ALTERNATIVE ELECTRICAL ENERGY SOURCES FOR MAINE

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Appendix C
GEOTHERMAL ENERGY CONVERSION

A. Waterflow

Prepared for the Central Maine Power Company.

Report No. MIT-EL 77-010
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This appendix is one of thirteen volumes; the remaining volumes are as follows: A. Conversion of Biomass; B. Conservation; D. Ocean Thermal Energy Conversion; E. Fuel Cells; F. Solar Energy Conversion; G. Conversion of Solid Wastes; H. Storage of Energy; I. Wave Energy Conversion J. Ocean and Riverine Current Energy Conversion; K. Wind Energy Conversion, and L. Environmental Impacts.

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Initial literature reviews and drafts of the various technical appendices were prepared by the following people:

Appendix A	Conversion of Biomass - C. Glaser, M. Ruane
Appendix B	Conservation - P. Carpenter, W.J. Jones, S. Raskin, R. Tabors
Appendix C	Geothermal Energy Conversion - A. Waterflow
Appendix D	Ocean Thermal Energy Conversion - M. Ruane
Appendix E	Fuel Cells - W.J. Jones
Appendix F	Solar Energy Conversion - S. Finger, J. Geary, W.J. Jones
Appendix G	Conversion of Solid Wastes - M. Ruane
Appendix H	Storage of Energy - M. Ruane
Appendix I	Wave Energy Conversion - J. Mays
Appendix J	Ocean and Riverine Current Energy Conversion - J. Mays
Appendix K	Wind Energy Conversion - T. Labuszewski
Appendix L	Environmental Impacts - J. Gruhl

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Preface

The Energy Laboratory of the Mass. Inst. of Tech. was retained by the Central Maine Power Company to evaluate several technologies as possible alternatives to the construction of Sears Island #1 (a 600 MWe coal fired generating plant scheduled for startup in 1986). This is an appendix to Report MIT-EL 77-010 which presents the results of the study for one of the technologies.

The assessments were made for the Central Maine Power Company on the basis that a technology should be:

1) an alternative to a base-load electric power generation facility. Base-load is defined as ability to furnish up to a rated capacity output for 6570 hrs. per year.

2) not restricted to a single plant. It may be several plants within the state of Maine. The combined output, when viewed in isolation, must be a separate, "stand-alone", source of power.

3) available to deliver energy by 1985.

APPENDIX C

GEOTHERMAL ENERGY CONVERSION

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1.0 INTRODUCTION

Geothermal energy is, most simply, the natural heat of the interior of the earth. Temperatures rise as you go deeper into the earth, reaching between 1000°C and 2000°C at 25-50 km and 3500°C - 4500°C at the earth's core. The earth's volume of approximately 10^{12} km^3 is mostly molten rock and represents what is frequently considered to be an inexhaustible energy source. Unfortunately, this energy is attenuated and generally diffuse by the time it reaches the surface, and appears as an average heat flow of 1.5×10^{-6} cal/cm^2. This average heat flow is far too small for extraction of any useful energy.

In a limited number of locations, geologic formations allow the molten rock of the interior to approach the surface, forming "hot spots." Evidence of some of these is familiar: hot springs, geysers, fumeroles, and volcanic activity. Other "hot spots" exist below the surface and have much less evident characteristics.

While it is not practical to consider extracting geothermal energy from the diffuse average heat flow from the earth, it is sometimes possible to extract energy from "hot spots." This appendix will consider the characteristics of geothermal resources and the technologies and estimated costs for extracting energy from them, with particular attention to the possibilities for geothermal production of electricity in Maine.

2.0 GEOTHERMAL ENERGY SYSTEMS

2.1 Geothermal Resources

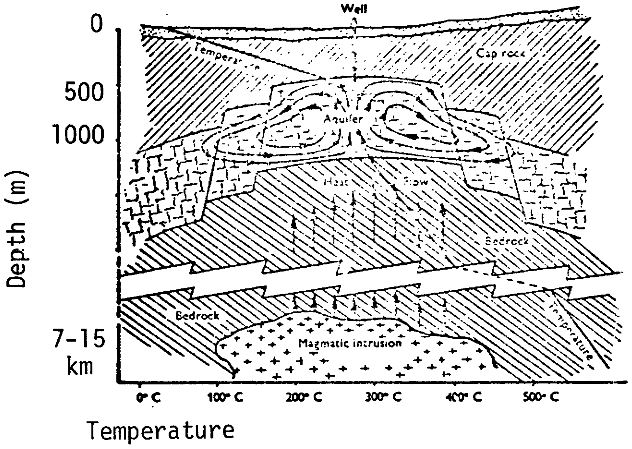
2.1.1 Resource Characteristics

Geothermal resources can be characterized in two different ways. The first characterization groups resources according to the geological structure which causes the naturally desirable levels of geothermal energy. The second characterization groups resources according to the form of the energy as it would be extracted from the "hot spots."

