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Process Applications for Geothermal
Energy Resources

MASTER

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CHAPTER 1. SUMMARY

A. Project Objective and Plan

The basic objective of this project was the demonstration of the suitability of geothermal energy as a source of industrial process heat. We intended to accomplish this goal by establishing a cooperative program with industrial firms. This program would first confirm the available analyses of the economic potential of geothermal energy. Then we intended to select attractive candidate industries and, within those, firms which were interested in working with us and which appeared to have a substantial opportunity to profit from employment of geothermal energy.

Having done this we would, in later phases of the project, work with these cooperating industries to develop specific demonstration plans and to conduct the demonstrations.

B. Early Stages of the Project

We first screened industrial sectors to find attractive candidates. We used the following criteria:

- Energy intensive industry
- Large user of low temperature energy
- Growing industry

We felt the industry should spend a significant

fraction of its cost on energy. Otherwise, potential savings in energy cost would not be large enough to capture the needed management attention and investment resources. Also DOE interest is justified only if the total energy substitution is significant.

Since geothermal sources are low temperature, i.e. less than 500°F, geothermal energy is probably economic only if the process can be carried out below that temperature.

The industry should be growing as growth provides the opportunity to use the new technology in a new plant instead of retrofitting a plant designed to use a different technology.

It also seemed likely that the individual operating units (plants) in the industry should be large enough to use all the output from a single geothermal well. Geothermal energy is capital intensive and using less than full output available from each well will increase the cost.

Applying these criteria we concluded that the pulp and paper industry and the food processing industry would be the most attractive candidate industries to demonstrate the technological feasibility and economics of geothermal energy use.

C. Workshops

We planned to conduct two industry workshops, one for food processing and one for pulp and paper. These workshops were to serve four purposes:

- Exchange ideas concerning use of geothermal energy among representatives of the industry, DOE and MIT;
- Establish contacts with individual firms in the industries;
- Identify firms which were willing and attractive candidates as collaborators or cooperators in the project;
- Review with the industry and DOE representatives our project plan and obtain suggestions for modifications to the project plan.

Pulp and paper workshop.

This workshop was held October 10, 1977. Representatives of fourteen pulp and paper companies were present. Of these, five firms^{*} agreed to participate in the project to the extent of supplying data and reviewing our findings.

No significant modifications were suggested to our

^{*} Mead, Weyerhaeuser, Champion International, Westvaco and Union Camp.

project plan. Some industry representatives suggested that the project was perhaps not needed since they "knew what to do with hot water." Further, some felt that our project was premature since very little information was available on geothermal resource characteristics (temperature, pressure, chemistry, flow rates) and costs.

Food processing workshop.

We were unable to develop enough interest in the food processing industry to justify a workshop even after the reasonably successful workshop we had with the pulp and paper industry. The reasons for this lack of interest seemed to be:

- Food processing operating units are relatively small with insufficient resources to invest in examination of new energy sources;
- Food processing technology is developed by the food machinery companies rather than the food processing companies;
- Food processing plants operate a relatively small fraction of each year, increasing the cost per unit of capital intensive geothermal energy;
- Feelings that they needed resource information rather than analysis of the technical, economic and managerial implications of geothermal energy (they, too, "knew what to do with hot water").

D. Original Project Plan

Our initial project plan included the following:

- Review of the literature on direct application of geothermal energy as process heat;
- Development of methods for screening industries to select attractive candidates on the basis of the quantity and quality of energy used;
- Development of computerized analysis tools to assist in evaluating the economic potential of geothermal energy in specific plants;
- Development of first order models for evaluation of the potential of specific geothermal resources;
- Determination of the criteria used by corporate managers for evaluation of potential investments in geothermal energy.

With these initial results in hand we expected to be able to identify attractive potential applications of geothermal energy among the plants operated or contemplated by the cooperating firms in the pulp and paper industry and the food processing industry. This identification would provide the basis for detailed planning of Phase II of the overall program, the development of specific application plans.

E. Industry Screening System

Akhil Gupta, a research assistant with the project, developed a system of analysis which developed first order estimates of the economic potential of geothermal energy in particular industries. The basic idea of this system is that of finding the cost of providing geothermal resources of specified characteristics and the benefit, in terms of avoided costs of fossil fuel, of using geothermal energy in a particular industry.

The resulting analysis system is very complex because the amount (and cost) of geothermal fluid required depends on the temperature and pressure of the geothermal resource and also on the energy flow (or cascade) characteristics of the energy using process. In many cases geothermal energy does not directly displace fossil fuel. Fossil fuel provides a high temperature energy source which can drive processes at temperatures above those common in geothermal resources. In some cases exhaust heat from these higher temperature processes can be used to drive the lower temperature processes which can also be heated by geothermal fluids. Thus, the saving in fossil fuel energy may be much less than the energy used by a low temperature process.

Most industrial plants which consume large amounts of energy include a variety of processes at several different temperatures. Analyzing the energy flow through

such a plant to find the best (most economical) way to use geothermal energy is, therefore, a complex task.

F. Detailed Analysis System

The system just described is concerned with analysis of an "industry typical situation". Since the situation definition depends on industry average data there may be no plant which exhibits these characteristics. Michael Packer, also a research assistant on this project, addressed this problem.

Packer developed a set of engineering design criteria which assist a plant engineer in selecting the best energy cascading system to use, given the process requirements for energy and the characteristics of the available energy sources (geothermal, fossil fuel, and exhaust heat from higher temperature processes).

The basic problem addressed here is very similar to that described earlier but, since it deals with specific streams in specific plants, requires more specific and detailed descriptions of energy resource utilization.

At this stage in the project, we were not able to develop any optimizing system which would develop a "best" energy cascade for given energy resource characteristics and cost. However, the system developed has been reduced to a computer program which can be used interactively.

In this way a plant engineer can quickly explore a variety of possible energy cascade configurations to arrive at the most promising overall design for a plant.

The primary output of the program is a financial analysis of a potential geothermal resource application. The system provides payback period, discounted cash flow and internal rate of return information under a variety of tax, inflation and depreciation assumptions.

In the course of this work Packer discovered that the current tax treatment of mineral resource depletion is unfavorable to the developer-user of a geothermal resource. He pursued this further and has suggested an alternative treatment to remove this barrier [1].

Finally, this analysis system and computer program is able to include a variety of intangible effects a decision maker may wish to consider in evaluating a proposed geothermal project. These include potential environmental effects such as surface subsidence, effluent disposal and the noise of pumps and flash chambers, and the positive and negative image effects which accompany fossil fuel conservation and potential stream pollution.

This analysis system and its supporting computer program can be used by anyone with standard FORTRAN compiler capability and is already being used by organizations outside MIT. We expect that it will be especially

helpful in the preliminary analysis of potential application of geothermal fluids. A wide variety of possible cascade configurations can be assessed quickly, allowing selection of the most promising for detailed manual analysis [2], [3].

G. Development of First Order Models

To understand the management decision problem we wanted to develop a better understanding of the position of geothermal energy relative to its competitors--the fossil fuels (coal, oil and natural gas), hydroelectric power, nuclear power and solar energy. We particularly wanted to see whether there were specific characteristics of the geothermal resource and the application which would make geothermal energy especially attractive. This would define a "market niche" for geothermal energy.

Comparison with fossil fuels.

We developed a simple model of the cost savings accruing to geothermal energy by substituting for oil. The cost of geothermal fluids per million pounds depends on drilling conditions, required depths, need for reinjection of the spent fluid, pumping cost, etc. The cost depends primarily on drilling, well completion and piping cost so geothermal energy is capital intensive. The costs of these items are much greater than the costs of

heat exchangers for the transfer of geothermal energy to an industrial process.

The cost of using fossil fuel is also primarily the cost of the fuel itself. The annual cost of boilers and heat exchangers is small by comparison (although greater than the cost of similar equipment used with geothermal energy).

Because of the uncertainty in the cost of fossil fuel and in the cost and temperature of geothermal fluid we developed a family of curves showing the relative benefits of geothermal water under various conditions. The major results are shown in Figure 1.

There are two basic conclusions to be drawn from that figure.

- The value of geothermal fluids depends strongly on the temperature drop available between the geothermal resource temperature and the process to be heated.
- The value of geothermal fluids depends strongly on the cost of competing energy sources.

These conclusions are, perhaps, obvious, now that we are familiar with them. However, the effects that these conclusions have in the development of geothermal energy are profound but not widely appreciated.

Very little is known about potential geothermal

Figure 1. Cost Savings Available by Substituting Geothermal Energy for Fossil Fuel.

Note: Approximate Corresponding Prices are:

	Fossil Fuel	Fuel Oil	Steam Coal	Natural Gas
	\$/10 ⁶ BTU	\$/bbl	\$/ton	\$/1000 cu ft
2		12	43	2
3		18	65	3
4		24	87	4

resources or the cost of developing them, until test and field development wells have been drilled. Since the value of the resource depends on cost and temperature, potential returns from drilling are very uncertain. Note the strong contrast with drilling for oil and gas. The probability that a particular exploration oil well attempt will be successful is relatively low and, as a consequence, the outcome is uncertain. However, if oil is found the value per barrel is essentially deterministic.

Use of geothermal fluids for process heat or electricity generation.

We found that the value of geothermal energy for process heat is strongly sensitive to the temperature of the geothermal fluid: the higher the temperature, the more valuable the fluid. (Of course, at the same temperature, steam is much more valuable than liquid water.) However, we were advised by DOE that we should not consider geothermal resources at temperatures above 350°F (175°C) as candidates for use as sources of industrial process heat.

It seemed to us likely that intermediate temperature resources (350-500°F, 175-260°C) would be more economically used for process heat because of the inherent inefficiency of the thermal-mechanical energy conversion required.

This proved to be the case. As shown in Figure 2, geothermal energy used directly as process heat saves more money in displacing fossil fuel (oil) used to provide that heat than is saved in displacing fossil fuel used to provide electric power at market rates. This conclusion depends on the geothermal resource temperature and on the process temperature as well as the relative prices of fuel oil and electricity. For a process at 200°F, use as process heat is always preferable to use as a generator of electricity. As the process temperature rises the resource temperature must increase to make process heat preferable to electricity generation.

These results depend on the cost of geothermal fluids and on the market prices of electric power and fossil fuel [4].

Competition with turbine exhaust steam (cogeneration)

In our work with pulp and paper companies we found that they often used the exhaust steam from a turbine (used to provide mechanical energy for pumping or for generating electricity) to provide process heat for processes operating in the 200-350°F range. In these cases the process heat is provided very economically as a co-product with providing mechanical energy. It became apparent that turbine exhaust heat is an important competitor of geothermal energy for any process heat user who uses

Figure 2. Substitution Value of Geothermal Energy
 - as Process heat, substituting for fuel oil @ \$22/bbl
 - for electricity @ 0.025/kwh.

enough mechanical energy to make investment in a boiler and turbines attractive.

As the process temperature rises, the required temperature of the turbine exhaust steam also rises and, therefore, some mechanical energy is lost. If we treat the process heat as a by-product of the primary process of providing mechanical energy, the cost of the process heat is the value of the lost mechanical (or electrical) energy. This proves to be a very economical source of process heat.

One cannot decide on the best mix of fossil fuel boilers, turbine exhaust steam and geothermal fluids to provide a given set of requirements for process heat without doing a detailed analysis of the potential energy streams through a plant (see Section J, below, and Chapters 4 and 5). However, a good first order approximation is available. If we compare the value of mechanical energy lost by using turbine exhaust steam for process heat in a single stage process with the cost of geothermal fluid to provide the same heat, we can learn the conditions under which one or the other is clearly preferred and also the conditions under which a more detailed analysis is required to reach a decision.

The comparison depends on a number of variables. The most important are:

- process temperature,
- cost of geothermal fluid,
- temperature and phase of the geothermal fluid,

- value of electrical energy.

Of these, the process temperature is the best known. The cost and characteristics of the geothermal fluid are the least well known until developmental wells have been driven. The "value" of electrical energy varies with the mix of fuels used by the local electric utility and whether the process heat user is a net buyer or seller of electrical power.

Because of these uncertainties it is not possible to present a simple comparison of the competing costs. Instead we have prepared a family of curves which show the conditions favoring each heat source. These curves are "break-even" lines, along which the cost of turbine exhaust steam and geothermal fluid are the same (Figure 3).

To use Figure 3, plot a point corresponding to the process temperature, T_p , and the difference between the geothermal water temperature, T_g , and the process temperature. (We use the difference instead of the source temperature directly so that one curve will serve for many difference resource temperatures.) Then find the curve which corresponds to the appropriate ratio of cost to the user to buy electricity (P_{eu} in \$/kwh) and to provide geothermal water (P_g in $\$/10^6 \text{ lb.}$). If the plotted point is closer to the origin than the curve, exhaust steam is more attractive than geothermal fluid. Conversely, if the plotted point lies beyond the curve, geothermal water is more

Figure 3. Breakeven Curves for Geothermal Water vs. Cogeneration Exhaust for Process Heat. (power production cost equal to purchase price; electric power demand greater than cogeneration capability)

attractive.

These curves assume that the demand for electricity is greater than the amount produced (i.e., the user is a net buyer of electricity at the indicated price). We also consider only the case of geothermal water; geothermal steam is much more valuable. We also assume that the cost of the geothermal water is adequately represented by a cost per million pounds.

One cannot conclude from these curves that geothermal fluids are generally attractive or unattractive. It is obvious that high temperature, inexpensive fluids are more attractive than low temperature, expensive resources. Also, attractiveness of geothermal fluids (relative to cogeneration) increases with the value of the lost electrical energy. Thus, in regions where low price hydroelectric power is available, geothermal energy is relatively more attractive. This is illustrated by the similar figures 4 and 5. These show the breakeven curves when the ratio between the cost of produced power and purchased power is greater than one.

The primary reason why turbine exhaust steam is an attractive source of heat is the fact that steam cannot be allowed to condense in the turbine. Therefore, the latent heat of condensation is available for use as process heat, if the process temperature is low enough.

