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Economic Analysis of a Geothermal Exploration and Production Venture

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ABSTRACT

A computerized Monte Carlo simulation model has been formulated and used to perform an economic risk analysis of a geothermal energy exploration and production venture. Expected present worths as well as the actual underlying distributions of present worths were computed for a series of cases. A study of the sensitivity of the economics to changes in the most important parameters is included. For the most likely values of the input variables, chance factors, and parameters, the expected present worth at a 12% discount rate is $3.6 million per exploration unit, while the rate of return is 18%. The break-even chance factor per play to yield an expected present worth of zero is 5%.

INTRODUCTION

Several factors have contributed to the recent renewal of interest in geothermal energy exploration and utilization. The accumulation of knowledge from many years of skimpy geothermal exploration efforts has established evidence of geothermal energy reservoirs being more widespread phenomena than previously thought. Advancements in the geosciences have improved the exploration odds. Increased steam and hot-water production know-how combined with enhanced power-generating technology have given geothermal power production a reputation of high dependability. Even though scaling, erosion, and corrosion can be serious problems, methods of dealing with them have been developed or are in the process of being developed. A third aspect, and probably the most important, is the change in the economic climate for geothermal power generation, which has occurred gradually over the last decade and abruptly during the past year. The cost of electric power generation from competitive sources has increased drastically because of increased cost of environmentally acceptable low-sulfur fuels (oil, gas, and low-sulfur coal) and higher power-plant construction costs (due to particulate, SO_2, and perhaps NO_x removal in fossil fuel-fired plants, the requirements for extraordinary earthquake protection, and, at times, air cooling due to lack of availability of cooling water for nuclear power plants, and high interest rates). On the other hand, the cost of geothermal power-generating plants has decreased, relatively speaking, over the last decade, due to improved technology and more intense price competition among turbine manufacturers along with benefits of scale associated with installation of larger geothermal power-generating units.

We began a study in 1972 (Juul-Dam and Dunlap, 1972) to enhance our understanding of the basic economics of geothermal exploration and production, and to assess its sensitivity to changes in key parameters, such as assumptions about the nature of the resource, exploration and drilling know-how, and the economic and technological environment of geothermal power generation. To this end we built a computerized simulation model incorporating the most significant steps involved in exploration for and winning of geothermal fluids. A Monte Carlo simulation model was decided upon to insure adequate description of the randomness of the intrinsic and extrinsic characteristics of the geothermal resource, the uncertainties about the time and monies required for exploration and production activities, as well as the stochastic nature of the outcomes of various events. This approach permits variabilities in the input variables to be integrated properly and reflected in the final result by using distributions on said variables to describe their randomness.

It is particularly useful in a venture analysis such as the present one, where many of the crucial input parameters vary greatly, as do the size and depth of a geothermal reservoir, time and cost of geological and geophysical exploration, and the geographical location of a geothermal discovery. Since in the Monte Carlo simulation the chance factors—the variations in each variable as well as their interactions—are appropriately accounted for, one can from the distribution of the final outcome (here present dollar value of effort, hereafter designated present worth) gauge the downside risk as well as the upside potential of the venture. This aspect becomes especially important when dealing with highly skewed distributions as in the present case. Besides allowing Monte Carlo simulation, computerization of the evaluation procedure enables calculation of a string of cases within a short period of time. Computation of a large number of cases is necessary to assess the sensitivity of the economics to changes in such single-valued parameters as discount rate, chance of success of exploratory drilling, and so on.

As the study progressed, rapidly changing technical and economic parameters (particularly during the last year) caused us to reassess the problem, and this report reflects our current thinking. The abstract which was printed in the symposium program represents an earlier stage in our work.

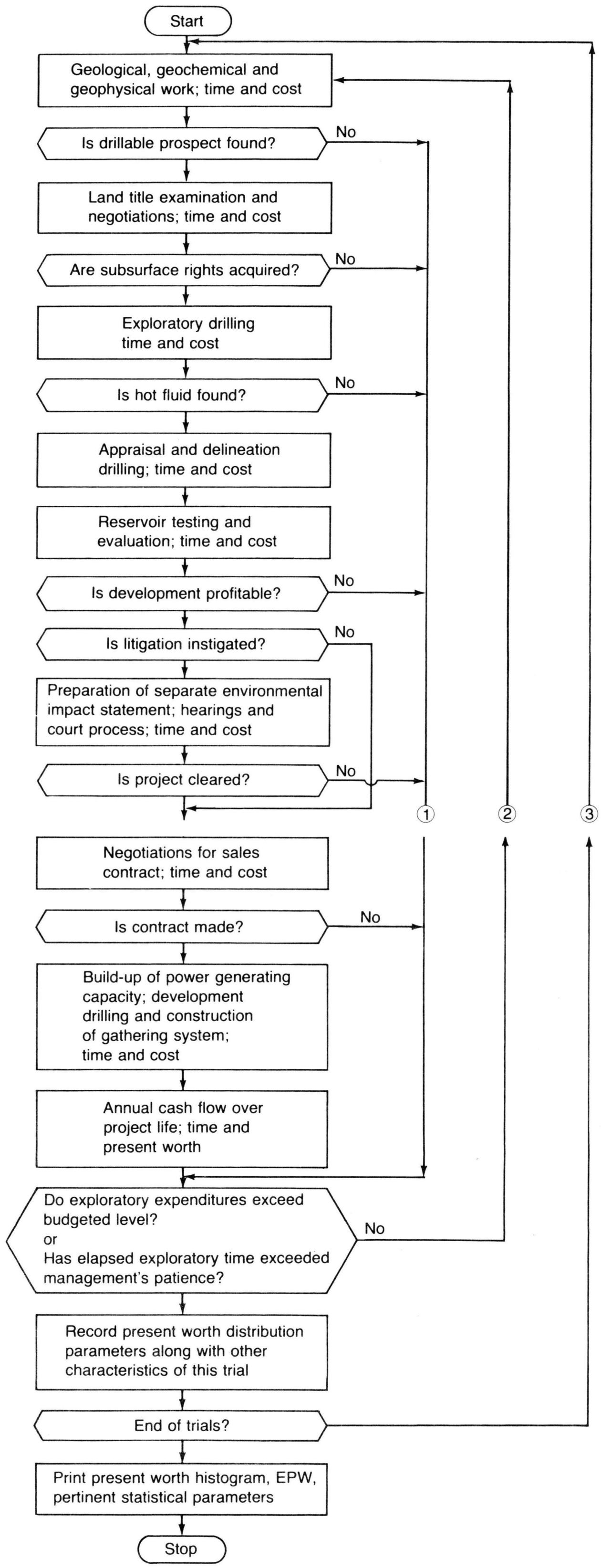

Figure 1. Geothermal venture analysis flow diagram.