Characterization by geological structure gives the following resource groups: hydrothermal, geopressurized, hot dry rocks, and magmas.

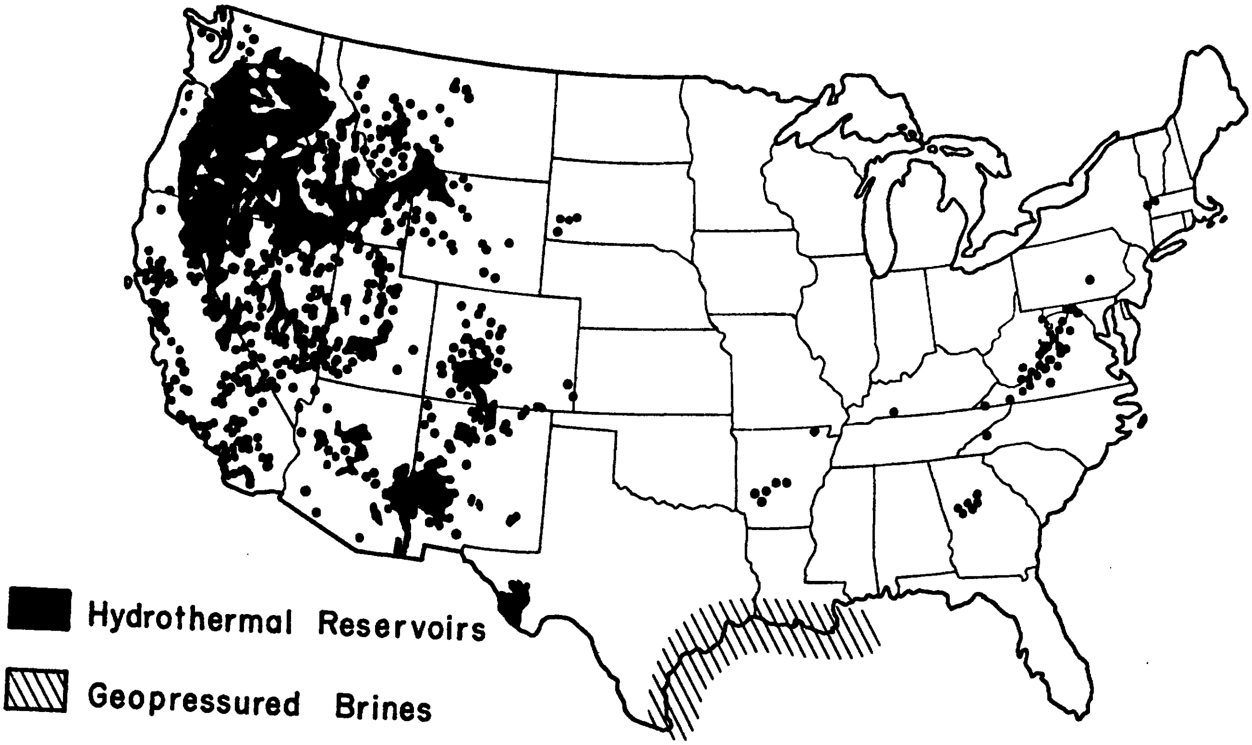
Hydrothermal resources occur when an aquifer, or underground water body, comes in contact with hot rocks below the surface (Figure 2.1). The water acts as a heat transfer agent and absorbs energy from the rocks. Depending on factors such as the permeability and temperature of the rocks, the flow rate and volume of water present and geologic structures above the aquifer, hot water, steam, superheated water, or some combination can be produced. Virtually all exploitable U.S. hydrothermal resources are in the western states (Figure 2.2)