Figure 4. Breakeven Curves for Geothermal Water vs. Cogeneration Exhaust for Process Heat

(electric power production cost 1.25 times power purchase price; electric power demand greater than cogeneration capability)

Figure 5. Breakeven Curves for Geothermal Water vs. Cogeneration Exhaust for Process Heat

(electric power production cost 1.5 times power purchase price; electric power demand greater than cogeneration capability)

H. Management Decision Criteria

At first it appeared that geothermal fluids were a very attractive source of process heat. The simple comparison (Figure 1) of costs of geothermal and fossil fuel (oil) resources indicates that geothermal fluids should be attractive to large users of low temperature energy.

Also, two feasibility studies ([5] and [6]) have shown that geothermal fluids are an economically attractive source of energy for sugar refining and for paper making. In spite of these positive indications no great interest has been evidenced by pulp and paper companies or, for that matter, any other potential users.

In order to learn the reasons for this lack of interest and also to learn what criteria geothermal investments would have to meet, we reviewed decision making methods and criteria with the firms working with us on the project. These firms clearly separate the investments involved into two groups:

- geothermal resource exploration and development,
- geothermal resource utilization.

Geothermal field development is an unfamiliar area of activity for managers of pulp and paper companies. Therefore they approach investments in that area very differently from the way they approach pulp and paper plant investments. The use of geothermal fluids (steam and hot water) is an area with which they are quite familiar, and they are quite comfortable in the evaluation of

investments in the area.

The pulp and paper company managers were found to be reluctant to make investments in field development. They said they would not change their view even if the projected returns were very high. The available information does not convince them that the returns would be realized. If more convincing information were available on resource characteristics and cost they might seriously consider the proposition.

This does not appear to be the usual problem of uncertainty. Until these managers have a more convincing demonstration of resource quality they just are not going to be interested.

The investments required for resource utilization are small compared either to a paper mill or to geothermal field development. Paper company managers seem to be quite willing to invest in resource utilization once they know the resource characteristics.

We also learned that paper companies use several different methods for evaluation of capital investments of the type considered here. These methods include pay-back period, accounting rate of return, discounted cash flow and internal rate of return. Large investments are often measured by more than one of these methods.

None of the companies we contacted is treating

uncertainty or risk in any consistent fashion. Most prefer to wait or to undertake further investigation of one sort or another to reduce the uncertainty to the point that it becomes negligible. Some companies say that they require a higher return rate (or discount rate) for an uncertain investment (or one outside their normal business activity) to be acceptable. However, such investments would be analyzed individually with the evaluation methodology varying with the situation.

From this analysis we conclude that the lack of resource characteristics and cost information is an important barrier to utilization of geothermal energy in the pulp and paper industry. Until such information is available, no pulp and paper company is likely to consider seriously the possibility of locating a new plant to take advantage of such a resource. Also they will not plan to invest in field development in the absence of proven resources, nor will they invest in plant retrofitting to use geothermal resources until these resources are proven.

I. Analyses of Example Plants

From the cooperating firms we obtained general process flow diagrams showing energy use and steam flow. One of these was analyzed using the computer analysis program developed by Michael Packer, and the other was

analyzed by Higinio Guillamon-Duch using conventional engineering methods.

The computer system is, of course, much more powerful than manual methods. It allows interaction of the analyst with the analysis system to produce quickly the result of small changes in the energy cascading arrangements.

The basic idea of this program is to substitute geothermal energy for fossil energy in the plant system whenever doing so is feasible and apparently economic. Use of the program allows sorting out the very large number of possible ways of using geothermal energy in a relatively simple plant involving, for example, six or seven related and energy connected processes.

This analysis considered using the same potential geothermal resource as had already been considered by the company's plant engineers. It came to a very similar result in terms of amount and flow pattern for the geothermal fluid and also essentially the same result for expected return on investment in geothermal field development and resource utilization. However, it required only about two person days of computer assisted effort to arrive at the result.

This result gave us confidence that the computer analysis program is indeed useful for the preliminary

evaluation of geothermal resource application proposals. Also it showed us that the specific characteristics of the plant process flow and energy use plan must be considered in evaluating the economic desirability of geothermal energy in any proposed industrial process application. Finally, the returns on investment indicated by the proposed application, although reasonable, were not large enough to encourage an urgent effort to undertake the project.

The second application examined was also a pulp and paper plant. Here, also, the result was discouraging. Very little is known of the geothermal resource potential in the vicinity of the plant, so this situation was analyzed to determine the combinations of temperature and cost that geothermal resources would have to have to be reasonably attractive substitutes for the existing fossil fuel used to provide process heat.

The results were discouraging because the required combinations of temperature and cost seemed very unlikely in the vicinity of the plant. One of the reasons for this is the fact that the plant currently obtains much of the low temperature process heat it uses from turbine exhaust steam. The turbines are used to generate electricity used by the plant. By substituting geothermal energy for exhaust steam the plant must either cut its

electricity generation (and buy make up power) or throw away the displaced steam.

This plant analysis also illustrated the importance of considering the specific characteristics of a plant process flow and energy use in substituting geothermal for fossil fuel energy. It also indicated that in such an application the economics of geothermal energy substitution are not strongly favorable.

The third application examined was a food processing plant. This analysis was also done with the computerized support system described above. The results were essentially the same as those obtained in the two pulp and paper plant analyses:

- The computer analysis system quickly and cheaply obtains the same preliminary result as that obtained with several person weeks of engineering effort;
- The specific characteristics of each plant must be considered to determine the economic feasibility of using geothermal fluids as a source of process heat; and
- In competition with conventional energy sources geothermal water is not very attractive as a source of industrial process heat.

J. Optimal Cascading Systems

In the course of evaluating the use of geothermal energy in the example plants, the nature of the cascading question became clearer. This showed up first in the course of determining the conditions under which one should use exhaust steam from a turbine, driven by steam from a high pressure boiler, geothermal energy, or fossil fuel in a low pressure boiler to provide industrial process heat [7]. In that analysis we found that it is always preferable to use exhaust steam, rather than fossil fuel directly, as long as the industrial process to be heated is below the boiling temperature in the high pressure boiler. Another way of stating this condition is to say that turbine exhaust steam provides cheaper heat than a low pressure boiler as long as the steam can be condensed at or below the boiling temperature of the high pressure boiler. The latent heat of vaporization cannot be used for mechanical energy (except, perhaps, by using that heat to vaporize some other substance in a binary cycle system) and therefore is economically used for process heat. This conclusion rests on the assumption that there is an unlimited market for the electricity generated in the process. Of course, that may not always be the case.

Further, we have found that only the latent heat of

vaporization should be used as process heat. That is, exhaust steam should be taken from the turbine at the temperature of the process to be heated and condensed at that temperature. This maximizes the amount of electrical energy that can be obtained from the fossil fuel used under the constraint that the process must be maintained at a specified temperature.

As we have already seen, geothermal energy may be cheaper than either fossil fuel burned in a low pressure boiler or turbine exhaust steam (Figure 3). This happens when the geothermal fluids are low in cost and high in temperature and the cost of sacrificed electric power is high.

While these relationships could be worked out fairly readily for a single process, the problem becomes very complex when there are several processes. The effluent ("waste heat") from each process becomes a candidate to heat any lower temperature process. We have developed two ways of looking at this problem. One of these is a unit process algorithm which looks at all the technically feasible ways of heating each process, and selects that combination which minimizes the heat energy available in the effluents. The second is a mathematical programming system which minimizes the total cost of energy used while looking at all possible connections among processes.

Unit process algorithm.

Consider a unit process j which requires $\dot{Q}_j$ Btu per hour at some minimum temperature T_j (Figure 6). There may be several possible sources for that energy. They must be at a temperature higher than T_j in order for the heat transfer to be feasible. (The possibility that a lower temperature stream could be "up-graded" by heating with fossil fuel is included by providing a low pressure boiler as a potential source of energy.)

Each source has a characteristic cost. The cost of heat from a low pressure boiler is the cost of the fossil fuel burned; the cost of turbine exhaust steam is the value of the displaced electricity; the cost of geothermal fluid is specified per pound at the temperature of the source; the cost of effluents from higher temperature processes is taken equal to zero.

We rank all the processes from those requiring the highest temperature energy sources (the "hottest" processes) to those requiring the lowest temperatures. First, we satisfy the hottest process ($j=1$) with the least cost primary fluid. This will require some flow rate $\dot{m}_j$ and the fluid will exit with enthalpy h_j . This effluent is then available for lower temperature processes, $j>1$.

Now go on to process 2. Satisfy its needs in the same way, first using the effluent from process 1 if it

Figure 6. Diagram of the General Cascading Problem

is hot enough since it has zero cost. If that does not provide sufficient heat we go on to the least expensive primary fluid, noting that the cost of that fluid depends on the process temperature T_2 . Now we have (or may have) two effluents. These can be combined since their temperatures must be higher than any lower temperature process.

By proceeding in this way we take the maximum amount of enthalpy out of any fluid used, minimizing the rejected enthalpy at the end. The algorithm has been extended to the case in which some fluids are used up or contaminated by the process they heat.

Minimization of cost by linear programming.

The process just described can be programmed for a computer or we can use the available mathematical programming systems to provide the result in a simpler and more direct fashion.

Suppose there are I processes, labeled with a subscript i , $i = 1, 2, 3, \dots, I$. Suppose further there are J sources of energy labeled with a subscript j , $j = 1, 2, 3, \dots, J$. In general, these sources of energy include all the processes, since waste heat is available from each, plus primary sources of energy such as a high pressure boiler, a low pressure boiler and a geothermal source.

Each process i has a heat requirement $\dot{Q}_i$ at a minimum temperature T_i . Each source j has a cost c_{ij} per unit of mass flow $\dot{m}_{ij}$ to process i . The enthalpy drop Δh_{ij} in the stream to process i from source j is given by the characteristics of the two processes, and the total heat which that stream can provide to process i is

$$\dot{Q}_{ij} = \dot{m}_{ij} \Delta h_{ij}$$

The total heat required by process i is

$$\dot{Q}_i = \sum_{j=1}^J \dot{m}_{ij} \Delta h_{ij}$$

summing over all possible sources.

The total heat required by all processes is

$$\dot{Q} = \sum_{i=1}^I \dot{Q}_i$$

The cost of providing heat to the i -th process $C(\dot{Q}_i)$ is given by the sum of the costs of the streams flowing into the process

$$C(\dot{Q}_i) = \sum_{j=1}^J c_{ij} \dot{m}_{ij}$$

where the cost of the stream from source j is assumed to be proportional to the flow $\dot{m}_{ij}$. (A more general cost formulation can be used if needed to provide the desired level of accuracy in cost representation.)

We wish to minimize the total cost of providing heat to all processes:

$$\text{Minimize} \quad C(\dot{Q}) = \sum_{i=1}^I C(\dot{Q}_i) = \sum_{i=1}^I \sum_{j=1}^J c_{ij} \dot{m}_{ij}$$

$$\text{Subject to:} \quad \sum_{j=1}^J \dot{m}_{ij} \Delta h_{ij} = Q_i \quad \text{for all } i$$

$$\sum_{j=1}^J \dot{m}_{ij} - \sum_{k=1}^J \dot{m}_{ki} = 0 \quad \text{for all } i$$

and several logical and physical constraints.

The first constraint requires that the total heat needed by each process be provided by the sum of the enthalpy drops in each of the incoming streams. The second constraint is a mass balance equation which requires that the flow out of each process equal the flow into each process. The physical constraints are used to require that no heat flow from a cooler stream to a hotter process.

The set of mass flows $\dot{m}_{ij}$, which minimizes the total cost of supplying heat subject to the constraints, provides a description of the optimal cascading system. If one of the processes is a turbo-generator the value of the electricity generated should be included in the objective cost function. In this way the increasing cost of flows bled from the turbine show up directly as reductions in the amounts obtained from the sale of electricity. This is described further in Chapter 5.

This method is very simple to use. It employs standard linear programming solution software. Various

kinds of fixed costs can be included but usually such inclusion will require the use of mixed integer programming solution methods. This complicates the solution and its interpretation.

K. Areas of Potential Further Investigation

Competition with cogeneration.

The preliminary work we have done indicates that turbine exhaust steam is a very attractive source of low temperature process heat. The primary reason for this is the availability of the latent heat of vaporization of the steam used to drive the turbine. That energy must be put into the steam to drive the turbine but cannot be recovered in the turbine since steam must not be allowed to condense in the turbine.

Taking steam from the turbine at higher than ambient temperatures reduces the amount of power generated. This reduction is an opportunity cost which provides a convenient way to cost the steam used to drive an industrial process. Even if the process in question (or the entire plant) may not use enough electric power to make the generation of their own electric power attractive, recent Federal Energy Regulatory Commission (FERC) regulations require the existing electrical distribution system to buy such power at attractive rates. Thus, any large user

of process heat has the possibility of selling electric power to defray a substantial portion of its cost of process heat.

In order to determine the conditions (if any) under which geothermal energy is attractive for use as process heat further investigation of the competitive economics is needed. The comparison depends on the local market rates for electricity, for fossil fuel and the cost and characteristics of geothermal sources. The comparison also depends on the investment and operating cost of a cogeneration installation; these, in turn, probably depend on the size of the installation, the amount of process heat needed and the temperatures of the processes requiring the heat.

A great deal is known about the design and costs of turbines to provide electricity. The market rates for electricity in various parts of the country are also known. Very little is known about the costs or characteristics of geothermal energy in various parts of the country.

These facts suggest that an effective way to proceed is to develop a model (set of cost relationships) describing the value of geothermal energy of various characteristics in various parts of the country. This value model would be an important input to the exploration decisions. Clearly it is better to explore (*ceteris paribus*)

where the finding of the resource is more valuable. If geothermal energy is worthless in some area (at present and projected costs of fuel, electricity and cogeneration facilities) there is very little point in spending money looking for it. A model of the conditions under which geothermal fluids are valuable would be useful to the Department of Energy in planning its geothermal energy exploration program.

Value of exploration information.

