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ASSESSING THE FINANCIAL RISKS OF GEOTHERMAL ENERGY: A MODELING APPROACH

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ABSTRACT

This paper proposes a modeling approach to the aggregation of the various uncertainties and for estimating the economic risks to electric utility companies of investing in an individual geothermal project. The 'intent of this conceptual model is to provide a structure for systematically examining the major uncertainties in developing and operating a geothermal plant and their potential effects on the busbar cost of electricity and its probability distribution.

INTRODUCTION

The plumes of steam rising from the geothermal steam-electric generators in Northern California only hint at the vast amount of energy stored in geothermal reservoirs throughout the western United States. Following the successful exploitation of this resource, both for generation of electricity (New Zealand, Italy, Mexico) as well as space heating (Iceland, Hungary, France, California) geothermal energy has emerged as a promising energy source during the last decade in the U.S., and has received serious attention from developers, potential users, as well as the federal and western state governments. Still despite apparent environmental advantages of this resource, including its potential cost competitiveness and public acceptance, the commercial development and use of geothermal energy has been rather slow. Main impediments to the development of this resource have been financial, environmental, technical and in some cases, regulatory uncertainties, Since geothermal power is unique in that the user facility is tied to a single fuel at a single site, these uncertainties are of particular concern to potential users.

Traditionally, there has been a difference of opinion between developers and potential users of geothermal energy regarding uncertainties and the degree of risk associated with the exploitation of a geothermal field. Part of the difference arises from institutional attitudes towards risk. Developers tend to be risk takers and, with some justification, do not view the development of geothermal fields very differently from the exploitation of oil and gas fields. On the other hand, electric utility companies are heavily regulated, and their management are generally risk-averse. To incorporate any unforeseen losses in their rate structures, utility companies have to demonstrate that their investment decision has been 'prudent' and that alternatives, as well as uncertainties associated with the investment, have been adequately addressed,

The areas of uncertainty are well known. During the last few years, several workshops and various studies have addressed potential risks and in particular, the financial risks of geothermal energy. (EPRI, 1978; Golabi 1980; Stock, 1981) From these discussions several viewpoints regarding the adequacy of available measures for reducing the financial risks of developing and using geothermal energy have emerged. These measures range from contractual agreements between developers and users that would place the risk of reservoir loss on the supplier, to government-sponsored insurance programs that would basically ask the taxpayers to shoulder the financial risks of developing geothermal energy. (Aidlin, 1978; Falick, 1978).

Each of these options covers risks to certain users with the possible exclusion of others, resulting in different groups having widely divergent views on the relative attractiveness and feasibility of one scheme versus another. In addition, each scheme is accompanied by either direct costs to the potential end user whose views would be represented either by public interest groups or regulatory agencies mandated with protecting the interest of the public. The main difficulty with evaluating the different alternatives has been the central question itself: How risky is a particular geothermal development, and how can the risks be quantified? From the point of view of electric utility companies and their customers who would be the main users of this energy source, this translates into the uncertainty associated with the price of the generated electricity, the busbar cost of geothermal power.

This paper proposes a modeling approach to the aggregation of the various uncertainties and for estimating the economic risks to electric utility companies of investing in an individual geothermal project. The intent of this conceptual model is to provide a structure for systematically examining the major uncertainties in developing and operating a geothermal plant and their potential effects on the busbar cost of electricity and its probability distribution. The modeling approach is not only useful in evaluating the costs of a specific geothermal project but is also a valuable tool in evaluating the effect of the various schemes in reducing the economic risks of geothermal power. It can also serve as a basis for comparing the cost of this energy resource to those of other alternatives.