Figure 2.1



Basic Model of a Hydrothermal Field

Figure 2.2



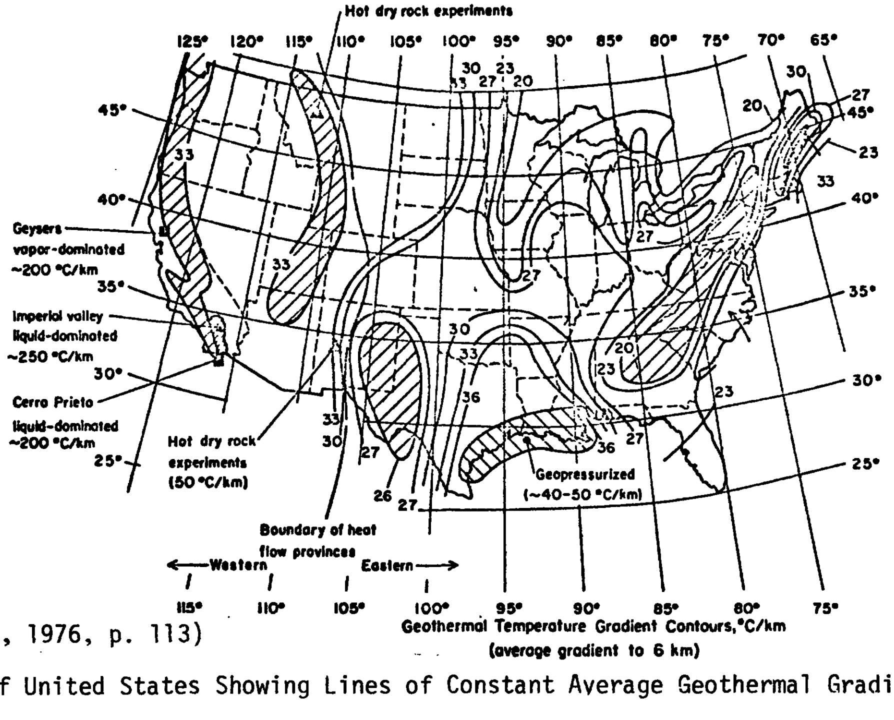
Distribution of U.S. Geothermal Resources

from (Dept. of Interior, 1973, Vol. I., P. II-17)

Geopressurized resources occur deep in sedimentary basins when steam and gases are trapped under pressure. Methane is the usual gas and contributes both kinetic and chemical energy. In the coastal regions of Texas and Louisiana geopressurized brines are found (Figure 2.2).

Hot dry rocks include all rock formations where insufficient rock permeability or a lack of water prevent the existence of a natural heat transfer agent. Hot dry rocks are more widespread than hydrothermal or geopressurized resources (Figure 2.3) but are also harder to locate and quantify accurately.

Figure 2.3



from (Milora and Tester, 1976, p. 113)

Map of United States Showing Lines of Constant Average Geothermal Gradient

Magma or molten rock is present at volcanic sites, where it is called lava, or at very great depths (25 km or more).

Characterization by energy form gives the following groups: vapor-dominated, liquid-dominated, geopressurized, and magma. Vapor-dominated resources are those in which the energy form is primarily dry steam. Liquid-dominated resources, contain superheated or hot water, perhaps mixed with steam. Geopressurized resources can deliver energy as a pressurized mixture of gases and steam or as pressurized gases and brine. Magma resources provide a supply of molten rock.

Grouping by geologic structure is most useful when considering the extent of resources. Grouping by energy form is of greater value when considering the technologies available for converting extracted energy into electricity. The liquid and vapor dominated energy forms are rearrangements of the hydrothermal and hot dry rock resource groups.

2.1.2 Resource Magnitude

What is the extent of the available resources? This is a difficult question to answer because of the inaccessibility of most of the resources. In drilling for petroleum or gas, it is recognized that a necessary condition for the accumulation of hydrocarbons is a sedimentary basin where large quantities of organic matter have collected. The existence of such a geological structure may offer the conditions for the existence of commercial oil or gas deposits, and is therefore evidence of a possible field. Similarly, a number of criteria can be used as indicators of a possible geothermal resource, since there is general agreement that it is the approach of magma towards the surface (7-10 km) which causes geothermal resources to exist.

The occurrence of recent volcanic activity, or the discovery of surface thermal manifestations are common criteria for the presence of geothermal potential. These indicate a likelihood that hot, molten rock is near the surface. If sufficient water is present and if there is permeable rock, a hydrothermal resource may exist. Hot dry rocks and magma have little or no surface manifestation. These criteria are not essential to geothermal resources which may be "capped," i.e., which may have an impermeable, intact rock layer between the hot rocks, magma, or hydrothermal source and the surface.