The exploration for natural resources, especially mineral deposits such as oil and geothermal fluids, is a very uncertain venture. In the main, these ventures have been undertaken in the past because the rewards for success were so large. Thus, the venture was worthwhile even though the probability of success in any one exploratory well was fairly low.

In such explorations a number of options are available to the explorers. They can proceed directly with the large investment in a test well. If they are not sufficiently confident of success they may defer that large investment until they have made smaller investments in geological investigations or one sort or another. Starting with a surface geological survey they may conduct progressively more expensive tests, including seismic surveys, conductivity measurements, even shallow wells for heat

flow measurements, to obtain more information about the probable presence of valuable geothermal resources.

This information may not always be worth what it costs to obtain. Techniques of decision theory have been used in other mineral exploration fields, including oil, to assist in estimating the value of further test information prior to undertaking a major investment such as geothermal field development. The basic notion of such an analysis is that further test information costs money but reduces the probability of making an expensive error. Such a technique should be useful to the Department of Energy in determining when further exploratory testing is worthwhile before geothermal test well drilling.

To use such a technique one must have a good estimate of the value of the resource if it is found. In the case of geothermal energy, the value of the resource depends on the resource characteristics which are, in advance of drilling test wells, known only as probability distributions. Thus, the value of the resource must be estimated using those distributions. Additional exploratory data are useful only because it changes our estimates of these probability distributions. These additional data have value only to this extent.

Our investigations thus far have provided clear evidence that the value of any geothermal resource depends

strongly on

- resource characteristics (cost, temperature, phase, flow rate), and
- application characteristics (process temperature, energy required, cascading opportunities).

Thus, to evaluate the worth of additional information we must process a large amount of data in a rather complex structure. The computer analysis system which we have developed is well suited to this task. A fruitful further area of investigation is the development of an evaluation system, using the computer aided analysis system we have in support of this, to determine the expected benefit from further exploration and testing efforts in a specific area. This should be helpful to the Department of Energy and to field developers in determining the best sites for further geothermal exploration and development.

General analysis of energy cascading.

The initial analysis of the "cost" of exhaust steam available from turbines used to provide mechanical (or electrical) energy provided valuable insight into the way in which "waste" heat from any process can be used to drive another process at a lower temperature. Bora Mikic and Higinio Guillamon-Duch have developed a general model of energy cascading which can be used to minimize the

cost of providing energy to drive a set of processes at various temperatures and with varying energy requirements. This scheme is described further in Chapter 4. While it can be used for any complex set of processes in a plant with several sources of energy, its application becomes difficult if the number of processes is more than four or five.

The mathematical programming method described in Chapter 5 provides a much more general approach to the problem. Such a system is well suited to the analysis of plants with large numbers of processes and with several potential energy sources. It is also well suited to the parametric study of the effects of variation of values of uncertain variables.

It should be possible to develop a general analysis tool which could be applied routinely by manufacturing engineers in developing the energy cascade in complex plants. Several examples are given in reference [9]. A single example is given in Chapter 5.

To make such a tool most useful systems are needed to describe specific plant configurations in the terms needed for input to the mathematical programming system. This includes development of all the logical, physical and thermodynamic constraints. Also it would be desirable to have available systems for displaying the results of the

analysis. In particular, graphic display of the resulting flows might be a very useful tool in analyzing and interpreting the results.

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CHAPTER 2. SURVEY OF LITERATURE

The LMP/MRP Report No. 80-09, [1] deals with detailed evaluation of the literature concerned with direct application of geothermal energy as industrial process heat. The purpose of the survey was to review some of the more important early reports dealing with industrial applications. By conducting a critical survey of the literature, it is hoped that a perspective can be established that would aid in understanding the subject and give direction to future work.

All reports reviewed were released in 1977 or earlier. The DSS Engineers report [2], done for NASA under the guidance of The Lawrence Livermore Laboratory, is perhaps the first major report to deal with industrial process heat applications of geothermal energy. TRW's report [3], released almost two years later, is more thorough though its' scope is more restricted. The Bechtel report [4] is less detailed and less significant than the two mentioned above. GEOCOST, Battelle's computer code [5] is also reviewed, because a computer code that models geothermal use in industry would find one half of GEOCOST useful.

DSS Report

This report makes a detailed analysis of the possibility of using geopressured thermal resources in the pulp, paper and cane sugar industries along the Northern Gulf of

Mexico Coast. It also briefly surveys a few other industries like petroleum refining and industrial chemicals.

The major task consists of developing and modifying process designs for the three cases: an existing plant, a conventional or "typical" plant and a "new" plant. For the first two cases, the maximum use of geopressure energy possible with minimum additional equipment is considered. For the "new" plant, flow diagrams are developed so that the use of geothermal energy is maximized. Using this approach for a pulp and paper mill, with a geothermal fluid temperature of 250°F (120°C), 8.4% of the gross energy requirements of an existing plant can be met by geopressure resources. The corresponding figure for "typical" and "new" plants is 15.6% and 31.1% respectively. The energy requirements that can be met in existing, "typical", and "new" sugar refineries are more dramatic: 27%, 37% and 80% respectively. In all of the above cases, using geothermal energy directly as process heat increases the demand for purchased electricity.

The economics of the entire geothermal energy system is presented. Based on mid-1974 costs, all equipment is amortized at 8% interest over 20 years, giving a fixed annual capital cost charge of 11.8%. Operation and maintenance costs are taken as 5% of initial capital costs per year. The cost of geoenergy fluid at the surface is

directly proportional to the cost of the supply well and varies from 3.2¢/barrel¹ (0.51¢/m³) for a 13000 ft. (3960 m.) well to 7.5¢/bbl (1.2¢/m³) for a 18000 ft (5490 m.) deep well. Waste disposal costs 1.0¢/bbl (0.16¢/m³) for 40000 bbl/day (251700 m³/day). Costs to process the gas are between 5¢/MCF (0.2¢/m³) and 10¢/MCF (0.35¢/m³). The cost of geothermal fluid, subtracting the value of electricity generated because of pressure energy and gas extracted, is only 0.89¢/bbl (0.14¢/m³) for the typical case. The disposal temperature is important because the available thermal energy depends on it. The value of this energy more than doubles from 2.63¢/bbl (0.42¢/m³) to 5.79¢/bbl (0.94¢/m³) when the disposal temperature is lowered from 200°F (93°C) to 140°F (60°C).

The report concludes that the recovery of thermal energy for process use is economical in pulp and paper mills but not economical in raw sugar mills because they are operated only 3 months of the year. These conclusions cannot be generalized since the whole analysis was limited to one site with a specific well depth, flow rate, fluid supply temperature and fluid disposal temperature.

TRW Report

This report [3] examines the feasibility of using low grade geothermal energy (below 300°F or 150°C) in new and retrofit beet sugar factories. It does this by looking at

one representative plant - the Holly Sugar factory at Brawley, California - in considerable detail. First, it provides a description of the process, presenting flow diagrams, steam balances, thermal energy demands, mechanical power demands and non-process heat demands. The Holly Sugar factory at Brawley has been chosen for this analysis because it has process flows representative of beet sugar factories, it is located near the Brawley KGRA¹ (tested production wells within 8 miles of the plant), and has available nearby the DOE (previously ERDA) East Mesa Geothermal Component Test Facility for demonstration experiments.

The report then looks at geothermal resources and at the location of beet sugar factories to see if and where matching occurs. Thirty-five of fifty-five beet sugar factories are located in the eleven western states where hydrothermal resources are known to be present. New plants can feasibly use geothermal energy if they are located approximately within 100 miles of beet growing areas. The most promising places for geothermal use in order of potential appear to be: The Imperial Valley in California; southwest Idaho; southeast Idaho; northern California; southern Arizona and central Washington.

The third section looks at alternate sugar refining systems, alternate pulp drying schemes, alternate energy

supply system concepts and then applies them to conceptualize a retrofit Brawley plant.

Considering the retrofit potential of eleven other sites, it is concluded that 15 to 35% of process steam for sugar refining can be met by geothermal resources.

In the Holly Sugar - Brawley plant, about 34% of process steam demand could potentially be met by geothermally generated steam. This saturated process steam is medium pressure - about 270°F (130°C). A geothermal boiler, optimally selected so that the brine flow rate is lowest and temperature drop highest, is designed to supply the needed steam. The wells are an order of magnitude more costly than the boiler. A total of sixteen pulp dryers fueled by geothermal energy are needed to replace the three existing fossil fuel units. In the lower temperature geothermal units, the pulp flow rate has to be reduced by a ratio of five to six and the required dwell of the pulp in the dryer has to be increased by a factor of four to five. Geothermal fluid from the boiler can be cascaded to beet pulp dryers and used in the main heating coils. The potential reduction in the demand for fuel oil is approximately 65% for the retrofit case and 86% for a new factory.

Section Four develops capital, operating and maintenance cost charges to arrive at a unit price of geothermal energy that can be compared to the unit price of fossil fuel energy. An annual fixed charge rate of 21.6% is arrived at. It is estimated that a typical 6000 tons/day beet sugar mill has a capital cost of \$64 million. The capital cost of the energy supply system, which includes production and injection wells, pumps, cost of acquiring land, surface exploration and environmental impacts, is estimated at \$940000 per 1000 gpm ($230 \text{ m}^3/\text{hr}$). Looking at the Brawley plant, it is calculated that cascading is the most economical way to use geothermal resources.

The cost comparison based on the projected price for fossil fuels and geothermal fluids has revealed the following:

- a) Cascaded 300°F (105°C) geothermal is not competitive with fossil fuels (excluding coal) until around 1986.
- b) Cascaded 350°F (180°C) geothermal is not competitive until about 1981.
- c) Cascaded 300°F (150°C) geothermal with off-season use is competitive with natural gas, LNG and RFO (residual fuel oil) almost immediately and with coal after 1986.

- d) Cascaded 350°F (180°C) geothermal brine with off-season use is competitive with all fuels immediately.

The report assesses the environmental impacts of using geothermal energy. Seven main areas of concern are identified: subsidence; seismicity; atmospheric impacts; hydrological impacts; noise; erosion and landslides; and aesthetic impacts.

The report also considers the possible effects of technological and institutional changes on geothermal use. It looks at four factors: The Geothermal Loan Guaranty Program; tax policy; technology improvements; and environmental and administrative regulations and constraints.

Overall, the report represents a very detailed study of geothermal potential in the beet-sugar industry. Its scope is very wide, covering everything from process description and resource location to process modification and environmental considerations. The strong points of this report are its sections on modified process designs, environmental impacts and policy and market considerations.

Bechtel Report

The report [4] examines the technical and economic feasibility of using low temperature geothermal water in the vaporation and crystallization industry. Three specific industries - preserved fruits and vegetables, sugar

and confectionary products and chemical industries - were chosen for detailed study. Three processes are selected from the candidate industries. They are: tomato paste production beet sugar production and sodium chloride production.

The next report examines process designs and modifications needed to use geothermal energy. For each process selected, an economic analysis is performed. For tomato paste production it is concluded that because of a limited operation schedule (typically 70 days per year) plant retrofit for use of geothermal fluid is not economical. The same conclusion holds for production of beet sugar. For sodium chloride production, which is chosen as a representative process from the chemical industry, it was shown that both a retrofit plant and a new plant have encouraging economic prospects.

The final section of the report identifies five main areas of concern related to implementation of geothermal energy in evaporation and crystallization industry. They are: accurate definition of resources; information dissemination to industry; information transfer to developers of geothermal resources; research and development work on the feed-and-bleed process; and a demonstration project in the evaporation and crystallization industry.

Review of "GEOCOST"

GEOCOST is a computer code that analyzes geothermal energy use as a source for electric power generation. It models the geothermal reservoir and the power plant as distinct components. The reservoir model, which includes fluid transmission and disposal, can be used to generate cost figures for geothermal fluid. These cost relations can then be used as inputs for a program that models industrial process heat substitution.

The report is divided in the following main sections: fluid transmission and disposal submodel; reservoir economic submodel; plant technical and economic submodel; and a routine that controls the iteration between plant and reservoir.

GEOCOST is a very detailed code that incorporates, to a very high degree, the current knowledge about geothermal energy systems (reservoirs, transmission and disposal systems, geothermally-fueled power plants). It is quite flexible, allowing a variety of configurations in designing the system. It is designed in a modular fashion, with 63 subroutines. Besides the program, the 1967 ASME Steam Tables, comprised of 63 subroutines, are used. GEOCOST consists of 8000 FORTRAN statements and the Steam Tables of 4000 statements. The program requires a large amount of

memory, but being essentially an input-output program it does not require large amounts of time to execute. It could be made much more efficient by cutting down on those iterations that are used for obtaining unnecessary accuracy. It could also be made more compact by combining some sub-routines, especially those that are not called more than a single time and do not function as independent units. Quite often, common declarations require more cards than executable statements.

The utility of GEOCOST in the context of industrial applications of geothermal energy lies in the fact that the reservoir model can be decoupled from the power plant model and linked instead to an industrial plant model. The reservoir model can, instead, be used to obtain a curve of geothermal costs vs. amount of flow.

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CHAPTER 3 - HEURISTIC COMPUTER SIMULATION METHODOLOGY

A. Introduction to the Model

A compact computer program has been developed which enables the analyst to evaluate quickly the potential of a specific proposed industrial process heat application of geothermal energy.¹ The program addresses the problem of matching process energy demands with geothermal and auxiliary fossil fuel energy supplies. It analyzes the interrelationships of three factors: utilizing more low quality geothermal fluid, burning less fossil fuel, and changing the size of process equipment.

The computer model attempts to optimize the use of geothermal fluids to the maximum extent possible. In connection with this goal, it is important to note some distinguishing facts about the utilization of geothermal energy sources.

Two different methods are available to develop a geothermal field: direct investment by the interested user and development by a second party who then sells fluid at "arm's length" to the user. In the first case, the cost to the user usually is concentrated at the outset, with charges mainly for pumping costs and no explicit cost for fluid. In the second, no initial charges are incurred, but the user must pay for the fluid itself over the lifetime of the project.

