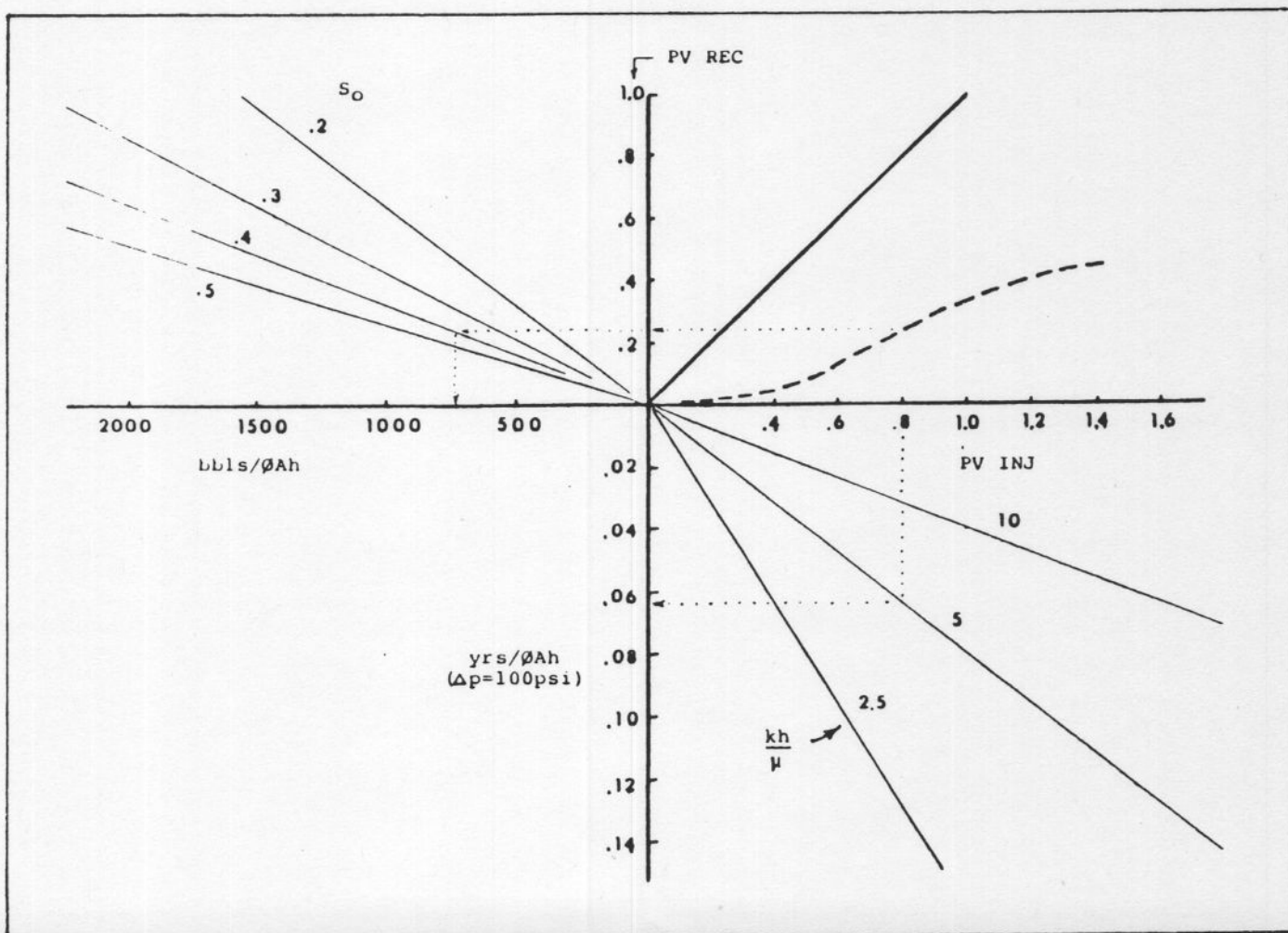


Figure 2--TIME-RATE OIL RECOVERY NOMOGRAPH



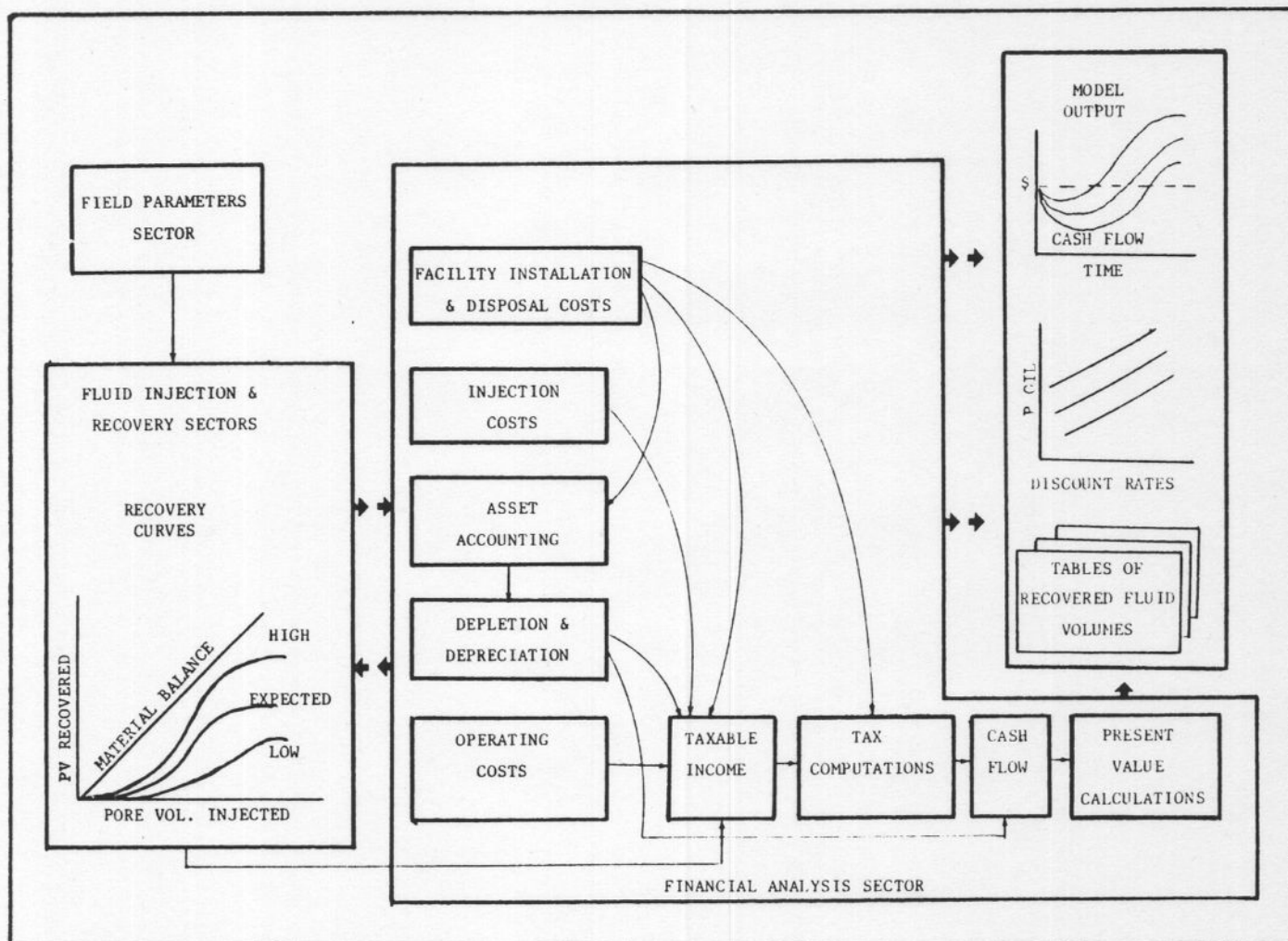


Figure 3-MODEL SYSTEM STRUCTURE OVERVIEW

volumes injected and recovered during the "tertiary" stage.

Tertiary processes are generally started fairly late in the secondary stage and generate a sigmoid shaped curve of pore volume recovered for the tertiary stage. In a waterflooded reservoir close to residual oil saturation (typically the case), the interval between the sigmoid curve and the material balance line represents water production.