Certain geological environments are also conducive to possible geothermal action. The two most likely are rift valleys and fault zones. In rift valleys, two continental masses or "plates," which are like ships afloat on the molten magma of the earth, tend to form a separation or rift as they float apart. Molten rock from deep in the earth then oozes into the separation toward the surface. Fault zones also tend to occur because of motion of the continental masses. Whereas rift valleys result when the masses move apart, fault zones can result when the masses move along each other. The friction of their movement creates stresses, periodically released as earthquakes, and fractures the crust, allowing molten rock to approach the surface.

To date, geothermal resources that have been developed for commercial use have relied on surface manifestations for their discovery. The oldest commercial geothermal field, for generating electricity (as early as 1904) is the Larderello field in Italy. In this country, the Geysers in California (390 MW) is the largest commercial operation. Both are situated in areas where volcanic activity has occurred in recent geological times (Quaternary Period: 0 - 2,000,000 years ago). In Japan, Mexico, Russia, and Iceland, geothermal systems are located on or near active volcanoes (Facca, 1973, p. 62).

The first problem in estimating resources of geothermal energy is the difficulty in assessing the presence of deep-seated intrusions of molten rock. The second problem is estimating the potential removal of energy (form and rate) from the resource. Our major commercial experience has been limited to hydrothermal resources, which make up a small fraction of the potential resource. Based on geological surveys and extrapolation of our limited geothermal experience, several groups have estimated the extent of geothermal resources in the United States. (Muffler and White, 1972), (White, 1973), (Rex and Howell, 1973). The most recent data is shown in Table 2.1.

Table 2.1

Geothermal Resources

in Quads

1 Quad = 10^{15} Btu

	ERDA-86*				USGS CIRCULAR 726**			
	Identified Resource		Recoverable Resource***		Identified Resource		Recoverable Resource***	
Resource Type	Known	Inferred	Known	Inferred	Known	Inferred	Known	Inferred
Hydrothermal								
Vapor dominated	100	100	2	2	104	200	-	1420
Liquid dominated								
High Temperature (> 150° C)	1500	4900	20	110	1470	6350	-	
Low Temperature (90°C < 150°C)	1400	4100	80	250	1370	5560	-	
Geopressurized	44000	132000	100	230	43300	17400	-	2180
Hot Dry Rocks	48000	150000	600	1900	31.7×10^6	31.7×10^6	-	317000
Magma	52000	150000	650	1900	99160	397000	?	?
TOTALS	146910	441100	1472	4162	31.8×10^6	32.3×10^6	-	320600

*(ERDA, 1975, p. I-5)

**(White and Williams, 1975) as shown in (Milora and Tester, 1976)

***Electricity production, present or near-term technology, without regard to cost.

To put the data in Table 2.1 in perspective, consider that in 1976 the entire energy consumption of the United States was about 98 Quads (1 Quad = 10^{15} Btu). Table 2.1 also does not include resources having a temperature rise above ambient of less tnan 15°C. These resources probably would have no application for electricity production, but might provide process heating or district heating (Table 2.2). There are considerable uncertainties in estimates of this type; it seems clear that, despite the uncertainties, geothermal resources are large enough to have an impact on our national energy economy. The critical questions are how soon and by what methods can geothermal energy be extracted? These questions involve the technology of geothermal energy prospecting, extraction, and conversion, which are addressed in the following sections.

Table 2.2
Principal Utilization (other than for Electricity)
of Geothermal Resources

USE	LOCATION
Space Heating	Iceland Hungary U.S.S.R. New Zealand Klamath Falls, Oregon Boise, Idaho
Air Conditioning	New Zealand
Agricultural Heating	Iceland U.S.S.R. Hungary Japan Italy Lakeview, Oregon
Paper Processing	
Paper	New Zealand
Diatomite	Iceland
Salt	Japan
Byproducts	
Dry Ice	Imperial Valley, California
Boron	Italy
Calcium Chloride	Imperial Valley, California

2.2 Geothermal Prospecting

Our scientific understanding of the earth's geothermal processes is incomplete. The knowledge we do have comes from surface exploration techniques and the technology developed from exploration for oil, gas, and mineral resources. Two types of exploration are being used: intrusive and non-intrusive.