In either situation, the costs of field development are essentially fixed by the number of wells drilled. Once a well has been drilled, extracting fluid at a somewhat higher flow rate may add little to the overall cost of the field. To lower the cost per kilogram of fluid produced, it is therefore advantageous to utilize the maximum flow rate attainable from the wells drilled that is consistent with an appropriate level of drawdown in the well. However, if the fluid temperature drops significantly as the flow rate increases, the drop in energy available from each kilogram of fluid may offset the lower cost. Similarly, if pumping costs rise quickly as the flow rate increases, a flow rate less than maximum may be optimal. In either case, once a flow rate has been chosen, the cost of fluid per unit mass will then be fixed.

This phenomenon distinguishes geothermal energy from alternative sources of energy. The price of oil or gas is frequently quoted on a "per kJ" or "per Btu" basis. For geothermal energy, this price would be undefined: the cost per unit energy of geothermal energy depends upon the amount of energy extracted from each kilogram of fluid. It is therefore desirable to maximize the drop in enthalpy of the fluid in order to obtain the most energy per dollar. To attain this objective, the fluid must be cooled to as low a temperature as possible by transferring heat to an even colder material.

This principle of extracting as much heat as possible from the geothermal fluid underlies the design of the energy supply and demand matching procedure used in the computer model. The output of the section of the computer program dealing with this procedure consists of figures for the amount of geothermal fluid used, for the quantity of auxiliary fossil fuel needed, and for the size of each piece of unit process equipment required. These figures then form the basis of the economic analysis to follow.

B. The Computer Program

The GEOTHM computer model developed in the course of this research is designed to aid in the evaluation of the technical and economic feasibility of geothermal process heat applications.

The computer program is designed to be well-documented, self-contained, and compact. The user's manual should enable a typical user to learn how to operate the program in one to three days. While other computer codes in the geothermal field frequently require that the user provide supplementary computer software such as steam tables, the present model is a self-contained package which incorporates sorting routines, steam tables, and other necessary software. Nevertheless, the program is compact, requiring less than 2600 lines of code including all program comments. Written in basic FORTRAN without extensions, it runs on a minicomputer in one to one and a half seconds. The program is in the public domain.

i. Methodology

Two modes of operation are available. The first, called the automatic matching mode, is illustrated schematically in Fig. 3-1. The second, designated the manual matching mode, is shown in Fig. 3-2. Detailed flow charts are given in Reference 1.

The objective of the automatic matching mode is the matching of geothermal and conventional energy supplies with the energy demands of industrial processes. The program attempts

to optimize the manner in which processes use energy by utilizing heuristic rules to select the most advantageous configuration of the system (i.e. which fluid flows should serve which heat exchangers; in what situations cascading of fluid streams should be employed, etc.). All process energy needs are satisfied either through use of geothermal fluid alone or, if necessary, by employing auxiliary fossil fuel. As this matching operation is performed, the program stores information concerning the heat exchangers, pumps, and compressors that were required to satisfy process energy needs.

The matching procedure is executed twice: once for a conventional base-line system (using no geothermal fluid) and once for the geothermal system.

FIGURE 3-1 - SCHEMATIC OF AUTOMATIC MATCHING MODE OF OPERATION

FIGURE 3-2 - SCHEMATIC OF MANUAL MATCHING MODE OF OPERATION

Finally, the program performs a full economic comparison of the two systems, including such considerations as the debt structure of the firm, tax incentives available to geothermal producers, depreciation schedules, and full cash flows. The economic model is discussed further in Chapter 4 of Reference 1.

In the second mode of operation (manual matching mode), the user must supply data concerning the technical results of matching energy supplies and demands. This information (which includes the quantity of fossil fuel used and the number and size of auxiliary equipment employed) then forms the basis for the economic comparison.

ii. Capabilities

The program can be used in the automatic matching mode as a design tool to investigate the potential for geothermal energy in process heat applications. However, the human operator retains considerable control over the computer through his ability to change input data and to alter the settings of decision variables. This degree of control permits substantial interaction between the operator and the program. It is also the key to the flexibility of the program. Such interaction may occur either off-line with a batch-type computer facility or on-line if a time sharing facility is available: with only slight modification, the program can be operated in either mode.

While the program optimizes the use of geothermal energy to a certain extent, human judgment and interaction with the program frequently permit further improvement. This feature of

the program has been retained intentionally to enable managers to understand the process by which results are obtained and to provide them the opportunity to ask the specific questions to which they desire answers.

Some of the capabilities of the automatic matching mode of operation are listed in Table 3-1.

The program can be used in the manual matching mode of operation to evaluate the feasibility of a proposed project by entering the design of the system (as determined by other means) as input into the economic analysis. Furthermore, this mode can be employed to investigate the sensitivity of the overall economics to changes in economic assumptions (e.g. in equipment costs, inflation estimates, etc.).

iii. Required data for operation

For operation in the automatic matching mode, required input includes: geothermal resource characteristics at plant entrance (temperature, pressure, etc.), process application characteristics (required fluid flow rates

The computer program allows for:

1. Input streams of any phase (liquid, steam, or mixture)
2. Choice of flashing pressurized water
3. Choice of separating two-phase streams to liquid and vapour components
4. Auxiliary heating of input streams to meet process requirements
5. Compression of steam in stages with desuperheating
6. Considerations of requirements for electricity as well as for process heat
7. Processes requiring clean fluid or geothermal brine; direct injection of fluid or heat exchange from fluid, etc.
8. Computation of changes in equipment size necessary for the change to geothermal fluid
9. Cascading: use of fluid streams exiting from one process as input to another.

TABLE 3-1 - CAPABILITIES OF THE AUTOMATIC MATCHING MODE

process energy needs, etc.), economic data (fossil fuel prices, well costs, tax rates, etc.), and a small number of decision variables which control the matching procedure. Output then consists of auxiliary equipment required (pumps, heat exchangers, etc.), fossil fuel and electrical energy consumption, and the resulting cash flows, rates of return, and payback periods. A full description of the necessary input is given in Appendix D of Reference 1.

For operation in the manual matching mode, input must include the economic data mentioned above, a list of auxiliary equipment necessary for the application under consideration, and auxiliary fuel consumption figures. Output consists of the cash flow and profitability measures mentioned above.

Any variable for which an exact value is not available may be left as a free parameter. For example, the geothermal resource temperature may be varied in the input to determine the temperature at which the application investigated would become economical.

iv. Advantages

The program possesses many advantages over previous computer models. First, it is well-documented and transportable; a potential user need not fear months of effort merely to make the program operational. Second, it is self-contained; additional software is not needed. Third, it is flexible; the discussion above hopefully highlights a few of the possible types of questions it can address.

C. The Economic Analysis

Economic conclusions are of foremost importance to decision-makers. An attempt has therefore been made in the program documentation to state explicitly all assumptions made in the course of developing the economic model.

Cost engineers divide investment estimates and economic analyses into five categories: order of magnitude, study, preliminary, definitive, and detailed. The present analysis would be termed a rough "study" estimate, with an accuracy of $\pm 25\%$ - 30% . Project authorization is usually given on the basis of a preliminary-type estimate with an accuracy of $\pm 12\%$: this estimate typically would cost approximately \$100,000 for a \$30 million project.² The purpose of the entire methodology developed here is to ascertain whether procuring this preliminary estimate is worthwhile and then to assist in the final decision-making process.

Many of the features included in the economic model presented below are somewhat superfluous, given the inaccuracies and uncertainties in more critical parameters. These options have been retained nonetheless for three reasons. First, their presence allows questions of public policy (e.g. appropriate tax incentives) to be addressed. Second, they permit performance of a more complete sensitivity analysis. Finally, their inclusion lends flexibility to the model and may help to answer the criticism of inflexibility that is often directed at cash-flow analyses.

D. Two Applications of the Methodology

Two direct-use geothermal applications are analyzed in the following pages with the aid of the computer model described in previous sections.

i. Retrofit of a Pulp and Paper Mill - Example 1

As a part of this research, several industrial firms provided data from their plants for analysis using the computer program. The data included energy costs, projected inflation rates, taxes, and other economic figures as well as steam flow drawings and technical data relating to present facilities.

The following analysis employs data furnished by a firm engaged in pulp and paper manufacturing. Pursuant to an agreement concerning confidentiality of data, firm-specific and location-specific information has been omitted from the following discussion.

General approach

For this analysis, the manual matching mode of the program is used. As was discussed above, the geothermal fluid must be cooled to as low as temperature as possible in order to maximize the quantity of heat extracted per dollar of fluid. The analysis thus begins by identifying the coldest temperature indicated on the facility steam flow diagram: the fluid at 15.6°C entering the boiler deaerators from the demineralized water storage tanks. Since deaerators operate at saturation temperatures, this fluid must be heated a substantial amount by hot steam. Clearly, replacing some of the steam heat with geothermal

heat would reduce the demand for steam and thus for fossil fuel.

Results

The most striking feature of the proposed system is the substantial reduction calculated by the program in usage of steam derived from fossil fuel: 35,650 kg/hr (78,600 lbm/hr). The geothermal system evidently saves at least this much steam. Approximately 8,000 kg/hr of additional steam savings, which result from balancing the flow between the fossil fuel boilers and the low pressure deaerator, are not included in the analysis. Fossil fuel savings thus are understated by roughly 18%. Neglecting this, approximately 25 MW(th) or 86 million Btu/hr of fossil fuel savings are realized.

Figure 3-3 displays the relationships among fossil fuel costs, geothermal fluid temperature at the plant entrance, and rate of return on investment. It must be noted that the internal rate of return ("IRR") refers to the entire cash investment and not merely to shareholders' equity.

Conclusions

The proposed geothermal preheater for the boiler deaerator under examination should be considered carefully as more information about the potential of local geothermal resources surfaces. Governmental cost-sharing might raise prospective rates of return substantially while reducing the risk to the firm.

ii. Retrofit of a Food-Processing Plant - Example 2

In November 1977, a subsidiary of H. J. Heinz Company, Ore-Ida Foods, submitted a proposal for federal cost-sharing in

FIGURE 3-3 - INTERNAL RATE OF RETURN AS A FUNCTION OF FOSSIL FUEL COST AND GEOTHERMAL FLUID TEMPERATURE - EXAMPLE 1

a geothermal retrofit of their potato-processing facility in Ontario, Idaho. The data contained in the proposal (which was subsequently approved) are sufficient for the application of the present computer methodology.

An analysis of the Ore-Ida facility using the methodology developed here serves two purposes. First, such an analysis provides a check upon the validity of the methodology: if the computer results were to differ significantly from those determined manually by the authors of the proposal, some doubt would be cast upon the methodology. Second, agreement between the results of the computer analysis and those of the proposal indicates that the computer methodology could be of value in the evaluation of future cost-sharing proposals submitted to the government.

General approach and assumptions

For this analysis, the automatic matching mode of the program is used. The characteristics of the seven processes indicated on the process flow sheet in the proposal are entered as input to the program along with values for economic variables and geothermal resource parameters. As far as is possible, the data used in the present analysis correspond to that used by Ore-Ida in the preparation of its proposal.

Results

Several features of the system arrived at by the automatic computer methodology should be noted. First, the geothermal fluid is reduced in temperature to an average of 53°C , approximately the same figure as given in the proposal. Second, the system designed by the computer utilizes seven heat exchangers

while the system shown in the proposal employs eleven. However, the computer required use of a small fossil fuel heater which was unnecessary in the proposal. Third, the computer succeeded in cascading geothermal fluid through a series of heat exchangers: one geothermal stream passes through three heat exchangers and one unit process before reinjection.

The economic results calculated by the computer closely parallel the figures given in Ore-Ida's proposal. The computer program overestimates the cost of retrofitting the plant (primarily due to the cost of the extra fossil burner) by 12%, well within the margin of error of 25% discussed previously. It should be noted that the program utilizes fewer heat exchangers yet estimates a somewhat higher cost. However, since the retrofit costs amount to 23.6% of the total cost of the geothermal system, the program overestimates system cost by only 2.6%. The most important figure for managerial decision-makers, the internal rate of return on the investment, was overestimated by only 0.6% (computer = 19.7%; Ore-Ida proposal = 19.6%). The economic analysis performed by the computer was comparable to that of the proposal in every respect save one: the former used the sum-of-years'-digits method of calculating depreciation, while the latter employed the double-declining balance method. This divergence has little effect upon the results.

Conclusions

The close agreement between the economic and technical results found by the present methodology and those contained in

Ore-Ida's proposal indicates that the computer program achieves, at least in this case, its goal of quickly and accurately analyzing the potential for geothermal energy in industrial process heat applications. Such agreement also points to the possibility of using the methodology as an evaluative tool in the assessment of new cost-sharing proposals submitted to governmental agencies.

E. Conclusion

The computer program described above is intended to provide a quick and accurate analysis of the use of geothermal energy in industrial process heat applications. It can be operated either as a design analysis tool to match energy supplies and demands, or as an economic analysis tool if a particular facility design has already been selected.

Two examples employing the computer model are presented in previous sections. In the first, the program is used to analyze the economics of a proposed geothermal application. The interactive feature of the model is used to perform a sensitivity analysis that outlines the economic conditions under which the application is profitable. In the second example, the program is employed as a design tool to automatically match process energy needs with geothermal energy supplies. Data are taken from a proposal for federal financial aid in constructing a geothermal facility. The technical and economic results yielded by the program closely parallel those found by the authors of the proposal using conventional design techniques. This correspondence attests to the validity of the computer model.

As the prices of conventional sources of energy continue to rise, geothermal resources will attract greater attention on the part of governmental policy-makers and industrial managers. These decision-makers will require the aid of analytical tools in evaluating the potential of geothermal energy. It is hoped that the present computer model will furnish such a tool.

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CHAPTER 4. SIMPLIFIED ALGORITHM FOR STREAM SELECTION PROCESS

In geothermal energy applications the hot fluid characteristics depend on the resource and the designer does not enjoy the freedom of choosing them, furthermore, the cost of geothermal fluids is by and large that of extraction and hence is a cost per unit of mass, the cost of heat depending on how much the fluid can be cooled before rejection. Consequently, good economic performance implies minimization of the mass flow, i.e., cascading.