DESCRIPTION OF SIMULATION MODEL

A model of a typical geothermal exploration and production venture was developed much along the lines of that of a conventional oil and gas play. As seen in Figure 1, the flow diagram contains such familiar stages as geological, geochemical, and geophysical surveying, land acquisition, exploration and appraisal drilling, field delineation, development drilling and construction of gathering systems—all known from oil and gas exploration and exploitation. In addition, such time-delaying events as possible environmental impact hearings, contract negotiations for the sale of hot fluids, and synchronization of field development with the power plant construction schedule have been included.

The above-mentioned activities (plus whatever outside contract work is stipulated for each stage) are those undertaken by a single team and are assumed to be carried out sequentially. For each stage, the time elapsed, the monies spent (both in undiscounted and discounted dollars), as well as the outcome, are noted: and if the outcome is favorable, the team proceeds to the next stage. If, however, the outcome of a stage is negative (for example, no drillable prospect found, or no steam or hot water encountered), the total time spent and the sum of cash flows associated with a given play are computed. Whenever the sum of expenditures or the total amount of time spent in a given trial (consisting of one or more plays) exceeds stipulated values (in this study 10 years elapsed time; \$10 million expenditure), the trial is terminated and its outcome recorded.

The model assumes that an individual or a private company will explore for and produce geothermal energy in the form of dry steam, flashed steam, or hot water, which is then delivered to a power-generating unit erected in the proximity of the geothermal reservoir by an electric utility company. The producer is responsible for all gathering of steam and liquids, separation of steam from hot brine, if appropriate, and disposal of hot brine and condensate by reinjection into the ground. Although a number of other uses for geothermal fluids in addition to electric power generation have been envisioned by scientists, only electric power generation is considered in the present study. Also, for the purpose of this analysis a geothermal reservoir is one capable of producing hot fluids: dry steam, flashed steam, or hot water. Each type of fluid stream has its own production characteristics and associated economics. Although in some instances an economic choice exists as to the mode of utilizing the geothermal energy, this study assumes the economics to be determined by the state of the produced fluid, envisioning dry and flashed steam being fed directly to a condensing turbine, while hot, pressurized water is utilized in power generation via the binary-cycle process. Negative contributions to cash flows stem from expenditures on exploration, drilling, and developmental activities together with operating and maintenance costs while positive contributions to cash flows are derived from selling the fluid to the electric utility.

The price which geothermal energy commands in a given geographical area depends upon the future cost of base-load electricity supply from competitive sources, such as nuclear, low-sulfur fuel oil, coal, and hydropower. The cost of new base-load electric power supply in the period 1975 to 1985 was determined from the projected cost of primary fuels and their respective capital requirements for conversion into electric power. Then, mean marginal power costs were

Table 1. Activity durations and cost in thousand dollars.

	Duration (Years)			Cost	
	Min	Mode	Max	Time Dependent, $M/year	Time Independent, $M
Geological, geochemical and geophysical work	0.5	1.0	2.0	120	200
Subsurface right acqusition					50
Land bonus: KGRA*					25†
Non-KGRA					5†
Annual land rental					1†
Exploratory and appraisal drilling	0.5	0.9	1.8	Two exploratory and four appraisal wells (plot)	
Reservior testing and evaluation	0.5	0.75	1.25	350	250
Delineation drilling	0.4	1.0	1.5	Four delineation producers	
Contract negotiation and litigation	0.2	0.5	1.2	300	200

*KGRA = Known Geothermal Resource Area
†Units: $/acre

calculated for various load centers in the western United States based on projections by the National Petroleum Council (1971) as to the market share held by each primary fuel in the electric power generating sector. The projected mean marginal city gate power cost in the western United States ranges from 20 to 30 mills/kWh, and the former figure was used as a base-case power cost in this study.

The price received by the producer for his geothermal fluid is determined from the cost of power and such other factors as the proximity of the geothermal reservoir to a load center; the capital, operating, and maintenance cost of power generation from geothermal fluids; and the conversion efficiency. The geothermal power generating costs employed in this study are synthesized from those previously published by the Mexican Electric Institute (1972); Holt and Brugman (1974); Walter, Stewart, and LaMori, (1974); Finney (1972); Meidav (1974; 1975); Kuwada (1972); and the National Petroleum Council (1971).

Table 2. Base case chance factors and parameter values.

Conditional Event	Probability
Drillable prospect | geophysics and geochemistry	1
Land rights | drillable prospect on hand	.625
Geothermal fluid discovered | drilling initiated	.5
Environmental impact litigation | profitable venture	.33
Project cleared | litigation	1
Making sales contract | dry steam discovered	.9
Making sales contract | hot water discovered	.8
Parameter Values	**Probability**
Probability of discovered fluid being dry steam | a geothermal fluid reservoir has been discovered	.1
Probability of discovered fluid being flashable | a geothermal fluid reservoir has been discovered	.3
Upper limit on present worth of cumulative exploration expenditures per unsuccessful trial (W limit), $\bar{M}$	10
Maximum cumulative exploration time permitted per trial, years	10

Table 3. Model inupt data.

	Min	Mode	Max
Number of reinjection wells per producing wells			
Dry steam		0.1	
Flashed steam		0.4	
Binary fluid		0.5	
Development well chance factor			
Dry steam field		0.85	
Hot water field		0.75	
Field operating cost (mills/kwh)	Min	Mode	Max
Dry steam	0.67	1.0	1.33
Flashed steam	2.0	3.0	4.0
Binary fluid	2.7	4.0	5.3
Annual operating hours		6 300	
Royalty		0.125	
Federal income tax (percent)		48	
Severance tax (percent)		7	
Depletion allowance, gross/net		0/0	
Discount rate (percent)		12	
Cost of reinjection well equal to 75% of development well dry hole cost			

INPUT DATA

Two types of input data are employed in the simulation model: durations (and attendant costs or revenues associated with the various activities), and chance factors (to indicate the outcome of these activities). The duration and cost data are presented in Table 1. A triangular distribution is assumed for all durations, while the attendant costs have a time-dependent as well as a time-independent component. The latter reflects such undertakings as geophysical and geochemical contract services, consultations, and fees.