2.2.1 Non-Intrusive Exploration

Non-intrusive exploration involves techniques which do not rely upon drilling into the potential geothermal resource to identify its characteristics. The advantage of non-intrusive exploration is its ability to consider large areas in a short time, with relatively small investments in manpower or equipment. This advantage is offset by the high uncertainty and lack of detail in results from non-intrusive methods. Seeking out geysers, fumeroles, hot springs, or lava flows is the most direct non-intrusive method. Unfortunately, these surface manifestations need not always exist, or may be deflected laterally many kilometers from their source by impermeable capping rock structures. For example, the closest water discharges are 7 km away from the center of heat upflow in the Russian Ahvachapan Thermal System (Armstead, 1973, p. 36).

Aerial infrared photography has been used to locate surface manifestations. Data collection and interpretation can be difficult, and many large geothermal resources do not exhibit abnormal surface temperature gradients. The Geysers in California and the Larderello Field in Italy, which are the largest producing systems in the world, exhibit "meager surface manifestations" (UNESCO, 1973, p. 36).

Geochemical methods have been increasingly applied to evaluate potential hydrothermal resources. Physiochemical parameters such as the concentration of arsenic and mercury in groundwater are circumstantial feasibility evidence in the planning of geothermal development. Usually these methods do not offer much help in locating completely new sources (Sigvaldason, 1973) (Stoker, 1975).

Geophysical prospecting relies on the study of the earth's structural behavior to indicate areas where geothermal instrusions of molten rock may have occurred. Signs of tectonic activity (the movement of the floating contenental masses on the sea of magma), such as faults, increase the possibility of intrusions. Gravity and magnetic surveys can delineate major geological structures while ground noise measurements and observation of microearthquakes can identify geothermal reservoirs. Study of the basic rock formations also gives information about the recent activity of a region. Since rocks conduct heat very slowly, intrusions from hundreds of thousands of years ago (Quaternary age) may still contain sufficient heat to warrant exploitation.

2.2.2 Intrusive Exploration

Usually non-intrusive exploration provides a first-pass assessment of a region's geothermal potential. Before any planning for geothermal facilities begins, intrusive methods are applied in an attempt to quantify the extent of the possible resource and the characteristics of its energy supply.

Intrusive methods for hydrothermal resources usually involve drilling several test wells and empirically measuring the quantity and quality of the resource. Such testing takes considerable time and money. Deep drilling (> 5 km) is often required since younger intrusions of molten rock have not yet diffused upwards significant amounts of heat. If successful test wells are found (one out of four typically [Milora and Tester, 1976, p. 79]), analysis of the heat content, pressure, chemical composition, and flow rates of the vapor or liquid must be performed to estimate the reservoir size.

Measurement of electric conductivity has had great success in geothermal exploration for hydrothermal sources. Because the earth's electrical resistance varies directly with temperature, porosity and salinity of interstitial fluids, hydrothermal reservoirs have high conductivity. Direct current measurements are usually made (Muffler, 1973, p. 258).

Intrusive exploration for hot dry rocks is not as well developed as with hydrothermal systems. Test wells can be drilled to determine temperature gradients, but there must be artificial methods applied to extract the heat. Usually these methods involve fracturing of the hot rock. The success of the fracturing depends on the extent and porosity of the fractured region. No methods, except experimentation, exist at present for determining fracturing potential in a region.

Geopressured resources can be explored much like hydrothermal. However, it is less likely that there will be noticeable heat above a geopressured resource because two of the major factors contributing to the viability of geopressured resources, pressure and methane gas, generate no thermal changes in the surrounding rock.

2.3 Geothermal Energy Extraction

2.3.1 Magma

At present there is no available technology for the controlled removal of energy directly from molten rock, which exists at temperatures in excess of 650°C. Only formative research is under way (Milora and Tester, 1976, p. 7).

2.3.2 Hydrothermal

Depending on the temperatures and pressures in a hydrothermal aquifer, the heated water will escape as steam (a vapor-dominated system), or as hot water (100°C) when a path to the surface is provided (Figure 2.4). As in analogous gas or oil recovery operations, a well drilled into the aquifer will provide the needed path. Critical parameters of the resulting flow include the flow rate (mass/sec), the thermal fluid temperature (°C), and the thermal gradient (°C/km).