The problem of finding and evaluating optimal thermal designs gets further compounded by the fact that there are usually several sources for providing the process heat that can be used in conjunction or alternatively. However, in those situations where no change in the production process are considered the problem can be formulated and solved by a simple procedure. We will assume that in geothermal applications fluid costs dominate the equipment costs, so that optimal designs are solutions where all fluid streams are cooled as much as technically feasible. That means that the hot fluid should always be cascaded from hotter to cooler processes.

In what follows the entire industrial operation being studied is assumed to be decomposed in elementary heat transfer operations that we will call unit processes.

Every elementary process will be designated by an index, i , $i=1,2,\dots$, and every stream by m_{ij} , representing the mass flow after process i of stream j .

The enthalpy and remaining characteristics of the stream are those determined by T_i , the temperature of the unit process and the changes experienced there. At the start, primary streams have the characteristics of the source generating them (cooler, geothermal field, turbine, etc).

The procedure

Given an industrial task consisting of $i = 1, 2, \dots, I$ unit processes with heat demands Q_i and temperatures T_i , the processes are classified by decreasing temperature in two categories, those whose effluent streams are re-usable, Group I, and those whose hot streams are either lost or rejected, Group II. The total energy used for the whole operation, H_T , consists of the sum of Q_i plus effluent energies after all processes, which we will divide into those coming from Group I (H_I) and those coming from Group II (H_{II}). Then,

$$H_T = \sum_{i=1}^I Q_i + H_I + H_{II}$$

Since $\sum Q_i$ is fixed (given), the optimum choice (within the assumptions of this procedure) is the one which minimizes the quantity of $H_I + H_{II}$. In the following we will describe an algorithm to achieve this goal.

1. Start with the Group I with processes ordered according to the process temperatures. Begin with the hottest process (1), satisfy this with the least expensive primary source, i.e., provide $Q_1 = m_{1,1}(h_p - h_1)$. $m_{1,1}$ is the mass of fluid from the primary source p with enthalpy h_p which is used to satisfy process 1. The enthalpy of the exhaust stream is h_1 , and the total effluent energy is $m_{1,1} h_1$. We proceed by looking in the

next hottest process, say process 2 (here we assume that the first two hottest processes have useful effluent streams). If $m_{1,1}(h_1-h_2)$ is larger than Q_2 we can supply the whole demand for process 2 from the effluent stream after process 1. This will be done by splitting the effluent mass $m_{1,1}$ to create a new stream which will just satisfy the energy demand for process 2, i.e.

$$m_{2,2} (h_1-h_2) = Q_2$$

and $m_{2,2} + m_{2,1} = m_{1,1}$. The energy left after process 1 in this case is

$$m_{2,2} h_2 + m_{2,1} h_1$$

If, on the other hand

$$m_{1,1} (h_1-h_2) < Q_2$$

the total energy demand for process 2 has to be satisfied from the effluent stream left after process 1, plus newly created primary stream of mass $m_{1,2}$ where

$$m_{1,2} (h_p-h_2) + m_{1,1} (h_1-h_2) = Q_2$$

After process 2 there will be - in this case - effluent energy left

$$m_{2,2} h_2, \text{ where } m_{2,2} = m_{1,1} + m_{1,2}$$

We proceed in this manner going to the next process, first trying to use the effluent stream(s) contained after the previous process. If this is not enough, we create a primary stream to complete the energy requirements. It is important to notice that if at the end of a process there are more than a single stream left this would mean that the energy available in the effluent stream(s) after the previous process was larger than the requirement for the process considered. If, on the other hand, there is only one stream left at the end of a process, then either the available effluent stream(s) after the last process were just enough to satisfy the energy demand, or a new primary stream was created to supplement the energy available from the effluents. Thus, if

$$Q_k < \sum_j m_{k-1,j} \cdot h_j$$

there would be more than a single effluent stream after process k.

If

$$Q_k \geq \sum_j m_{k-1,j} \cdot h_j$$

there would only be one effluent stream left after process k with energy $m_{k,k} \cdot h_k$. The outlined procedure is carried out until the last process (say n) in Group I is satisfied.

To summarize:

- i) A primary fluid stream will be added to satisfy process heat demand for a specific process at T_i only if streams coming out from processes at higher process temperature could not satisfy the total energy demand for this process.
- ii) Conversely, if primary supply stream had to be added - all existing streams before the process considered are used in this process

and they will come out at enthalpy corresponding to the process temp. T_i . The total flow out ($m_{k,k}$ is the sum of all secondary streams plus the amount of primary fluid added to the process.

iii) This procedure assumes mixing of streams which are used in each process.

2. a) If after process n there is only one effluent stream left (with energy $H_n = m_{n,n} \cdot h_n$) no further improvement of the Group I supply can be made. We move to Group II, the group consisting of processes which have no re-useable effluents. Let the last process in Group I have temperature T_n . We seek, in Group II, a process whose temperature is just below T_n . If there is no such process, we will supply all the energy demands for all processes in this group from the least expensive primary streams. If, however, there are processes with respective process temperatures below T_n , we take the one with the highest process temperature (still below T_n), say T_ℓ , and compare H_n with Q_ℓ . If $Q_\ell > H_n$, we use all H_n and add a primary stream to satisfy Q_ℓ . If $Q_\ell < H_n$, we will use only the necessary amount of effluent energy in the ℓ -process and the rest in $\ell + 1$, (the next lower temperature).

2. b) If after process n there is more than a single effluent stream, then there is a chance to improve on the heat supply in Group I. The procedure for this case is as follows.

Looking from the lowest process temperature going up, find, in Group I, the first process after which there was only one effluent stream. We may conclude that for all processes above this one, no improvement is possible. The rest of the system should be re-examined again. Let the process temperature for this process be T_k . If in Group II there is no process below T_k - no improvement is possible.

Group I should be taken as calculated in Section 1. If this is not the case, then we take the process from Group II with the highest temperature still below T_k , say temperature T_ℓ , and insert it in Group I in its appropriate place: the process from Group I above it should have temperatures higher than T_ℓ and the process just below it - lower temperature. We proceed with re-evaluation of Group I starting with the inserted process ℓ (all above it remains unchanged). After process ℓ , taking care to reject effluent streams from it, (i.e. not to make it available for further cascading), we proceed as in Section 1 until we reach the end of the group. At this point, we repeat the procedure outlined starting with 2a. The outlined procedure would minimize the energy use for the whole operation.

The method described in this section should be viewed clearly as the first approximation intended only to give a rough estimate on the economics of energy use. The method does not address the equipment cost issue, effect of mass flow on the cost of most energy of primary streams, and it does not provide any direct connection between the process heat demand and electrical energy requirements for a given industrial operation. Consequently, the user should be aware of these limitations before extending the findings obtained by the methodology outlined in this section.

CHAPTER 5. CASCADING BY LINEAR PROGRAMMING

A. General Approach

The evaluation of the potential of geothermal energy should be made under the most economically efficient process configuration. In Chapter 3 we assumed that these process designs could be found. Chapter 4 presents a heuristic which should assist in finding these optimal designs. This chapter presents a simple formulation of the problem in terms of a mathematical program that can be solved by standard optimization techniques. The use of such a method should assure that optimal or near optimal process designs are used for the evaluation of geothermal fluid potential.

To implement the mathematical programming approach, an industrial process is divided into elementary heat transfer operations, henceforth called tasks. Assuming that the production process, that is, the way raw materials are converted into the final product, is not changed and that only the powering of the process is to be redesigned, the heat demand for each task and the conditions under which this heat must be supplied are known.

Also known are the thermodynamic and chemical properties of the energy transmission fluids, hot streams.

More explicitly, assume a process consisting of I tasks designated i , $i = 1, 2, 3, \dots, I$; that can be powered

by J hot streams designated j , $j = 1, 2, 3, \dots, J$. Some of these streams are primary streams, that is, fluid coming directly from the primary energy sources, boilers or geothermal field. It is easier to see this in an example; one is given in Figure 5.1. In it the primary streams are those originating at the hydrothermal well, labeled G , or at the boilers, labeled L for low pressure and H for high pressure. The rest of the streams are called secondary and they consist of fluid already cascaded through at least another operation and/or a turbine.

The heat demand rate Q_i of task i , as well as other conditions, such as temperatures, phases, products, etc., are known. Also known are the properties of the J hot streams before entering operation i .

If the total heat demand rate for the process is Q , the following relationships hold,

$$Q = \sum_{i=1}^I Q_i,$$

$$Q_i = \sum_{j=1}^J m_{ji} \Delta h_{ji} = \sum_{j=1}^J Q_{ji}$$

where m_{ji} is the mass flow of stream j used in task i , and Δh_{ji} its enthalpy drop. Clearly m_{ji} can be different from zero only if Δh_{ji} represents a feasible application

FIGURE 5.1 DIAGRAM OF PROCESS MODEL

Symbols

i	Task i, i = 1, 2, 4, 5	FW	Feed Water
T	Turbine	R, S	Rejection Systems
HPB	High Pressure Boiler	M_{ij}	Mass Flow from i to j
LPB	Low Pressure Boiler	+	Line crossover
G	Geothermal Field	+	Line connection

and, thereby, obeys all laws of thermodynamics.

The enthalpy drop of a hot stream in a task, Δh_{ji} , determines the amount of fluid from stream j needed per unit of heat supplied to i , and also the area of the heat exchanger required. If the Δh_{ji} could be predetermined to their optimal value by some external rule, the optimization problem is greatly simplified on two accounts. First, the task energy balance equations become linear in the unknown variables m_{ji} . Second, the equipment size for each hot stream in each task becomes fixed, and the whole set of constraints relating heat exchanger area to enthalphy drop, is superfluous and can be excluded from the optimization problem. The results developed in Chapters 3 and 4, and references [1] and [2] provide rules for determining values of Δh_{ji} that give economic solutions that do not differ from the optimum by more than a few percentage points. Given the uncertainty in the rest of the data, this accuracy is largely sufficient to take these values as optimal for economic feasibility studies.

The total cost per unit time of providing heat to the process, C , is the sum of costs of the I tasks, $C(Q_i)$

$$C = \sum_{i=1}^I C(Q_i)$$

For each task i , the cost can be further broken down in the

sum of the costs $C(Q_{ji})$ of the Q_{ji} contributions of the J streams to Q_i ,

$$C(Q_i) = \sum_{j=1}^J C(Q_{ji})$$

and for each stream j , the cost $C(Q_{ji})$ is composed of a fluid cost and an equipment cost,

$$C(Q_{ji}) = c(M_j) \times m_{ji} + R(\text{Area } ji)$$

where $M_j = \sum_{i=1}^I m_{ji}$ is the total flow out of source j , and $c(M_j)$ its average cost per unit of mass. $R(\text{Area } ji)$ represents an equipment charge per time unit.

Once Δh_{ji} has been fixed, the heat exchanger area needed can be approximated by a linear relationship on the quantity of heat transferred and, hence, in the mass flow m_{ji} . The time charge rate for the equipment, $R(\text{Area } ji)$, can then be decomposed into a per unit of mass charge, $r(\text{Area } ji)$, plus, perhaps, a fixed cost, f_{ji} , that is incurred whenever stream j provides heat to task i (i.e., whenever $m_{ji} > 0$; consequently,

$$C(Q_{ji}) = \begin{cases} 0 & \text{if } m_{ji} = 0 \\ [c(M_j) + r(\text{Area } ji)m_{ji} + f_{ji} & \text{if } m_{ji} > 0 \end{cases}$$

The cost of the j -ith hot stream, $C(M_j)$ is taken as

$$C(M_j) = \begin{cases} 0 & \text{if } M_j = 0 \\ S_j + c(M_j) \times M_j & \text{if } M_j > 0 \end{cases}$$

where S_j is the fixed cost of the j -th stream (e.g., geothermal well, boiler, etc.)

Per unit of time, e.g., per year, the total cost of supplying energy to the process is

$$C(Q) = \sum_{j=1}^J S_j + \sum_{j=1}^J \sum_{i=s}^I [c(M_j) + r(\text{Area } ji)m_{ji} \\ + \sum_{j=1}^J \sum_{i=1}^I f_{ji} - E^+ \times e^+ + E^- \times e^-]$$

where all symbols have the meanings already defined; and E^+ , E^- represent the electrical surplus or deficit and

e^+ , e^- their respective rates.

Letting E_j represent the electricity produced from stream j , the total electricity produced is $E = \sum_{j=1}^J E_j$,

and, if E_D is the total demand for electricity of the process, $(E - E_D)$ represents the net electricity for sale or purchase. If $E > E_D$, there will be a surplus, $E^+ = E - E_D > 0$, which will be assumed can be sold at a rate e^+ . On the other hand, if $E_D > E$ there will be a deficit of electricity that will have to be bought at a rate e^- . Thus, the term $(-E^+e^+ + E^-e^-)$ represents the cost or revenue from cogeneration.

The one period mathematical programming problem for optimization of process configuration essentially becomes

$$\begin{aligned} \text{Minimize } C(Q) = & \sum_{j=1}^J S_j + \sum_{j=1}^J \sum_{i=1}^I [c(M_j) + r(\text{Area } ji)] m_{ji} \\ & + \sum_{j=1}^J \sum_{i=1}^I f_{ji} - E^+e^+ + E^-e^- \end{aligned}$$

Subject to:

$$\sum_{j=1}^J m_{ji} \Delta h_{ji} = Q_i \quad \text{for all } i$$

$$\sum_{j=1}^J m_{ji} - \sum_{k=1}^J m_{ik} = 0 \quad \text{for all } i$$

$$E - \frac{\eta_g^t}{3413} \sum_{i=1}^I m_{Ti} \Delta h_{Ti} = 0 \quad \text{Turbogenerator}$$

$$E - E_D \leq E^+$$

$$E_D - E \leq E^-$$

All variables non-negative

This formulation must be specialized to the particular case under study by including additional physical and logical constraints, but the general form remains as above.