Three production periods can be identified as shown in Figure 1<sup>b</sup> for tertiary processes started under post-water flood saturation conditions: (a) a period prior to arrival of the tertiary oil bank characterized by high producing WOR--e.g., typically greater than 20:1, (b) a period during which the tertiary oil bank arrives at the producing wells and is produced at lower WOR--e.g., typically no lower than 3:1, and (c) a period after production of the oil bank during which the WOR gradually increases to an economic limit.

The economic viability of an EOR process is governed by the time-rate of recovery of oil versus the time-rate of expense required to recover this oil. Cronquist (1976) devised a procedure based on Smith's (1968) five spot injectivity relations to convert pore volumes to barrels and to relate these barrels to time. The Cronquist technique as conceptualized by the Figure 2 nomograph served as the physical process foundation

for development of the EOR project evaluation simulation model.

The first quadrant of Figure 2 is the same as Figure 1<sup>b</sup>. It characterizes EOR process performance with pore volume curves. Economic viability of these processes is governed by the time-rate of recovery of oil versus the time-rate of expense required to recover the oil. Cumulative pore volumes injected into a reservoir pattern element of area A, thickness h, and porosity  $\phi$  (Reservoir barrels of pore space in this pattern element are numerically equal to  $7758\phi Ah$  where 7758 converts from acre-feet to 42 gallon barrels.) can be time related by use of Muskat's five-spot injectivity relation (Smith, 1966, p. 92) which, in turn, reduces (Cronquist, 1976, p. 554) to

$$t = 140 \mu / kh \Delta P \text{ (Yrs/AF)} \quad (1)$$

where k is the reservoir permeability in darcys,  $\mu$  is the fluid viscosity in centipoise,  $\Delta P$  is the pressure differential in psi, and t is time in years per acre-foot. Thus the time in years required to inject an acre-foot (7758 reservoir-barrels) of liquid of 1 centipoise into a 1 darcy-foot reservoir with 100 psi pressure differential between injection and production wells is .40 Yrs/AF.

The dotted line in Figure 2 illustrates usage of this technique. With 100 psi differential, the time to inject 0.8 pore volume using a process in a reservoir with an effective transmissibility of five darcy-feet per centipoise is 0.064 years per acre-foot of porosity. If the reservoir is processed on 5-acre patterns and has an average of 20 net feet of pay and porosity of 0.25, this would require 1.6 years ( $0.064 \times 5 \times 20 \times 0.25$ ). At the end of this time cumulative oil recovery would be 0.24 pore volumes. If the reservoir had a residual oil saturation  $S_o$  of 0.40 at process initiation, recovery would be 745 barrels of oil per acre-foot of pore volume in the pattern, or 18,625 barrels.

Pore volume input curves are translated in the model to time-rate of injection and recovery through use of the five-spot injectivity formula. For a given value of the parameter  $kh/\mu$  the injection line shown in Figure 2 is a limiting case. Any injection line between the vertical axis and the limiting line represents a physically feasible injection profile.

### Structure Of The EOR Simulation Model

The system dynamics computer simulation model of EOR decision-making processes concentrates on the role that financial analysis plays in project evaluation. The model is designed to (a) allow rapid assessment of the economics of an EOR project and (b) evaluate the sensitivity of the economics to the parameters of the reservoir and to the efficiency of the recovery process. Physical reservoir processes are described in terms of the Cronquist (1976) scheme. Three different assumptions concerning the shape of the recovery efficiency curve can be evaluated simultaneously. The financial investment and resultant revenue structure of an EOR project is simulated in detail to allow for a set of discount factors the computation of the net present value of discounted streams of revenue and expenses and the discounted costs per discounted barrel of oil.

A concise overview of the structure and key features of the model is desirable as it will provide the foundation required to discuss the output produced from the model. Figure 3 presents a simplified sector description diagram of the important relationships governing EOR project evaluation.

A logical grouping of the EOR system variables indicated that the model be developed in four major sectors: a field parameters sector, a fluid injection sector, a fluid recovery sector, and a financial analysis sector. An abridged influence diagram for the field parameters, fluid injection, and fluid recovery sectors is contained in Figure 4.