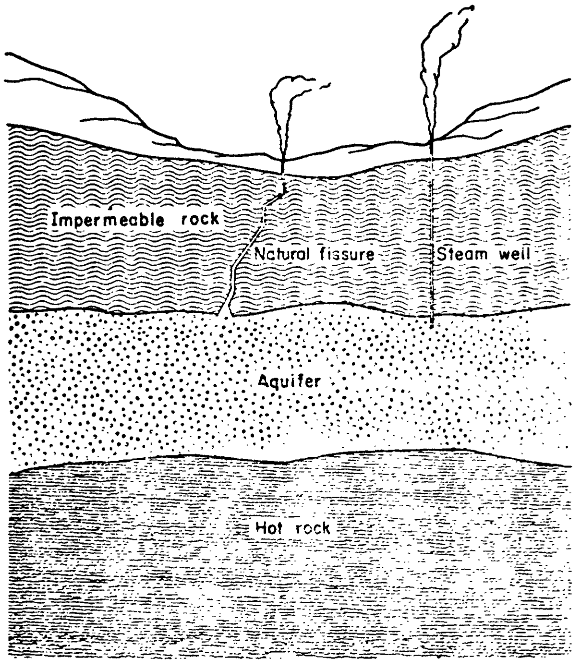
Thermal gradient values are, in general, a function of the type of resource formation. Intrusive exploration can identify regions of greatest thermal gradient within a given resource. Thermal fluid temperature increases with drilling depth since deeper reservoirs are subject to greater temperatures. With a normal surface temperature of 15°C and knowledge of the thermal gradient, one can approximate the drilling depth needed for a desired fluid temperature. This is only an approximation since locally the gradient need not be linear with depth. Complex three-dimensional distributions of temperature are typical, and result from the unknown distributions in space of the original intrusion of heated rock, the intermediary conductive rock, the porous rock forming the aquifer and the capping formation. The fluid flow rate depends on aquifer porosity, which limits the replacement of fluid around the well casing, aquifer pressures and the available flow of water into the drilled region of the aquifer.

The designer can compensate for these natural parameters through choice of drilling parameters, e.g., numbers of wells, diameter of bore and depth. Considerable oil and gas drilling experience is available and depths of over 16 km (Berman, 1975, p. 120) have been achieved. Bore size is related to well depth since the upper casing must allow the passage of later drilling sections. Upper casing sizes range from about 12 to 18 inches in inside diameter. Spacing of wells must be far enough to avoid the extraction of heat energy at a faster rate than it can be replaced with heat from the earth's core. On the other hand, wells should be as close as possible to maximize extraction and minimize piping costs. Spacing on the order of 200-300 m has been suggested in a generalized analysis, but must be designed on a case-by-case basis. Energy losses are typically on the order of 5-10% between wellhead and point of utilization (Armstead, 1973, p. 165).

For most hydrothermal systems, it will be necessary to drill additional wells for reinjection of the fluids removed from the aquifer. This helps to replenish the aquifer and to dispose of the high mineral content fluids after the heat has been extracted. This brinish water presents a surface disposal problem. Reinjection wells are generally simpler than extraction wells which require a permanent casing to prevent turbulent erosion of the well shaft. Often unsuccessful exploratory wells can serve as reinjection wells. Since some fluid condenses, is lost, or is used at the surface for cooling purposes, the total flow down the reinjection wells is less than the extraction rate, so reinjection wells are fewer than extraction wells.

Figure 2.4

Schematic Diagram of a Hydrothermal Reservoir



At the surface the flows from the various wells must be collected and fed to the conversion equipment for electricity production. This requires established pipe construction methods and presents no technical obstacles. In general, it can be said that the technology for commercial vapor dominated or liquid dominated geothermal energy extraction is available.

2.3.3 Geopressured

The technology for extraction of geopressured geothermal energy is essentially the same as for hydrothermal reservoirs. Additional equipment is required to separate and handle the methane which enters the well. Reinjection of brine or condensed steam presents a slightly different problem since the original reservoir is under high pressure. Usually the fluids are reinjected into other formations in the ground as a disposal technique. Gases from geopressured sources are highly corrosive to the well casings and surface piping.