The one period problem has been chosen as an illustration for its greater simplicity and because it forms the basic building block for treating more complex and multiperiod problems.

To use this technique, the industrial process being studied has to be described in a suitable form; heating operations have to be decomposed into elementary tasks and cost functions for the different components must be derived. The

rules for decomposing heating operations into tasks are given in the next section.

Non-linear and more complex cost functions than those considered here can be dealt with by different techniques - the operations research literature abounds in them. They are not included because they add nothing of substance to the problem formulation.

B. Task Characterization

A task - much like a prototypical unit process - is defined as an elementary heat transfer operation. The cold side, heat sink, represents some substance at some stage of a production process. The hot side, heat source, represents any combination of hot fluids (essentially water or steam) that can provide heat to the process. A unit task will be designated by an index $i = 1, 2, 3, \dots, I$.

There are essentially four types of tasks: tasks where both the heat source and the heat sink change in temperature, (a); tasks where only the source or the sink change in temperature, (b) and (c); and tasks where neither the heat source nor the sink change in temperature (d). More general operations can be decomposed into 2 or more unit tasks. In the next section several processes will be considered that practically cover the scope of possibilities, but first we show how the unit processes are cast into a form suitable for the model described.

TYPE A. Non-condensing on either side heat exchanger.

Consider the counterflow heat exchanger. Call it task i.

Known quantities:

Heat demand, $Q_i = (\text{mass flow of product}) \times (T_{\text{OUT}}^C - T_{\text{IN}}^C)$

Hot fluid incoming temperature, T_{IN}^H

Define the task temperature, $T_i = T_{\text{OUT}}^H$, to be as close as possible to T_{IN}^C ; $T_i = T_{\text{IN}}^C + \Delta T_1$. Finally, if the stream proceeding from source j provides an amount Q_{ji} of the heat demand, Q_i , the mass flow of this stream will satisfy

$$Q_{ji} = m_{ji} c_p (T_{\text{IN}}^H - T_i) = m_{ji} c_p (T_j - T_i) = m_{ji} \Delta h_{ji}$$

and

$$Q_i = \sum_j Q_{ji} = \sum_j m_{ji} \Delta h_{ji}$$

where Q_i and the Δh_{ji} are known quantities,

TYPE B. Heating a non-vaporizing fluid with a condensing one.

The heat demand Q_i and the fluid temperatures are known, and the heat exchanger area per unit of heat transferred is calculated from them. If the stream coming from j as saturated steam at temperature $T^H = T_i$, provides an amount Q_{ji} of the demand Q_i , the mass flow required will meet

$$Q_{ji} = m_{ji} h_{fg}^{T^H} = m_{ji} \Delta h_{ji}$$

and

$$Q_i = \sum_j Q_{ji} = \sum_j m_{ji} \Delta h_{ji}$$

TYPE C. Vaporizing a fluid with a non-condensing one.

The heat demand Q_i , the boiling temperature T^C and the hot fluid incoming temperature, T_{IN}^H are known quantities. From these values the hot fluid exit temperature, $T_{OUT}^H = T_i$, is again set to its boundary value, $T_i = T^C + \Delta T_2$.

Under these conditions if the stream (ji) supplies an amount Q_{ji} of Q_i , the mass flow will be given by

$$Q_{ji} = m_{ji} c_p (T_{IN}^H - T_i) = m_{ji} \Delta h_{ji}$$

TYPE D. Both sides condensing heat exchanger.

Q_i , T^C , $T^H = T_i$ and $h_{fg}^{T_i}$ are known.

Calling Q_{ji} the portion of Q_i supplied by stream j ,

$$Q_{ji} = m_{ji} h_{fg}^{T_i} = m_{ji} \Delta h_{ji}$$

Since all the task heat demand must be supplied

$$Q_i = \sum_j m_{ji} \Delta h_{ji}$$

C. Decomposition of General Heat Transfer Operations
Into Elementary Tasks

1. Task with potential heat streams in different phases.

First consider the case of steam and hot water. Let s denote the steam source and ℓ the liquid source, and let their thermodynamic conditions be known. Assume that on the product side the substance varies in temperature, and call the task the i -th. The task can be decomposed into 2 unit tasks, one of Type A and another of Type B as follows.

$$Q_{1B} = m_{S,1B} h_{fg}^{TB}$$

$$Q_{1A} = m_{\ell,1A} \Delta h_{T^{\ell}T^A} + m_{1B,1A} \Delta h_{T^B,T^A}$$

and

$$Q_1 = Q_{1B} + Q_{1A} = m_{S,1B} h_{fg}^{TB} + m_{1B,1A} \Delta h_{T^B,T^A} + m_{\ell,1A} \Delta h_{T^{\ell}T^A}$$

Mass balances:

$$m_{S,1B} = m_{1B,1A} + m_{1B,0}$$

$$m_{\ell,1A} + m_{1B,1A} = m_{1A,0}$$

ii. Simultaneous heating and boiling of a liquid with a non-condensing one. Treatment of pinch point problems.

Assume the operation is as depicted in the diagram below

The operation is decomposed into a Type A task and a Type C task as follows,

Heat balances:

$$Q_{1C} = m_{j,1C} h_{T_j, T^P}$$

$$Q_{1A} = m_{j,1A} \Delta h_{T_j, T_{1A}} + m_{1C,1A} \Delta h_{T^P, T_{1A}}$$

$$Q_1 = Q_{1C} + Q_{1A} = m_{j,1C} \Delta h_{T_j, T^P}$$

$$+ m_{j,1A} \Delta h_{T_j, T_{1A}} + m_{1C,1A} \Delta h_{T^P, T_{1A}}$$

Mass balances:

$$m_{ji} = m_{j,1C} + m_{j,1A}$$

$$m_{j,1} = m_{1C,1A} + m_{1C,0}$$

$$m_{j,1A} + m_{1C,1A} + m_{1A,0}$$

Here the assumption was made that the new and cascaded fluid will be cooled in task 1A to the same final temperature.

By combining both of the former examples it is easy to see how more complex cases can be expressed as collections of unit tasks.

D. Boilers and Turbogenerators

Boilers and turbines are the common devices for converting the chemical energy in fuels into usable process heat and work (electricity). They are modelled as follows.

i. Boilers

In a fuel fired boiler the combustion heat of the fuel is transmitted to the water, increasing its enthalpy. For low temperature applications the amount of heat extracted from a given amount of fuel is approximately constant regardless of the cold side temperature; if the fuel input rate is F units of heat ($\approx$ units of mass) and the boiler is fed by I streams i , $i = 1, 2, \dots, I$, the energy balance is

$$F = \frac{1}{\eta_B} \sum_{i=1}^I m_i \Delta h_i$$

where η_B is the boiler First Law Efficiency ($\eta_B \approx .85$ for modern boilers), and Δh_i is the enthalpy increase per unit of mass incoming stream i needs to reach the boiler exit conditions; m_i as before stands for the mass flow of the stream.

The investment in the boiler and ancilliary equipment, once the exit conditions of the steam have been fixed, are approximately linear with the mass flow within very wide ranges. When more accuracy is desired the boiler cost can be approximated by a piece-wise linear function over an increasingly finer grid of intervals.

ii. Turbogenerator

The steam from the high pressure boiler can be used in a cogeneration fashion to obtain both work and process heat. Most frequently a generator is coupled to a turbine to convert the expansion work of the steam in this into electricity, as in the diagram below

The electricity generated, W , in such a plant is

$$W = \eta_g \eta_t m(h_1 - h_2)$$

where, as usual, m is the mass flow of steam through the turbine and h_1, h_2 its entry and exit conditions. η_g is the generator efficiency, and η_t the thermodynamic efficiency of the turbine.

As with boilers, once the entry and exit conditions of the steam have been fixed the investment in turbogenerators is approximately linear in the mass flow for rather large output ranges. More accuracy is again easily obtainable by using finer piecewise linear functions in the ranges of interest. Reference [2] suggests how the steam inlet, h_1 , and exit, h_2 , conditions should be set in an optimal operation of the plant.

In complex processes with operations at widely different temperatures, it may be more efficient to use a multistage turbine with the exit conditions of the stages set according to the temperatures of the specific operations they heat. The extension of a formulation to this case is straightforward. Let the diagram below represent two stages of such a turbine,

The power output, w_i , from a stage i is

$$w_i = \eta_g \eta_i m'_i (h_i - h_{i+1})$$

where η_i is the thermodynamic efficiency of stage i , and all other symbols have their customary meaning. Assuming there are I such stages in the turbine, the total electricity output is

$$W = \sum_{i=1}^I w_i, \text{ or, substituting,}$$

$$W = \eta_g [\eta_1 m'_1 (h_1 - h_2) + \eta_2 m'_2 (h_2 - h_3) + \dots + \eta_I m'_I (h_I - h_{I+1})]$$

The former comments regarding investment costs are applicable here to individual stages. It should be noted, though, that the flow out of any stage affects the flow of all the stages upstream of it.

The efficiency of the generator, η_g , the fraction of the turbine of the turbine shaft power converted to electricity in the generator, is practically constant, independent of the regime. Not so the efficiency of the turbine, η_t , which changes with the throttle flow, m , or load, W . This may not be of much consequence when designing new equipment for continuous processes because the turbine may be designed to the same required efficiency irrespective of the continuous mass flow. However, when off-the-shelf components have to be used or the process load fluctuates widely the efficiency of the turbine will depend on the steam flow through it. For the single stage case, if W_o is the rated output of the turbine and η_t its efficiency at rated output, the part load efficiency, η'_t can be expressed as $\eta'_t = \eta_t \times f$, the product of the rated output efficiency and a load correction factor. Letting the actual output when a steam flow m is passed through the turbine, W , be equal to the product of the rated output and a load correction factor, α , $W = \alpha W_o$, expression, becomes

$$W_o = \eta_g \eta_t m (h_1 - h_2) \frac{F}{\alpha}$$

(α/F is an approximately linear function in α , [3],

$$\frac{\alpha}{F} = \theta_0 + \theta_1 \alpha$$

and, substituting,

$$W = A_0 + A_1 m$$

where

$$A_0 = \frac{-\theta_0}{\theta_1} W_0$$

$$A_1 = \frac{\eta_g \eta_t (h_1 - h_2)}{\theta_1}$$

The result can be extended in a straightforward way to the multiple stage case [3]. These expressions which linearize the relationship between output and steam flow through the turbine, allow the explicit consideration of load fluctuations and turbine throttling in a linear model of the process.

E. A Simple Example

i. Model Description

As an illustration of the approach, it will be applied to the problem of minimizing the hourly cost of powering a process consisting of the following operations.

INDEX I	DESCRIPTION	HEAT DEMAND Q_i (10^6 Btu/hr)
1	Boil liquid at 300°F	4.2
2	Heat substance from 190 to 260°F	5.6
3	Heat substance from 140 to 200°F	2.5

The energy supply alternatives or primary streams are:

SOURCE	SYMBOL	PHASE	TEMP. °F	PRESSURE PSIG
Geothermal	G	Liquid	350	
High Pressure Boiler	HPB	Steam	900	1250
Low Pressure Boiler	LPB	Steam	550	150

In the example, the steam from the high pressure boiler, HPB, is not taken directly to the processes, instead, it is expanded first in a multi-stage turbine generating electricity, and then supplies heat to the processes. Only such amount of steam as can be used for process heat in some operations is allowed to generate electricity. This was done because pure generation of electricity was not considered interesting in the example.

The rules followed to derive the model are:

- The minimal temperature difference between sides of heat exchange operations is 10°F.

- The turbine is bled at 10°F above process temperature.
- Except for turbine exhaust, all other task effluents mix.
- The geothermal liquid is assumed clean enough to be fed into the boilers and processes (if it were not, a heat exchanger could be interposed between the geothermal and the feed water).
- The task effluents are mixed before entry to the boilers.

For simplicity, the process is assumed to have no demand for electricity and that all the electricity generated can be sold.

The decomposition of the operations into tasks is given next. The symbols used have the meaning of Figure 5.1.

a. OPERATION 1

Potential Streams	Stream Inlet Conditions	Δh_{ji} (Btu/lb)	Stream Exit Conditions
MT1	Sat. steam at 310°F	902	Sat. liquid at 310°F
ML1	Steam at 150 psig/550°F	1020	Sat. liquid at 310°F
MG1	Sat. liquid at 350°F	42	Sat. liquid at 310°F

The evolution of the different streams will be

And the operation can be represented by a single task as follows

The heat and mass balances are

$$Q_1 = 902 \text{ MT1} + 1020 \text{ ML1} + 42 \text{ MG1} = 4200 \quad (\text{OPIE})$$

$$\text{MT1} = \text{N12} + \text{N15} + \text{N14} + \text{M1H} + \text{M1S} \quad (\text{OPIH})$$

$$\text{ML1} + \text{MG1} = \text{M12} + \text{M15} + \text{M14} + \text{M1L} + \text{M1R} \quad (\text{OPIM})$$

(Heat is in 10^3 Btu/hr and flow in 10^3 lb/hr)

b. OPERATION 2

Potential Streams	Stream Inlet Conditions	h_{j2} (Btu/hr)	Stream Exit Conditions
MT2	Sat. Steam at 270°F	924	Sat. liquid at 270°F
ML2	Steam at 150 psig/550°F	1132	Sat. liquid at 200°F
MG2	Sat. liquid at 350°F	154	Sat. liquid at 200°F
M12	Sat. liquid at 310°F	112	Sat. liquid at 200°F
N12	Sat. liquid at 310°F	112	Sat. liquid at 200°F
N22	Sat. liquid at 270°F	71	Sat. liquid at 200°F