The basic reservoir parameters are defined or specified in the *field parameters sector*. Input parameters include reservoir permeability, well depth, thickness of the oilbearing layer, spacing of the injection and recovery wells, porosity of the formation, area per injection well, total area of the field, and pressure differential maintained during the process. Computation of the viscosity-limited injection rate for a fluid of unit viscosity is made from these input parameters for the reservoir. Also calculated is the pore volume per injection well.

The fluid injection and recovery sectors define the part of the model that stimulates the physical activities in an EOR

project as described by Figure 2. The *fluid injection sector* contains processes for cumulative injection accounting and simulates the injection phases for the preparatory chemical solution, the chemical slug, the buffer, and the water. Equations for each phase simulate fluid injection to a predetermined cumulative fractional pore volume. Two injection schedule options provide for the injection of (a) a predetermined cumulative fractional pore volume at a constant specified rate or (b) each phase at the viscosity-limited rate for the formation. The buffer injection equations relate viscosity of the buffer phase to the concentration of the polymer in the buffer solution and provide for a constant polymer concentration, or a tapered polymer concentration, or a combination of the two. Water injection is stopped either at a fixed cumulative pore volume injected or when marginal costs of operation exceed marginal revenue.

The *fluid recovery sector* consists of water production and disposal processes and an oil recovery process. As previously explained, the fluid recovery process is modeled as a fractional pore volume recovery efficiency curve. Parallel computations are made for three different recovery curves: an expected recovery curve, the most optimistic recovery curve, and a pessimistic recovery curve. These three process curves are inputs to the model. Oil recovery is derived for each case from the input recovery efficiency curve. Water recovery (or production) is obtained from material balance calculations. Also computed are the expected values for the three recovery profiles based on subjective probabilities assigned to each conditional profile (Schlaifer, 1959).

The subsectors that define the *financial analysis sector* are concerned with (a) accounting for activity installation and disposal costs, (b) maintaining fluid injection costs, (c) assets accounting, (d) determination of operating income and expenses, and (e) economic analysis of the EOR project.

The facility installation and disposal costs computations provide for the recording of expenditures for drilling activities and equipment purchases. Salvage value and cleanup costs are computed by using either fixed pore volume or economic water phase termination equations. The fluid injection costs are determined by the injection rates from the fluid injection sector and unit costs input values for the various injection phases. The project development and equipment costs are recorded in tangible and intangible assets accounts. Depreciation is calculated and model options allow depletion to be computed according to either cost basis or statutory basis income tax procedures, whichever approach is employed by the operating company using the simulation model.

Operating income and exenses are simulated as the accounting income and expense statements and are handled according to standard United States accounting practices. Computations start with the generation of revenue (net of royalty) as a function of recovered oil and oil price. (The price of oil or the price of oil relative to the inflation factor in costs can be varied over the project's life.) All tax deductible expenses are then subtracted from revenue to arrive at the taxable income. Federal income tax is calculated on the basis of taxable income. Tax rates and computational procedures can be set to fit the tax situation of a specific operating company. Taxable income is reduced by federal income