Chance factors are assigned to each diamond-shaped block in the flow diagram (Fig. 1). When simulating a given case, single-valued chance factors are used, which are then treated as parameters when examining the effects of variations in one or more of them.

A base case has been established as a point of reference in comparing alternate cases. It is characterized by the chance factors and parameters assuming their most likely or appropriate values. The base-case values are displayed in Table 2.

Additional model input data is presented in Table 3 and Figures 2 through 10 (sources: Grose, 1972; Facca, 1970; New Zealand, Ministry of Works, 1972; Wehlage, 1974; Suter, 1974).

MODEL ASSUMPTION

A number of assumptions have been made in structuring the simulation model and applying the data, the most important of which are:

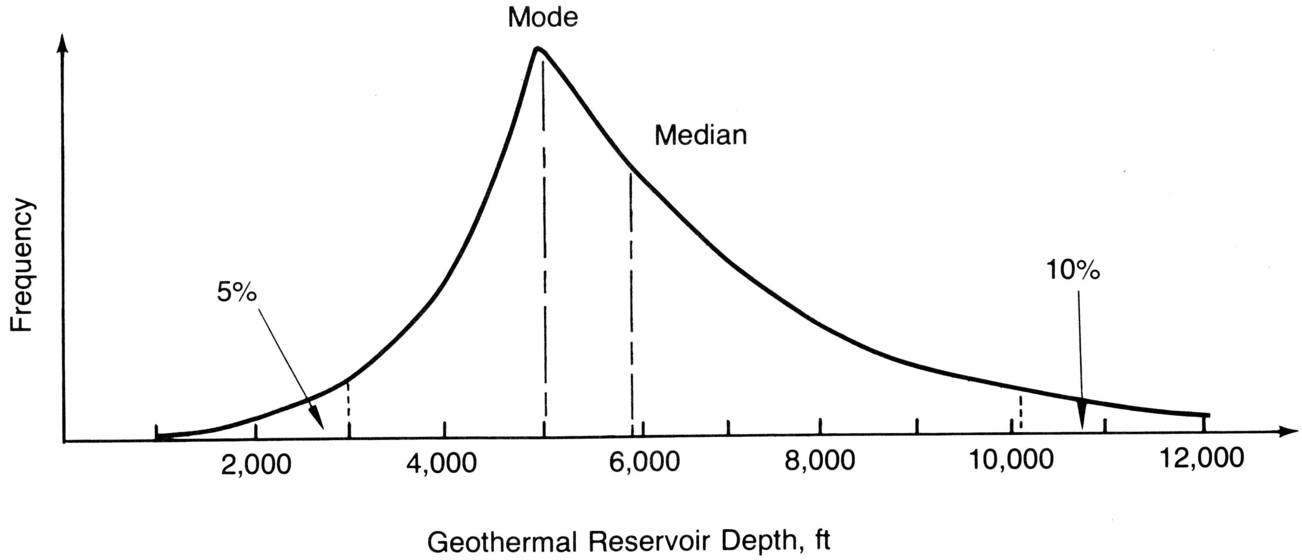

Figure 2. Exploratory drilling.

1. A sufficient number of undiscovered geothermal fluid reservoirs exist so that the chance of finding a geothermal reservoir is independent of the number of geothermal reservoirs already found.
2. The productive capacities of the geothermal reservoir found are independent (refer to 1.), and they are not a function of whether steam or hot water is discovered.
3. The team works sequentially on the various tasks according to the block diagram of Figure 1.
4. All cash flows are in constant 1975 dollars; future inflation has been ignored.
5. All present worths and rate-of-returns are after tax measures.
6. The only use of geothermal energy is for electric power generation.

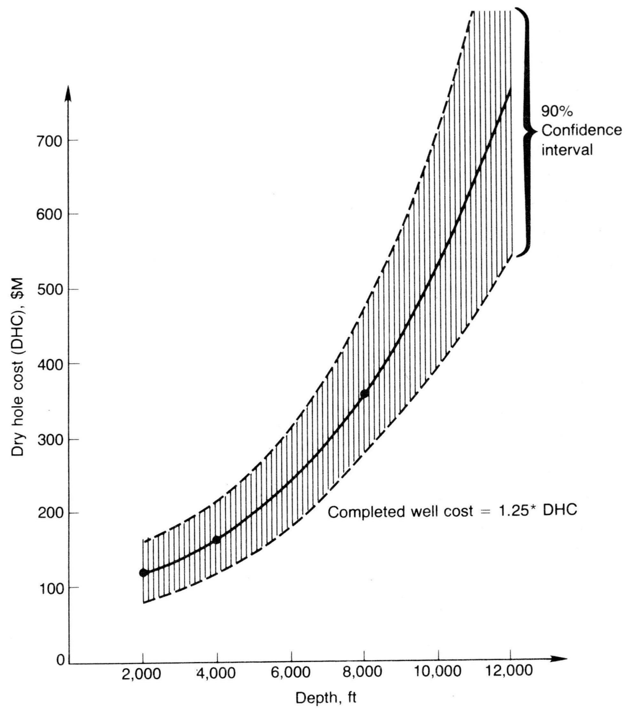

Figure 3. Effect of depth on geothermal drilling costs.

COMPUTER PROGRAM

The computer program used in performing the Monte Carlo simulation requires very little core, less than 5000 bits. Due to the highly skewed distributions used for two of the key variables, reservoir depth and reservoir capacity, and the low, but not insignificant, chance of proceeding to the most profitable ventures (namely power generation from dry steam) a large number of trials is required in each run in order to arrive at a sample representing the underlying distribution satisfactorily. However, since the core requirement is small, computing cost is low. For each run a present-worth frequency table is calculated and the cumulative probability distribution of present worths is plotted. Graphic displays of the frequency plot and the cumulative probability distribution for the base case are shown in Figures 11 and 12. The skewed shape of the distributions is to be expected since the chance of proceeding to the revenue-generating stage is relatively low. This type of distribution has the characteristics of a hybrid binomial-lognormal distribution. To elucidate the changes in the simulated activities caused by varying the parameters, several additional characteristics of the venture are computed, such as average time spent on a play, average time spent before a discovery, average expenditure on a play which fails, average value of a commercial geothermal power production venture, and so on.