The evolution of the streams is

Operation 2 can also be represented as a single task.
The heat and mass balances are,

$$Q_2 = 924 \text{ MT}_2 + 1132 \text{ ML}_2 + 154 \text{ MG}_2 + 112 \text{ M}_2 + 112 \text{ N}_2 + 71 \text{ N}_{22} = 5600 \quad (\text{OP2E})$$

$$\text{MT}_2 = \text{N}_{22} + \text{N}_{25} + \text{N}_{24} + \text{M}_{2\text{H}} + \text{M}_{2\text{S}} \quad (\text{OP2H})$$

$$\text{ML}_2 + \text{MG}_2 + \text{M}_2 + \text{N}_2 + \text{N}_{22} = \text{M}_{24} + \text{M}_{2\text{L}} + \text{M}_{2\text{R}} \quad (\text{OP2M})$$

c. OPERATION 3

The effluent from 2 cannot raise the temperature of the product of Operation 3 beyond 190°F, but is a potential heat source for heating to this temperature. To take this into account, operation 3 is decomposed into tasks 4 and 5 as follows:

Task 4: Heating the process substance from 140 to 190°F. Assuming the specific heat of the product does not change while being heated, the heat demand for task 4 is $Q_4 = 2.086 \times 10^6 \text{ Btu/hr.}$

Task 5: Heating the product from 190 to 200°F. Under the same assumption as before, the heat demand of task 5 is $Q_5 = .416 \times 10^6 \text{ Btu/hr.}$

The diagram of the tasks is

Except for turbine steam, the effluents from all other streams in task 5 are forced to go through task 4. The mass and heat balances, see Figure 5.1, for each task are given below.

i) Task 4

Potential Stream	Stream Inlet Conditions	h_{i4} (Btu/lb)	Stream Exit Conditions
MT4	Sat. steam at 210°F	970	Sat. liquid at 210°F
ML4	Steam at 150 psig/550°F	1180	Sat. liquid at 150°F
MG4	Sat. liquid at 350°F	202	Sat. liquid at 150°F
M14	Sat. liquid at 310°F	160	Sat. liquid at 150°F
N14	Sat. liquid at 310°F	160	Sat. liquid at 150°F
M24	Sat. liquid at 200°F	48	Sat. liquid at 150°F
N24	Sat. liquid at 270°F	121	Sat. liquid at 150°F
N44	Sat. liquid at 210°F	62	Sat. liquid at 150°F
M54	Sat. liquid at 200°F	48	Sat. liquid at 150°F
N54	Sat. liquid at 210°F	62	Sat. liquid at 150°F

The heat and mass balances for task 4 are

$$Q_4 = 980 \text{ MT4} + 1180 \text{ ML4} + 202 \text{ MG4}$$

$$+ 160 \text{ M14} + 160 \text{ N14} + 121 \text{ M24} + 121 \text{ N24}$$

$$+ 62 \text{ N44} + 62 \text{ N54} = 2086 \quad (\text{OP4E})$$

$$\text{MT4} = \text{N44} + \text{M4H} + \text{M4S} \quad (\text{OP4H})$$

$$\text{ML4} + \text{MG4} + \text{M14}$$

$$\text{N14} + \text{M24} + \text{N24}$$

$$\text{N44} + \text{M54} + \text{N54} = \text{M4L} + \text{M4R} \quad (\text{OP4M})$$

(ii) Task 5

Potential Streams	Stream Inlet Conditions	Δh_{i5} (Btu/lb)	Stream Exit Conditions
MT5	Sat. steam at 210°F	970	Sat. liquid at 210°F
ML5	Steam at 150 psig/550°F	1132	Sat. liquid at 200°F
MG5	Sat. liquid at 350°F	154	Sat. liquid at 200°F
M15	Sat. liquid at 310°F	112	Sat. liquid at 200°F
N15	Sat. liquid at 310°F	112	Sat. liquid at 200°F
N25	Sat. liquid at 270°F	71	Sat. liquid at 200°F
N55	Sat. liquid at 210°F	12	Sat. liquid at 200°F

The heat and mass balances are

$$Q_5 = 970 \text{ MT5} + 1132 \text{ ML5} + 154 \text{ MG5}$$

$$+ 112 \text{ M15} + 112 \text{ N15} + 71 \text{ N25}$$

$$+ 12 \text{ N55} = 416 \quad (\text{OP5E})$$

$$\text{MT5} = \text{N54} + \text{N55} + \text{M5H} + \text{M56} \quad (\text{OP5H})$$

$$\text{ML5} + \text{MG5} + \text{N15}$$

$$+ \text{N25} + \text{N55} = \text{M54} \quad (\text{OP5M})$$

d. BOILERS

The fuel assumed for the boilers is 24×10^6 Btu/short ton coal. The feedwater is saturated liquid at 60°F.

In the example, two boilers are included, see Figure 5.1. The high pressure boiler, HPB, is part of a cogeneration scheme, and supplies high pressure steam to a multistage turbine. Its energy and mass balances are,

$$20.40 \text{ FH} = 1117 \text{ MGH} + 1159 \text{ M1H} + 1190 \text{ M2H}$$

$$+ 1259 \text{ M4H} + 1259 \text{ M5H} + 1410 \text{ MFH} \quad (\text{HPE})$$

$$\text{MHT} = \text{MGH} + \text{M1H} + \text{M2H} + \text{M4H} + \text{M5H} + \text{MFH} \quad (\text{HPH})$$

where FH is the amount of fuel consumed in the boiler.

The low pressure boiler, LPB, provides steam directly to the processes. Its heat and mass balances are,

$$\begin{aligned} 20.40 \text{ FB} &= 978 \text{ MGL} + 1271 \text{ MFL} + \\ &+ 1020 \text{ M1L} + 1132 \text{ M2L} + \\ &+ 1180 \text{ M4L} \quad \quad \quad (\text{LPE}) \end{aligned}$$

$$\text{MGL} + \text{MFL} + \text{M1L} + \text{M4L} = \text{ML1} + \text{ML2} + \text{ML4} + \text{ML4} \quad (\text{LPM})$$

where FB is the amount of fuel.

e. TURBOGENERATOR

The steam from the high pressure boiler passes through a multi-stage turbine where it expands producing electricity, and then goes to the processes to provide heat. The energy and mass balances are

$$\begin{aligned} E &= 60.568 \text{ MT1} + 63.408 \text{ MT2} + 68.376 \text{ MT4} \\ &+ 68.376 \text{ MT5} \quad \quad \quad (\text{TE}) \end{aligned}$$

$$\text{MHT} = \text{MT1} + \text{MT2} + \text{MT4} + \text{MT5} \quad \quad \quad (\text{TH})$$

f. COST FUNCTION

The basic prices used in the model were:

steam coal - \$26/short ton
geothermal fluid - \$100/10⁶ lb.
electricity - \$0.033/kwh

** OPTIMAL PAYOFF IS

3.01303 **

** PRIMAL SOLUTION **

ACTIVITY	ACTIVITY LEVEL	OBJECTIVE COEFFICIENT	LOWER LIMIT	UPPER LIMIT
FM	0.691	26.000	26.000	27.075
FL	0.000	26.000	6.011	UNBOUNDED
MG	7.791	0.100	0.100	0.120
MGM	7.791	0.000	0.000	0.020
MGL	0.000	0.000	-0.052	UNBOUNDED
MS1	0.000	0.000	-0.052	UNBOUNDED
MS2	0.000	0.000	-0.054	UNBOUNDED
MS3	0.000	0.000	-0.052	UNBOUNDED
MS4	0.000	0.000	-0.069	UNBOUNDED
M1M	4.656	0.000	-0.041	0.011
M2M	0.000	0.000	-0.018	UNBOUNDED
M4M	0.000	0.000	-0.000	UNBOUNDED
M5M	0.000	0.000	-0.090	UNBOUNDED
MFM	0.000	0.000	-0.273	UNBOUNDED
MFL	0.000	0.000	-0.039	UNBOUNDED
MHT	12.447	0.000	0.000	0.073
E	786.765	-0.020	-0.020	-0.019
MT1	4.656	0.000	-0.041	0.884
MT2	5.628	0.000	-0.093	0.045
MT3	1.733	0.000	0.000	0.090
MT5	0.429	0.000	UNBOUNDED	0.000
MTL	0.000	0.000	-0.999	0.005
M2L	0.000	0.000	-0.005	UNBOUNDED
M4L	0.000	0.000	-0.012	UNBOUNDED
M1L	0.000	0.000	-0.999	0.046
ML2	0.000	0.000	-0.046	UNBOUNDED
ML4	0.000	0.000	-0.157	UNBOUNDED
ML5	0.000	0.000	-0.157	UNBOUNDED
M1S	0.000	0.000	-0.046	UNBOUNDED
M12	0.000	0.000	-0.005	0.011
M14	0.000	0.000	-0.011	UNBOUNDED
M15	0.000	0.000	-0.011	UNBOUNDED
M1R	0.000	0.000	-0.035	UNBOUNDED
M2S	0.000	0.000	-0.025	UNBOUNDED
M24	5.628	0.000	-0.013	0.007
M2R	0.000	0.000	-0.007	UNBOUNDED
M4S	0.000	0.000	-0.009	UNBOUNDED
M4R	7.791	0.000	0.000	0.000
M5S	0.000	0.000	-0.000	UNBOUNDED
M54	0.000	0.000	0.000	UNBOUNDED
M12	0.000	0.000	-0.011	UNBOUNDED
M15	0.000	0.000	-0.022	UNBOUNDED
M15	0.000	0.000	-0.022	UNBOUNDED
M22	5.628	0.000	-0.099	0.007
M24	0.000	0.000	-0.007	UNBOUNDED
M25	0.000	0.000	-0.007	UNBOUNDED
M44	1.734	0.000	0.000	0.010
M54	0.922	0.000	UNBOUNDED	0.000
M55	0.000	0.000	0.000	UNBOUNDED

TABLE 5.1 OPTIMAL SOLUTION FOR LOW ELECTRIC RUN

The mass flows of the streams are under the column labeled ACTIVITY LEVEL.

FIGURE 5.2 SOLUTION FOR "BASIC" RUN OF EXAMPLE

Coal price \$26/short ton. Geothermal Fluid
 cost \$100/10⁶ lb. Electricity price \$.03/kwh
 Payoff = \$-7.809/hr (Profit)

FIGURE 5.3

SOLUTION FOR "LOW ELECTRIC"
RUN OF EXAMPLE

Price of electricity \$.02/kWh.

Price of coal \$26/short ton.

Geothermal fluid cost $\$1./10^6$ Btu

Payoff \$3.013/hr (cost)

FIGURE 5.4

SOLUTION FOR "VERY LOW ELECTRIC"
RUN OF EXAMPLE

Price of electricity \$.01/kWh.

Price of coal \$26/short ton.

Geothermal fluid cost \$100/10⁶lb.

Payoff \$7.22/hr (cost) .

FIGURE 5.5 SOLUTION FOR "VERY LOW ELECTRIC & NO GEOTHERMAL"
RUN OF EXAMPLE

Price of electricity \$.01/kWh. Price of coal \$26/short ton. Geothermal fluid not allowed. Payoff \$11.782/hr (cost).

The hourly cost of powering the process is

$$26FH + 26FB + 0.10 MG - .033 E \quad (C1)$$

where MG represents the total consumption of geothermal fluid, in thousands of pounds per hour,

$$MG = MGH + MGB + MG1 + MG2 + MG4 + MG5 \quad (G)$$

2. Model Results

Although the data in the model are realistic, we will not discuss the specific model results. We are more interested in the qualitative information the model can provide and the suitability of the technique for designing efficient processes when geothermal energy is available.

A sample solution of the problem is shown as Table 5.1. It corresponds to the run labeled Low Electric. It is standard output of linear programming codes and the meaning of the different items is explained in most linear programming texts, e.g., Bradley et al [4]. The most important information in the linear program solution print-out can also be displayed graphically, as done in Figures 5.2 through 5.5. We will discuss these before returning to the computer print-out to examine its more complete information.

Figure 5.2 shows the solution to the problem with the basic costs assumed in the previous subsection; this problem run is labeled Basic. Figure 5.2 reproduces Figure 5.1 but on it the streams giving the optimal solution have been

stressed. The flows corresponding to these streams are written alongside them. The consumption of fuel and geothermal fluid and the electric output are shown in the same way. The same conventions apply to the similar Figures 5.3 through 5.5. The flows not stressed are all equal to zero. It is interesting to note that all the operations are heated through cogeneration. No combination of coal, electricity and geothermal prices was found in this example that would make optimal the use of the low pressure boiler. This may be a result of things like differential equipment investment not being included in the example and not much weight should be placed on this conclusion. It is interesting to note that some geothermal fluid is used to substitute (preheat) for the cascaded streams M4S and M5S. This is because the geothermal fluid is hotter than streams M4S and M5S and represents a straightforward substitution of geothermal for fossil fuel. This is also not a general result but is a consequence of the example formulation, but, nevertheless, illustrates the capability of the technique to find logical but not at first thought intuitive solutions and to suggest additional possibilities to those originally considered. For example, could the solution be improved by allowing turbine exhaust steam as a preheating fluid in addition to geothermal?

Figure 5.3 shows the optimal solution when the price of electricity drops to 2¢/kWh and the coal and geothermal fluid

keep their prices. This run is labeled Low Electric. The most remarkable feature is the removal of sensible heat from the cogeneration streams and the increased use of geothermal. Although once more the specific streams and flows are particular to the example, the fundamental trade-off of the problem among the costs of the different energy sources is clearly illustrated.

Figure 5.4, labeled Very Low Electric, corresponds to the optimal solution when the price of electricity drops still more to 1¢/kWh and those of coal and geothermal stay at their original levels. The comparison of Figure 5.4 with Figure 5.3 shows that in the former, when the price of electricity is very small, not only is sensible heat removed from the cogeneration streams but geothermal fluid is used directly to heat the operations.

Figure 5.5, labeled Very Low Electric & No Geothermal, uses the same prices of the former run (Figure 5.4) but here geothermal fluid is not available. In this case sensible heat is not removed from cogeneration streams, showing that Figure 5.4, Very Low Electric run, represents a substitution of cogeneration steam for geothermal fluid.