THE DECISION PROCESS

Before presenting the interconnection between the various submodels that comprise the model and the relationships between externalities such as environmental effects and costs, it is helpful to divide the decisions and activities that lead to commissioning of a geothermal plant into three general stages (See Figure 1):

- Pre-construction feasibility studies
- Plant construction and start-up
- Operation and maintenance

There are uncertainties at each stage of the process and risks which should be evaluated and accepted before proceeding. At each step, more information becomes available and many uncertainties are reduced or bounded. However, a tool is needed to quantify the uncertainties and the reduction in these uncertainties. As the model can be used at each decision point, with the input to the model differing to reflect the changing information base, the risk model provides a framework for the utlity company to make appropriate decisions at each step. Five major decision models are identified in Figure 1:

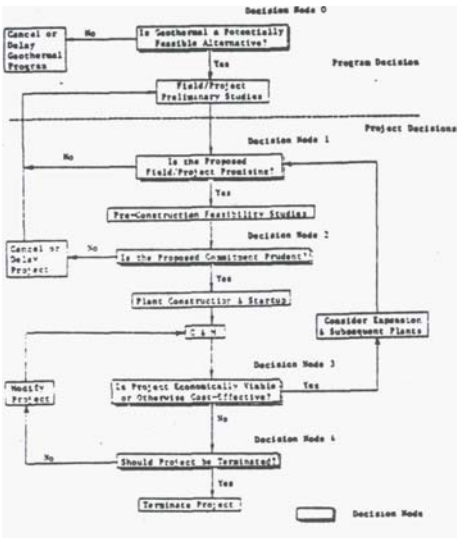


Figure 1. THE DECISION-ACTION SEQUENCE

0 - Is geothermal a potentially feasible alternative (relative to other alternatives)?

1 - Is the proposed field/project promising? This is a specific field/project-related decision node. It involves a commitment of funds for pre-construction studies and activities.

2 - Is the proposed comnitment prudent? This is the final decision node prior to accepting liabilities or committing resources to construction and operation. Once the decision has been made to proceed with a particular project, the risk increases due to the relatively high costs of construction (compared to pre-construction feasibility studies).

3 - Is the project economically viable or otherwise cost-effective? Even if the project is not economically successful by itself, it may be considered cost-effective. For example, a small-scale, first generation plant may provide useful information about the reservoir and valuable experience which can be used as a basis for subsequent capacity expansion and field development recognizing that the average cost of power from a field is likely to be significantly lower than that for the first generation plant.

4 - If the project turns out to be non cost-effective, should the project be terminated? The options open in this stage would include modifications in the project or termination.

The loop following decision node 3, in Figure 1 indicates the decisions concerning expansions of capacity or commissioning additional plants. In making this decision, information generated from the first plant will be available to reduce uncertainties. A risk model should be able to accommodate this sequential decision making process with the inputs reflecting the changing information base.

The model construction begins by a characterization of the uncertainties at each of three stages of development of the geothermal power plant.

MAJOR SOURCES OF UNCERTAINTY

In considering potential variations in cost, it is important to be able to identify those factors and their associated uncertainties, which can cause the various components of the cost of power to exceed or drop below given critical levels. Once such factors and the costs they affect have been identified, the relationship between them and the cost of power can be examined, i.e., the likelihood of occurrence and the effect on total cost of each factor can be modeled.

A list of uncertainties (factors) which could impact the cost of geothermal power is provided by Table 1. In order to focus on the most important factors the uncertainty associated with each factor needs to be evaluated.

The uncertainty comes from *two* sources: (1) uncertainty associated with the magnitude and occurence of the factors, and (2) uncertainty associated with the ability to predict the consequences (i.e. cost effects) associated with the occurrence of these factors. The latter source of uncertainty is related to the degree to which submodels that will be shortly discussed, depict the real world and is a function of modeling ability. One way that each factor in the list can be classified on these two uncertainties is using the following scheme:

> if the range of possible values is ± 10 percent of the most likely value assign the numerical value of 1; if the range is ± 25 percent assign 2, and if greater than ± 25 percent assign 3. "Possible value" refers to the ranges within which 90% of all values would fall.

In Table 1, based on the judgment of Woodward-Clyde staff and the San Diego Gas and Electric Co., the factors that were considered significant (either a score of 3 on one of the two sources of uncertainty, or 2 on both) for a 50MW geothermal power plant in the Imperial Valley are denoted by (*).