RESULTS AND DISCUSSION

Some of the more significant results of our economic analysis will be presented in the form of a series of graphs shown in Figures 13 through 17. The effects on the results of a number of model input variables are not presented here. For example, manpower costs, steam-gathering system costs, and land costs were not critical as long as reasonable values were assumed for these variables. (Recent escalation in bonus bids for KGRA land may change this conclusion for land costs, however.) Each figure actually contains two plots: one (the full-drawn curve) of the Expected Present Worth (EPW), and one (the dashed curve) of the Upper Decile Value (UDV). The latter is defined to have the

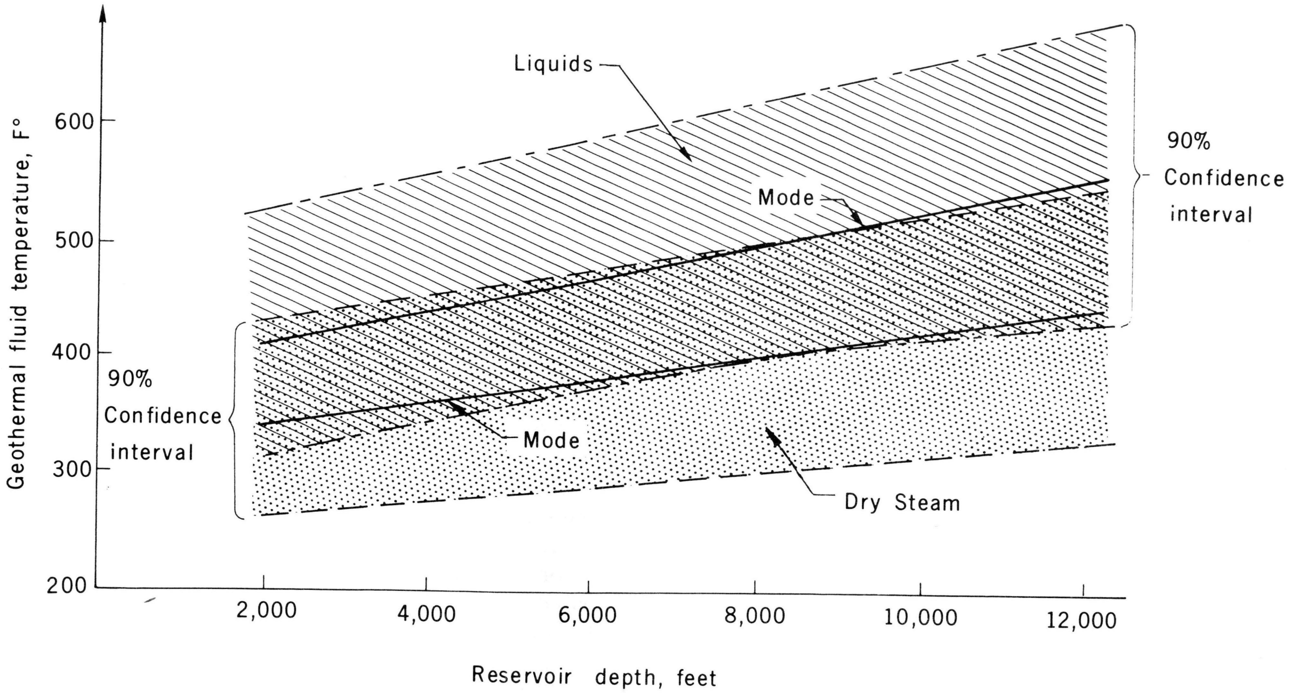

Figure 4. Effect of reservoir depth on geothermal fluid temperature.

characteristic of a 10% chance of the present worth of a given venture exceeding this value. Hence, the UDV conveys information as to the economic opportunity associated with a given geothermal venture. The ordinates of the two curves read separately on each side of the graph.

Figure 13 shows the effect of discount rate on EPW and UDV. For the base case an EPW_{12} of \$3.6 million and a rate-of-return of 18% are obtained, while the UDV_{12} is \$13.5 million. The cash-flow pattern underlying these project worths is characterized by relatively modest initial cash outlays on exploration followed by substantial capital investments in field development. The subsequent sale of fluid results in large, sustained positive cash flows, which, however, are discounted heavily since they occur late in the life of the project. For the base case, revenues start on the average nine years after initiation of prospecting.

Recall that the above economics are based on 1975 cost figures and noninflated 1975 dollars. Hence, continued increases in fuel prices and nuclear power plant construction costs would make the value of a geothermal power project somewhat better since the latter is less capital intensive.

Figure 14 brings out a very important characteristic of the geothermal exploration and production venture, namely the break-even point in terms of the chance of finding flowable steam or hot water, or, in the oil industry jargon, the "drill chance factor." The graph depicts the changes in EPW_{12} and UDV_{12} with variations in the chance of finding steam or hot water (given that drilling has been initiated).