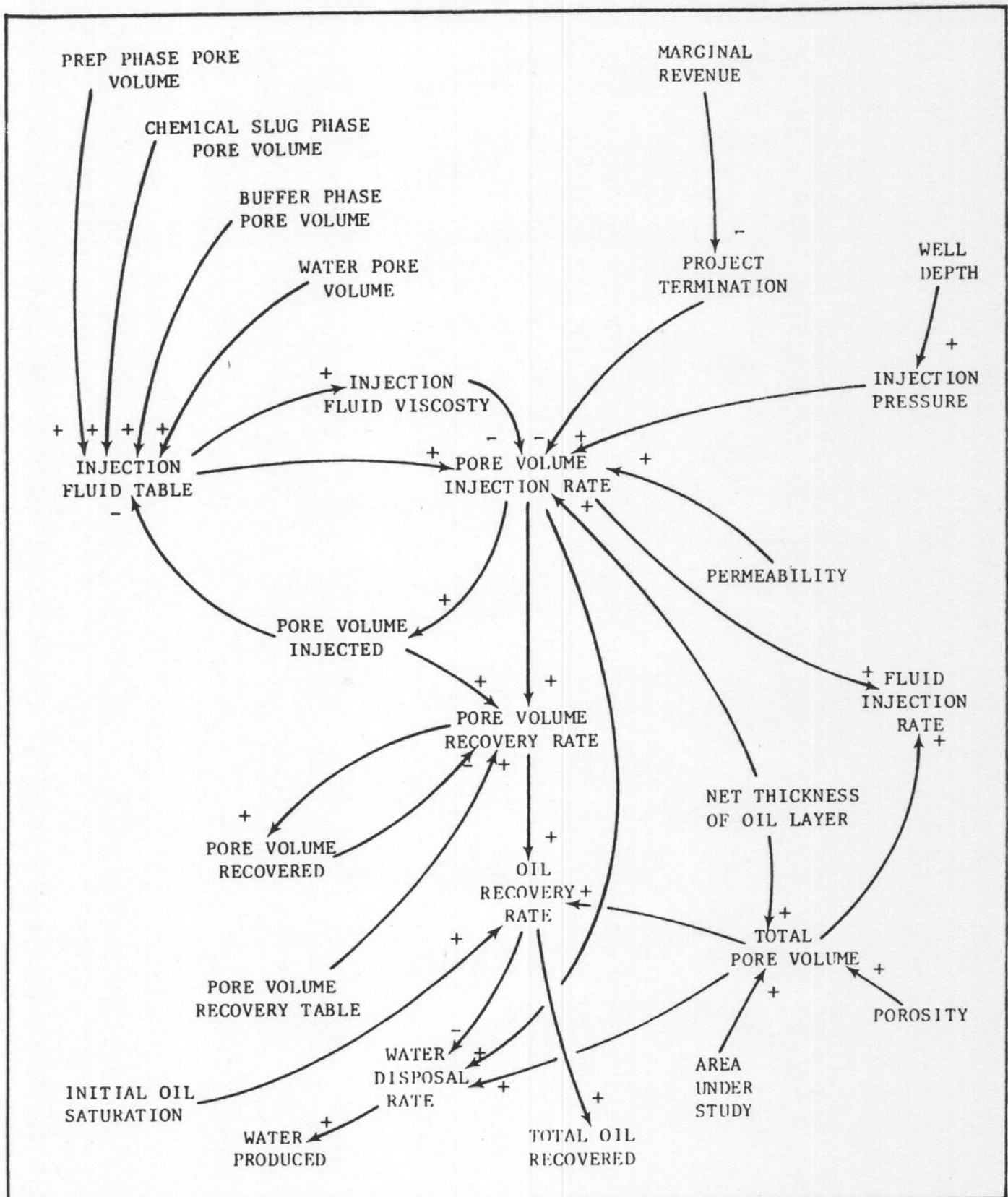


Figure 4-INFLUENCE DIAGRAM FOR FLUID INJECTION AND RECOVERY

taxes to arrive at net income. Cash flow calculations are made in accordance with Bierman and Smidt's (1968) guidelines by subtracting drilling and equipment costs from and adding salvage value to taxable income. The model contains a special DYNAMO MACRO which continuously discounts and accumulates the cash flow to determine a net present value for any specified discount rate. This allows the project's internal rate of return to be easily determined by first calculating the net present value for a number of discount factors and then interpolating to arrive at the zero discount rate. A second DYNAMO MACRO generates the discounted cost per discounted barrel of oil for the total quantity of oil produced from the EOR project for the previous set of discount factors.

The EOR simulation model generates both tabular and graphical outputs. The tabular output displays discounted cost per discounted barrel of oil recovered (net of royalty) for five discount factors for all three recovery profiles plus a weighted profile. The net present value of the project is presented as a function of the expected profile for all discount factors. Other tabular output includes such items as pore volumes and barrels of injected materials, barrels of oil and water recovered, and pore volumes of oil and water recovered. Graphical plots are presented of the time-path behaviors of eleven critical financial and recovery process variables.

