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Authors

Green, M.A.
Pines, H.S.
Pope, W.L.
et al.

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M.A. Green, H.S. Pines,
W.L. Pope and J.D. Williams

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Lawrence Berkeley Laboratory University of California/Berkeley

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DISCLAIMER

THERMODYNAMIC AND COST OPTIMIZATION USING PROGRAM GEOTHM

M. A. Green, H. S. Pines, W. L. Pope, J. D. Williams

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 U.S.A.

This report shows some of the unique features of the Lawrence Berkeley Laboratory Computer Program GEOTHM. This program designs and optimizes thermodynamic process cycles. Several examples of geothermal cycle optimization are given in this report. Three dimensional plots generated by the computer show how the optimization process works. GEOTHM should see considerable use in electrical and non-electrical application of geothermal energy.

1. INTRODUCTION

Program GEOTHM is a thermodynamic process computer program which can model, design and optimize a wide variety of thermodynamic process cycles. The program name GEOTHM reflects the fact that the Lawrence Berkeley Laboratory geothermal energy group developed the computer model with funding provided by the Energy Research and Development Administration (ERDA).[1,2,3] The program is not restricted to geothermal power cycles; it can be used to model a wide variety of thermodynamic and refrigeration cycles including fossil fuel, solar, ocean thermal and non-electrical applications. Because of its unique optimizing capability, GEOTHM can provide a broad spectrum of applications in the process and energy industries. The program's single step optimization mode reconciles the many individual thermodynamic and cost parameters of a system generating an optimum total system design.

GEOTHM is a versatile thermodynamic cycle simulator for a number of reasons:

1. The thermodynamic processes are modularized into fundamental building blocks. The blocks can be arranged in many different ways to simulate virtually any type of thermodynamic process system.

2. The calculation of the fluid thermodynamic and transport properties is separated from the thermodynamic process calculation. This factor facilitates the development of new process models and the packaging of a separate fluid properties program.

3. The program is fast. Due to efficient programming in all of GEOTHM's iterative convergence routines, a typical geothermal power plant cycle calculation requires only about 0.075 seconds of computation time on a CDC 7600 computer.

4. The thermodynamic cycle generator in GEOTHM can be used like a function generator which can be driven by mathematical optimizer routine which optimizes the design of the cycle with respect to any user-specified criterion.

GEOTHM's major disadvantage is its size. It has over 90 subroutines and 8000 FORTRAN statements. Since the program is so flexible, facility in its use requires considerable user orientation. It would be difficult to transfer GEOTHM from the CDC system to another computer system. A documented user's manual which permits the program to be used on the LBL computer is forthcoming.

2. GEOTHM AS A THERMODYNAMIC CYCLE OPTIMIZER

GEOTHM can calculate thermodynamic cycles with many types of components. These components include: turbines, pumps, fans, flash tanks, heat exchangers, cooling towers, condensers, desuperheaters, burners and so on. The program designs each of the components in sufficient detail so that a reasonable cost estimate can be made. Since the process routines are modularized, new equipment models can be developed.

GEOTHM designs a thermodynamic cycle using the following user specified input data: heat source and sink conditions, net power production or refrigeration constraint, the configuration of the thermodynamic cycle, and the plant efficiency and cost factors. GEOTHM also requires a set of thermodynamic cycle or "state" parameters which provide the minimum information necessary in order to calculate the thermodynamics of the entire process cycle.

As an example, the simple bi-fluid geothermal power cycle shown in Figure 1 is completely specified by the following six state parameters: 1) turbine inlet pressure, 2) turbine inlet temperature, 3) condenser exit temperature or pressure (assuming saturated liquid), 4) the pinch point temperature difference across the brine heat exchanger, 5) the pinch point temperature difference across the water cooled condenser, and 6) the cooling tower wet bulb approach temperature difference. Given the system state parameters and other required input data, the thermodynamic process and fluid properties routines which are the

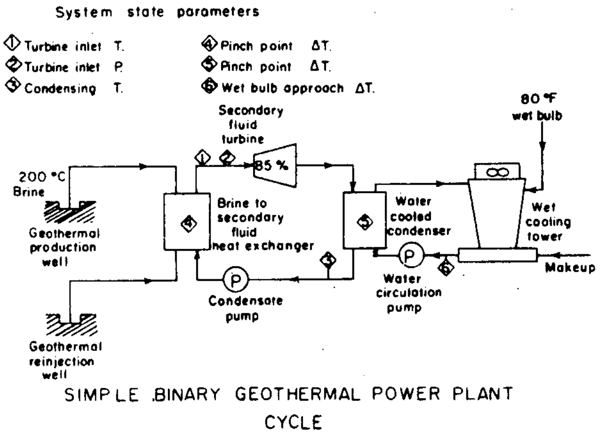

Fig. 1. Simple binary geothermal power plant cycle.