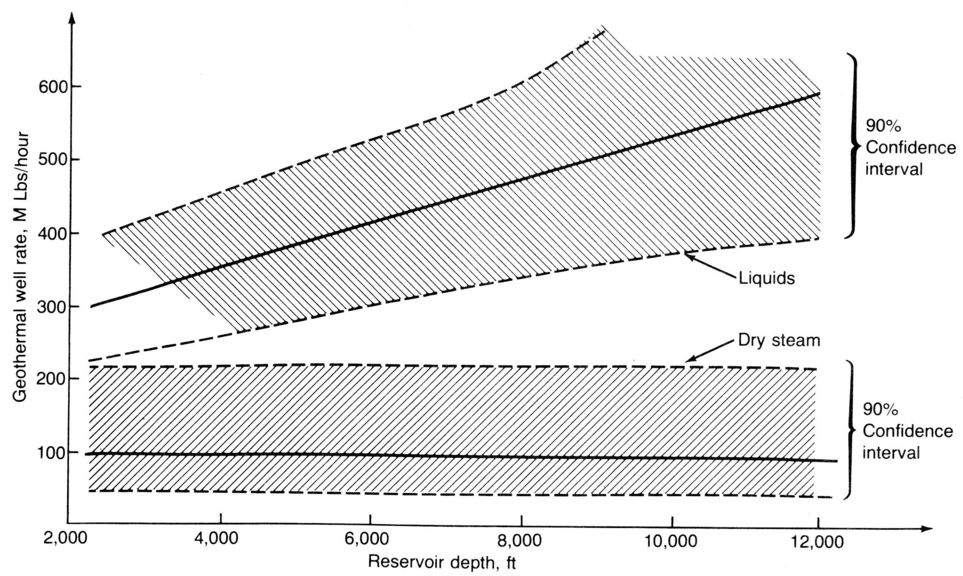

Figure 5. Effect of reservoir depth on well production rate.

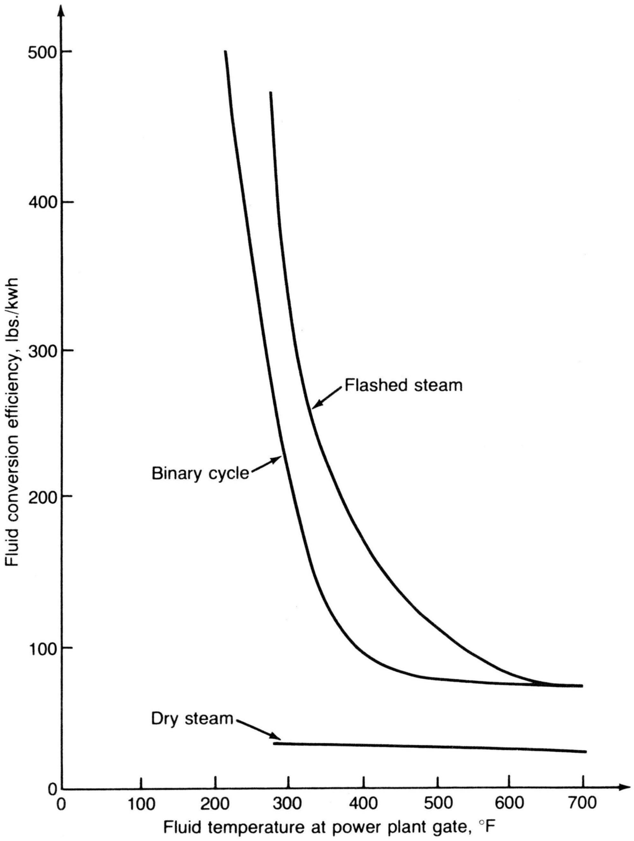

Figure 6. Effect of fluid temperature on power generation efficiency.

As expected, both EPW and UDV are strongly affected by the drill chance factor. The break-even drill chance factor is about 0.10 for the base case. The break-even drill chance factor per exploratory *well*, as distinguished from that per *play*, is approximately 0.05, since the exploratory program in a play is assumed to consist of two wells.

It should be remembered that a per-play break-even drill chance factor of 0.10 corresponds to a total-play chance factor of 0.05, since we assume chance factors less than 1 in acquiring subsurface rights and making a sales contract. The significance of this graph becomes evident when it is realized that statistical information as to these factors for geothermal ventures is all but absent, which renders even reasoned guesses like the ones used in the base case subject to criticism. Inasmuch as the calculations presented in Figure 14 suggest a lower limit on what is probably the most crucial chance factor, management is provided with an important reference point in its assessment of the venture.

In order to gauge the sensitivity of the economics to variations in the dry-steam chance factor, Figure 15 was prepared. Increasing the dry-steam chance factor from 0 (only hot water reservoirs are found) to 1 (all dry-steam reservoirs) results in a sixteen-fold increase in EPW_{12} from \$1.5 million to \$25 million, while the corresponding UDV_{12} values are \$7.0 million and \$53 million. Note that even if the pessimistic view is taken that no dry steam reservoirs remain to be discovered, the economics are still fairly attractive.

Although some effort went into assessing the future electric power supply costs and hence the value of geothermal fluids, uncertainties exist. To show the effects on the

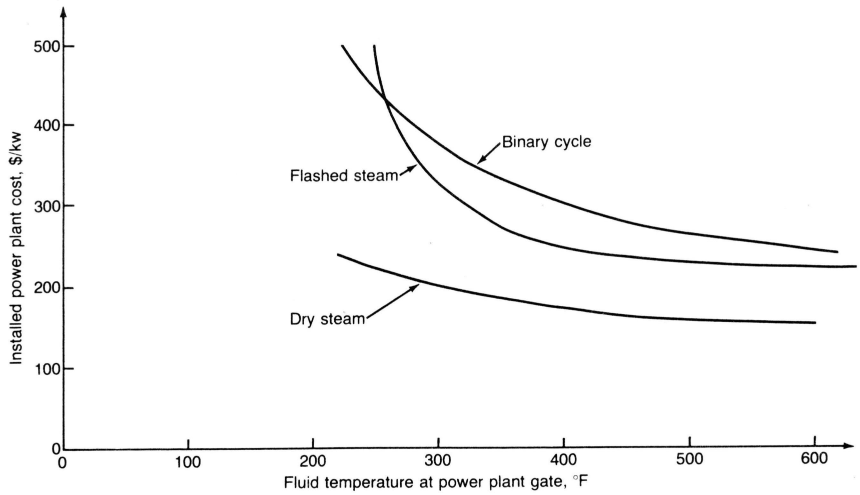

Figure 7. Effect of fluid temperature on power plant cost.