Table 1 A LIST OF UNCERTAINTIES

Area of Uncertainty

I. Technical and Environmental

A. Reservoir

1. Proven Reserves of Resource
   - * State of the Art
   - Instrumentation and Access
   - * Extent
   - Recoverability
   - Failure Modes
   - In Situ Constituents
   - Strength and Integrity
   - Horizontal & Vertical Permeability
   - * Convection or Drainage Flows

2. Reservoir Operation
   - Placement of Wells
   - Down Hole Data Collection
   - Thermal and Fluid Recharge
   - Transient Response
   - Fault or Fracture Flows
   - Effect of Major Events
   - Effect of Withdrawal and Injection
   - * Performance with Time
   - Performance with Use
   - Liability
   - Fault Lubrication
   - Induced Subsidence/Bulging
   - Induced Seismic Activity
   - Reaction of Injected Fluid with In Situ Materials
   - Affect of Neighboring Springs, Mud Pots, Wells
   - Cooling Front Location and Material Contraction
   - Bacteria Growth Affects

3. Brine Supply, Wellhead
   - * Temperature
   - * Pressure
   - Flowrate
   - Chemical Analysis
   - Phase Quantity and Distribution
   - * Heat Content
   - Stability
   - Transient Response
   - * Changes with Time
   - * Changes with Use
   - Fixed and Variable Costs
   - * Reliability
   - Materials Compatibility
   - Failure Modes
   - Location of Wells
   - Reservoir Drawdown
   - Well Bore Flash Point
   - * Effect of Major Event
   - * Well Scaling or Blockage
   - * Well Corrosion
   - Cost Escalation
   - Noise
   - Air Emissions
   - Intrusion or Leakage from or into other Strata
   - * Surface Leakage
   - Cement Leakage
   - Pump Performance and Reliability
   - Waste Disposal
   - * Expected Life

4. Injection Well
   - Temperature
   - Pressure
   - Flowrate
   - Solids Content
   - Chemistry
   - Transient Response
   - Changes in Time
   - Changes in Usage
   - Fixed and Variable Costs
   - Failure Modes
   - Reservoir Pressure Buildup
   - Location of Wells
   - Scaling or Blockage
   - Well Corrosion
   - Cost Escalation
   - * Expected Life
   - Cement Leakage
   - * Intrusion or Leakage from or into other Strata

B. Plant

1. Design
   - Two Phase Flow Supply Regime
   - Stability
   - Scale
   - * Corrosion
   - * Plant Efficiency
   - Reliability
   - * Separator and Scrubber Performance
   - Effluent Treatment
   - Solids Removal
   - * Cooling Water Chemistry and Supply
   - Non-condensible Gas Removal & Treatment
   - Fouling Factors
   - Planned Maintenance

Transmission
Brine Supply Lines
Brine Injection Lines
* Brine Effluent Treatment
Permit Conditions
Gas "Burps"
Cooling Tower Emissions
Seismic, Flood, Wind and Subsidence Criteria

2. Construction
Capital Cost
Cash Flow
Schedule.
Interest Charges
Escalation
Start Up Problems
Scope Changes
Taxes

3. Operation and Maintenance
Size of Operating Crew
Failure Rates
Spare Parts Inventory
Escalation
Expendable Materials Required
* Chemical Treatment Required
Size, Location and Capability of Maintenance Crew
Waste Disposal Charges
Taxes
* Plant Reliability
* Availability of Transmission
Scheduled Maintenance
Expected Life of Equipment
Scaling and Scale Removal
* Corrosion
Learning Curve

Area of Uncertainty

I. Technical and Envfronmental (continued)

3. Operation and Maintenance (con'd)
Ambient Conditions
* Resource Availability .

II. Social and Institutional

A. Contractual Relationships
1. Architect and Engineering Firm
Type of Contract
Performance
Schedule
Liability
Financial Integrity

2. A & E Review Firm
Type of Contract
Performance
Liability
Financial Integrity

3. Construction Firm(s)
scope
Type of Contract
Bonding
Insurance
* Liability
* Financial Integrity
Warrantees

4. Major Equipment Vendors
Performance Guarantees
Liquidated Damages
Maintenance Contracts
Warrantees
Lease Conditions
Scope of Responsibility