heart of program GEOTHM will design the plant to satisfy the net power production constraint. While designing the plant, the program calculates and prints out a set of system design performance factors such as cycle efficiency, resource utilization efficiency, fluid mass flows, heat exchanger areas, equipment power requirements, the associated costs of the plant equipment, and the cost of energy produced by the plant. When the plant has fixed efficiency and cost factors, the final plant design is completely determined in GEOTHM by the user-dictated set of system state parameters. The program is said to be operating in the "passive design mode".

The logical structure of the passive design mode permits the program to serve as a function generator which is steered by an optimizer routine which optimizes the design of the thermodynamic cycle with respect to that particular function. This is achieved by introducing the optimizer routine into a feedback loop modification of the passive design mode. The user initiates the optimization process by inputing a first guess set of system state parameters which we now call "optimizable" parameters. The user must also specify which one of the system's particular design performance factors is the objective function to be minimized or maximized. The optimizer steers the program in an iterative fashion computing an improving sequence of optimizable parameters which rapidly converges upon the optimum system design. When the optimizer directs the program to design and optimize the cycle, GEOTHM is said to be operating in the "dynamic design mode". Examples of objective functions which could be optimized in a geothermal power plant are: 1) minimize capital cost of the plant, 2) minimize cost of energy from the plant, 3) maximize the plant efficiency, and 4) maximize the resource utilization efficiency of the plant.

3. EXAMPLES OF GEOTHM OPTIMIZATION CAPABILITY

The capability of the dynamic design mode is illustrated by the cycle shown in Figure 1. The design of the simple bi-fluid plant is completely determined by the previously described set of six optimizable parameters. The set of all possible designs for this plant can be described by a design surface in a seven dimensional mathematical space corresponding to the six optimizable parameters and the objective function. Optimizing by brute force methods in seven dimensional space is impossible to visualize and it takes weeks, even months of computer time to achieve. On the other hand, GEOTHM with its optimizer performs this task in one step using less than 30 seconds of CDC 7600 computer time.

Two examples of optimization are given for the cycle shown in Figure 1. One uses energy cost (in $ per kWhr) as an objective function. The other uses resource utilization efficiency as an objective function. Resource utilization efficiency for a geothermal power plant is defined as follows:

$$\eta_{bu} = \frac{\text{Net power}}{\mathring{m}_b \ \Delta H_s}$$

where η_{bu} is the brine utilization efficiency, $\mathring{m}_b$ is the brine mass flow, and ΔH_s is the enthalpy change of the brine when it is expanded isentropically from the inlet brine state to the sink temperature (defined as the lowest temperature in the cycle).

The cycle assumed pure water entering the cycle at a pressure of 19 bar (275 psia) and temperature of 200°C (392°F). The sink is air with a wet bulb temperature of 26.7°C (80°F which is the lowest temperature in the system) and a dry bulb temperature of 43.3°C (110°F). The secondary working fluid is isobutane. The plant is constrained to produce 50 MW net power at the bus bar at an 85% load factor. The efficiencies of the turbine, major pumps and fans are 85%, 80% and 50% respectively. The generator and motor efficiencies are 98%. The cost data and equipment cost models utilized in this study are based upon information gathered from ERDA source documents, from vendors of major capital equipment and from the conceptual design studies of reputable A & E contractors. Since there is no unanimity of agreement among these various parties concerning this cost data, the examples shown here are only examples, and should not be taken as real plant design data.