A data base of sixty-four input parameters is employed to describe the physical and financial dynamics of an EOR project. The physical part of the model is general enough that by making a few adjustments to input parameters a number of different possible EOR processes can be studied in the same reservoir. Input parameters are conveniently grouped into eight major categories: reservoir parameters; injection parameters; drilling facility, and cleanup costs; chemical-polymer injection costs; financial parameters; recovery profile probabilities; simulation run parameters;

and project table functions. Any of these parameters (or groups of parameters) can be varied between simulation runs to explore alternative EOR project scenarios.

#### Example Application

A simple example will demonstrate model use. Parameter data used to initialize the model are chosen so as to fall within the range commonly observed in field testing. Reported historical cost data is employed for the example in conjunction with current oil price and inflation rate figures. This results in an eclectic example for demonstration purposes.

A five scenario set that management envisions an EOR project might experience over a projected ten year project lifetime is described in Table 1. For all scenarios, the inflation factor is assumed to remain at ten percent per year over the projected project life and affects price and all costs. The initial wellhead price of oil is \$30.00 per barrel. Discount rates of 10, 15, 20, 25, and 30 percent have been selected for project evaluation purposes.

Scenario I reflects a base-line oil recovery profile that management believes will most likely be encountered. Accordingly, a subjective probability of occurrence of sixty percent has been assigned to the scenario. (The subjective probabilities are used in the model to obtain an "expected" oil break-even price profile.) The possibility that the base-line oil recovery profile is too optimistic is recognized by Scenario II where the oil recovery profile is assumed to be one-half the base-line rate. A thirty percent probability of occurrence is given to this profile. On the other hand, there is the possibility that the field might yield a quantity of oil greater than expected from the base-line case. This situation is acknowledged in Scenario III where an oil recovery profile with twice the recovery rate of the base-line scenario is described. However, only a ten percent probability of occurrence is expected for this scenario.

TABLE 1 - SCENARIO DEFINITIONS\*

SCENARIO	OIL RECOVERY PROFILE	PROFILE PROBABILITY	DISCOUNT FACTORS
I: BASE CASE	BASE-LINE	.60	
II: LOW CASE	.50 * BASE-LINE	.30	.10, .15, .20, .25, .30 FOR ALL FIVE SCENARIOS
III: HIGH CASE	2.0 * BASE-LINE	.10	
IV: 4-YR DRILL	BASE-LINE	.60	
V: ECONOMIC LIMIT OPTION	BASE-LINE	.60	

\*ALL SCENARIOS ASSUME A TEN PERCENT YEARLY RATE OF INFLATION

Two other investment situations are described by Scenarios IV and V. First, the model is initialized with a parameter set that assumes all drilling, equipment purchases, and equipment installation, are completed by the end of the project's first year. Scenario IV relaxes this condition and allows drilling and equipment installation to proceed uniformly over a four year period. Second, Scenario V activates a model option that stops injection when the project becomes unprofitable i.e., when marginal revenue becomes negative.

Figure 5 presents the summary of financial results generated by the model for the five scenarios in terms of *oil break-even price profiles*. The dependent variable is the "discounted cost/discounted net barrel" and is a measure of the total (excluding federal income tax) present day cost per present day net (after royalty) barrel of oil recovered. The numerator is the present day value of all costs (including initial capital expense, chemical costs, well operating expense, fluid handling expense, etc.) discounted in the year incurred to project initiation time at the discount rate shown on the abscissa. The denominator is the present day value of the after-royalty barrels discounted the same way. (Actually, there need be no assumption about the wellhead value of the produced oil in arriving at this figure since the parameter is a "break even" discounted cost.)