5. Resources Company
• Min. Guaranteed Supply
* Financial Resources and Integrity
* Type of Contract
Insurance
* Performance
* Liquidated Damages
* Escalation
* Rate of Return

6. Utilities (Water, Electricity, etc.)
Availability of Resources
Reliability of Service,
Cost of Service
Liability

7. O & M Service (Cleaning, Repair, Materials, etc.)
Scope of Responsibility
Reliability
cost
Liability
Type of Contract
Financial Integrity
Warrantees

8. Lease or Purchase Agreements (Land, Easements, Bldgs., etc.)
Size
Flood or other Easements
Liability

9. Financial Institution
Loan Size
Interest Rate
Liability
Risk Acceptance

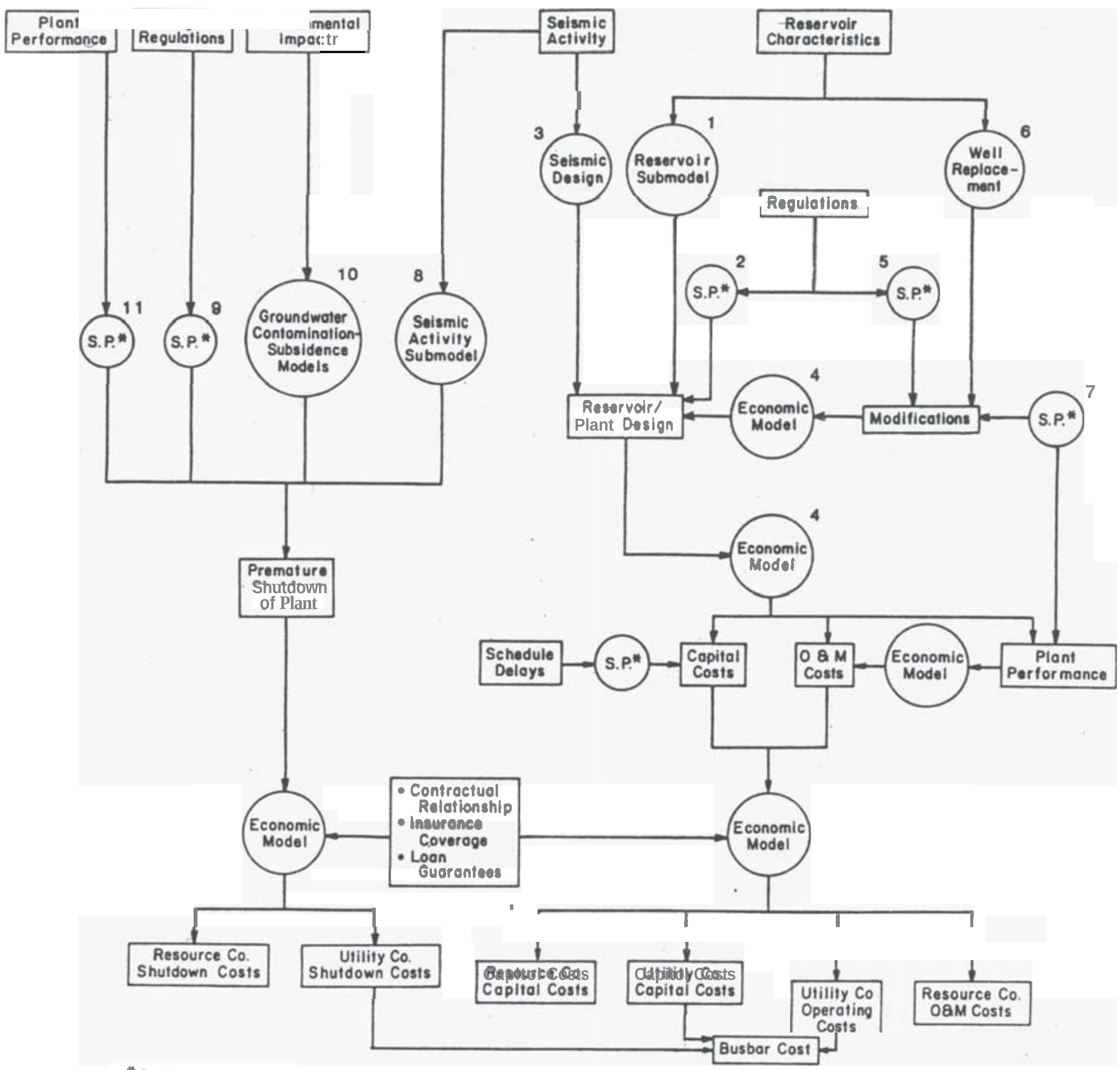
B. Regulatory
1. County and Regional Permits
Authority
* Conditions
Fees
* Schedule
* Limitations
Modifications