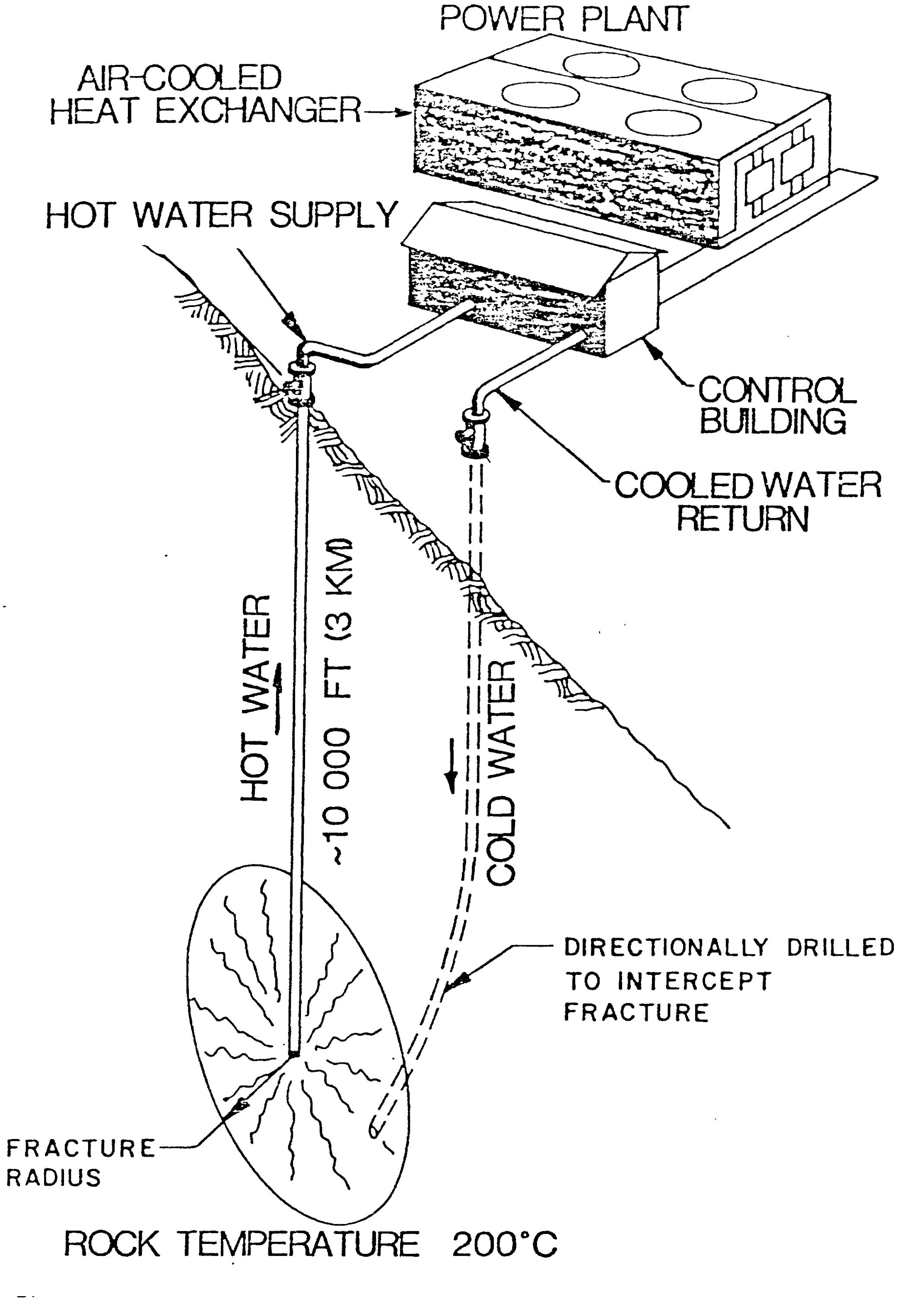
2.3.4 Hot Dry Rocks

Hot dry rocks must be converted into a form of hydrothermal resource in order to extract their geothermal energy. This first involves making the rocks porous through fracturing methods. A variety of techniques such as explosive fracturing, small nuclear devices, or chemical leaching have been proposed in the past. The only prospect being actively investigated involves hydraulic fracturing, (Figure 2.5) (Blair, et al., 1975). Los Alamos Scientific Laboratory has designed a system to hydraulically fracture hot dry rock as follows (Berman, 1975). A hole is drilled until a depth with satisfactory temperature levels is reached and the well casing is inserted. This well will extract the hot water produced later. A second hole is drilled 10-20 m away and sufficient high-pressure water is pumped into the well to cause the rock to fracture. A critical feature is the development of connecting cracks between the two wells which serve as pathways for water. When operating, water pumped down the second well will flow to the first through the cracks and become heated along the way. Theoretically, thermal stresses caused by the flow of relatively cold water over the hot rocks will cause further fracturing and a continual enlargement of the fractured zone (Kruger, 1975, p. 4).