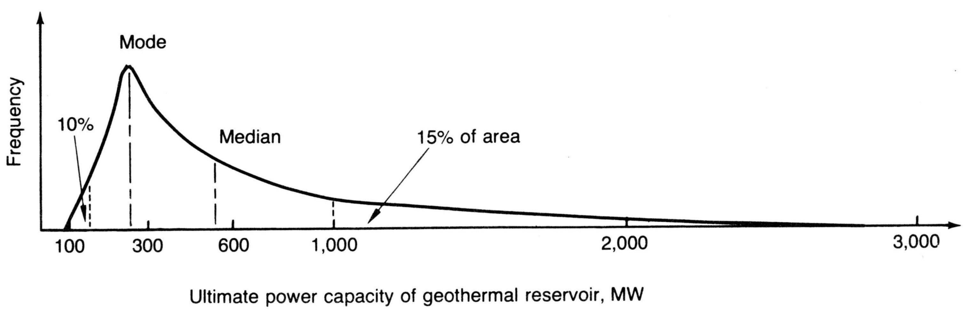

Figure 8. Ultimate power capacity.

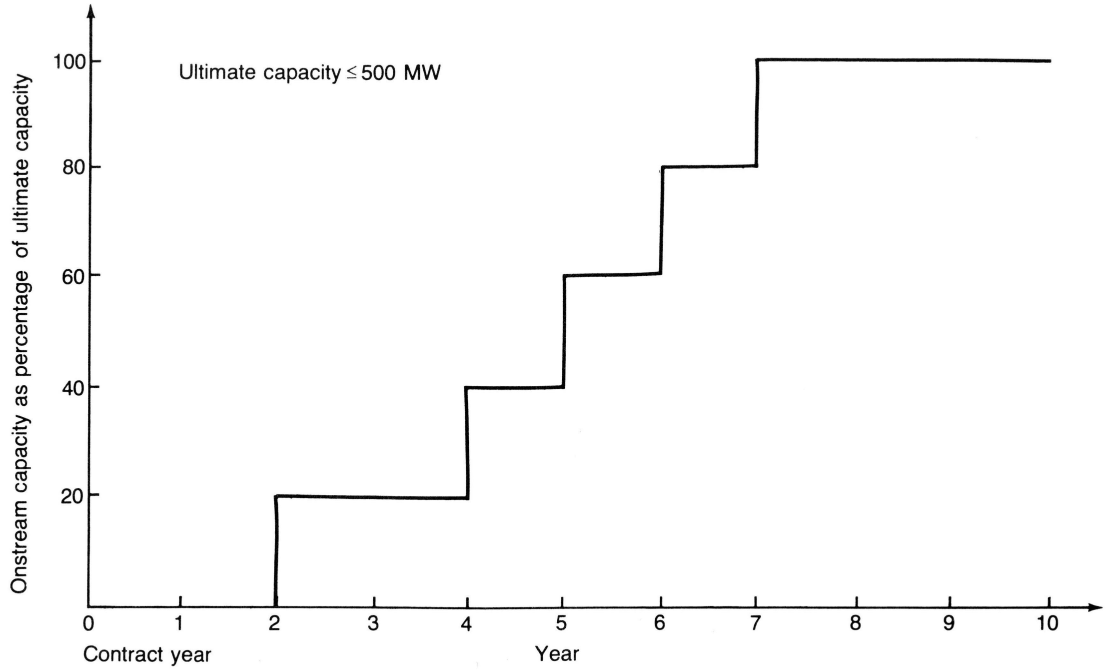

Figure 9. Rate of buildup of power generation in percent of ultimate capacity.

economics of variations in steam value, Figure 16 is presented. Along the abscissa is plotted the cost of power in mills/kWh. If the cost of electric power is 10 mills/kWh, the EPW_{12} (UDV_{12}) is −\$1.8 million (−\$0.5 million), while a power cost of 30 mills/kWh—a likely cost of power in the not too distant future—results in an EPW_{12} (UDV_{12}) of \$30 million (\$68 million). Also an increase in power cost of 50% (from 20 to 30 mills/kWh) leads to an eight-fold increase in the expected present worth of a geothermal venture.

Figure 17 shows the effects on the economics of delays (due to various causes) in building the power-generating plant and hence the start of fluid production and attendant revenues. While it is obviously desirable from the producer's point of view to minimize this lag, a delay of several years beyond the two years assumed in the base case is not fatal.

CONCLUSIONS

A computerized Monte Carlo simulation model has been built which provides economic risk analysis of a geothermal exploration and production venture. The economics of such

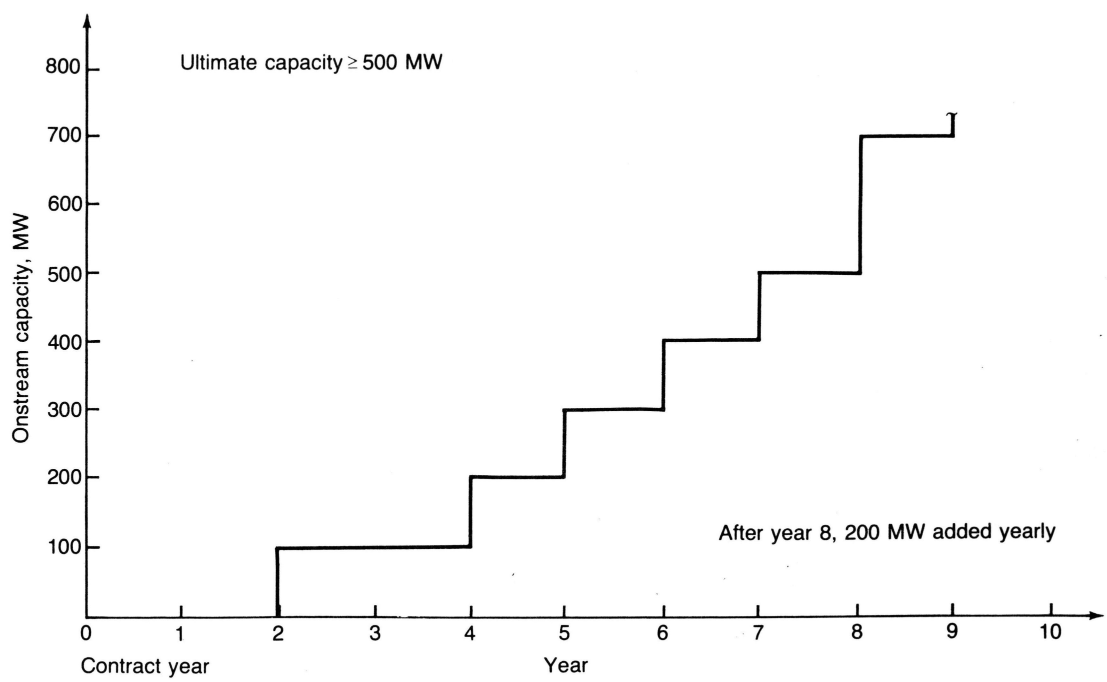

Figure 10. Rate of buildup of power generation in terms of ultimate capacity in MW.