2. State and Federal Agency Licensing
Authority
• Conditions
Fees
* Schedule
* Limitations
Modifications

3. Public Utility Commission
* Rate Treatment
* Rate of Return Allowed
Rate Base
Schedule
* Customer Charges

FIGURE 2

SUBMODELS FOR RELATING UNCERTANTIES TO BUSBAR COSTS



*Subjective Probability

In general, uncertainties can be divided into two groups, those that significantly affect the expected cost of power at an operating plant (Level I), and those which could affect cost by resulting in a premature shutdown of the plant (Level II). Level I uncertainties are factors which are most likely to impact the cost of power of an operating plant. These uncertainties are generally related to the economics of the project construction and reservoir plant operation over time.

Projected characteristics of the reservoir, projected seismic activity, and existing and anticipated regulations, all influence the design (and therefore the cost) of the plant. Once the design has been specified, and assuming the plant will continue to operate over its design life, the remaining major uncertainties are those related to the costs of construction and operation of the plant, the terms of the heat contract with the resource company, and any modifications to the plant or reservoir design that may be necessary over its expected life.

All of these uncertainties may affect the busbar cost of power generated by the plant, but are unlikely to result in a premature shutdown of the plant.

Level II uncertainties are those which could potentially result in a shutdown of the plant prior to its design life and hence should be distinguished from Level I uncertainties. A premature shutdown could be caused by: new regulations that make it economically unattractive to operate the plant; major seismic activity severely damaging the plant and/or the reservoir; major environmental impacts such as subsidence or groundwater contamination, resulting in a shutdown of the plant by regulators; poor reservoir and/or plant performance due to inadequate or faulty design, resulting in an economic decision to close the plant.

THE MODEL

The objective of the risk model is to provide a framework for integration of various submodels that address the environmental, economic and reservoir-related uncertainties. This framework defines the major decision points in the exploitation of geothermal energy for electric power generation., and develops the relationships between major uncertainties and costs. It allows subsequent efforts to focus on those factors which significantly influence the cost of geothermal power.

The inputs to the model are the factors that influence each cost component. This would entail development of probability distributions (mostly subjective) for the input variables and a mechanism for combining the probabilities. The techniques of scenario generation and assessment of subjective probabilities are well known (see Tversky and Kahneman (1974) for example) and we do not discuss these here. It suffices to note that the uncertainties associated with many factors cannot be based on objective data or on evaluation of specific submodels, and that these probability distributions need to be assessed. The set of output distributions on each cost component are then combined into a single distribution for each cost component--the model takes the set of conditional probability distributions for each component (conditional on the factors) and combines these into an unconditional probability distribution on each cost component. Finally, the distribution on all cost components are combined into a single distribution on total busbar cost of geothermal power.

The emphasis of this section will be on the demonstration of the fact that nearly all of the uncertainties related to geothermal power development (seismic, environmental, economic, regulatory, and physical) can be translated into economic uncertainties, and that through the use of submodels (mostly existing models in different areas related to geothermal development) these uncertainties can be combined into a single measure. Figure 2 shows the relationship (via submodels) of the factors and their associated uncertainties to the busbar cost. Numbers in the figure correspond to submodels belaw.

Level I Uncertainties

Submodels far Estimating Plant Design

The initial plant design is a function of the estimated reservoir characteristics, site conditions, existing and anticipated regulations, and projected seismic activity. Each of these submodels are briefly described below.