Table 1 compares the optimized designs for minimum energy cost and maximum brine utilization

Table 1. Parameters of Two Types of Optimization on the Simple Bi-Fluid Cycle shown in Figure 1 (Net Power 50 MW electric)

	Minimum Cost Energy (see Fig. 2)	Maximum Brine Utilization Efficiency (see Fig. 3)
Optimizable parameters		
turbine inlet temperature (°C)	173.5	183.3
turbine inlet pressure (bar)	50.8	78.4
condenser pressure (bar)	6.23	4.21
brine heat exchanger pinch point ΔT (°C)	12.66	0
condenser pinch point ΔT (°C)	6.74	0
cooling tower approach ΔT (°C)	3.39	0
Other parameters		
bus bar energy cost ($ per kWh)	0.0616	∝
brine utilization efficiency (%)	42.3	60.5
cycle efficiency (%)	12.8	14.5
power plant capital cost (M$)	43.1	∝

efficiency. As expected, the minimum energy cost plant does not conform to the design standards for a plant which utilizes the brine most efficiently. The former has non zero pinch point temperature differences and wet bulb approach while the latter has all of these optimizable parameters forced to zero. Maximum brine utilization and minimum cost energy are not compatible design criteria. It is rather naive to think otherwise.

For purposes of visualization, four of the six optimizable parameters (pinch point temperature differences, wet bulb approach and condenser pressure) are set to the optimum values. The three dimensional plots shown in Figure 2, 3, and 4 show how the objective function varies with turbine inlet temperature and pressure. The figures which were generated by the computer show a landscape like surface which contains a unique optimum point.

Figure 2 and 4 show energy cost as a function of turbine inlet temperature and pressure. The primary difference between Figure 2 and 4 is that the former assumes a continuously varying well cost versus well flow while the latter only allows for discrete integer number of wells. The latter figure also assumes lower priced wells. The program finds the minimum energy cost at the bus bar in either case. The computer program finds the global minimum on this surface and the other four dimensions very quickly (usually in less than 30 iteration steps). Figure 2 required 900 calculations to create. If Figure 2 could be drawn in seven dimensional space, it would take 7.3×10^8 calculations or 1.76 years of CDC 7600 computer time to create. The optimum was found by GEOTHM in seven dimensional space in just over 20 seconds of CDC 7600 computer time.

Figure 3 shows brine utilization efficiency as a function of turbine inlet temperature and pressure. The maximum utilization efficiency point does not correspond to the minimum energy cost point shown in Figure 2. In fact, the shape of the hill in Figure 3 does not correspond to the shape of the valley in Figure 2. The orientation is entirely different because the factors governing the optimal design are different. The energy cost which corresponds to the optimum point in Figure 4 is infinite because the pinch point temperature differences and the wet bulb approach are zero, requiring infinite area heat exchangers.

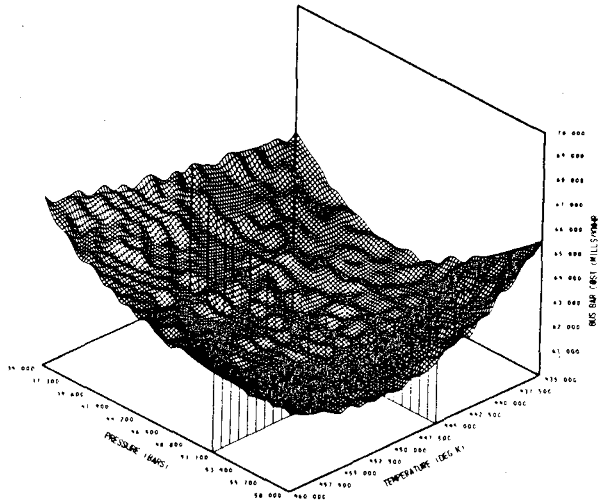

Fig. 2. Energy cost design surface for a 50 MWe binary cycle power plant-isobutane (continuous well cost)

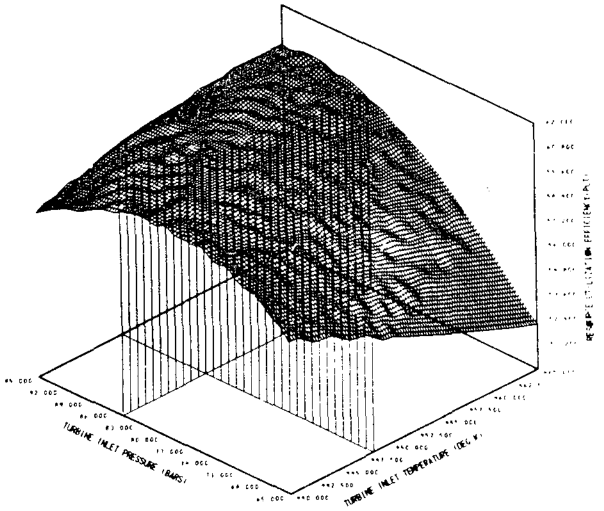

Fig. 3. Brine utilization efficiency design surface for a 50 MWe binary cycle power plant-isobutane.