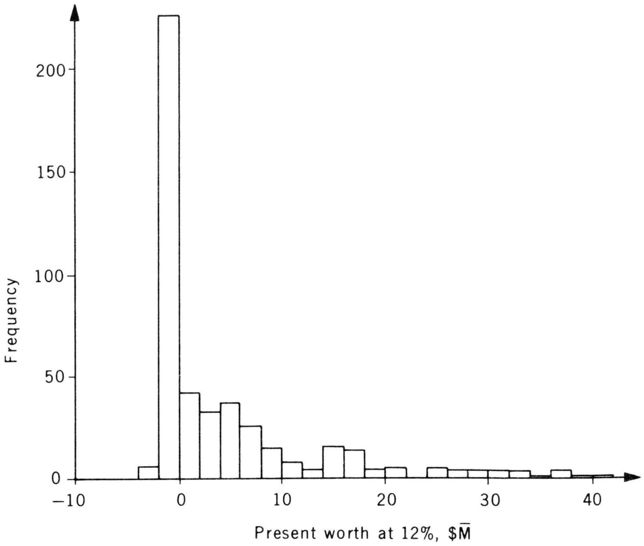

Figure 11. Histogram of present worth distribution of a geothermal exploration and production venture.

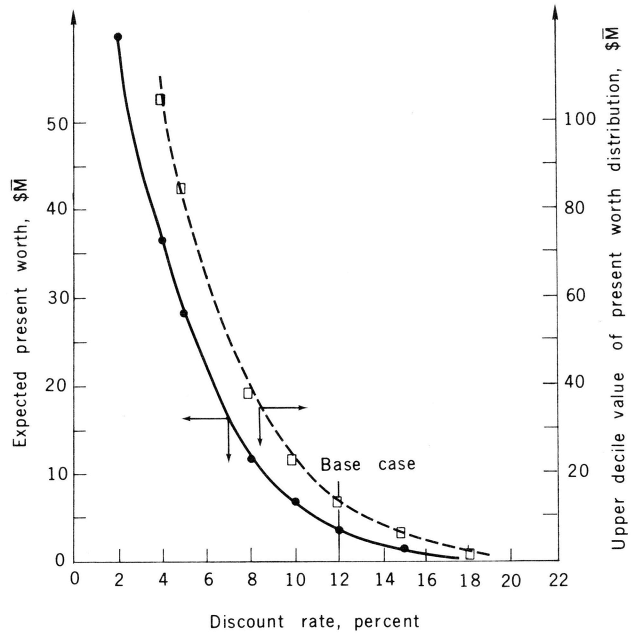

Figure 13. Effect of discount rate on expected present worth.

a venture are characterized by long lead times, small front-end investment load, and, if commercial quantities of steam or hot water are found, slowly rising, but eventually large, cash flows. The long lead times are attributable to exploration and land acquisition activities and later to a slow rate of development of productive capacity. The major cash outlays are associated with exploratory and, if successful, appraisal and delineation drilling along with capital investments in field development. When completely developed, annual revenues to the steam or hot water supplier reach \$15 to \$30 million, depending upon reservoir characteristics and geographical area. The long lead times combined with the relatively low chance of commercial development perceived are responsible for the only moderately attractive economics.

Based on the assumptions made in this study, the following specific conclusions as to the economics of exploration for and production of geothermal steam and hot water for electric power production can be drawn:

1. Based on a mean city-gate power cost of 20 mills/kWh and a 31% chance of discovering flowable steam or hot water, the expected present worth at 12% discount rate (EPW_{12}) and \$3.6 million per exploration and development team and the rate-of-return is 18%.
2. The probability of an exploratory drilling program discovering flowable steam or hot water, given that drilling has been initiated, must exceed 10% if EPW_{12} per team is to be positive (dry steam found in 10% of the discoveries).

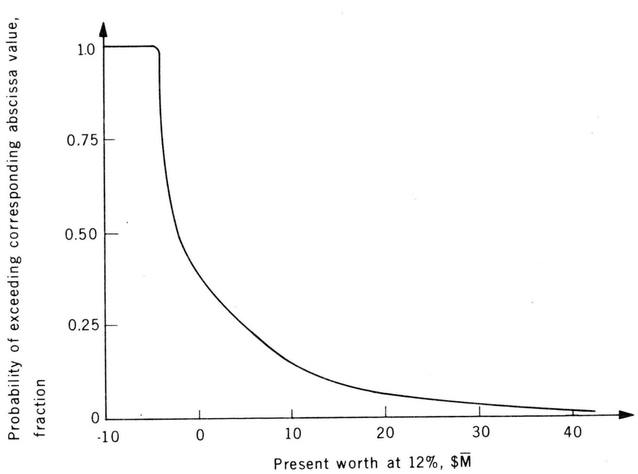

Figure 12. Cumulative probability plot of present worth distribution of a geothermal energy exploration and production venture.

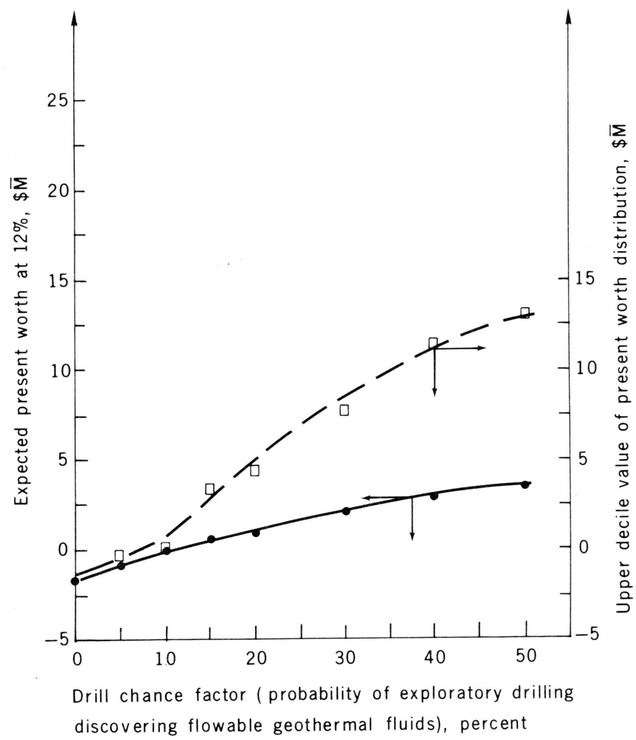

Figure 14. Effect of drill chance factor on expected present worth.