1. Reservoir Submodels

The characteristics of the reservoir and the brine and their spatial and temporal variations have a significant effect on the economics of geothermal power and reliability of the resource. Since the power plant may become inoperable if the pressure and temperature of the heat source and the flow rate drop below certain critical levels, the likelihood and magnitude of decline in these parameters over time and the variation of the physical parameters over space should be estimated.

These three parameters, particularly temperature and pressure, are interrelated in the sense that variations in one parameter may be partially or completely compensated by adjustments in the other two. Assuming that the reservoir total heat content is adequate, gradual declines in one or more of these parameters may be offset by providing additional wells.

The plant design can be specified based on initial estimates of these parameters at the selected site. The relationship between these initial estimates and the cost of geothermal power is well known through various engineering cost estimates and can be used as the submodel, with judgmental probability distributions assessed for the significant parameters (e.g., temperature, pressure, and flow rate) to account for the uncertainties in these parameters.

To estimate the variations of the fluid characteristics over time, a dynamic reservoir model should be used to predict the reservoir behavior as a function of its physical parameters and production and reinjection flow rates. The model should be able to reflect the unique characteristics of the reservoir and should be updated as more information about the reservoir becomes available.

One or more of the models currently available can be used to predict the reservoir behavior. Among these are the models developed by Tsang, Witherspoon and Gringarten (1976), Tsang, Bodvarsson, Lippman and Rivera (1978), Coats (1977), and Pruess et al. (1979).

2. Anticipated Regulatory Decisions Submodel

Existing regulations will have to be accommodated in the initial plant design. Regulations on plant effluents (gaseous, solid and liquid), for example, have to be incorporated in plant processes and equipment. Other regulations will affect plant components and operation in different ways. Altogether, their effect will translate into higher capihal and O & M costs.

In this submodel, the effects of regulatory decisions will be limited to the uncertainty associated with anticipated future regulations. These are assumed to affect the plant design, and will be estimated using subjective probability assessment. The effects of unanticipated regulatory decisions are discussed belw.

3. Seismic Activity Models

Even though the probability of occurrence of natural hazards cannot be affected, actions can be taken to reduce the damage to the plant and its operations. The procedure is to (1) identify those seismic events that could severely impact plant operations and assess their probabilities by one of several seismic prediction models; and (2) determine the critical level(s) at which plant operations may be impared. It must be recognized that both tasks are dependent on current regulations, plant design, and the number and level of prevention mechanisms built into it. The optimal plant design is one that balances high initial capital costs due to more conservative seismic design against lower probabilities of damage given a major earthquake.

Some relevant models are: Esteva (1970), Patwardhan et al. (1980), and Knopoff and Kagan (1977).

4, Economic Submodels

Economic models can be used to describe the cost and revenues associated with extraction and power generation. The revenue model should include taxes and depletion allowances, royalties, interest rates and the rate of increase in value of energy over time. The cost model should include factors such as capital and O & M costs as a function of extraction rate, interest rate, and other design parameters. The revenue and cost models, coupled with an appropriate reservoir model can be used to determine optimal extraction rates. Such models may also provide useful and timely information on the effect of changes in economic parameters, tax incentives and regulatory decisions on the profitability of the project and optimal extraction rate. Two models with this approach are Golabi et al. (1981) and Golabi and Scherer (1977, 1981). Other relevant models are Bloomster (1975), Ramachandran et al. (1977) and Rao et al. (1979)

Submodels for Estimating Effects of Modifications to Reservoir/Plant

Modifications to an operating reservoir/plant may become necessary due to unanticipated regulatory decisions, changes in the reservoir characteristics, or actual plant performance.

5. Unanticipated Regulatory Decision Submodel

Changes to existing regulations or new regulations in the future & require modifications to the plant and would affect the busbar cost of an operating plant. These effects will be estimated using judgmental probabilities (to asses potential future regulations) and accounting/economic models (to assess their effect on cost).

6. Changes in Reservoir Characteristics

Once the plant design is fixed, the model assumes that differences between the actual and estimated reservoir parameters will be accommodated through changes in the rate of well replacement. That is if temperature and/or pressure were overestimated, then additional wells need to be drilled over the design life of the plant. The effect of estimation errors will therefore be in the replacement rate and cost.