Returning to the computer print-out, Table 5.1 shows the optimal solution for the run called Low Electric. The headings used are standard linear programming terms. The streams (variables) are called "activities" and their values (flows) "activity levels" (the two leftmost columns in Table

5.1). The "objective function coefficient" is the unit cost of the variable. Finally the two rightmost columns, called Lower Limit and Upper Limit, define ranges for the objective function coefficients such that the values of the variables in the optimal solution remain unchanged when a single one of these coefficients varies within its range. The current solution also remains optimal when several coefficients vary simultaneously but remain within a convex combination of the individual ranges. This is a conservative bound since optimality may be preserved for some simultaneous changes beyond the convex combination of the individual ranges. These true ranges can be found by parametric exploration in the coefficient space, a standard linear programming technique also.

Table 5.2 shows the reduced costs of the variables and the shadow prices of the constraints in the Low Electric run of the example. These represent the change in the value of the objective function (called "payoff" in Table 5.1) from positive unit increments of the optimal values of the variables or of the right-hand side of the constraints, respectively. The constraint formulation chosen has the advantage that these increments can be interpreted as the cost of losses or inefficiencies, and, thus, have a physical meaning. As said before for the lower and upper limit of the objective function coefficients, the lower and upper limits of the right hand side values define ranges for these such that the current solution remains optimal whenever any single right hand side value

** SHADOW PRICES **

ROW NAME	SHAD.PR.	RHS VALUE	UPPER LIMIT	LOWER LIMIT
G	-0.100	0.000	7.791	UNBOUNDED
HPE	-0.001	0.000	14098.980	UNBOUNDED
HPH	-1.524	0.000	7.791	UNBOUNDED
TE	-0.020	0.000	UNBOUNDED	-786.765
TH	-1.524	0.000	7.791	UNBOUNDED
LPE	-0.000	0.000	4200.000	0.000
LPM	-0.336	0.000	4.118	0.000
OP1L	0.000	4200.000	UNBOUNDED	-0.000
OP1H	-0.046	0.000	7.791	-4.656
OP1M	-0.035	0.000	42.004	0.000
OP2E	0.000	5600.000	42689.859	0.000
OP2H	-0.025	0.000	40.141	-6.061
OP2M	-0.007	0.000	37.276	-5.628
OP4E	0.000	2086.000	UNBOUNDED	296.740
OP4H	-0.009	0.000	28.859	-1.845
OP4M	0.000	0.000	UNBOUNDED	-7.791
OP5E	0.000	416.000	28409.254	0.000
OP5H	-0.009	0.000	28.859	-0.429
OP5M	-0.007	0.000	37.276	0.000

** REDUCED COSTS **

ACTIVITY	RED.COST
M1L	19.989
ML1	0.052
ML2	0.052
ML4	0.054
ML5	0.069
M1S	0.069
M14	0.018
M15	0.090
M1R	0.090
M2S	0.273
M24	0.039
N14	0.005
N15	0.012
N24	0.046
N25	0.157
N44	0.157
N54	0.046

TABLE 5.2 REDUCED COSTS AND SHADOW PRICES
FOR THE LOW ELECTRIC RUN OF EXAMPLE

changes within its limits or several of them vary simultaneously within the convex hull of their ranges; as previously, this last region is a conservative bound.

The present example, developed mostly for illustrative purposes, was solved using a standard linear programming code for very small problems. The data and coefficients were elaborated and then fed manually to the computer, an awkward procedure for large problems. Fortunately, it can be easily automated. Once the basic case is in the computer, doing parametric analysis is straightforward and alternatives can be analyzed in a few minutes (CPU Time is only a few seconds).

The attractiveness of the approach is that it can be extended in a number of directions (multiperiod problems, load fluctuation problems, etc.) and that as different alternatives are almost effortlessly solved, their solutions immediately suggest more possibilities, thus enriching the original problem and increasing the understanding of it.

REFERENCES

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3. Hosein-Falla, M. "Integrated Energy Conversion Systems: A Mathematical Model of an Extraction Steam Turbine," Energy Conversion, Vol. 18, p. 11-15.
4. Bradley, S.P., A.C. Hax and T.L. Magnanti, Applied Mathematical Programming, Addison-Wesley Publishing Co., Reading, MA, 1977.

CHAPTER 6 - THERMODYNAMIC PROPERTIES OF GEOTHERMAL FLUIDS

In order to evaluate the performance of proposed processes utilizing geothermal energy, it is essential to determine the thermodynamic properties of fluid streams at various points in the system. The method described in Reference 1 ascertains the values of these properties for either pure water or salt solutions, correlating temperature, pressure, enthalpy, and entropy in the liquid, two-phase, and vapour regions.

The corresponding FORTRAN computer formulation is coded in one subroutine and twenty-six function subprograms, sixteen of which represent correlations of the properties of pure water. The subroutine chooses the appropriate correlations, validates input data, and embodies a large fraction of the salt solution algorithms. Including nonexecutable comment lines, the entire formulation requires less than 910 lines of code.

For the purposes of choosing between the pure and saline water algorithms, the computer program considers fluid to be saline if its total dissolved solids content exceeds 10^{-5} (mass fraction basis). The correlations given in the program assume that the salt content of the brine is composed of potassium, calcium, and sodium chlorides in the ratio 1.00:1.95:3.55 respectively. However, the specific heat equation uses data for pure sodium chloride solutions.

REFERENCE

1. Packer, M. B., Thermodynamic Properties of Pure and Saline (Geothermal) Water, MIT Technical Report LMP/MRP-80-02, January, 1980.

CHAPTER 7 - OPTIMIZATION AND THE VALUE OF INFORMATION

A. Optimization

The decision to invest in geothermal energy depends largely upon the economic return. It is therefore important to optimize the use of geothermal energy in order to maximize this return.

i. What to optimize?

One portion of the heuristic computer methodology which could be optimized is the matching procedure described in chapter three. While the procedure incorporates one method of matching energy demands and supplies in a geothermal facility, the particular method adopted is not the only possible or feasible one. Even with the same values chosen for input parameters, each method will generally lead to a different facility design and thus to a different economic rate of return.

Three aspects of the matching procedure require the exercise of judgment and therefore present opportunities for optimization. The first may loosely be called technical rules. This rubric encompasses technical decisions such as the policy of desuperheating between stages of vapor compression and the value of effectiveness assumed for the secondary heat exchanger. The second flexible aspect of the matching procedure is the choice of geothermal fluid flow rate; any flow rate short of the maximum production capacity of the resource can be utilized if desired. The final aspect of the procedure is the stream

selection logic used to match each unit process with a hot fluid stream. A wide variety of selection logics could be employed. A discussion of these problems from a theoretical as well as practical perspective is presented in Reference 1, Chapter 5.

B. Value of Information

One of the most important factors involved in the evaluation of geothermal energy is the uncertainty that surrounds the geothermal resource itself. This uncertainty, which relates primarily to the temperature and production flow rate of the resource, is translated into a corresponding uncertainty in the anticipated cost of the project.

A potential user of geothermal energy might wish to reduce this uncertainty by commissioning additional geological studies or even by drilling an initial production well. In the present context, these activities will be termed experiments. However, the user should weigh the cost of such experiments against the potential value of the information to be gained from them.

The value of information derived from experiment to a potential user of geothermal energy depends upon the effect possession of the information will have upon his decisionmaking. At one extreme is the situation in which the decision to utilize geothermal energy and the choice of plant design are made in advance. In this case, possession of information from an experiment cannot alter the expected net present value of the project.

At the other extreme lies the situation in which the decision to use geothermal energy and the choice of plant design can be postponed until the information has been obtained. If no experiment is performed, the user will design the plant on the basis of the expected resource characteristics. Thus if resource characteristics are found to differ in actuality from their expected values, the user will have built a suboptimal plant. However, if an experiment is performed, the user can design the plant to make optimum use of the discovered characteristics of the resource.

The value of the information to the user is represented by the difference between the expected value of the project without experimentation and the expected value of the project with experimentation.² Therefore, a rational decision-maker who has the opportunity to perform the experiment at a cost less than this value should choose to do so. If the cost of the experiment will exceed the value of the information to be obtained, the decision-maker should proceed without the experiment.

This concept has important implications for the practice of geothermal resource assessment as well. The most important of these implications is that location-specific assessment efforts can be rigorously justified on the basis of the value of the information to be procured. Furthermore, such a justification cannot be made without consideration of a particular application, since the economics of the specific application determine in part the value of the information to be gained from the experiment.

The procedure used to calculate the value of information for a given application and an example are given in Reference 1, Chapter 5.

REFERENCES

1. Packer, M. B., A Method for Evaluating the Potential of Geothermal Energy in Industrial Process Heat Applications, Ph.D. Thesis in Mechanical Engineering, MIT, June 1980. [Report No. LMP/MRP-80-04.]
2. Raiffa, Howard, Decision Analysis - Introductory Lectures on Choices under Uncertainty, Reading, MA: Addison-Wesley, 1968.

CHAPTER 8 - THE PERCENTAGE DEPLETION ALLOWANCE
AND GEOTHERMAL ENERGY

While the Energy Tax Act of 1978 has explicitly extended the percentage depletion deduction to geothermal resources, it neglects the issue of how to compute gross income for depletion purposes. Three generic methods of calculating gross income are given in the Income Tax Regulations: income from actual sales, income from constructive sales based on a representative market price, and income imputed to the taxpayer in proportion to the annual cost incurred for resource extraction.

Since direct-use geothermal applications frequently involve an integrated field developer-fluid user, no sale is made and the first method fails. The second method succumbs to the lack of a representative market for geothermal fluid or energy. Finally, the last method yields an inappropriate estimate of gross income because the annual costs of extracting geothermal fluid are minor in comparison to the initial capital investment. As a result, integrated developer-users will not be able to benefit from the change in the tax laws, inhibiting the development of geothermal resources.

One additional method, based upon the return expected on the capital investment, is listed in the Regulations although no details are given. Reference 1 expands upon this suggestion to offer a detailed alternative method of calculating gross income. Gross income as determined by this method depends upon three

factors: the rate base, a rate of return, and operating expenses. To integrate the method into the present framework of the Internal Revenue Code, the definitions of cost depletion basis and allowable expenses given in the Code are adopted for the rate base and operating expenses respectively. By multiplying the geothermal investment (rate base) by the rate of return, the net income required by the developer may be estimated. If operating expenses and taxes are added to this figure, the gross income which yields this net income can be found. The method is thus independent of the need for either an actual sale or a representative market. Moreover, since it explicitly includes the capital investment, it avoids the pitfalls of methods based solely on annual costs.

The rate of return method presented in Reference 1 offers some respite for the taxpayer who can justify it as an alternative method of calculation. As with all regulatory procedures, its efficiency and durability must await the test of innovations to come.

REFERENCE

1. Packer, M. B., "Percentage Depletion for Geothermal Energy: An Alternative Method for Calculation of Gross Income," Land & Water Law Review, Vol. 15, No. 2, June 1980, pp. 427-443.

CHAPTER 9. CONCLUSIONS

The principal goal of the program was to demonstrate economical and technical suitability of geothermal energy as a source of industrial process heat through a cooperative program with industrial firms. To accomplish that we:

- 1) performed a critical literature survey in the field (Chapter 2).
- 2) organized a workshop with the paper and pulp industry representatives (described in Chapter 1) and
- 3) developed four parallel methods dealing with technical and economical details of geothermal energy use as a source of industrial process heat. They are presented respectively in i) Ref. 1 of Chapter 2, ii) Chapter 3 (Heuristic Computer Simulation Methodology), iii) Chapter 4 (Simplified algorithm for cascading, and iv) Chapter 5 (Cascading by Linear Programming). The most complete and detailed approach - Heuristic Computer Modeling Methodology - is available on tape in Fortran language as well as on a diskette (in BASIC) for use on Apple III Computer Systems.

In addition to these, significant contributions were made in the area of optimization and the value of information (Chapter 7).

The workshop with the paper and pulp industry were successful. Two companies agreed to work with us to the extent that they have provided detailed technical information necessary for the analysis and stayed in contact with us throughout most of the program. An attempt to hold a similar workshop for the food processing industry was not successful. Nevertheless, we established cooperation with a company whose case we ran using the methodology described in Chapter 3. Some of the examples have shown - subject to assumed energy and geothermal fluid price structure for

the immediate future - that the use of geothermal energy as industrial process heat represented technically and economically an acceptable choice. Still, the firms we worked with did not show any enthusiasm for following up the findings and plan for actual investment at this time.

There were two main reasons which led to this attitude. The first and most important one was uncertainty in geothermal resource information, exploration and development aspects of the program. They, as a group, did not have any prior experience in this area, and they felt reluctant to make any commitment before more convincing and complete information on the resources are available. The second problem was related to the way economic advantages of geothermal resource utilization were assessed. Specifically, the suitability of geothermal utilization in any specific case was based on a comparison with economic performance of the same plant using present day conventional energy supply practices (i.e., oil or gas rather than coal, cogeneration, solar or others). This procedure is clearly questionable. The fact that geothermal utilization can improve the return on investment over present day practices, does not mean that there are not other new advanced systems which could prove even more superior. The results of this type of comparison - geothermal versus available advanced system options - would be strongly dependent on a number of specific parameters (type of industry plant details, location, etc.). In any event, we do feel that it is necessary to re-examine the target list of suitable industries for geothermal energy utilization by expanding the criteria for suitability beyond those used widely at this time in the existing analysis (Chapter 1 lists the present criteria). Summarizing the

main findings which resulted from cooperation with the industry:

- there is no confidence in the resource confirmation and development data. Neither does there exist a methodology which could allow for quantification of the value (and cost) of any specific information concerning the resource.
- Any future analysis on economic suitability of geothermal energy utilization should be based on comparisons with all presently available options (rather than present practices).

Continuation of the present program could deal with the issues raised above. The work described in Chapter 7 could be extended to address the question of value of information in any specific case, and the developed computerized algorithm could be easily adopted to include all presently available options in the economic analysis of geothermal utilization.

Further use of the program may include development of a new target list of suitable industries for geothermal energy use.

The program can also be used directly, either by various industries to assess economic consequences of converting to geothermal energy, or by various governmental agencies in evaluating proposals for conversions to geothermal energy use.