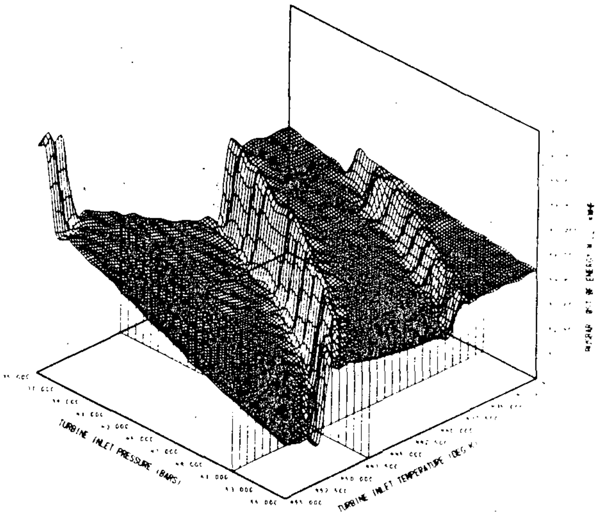

Fig. 4. Energy cost design surface for a 50 MWe binary cycle power plant-isobutane (discrete well cost).

One final example of GEOTHM's unique capability is shown in Figure 5. This figure shows a plot of bus bar energy cost as a function of brine utilization efficiency and brine inlet temperature. The thermodynamic cycle is the same as the previous case (see Figure 1). The component efficiency and cost factors are the same as the previous cases. Figure 5 demonstrates that cost of energy drops dramatically as the temperature (enthalpy) of the liquid dominated resource rises. The lowest cost for a given resource temperature is neither at the highest or at the lowest brine utilization efficiency. The lowest cost energy occurs at brine utilization efficiencies of around 40 percent. When the brine utilization efficiency is above the minimum cost trench in Figure 5, the energy cost is dominated by plant energy conversion equipment (heat exchangers primarily). When the brine utilization efficiency is below the minimum cost trench, the energy cost is dominated by the geothermal wells and the brine handling equipment. It is clear that a compromise must be struck between the lowest cost electric energy and brine utilization efficiency.

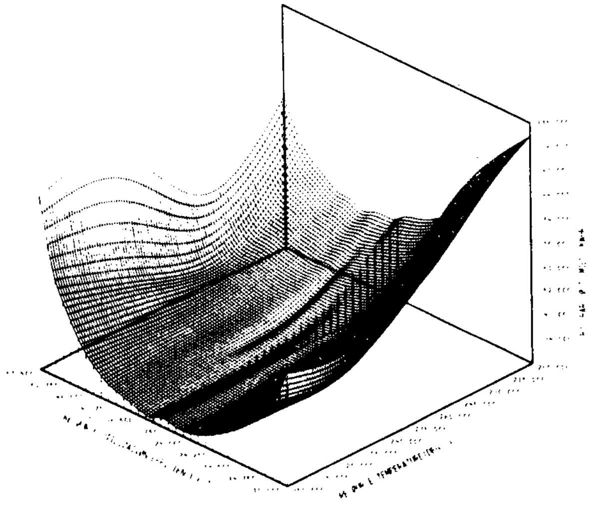

Fig. 5. Energy cost as a function of resource temperature and resource utilization efficiency for a 50 MWe binary cycle-isobutane.

4. A FUTURE FOR GEOTHM

GEOTHM can go much further than merely designing and optimizing geothermal power plants. Once the plant has been designed and built, GEOTHM can be used to dictate the control of the plant to maximize the energy output from the plant. For example, GEOTHM will specify an optimum plant design for given source and sink conditions. The source will change with time (usually the temperature drops) the sink will vary depending on the season and local weather patterns. GEOTHM can calculate the optimum operating conditions needed to maximize the financial return from the plant to the invester after it is built.

GEOTHM can be used to analyze cycles, as yet undreamed of, before they are built. The program will optimize these designs using site specific parameters. The program undoubtedly will be extended to other types of thermodynamic and process cycles. These cycles can be analyzed over their useful life before the plant or process is built. The economic impact of GEOTHM on the power and process industries should be substantial.

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TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720