7. Plant Performance Submodel

Characteristic of plant performance during operation may require modifications to the original plant design. Such characteristics include, for example, plant reliability, capacity factor, waste disposal maintenance, etc. The probability of changes in these characteristics will be estimated by subjective probability assessment with design and process engineers. The cost effect will be estimated using standard economic/accounting models.

Level II Uncertainties

An operating plant could be shutdown prior to its expected design life due to: damage from a major earthquake; marked changes in existing regulations; unacceptable plant or reservoir performance due to faulty design, or major plant or reservoir-induced environmental impacts such as subsidence or groundwater contamination.

All of these are low probability, high consequence events. The submodels that will be used to estimate the probabilities of these events and their cost consequences are shown in Figure 1. The numbers in the figure correspond to the submodels described below.

Costs of a premature shutdown will depend on the year in which the shutdown occurs, the amount of revenue the plant has generated, and the extent to which the capital costs have been amortized. These shutdown costs will be estimated using standard economic/accounting models.

8. Seismic Activity Submodel

Once the design level acceleration has been determined and the plant has been constructed, it is still possible (although unlikely) that an earthquake of an acceleration level greater than that which the plant was designed to withstand will occur. Current seismic predictive models account for the significant earthquake parameters: occurrence, attenuation, ground response, and structural design.

9. Unanticipated Regulatory Changes Submodel

It is possible, although unlikely, that future regulation may be so stringent that it becomes economically infeasible to continue to operate the plant. The probability that the utility company will decide to prematurely shutdown the plant due to regulatory decisions can be estimated using judgmental probabilities.

10. Environmental Impacts Submodel

Subsidence and groundwater contamination are examples of major environmental impacts that could result in a shutdown of the plant by regulatory agencies.

Groundwater Contamination Models: An area of potential importance to many geothermal operations is the possibility of unintentionally contaminating groundwater resources. Although this is thought to be a risk of acceptable magnitude in the proposed geothermal developments, regulatory considerations (e.g.* EPA guidelines) may require that the potential for such problems be considered and evaluated. There are well established models and techniques for the design of waste injection systems (EPA 1977).

Subsidence Models: The development of geothermal resources will cause changes in hydrodynamic regimes. These regimes in the geothermal zones can be assumed to be in a state of equilibrium before exploitation. Reservoir exploitation will require fluid withdrawal, injection, and recharge and will introduce disturbances in these regimes. These conditions may induce stresses and deformation in the overburden that could result in subsidence or bulging at the ground surface.

To compute overburden deformation, numerical mathematical techniques may be used. These techniques include the finite element approach and the nucleus of strain approach. The finite element method (e.g., Nair, 1979, Chang and Nair, 1973) is the more versatile. This method enables complex geometrics, arbitrary boundary conditions, heterogeneity, and nonlinearity, to be included in the calculations.

11. Plant Performance Submodel

Actual plant performance could be so poor that the utility company may decide it is uneconomical to continue to operate the plant. Although unlikely, such a decision could result from inadequate or faulty plant design, major problems with scaling and corrosion, major and frequent breakdowns, unreliable operation or unstable output. The probabi'lity can be estimated using subjective probability assessment techniques with design and process engineers and knowledgeable experts.

CONCLUSION

The conceptual model presented in this paper provides a framework for a systematic examination of the uncertainties that may affect a commitment to a geothermal project. The model utilizes existing information about the effect of key uncertainties and incorporates professional judgment of experts in areas where adequate data is not available. The goal is to quantify and integrate these uncertainties and to demonstrate that the main uncertainties, whether environmental, reservoir-related or regulatory, can be related to economic aspects, and should be treated as such. The tools for this, derived from the areas of operations research, engineering and economics are well developed and have been used by many industries for many years. NOW that the main technical difficulties of geothermal energy production have been overcome, it is time to concentrate on long-term objectives. A first step in this direction is to reduce the gap between perceptions regarding the financial risks of geothermal development and a realistic assessment of costs and benefits.

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