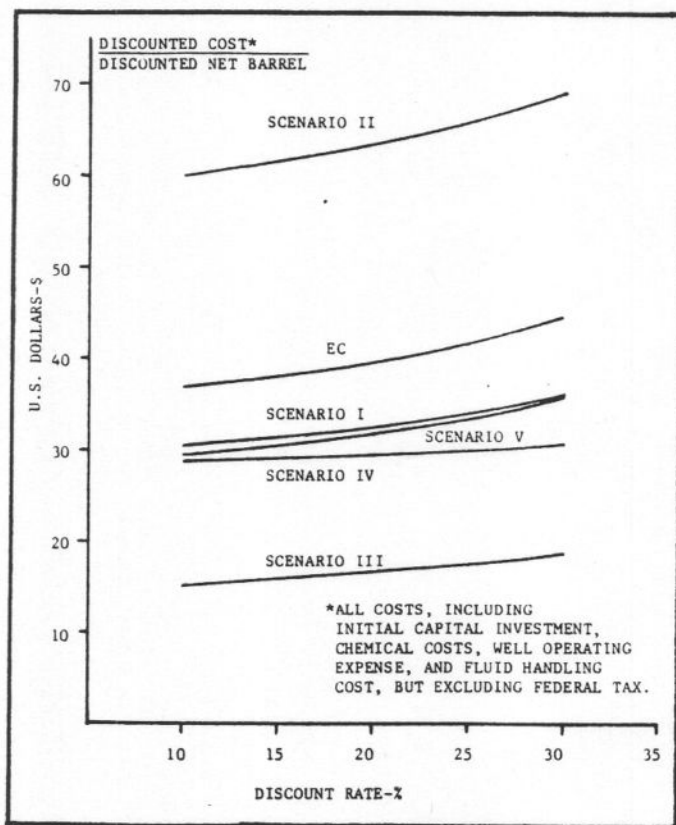


Figure 5--OIL BREAK-EVEN PRICE PROFILES

The highest oil break-even price profile is seen to result from Scenario II where the less than expected oil recovery profile is encountered (Only a total of 49,154 barrels of oil are recovered). The lowest oil breakeven price profile is naturally achieved in Scenario III when the field yields a higher than expected quantity of recovered oil (198,600 barrels). For

Scenario I, the baseline case produces an oil price profile ranging from \$30.43 to \$36.34 per barrel (A total of 98,054 barrels of oil are recovered). The profile identified as EC results from applying the subjective probabilities assigned to Scenarios I, II, and III to arrive at an "expected" oil break-even price profile (See Schlaifer (1959) for computational details).

The "break-even" price of oil for the "expected" price profile (where 93,438 barrels of oil are recovered) ranges between \$37.76 and \$44.43 in Figure 5. Since this break-even range exceeds the \$30.00 market price for oil assumed for the scenario set, one can conclude that the project presently under consideration would not be an acceptable venture. A closer examination of the price profiles for Scenarios I, II, and III will show that only for the case where a higher than base-line quantity of oil is recovered -- i.e., Scenario III -- is the break-even price profile less than \$30.00. Since the probability of this scenario occurring is so small, it has only a minimal effect on the final project investment decision.

The conclusion reached above concerning the project's investment attractiveness is reinforced when the two remaining profiles are examined. Only when the drilling and installation costs are stretched over a four year period -- i.e., Scenario IV -- does a significant portion of the base-line price profile fall under \$30.00. This occurs because the distribution of costs into future years results in higher discounts being applied to these costs in cash flow computations. Notice that Scenario V produces a slightly lower base-line profile than Scenario I. Here the project is terminated early when marginal revenue becomes negative -- i.e., total well operating expenses, injection cost rate, and fluid disposal cost rate exceed revenue. As is typical of tertiary processes initialized at relatively high water saturation and low oil saturation, the pore volume recovery rate starts up rather slowly in comparison to the pore volume injection rate. Pore volume recovery then increases rather rapidly and finally drops again. This drop at some point causes marginal revenue to go negative and the project is terminated. This occurs slightly over eight years into the project. Still, it is only at the lowest discount rate that the project becomes barely viable.

#### Conclusion

Investment in an EOR project falls into the unstructured portion of the managerial decision environment -- i.e., sound investment decisions rely on the intuition, experience, and judgement of the decision makers. The EOR computer simulation model as presented is designed to enhance this decision-making process by providing to managers a wide range of quantitative data (In addition to the Figure 5 information, the model is also providing with each run the wealth of other physical and financial information described in Figure 3) for various EOR scenarios that can be combined with other hard and soft information to arrive at optimal investment decisions.

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