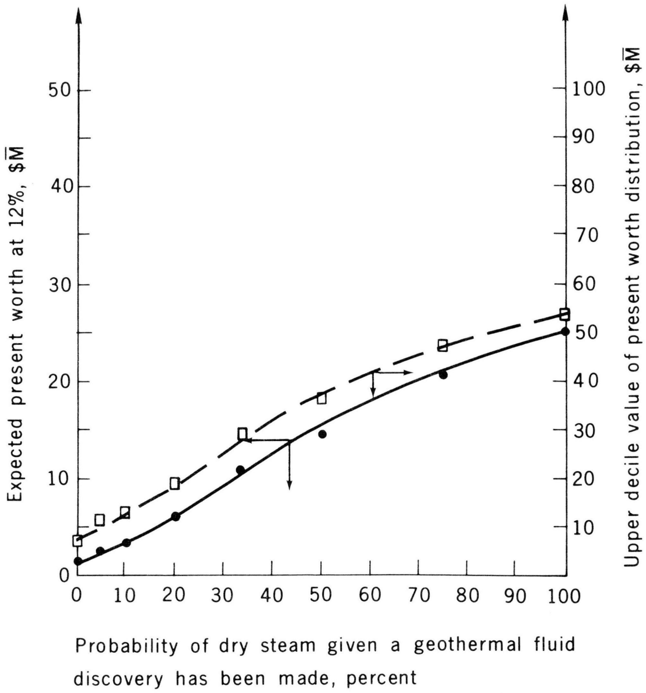

Figure 15. Effect of frequency of dry stream discovery on expected present worth.

The overall chance of commercial steam production per play, corresponding to the minimum drilling chance factor of 10%, is 5%. A 50% chance of finding flowable steam or hot water after geological, geochemical, and geophysical screening and land acquisition is regarded as plausible.

3. When the percentage of dry steam found varies from 0 to 100, the EPW_{12} increases sixteen-fold. If no dry steam is found, the EPW_{12} is 40% of that of the base case, which assumes a 10% chance of a geothermal fluid discovery yielding dry steam.

4. If the mean power cost (at city gate) increases 10 mills/kWh above the base price of 20 mills/kWh assumed here, the EPW_{12} increases eight-fold, while a reduction to 10 mills/kWh results in an EPW_{12} of −$1.8 million. The break-even cost ($EPW_{12} = 0$) is approximately 16 mills/kWh.

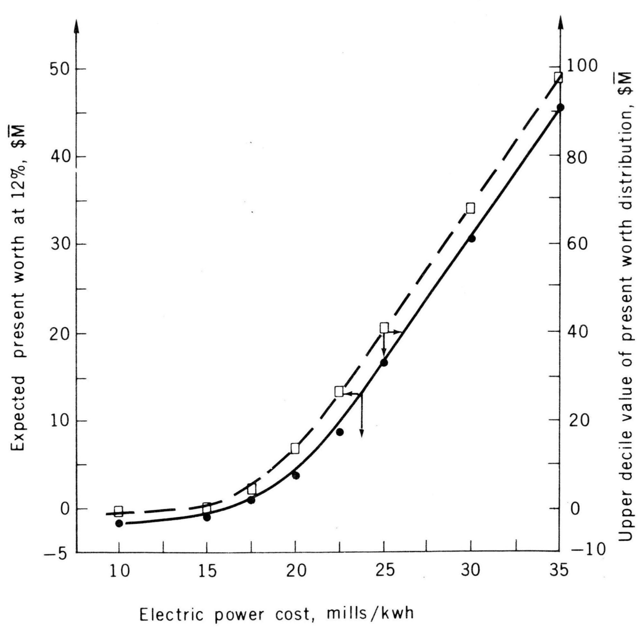

Figure 16. Effect of power cost on expected present worth.

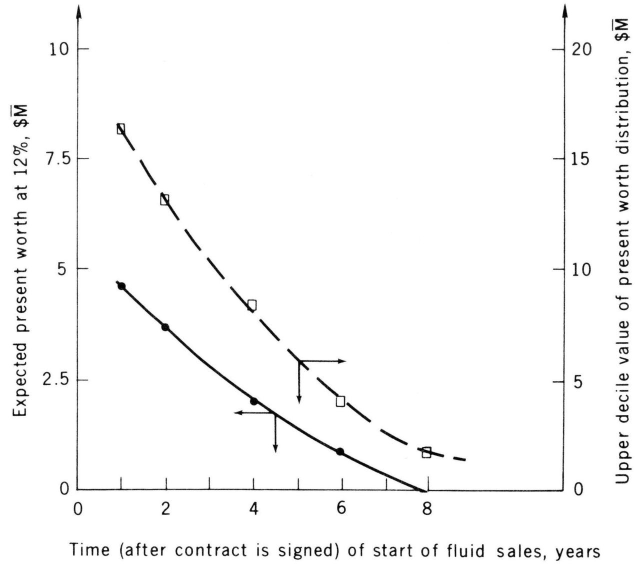

Figure 17. Effect of time of start of fluid sales on expected present worth.

While data supporting these points are not presented in this paper, additional computer simulations also suggest the following two conclusions:

5. With a mean city-gate power of 20 mills/kWh, a dry-steam field is profitable at just about any depth and well productivity (MW), while hot-water producing fields typically are uneconomic to develop if encountered below 7 to 10 thousand feet, the critical depth being a function of well productivity (in MW).

6. Such factors as land bonus and rental, steam-gathering system costs, and manpower assignment per team do not significantly affect the economics as long as reasonable values are ascribed to these parameters.

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