To date, the use of hydraulic fracturing has been demonstrated in granite up to 9600 ft. and 200°C but continuous energy extraction is not yet operational. At the Los Alamos Fenton Hill site a pumping pressure of 1750 psi was used (Smith, 1977, p. 2). The first well was also fractured when no connecting cracks developed from the fracture of the injection well. The resulting fractures are elliptical in a vertical plane and do not intersect. However, connecting cracks have developed between the ellipses allowing the system to operate (Smith, 1977, p. 4).

Figure 2.5

Fractured Hot Dry Rock Geothermal System



Another problem can plague hot dry rock thermal recovery besides the uncertainty of fracture patterns. If the fracture opens to an existing fracture or fault, the wells may lose most of the injected water into the earth instead of collecting it at the wellhead. At Los Alamos this has been only a minor problem as 90-98% of the injected water is ultimately recovered.

Small (10 MWe) demonstration plants for hot dry rock thermal systems may be operating by 1980; under the best conditions two to four 80 MWe plants may begin commercial operation by 1985 (Smith, 1975, p. 6).

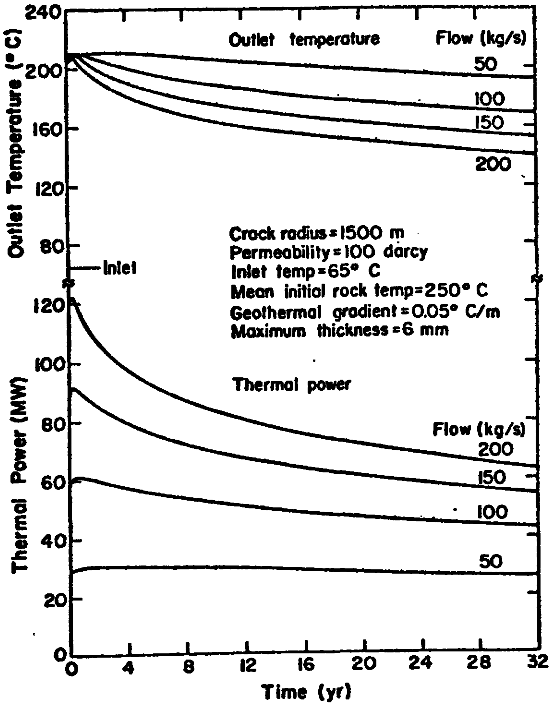
2.4 Reservoir Lifetimes and Production Rates

Because the detailed structure of natural and artificial geothermal resources is not known, it is difficult to predict their lifetime and production rates. Natural vapor dominated reservoirs have maintained output above 50% of initial production rates from less than eight years (the Geysers), to more than 30 years (Lardarello, Italy). Field experience with geopressured and hot dry rock systems does not exist (Milora and Tester, 1976, p. 82).

Hot dry rock systems can be controlled through an equilibrium flow rate and thus may supply an indefinite source of energy. Figure 2.6 shows computer-simulated results for the projected performance of a hydraulically fractured reservoir, indicating the variation of both thermal power and outlet temperature as functions of flow rates.

Figure 2.6

Power and Temperature Drawdown Curves for a 1500 m Radius Crack with No Thermal Stress Cracking (taken from McFarland, 1975).



Numerous problems can arise to limit well life. The most obvious problem is exhaustion of the aquifer supply of steam or hot water, or at least recession of the aquifer below the well opening. Corrosion of the well casing by corrosive fluids can cause shutdown. If reservoir output falls off at a rate such as the Geysers have experienced (drop below 50% in eight years), new drilling will be required to maintain output. Approximately 6% new capacity will be needed each year as old output drops off, resulting in nearly continuous drilling.

2.5 Conversion Technologies

2.5.1 Cycle Efficiency

The maximum efficiency of any engine converting heat to electricity is limited by the second law of thermodynamics which describes an ideal Carnot heat engine:

$$\eta = \frac{\text{work out}}{\text{work in}} = 1 - \frac{T_1}{T_2} \qquad (2.1)$$

T_1 = final temperature °K

T_2 = initial temperature °K

For geothermal generation at the Geysers, where T_1 = 26°C (300°K) and T_2 = 180°C (453°K), η = 33.8%. This is a maximum <u>theoretical</u> efficiency and can be compared to the theoretical efficiency of conventional coal-fired power plants where $\eta \approx 61\%$.

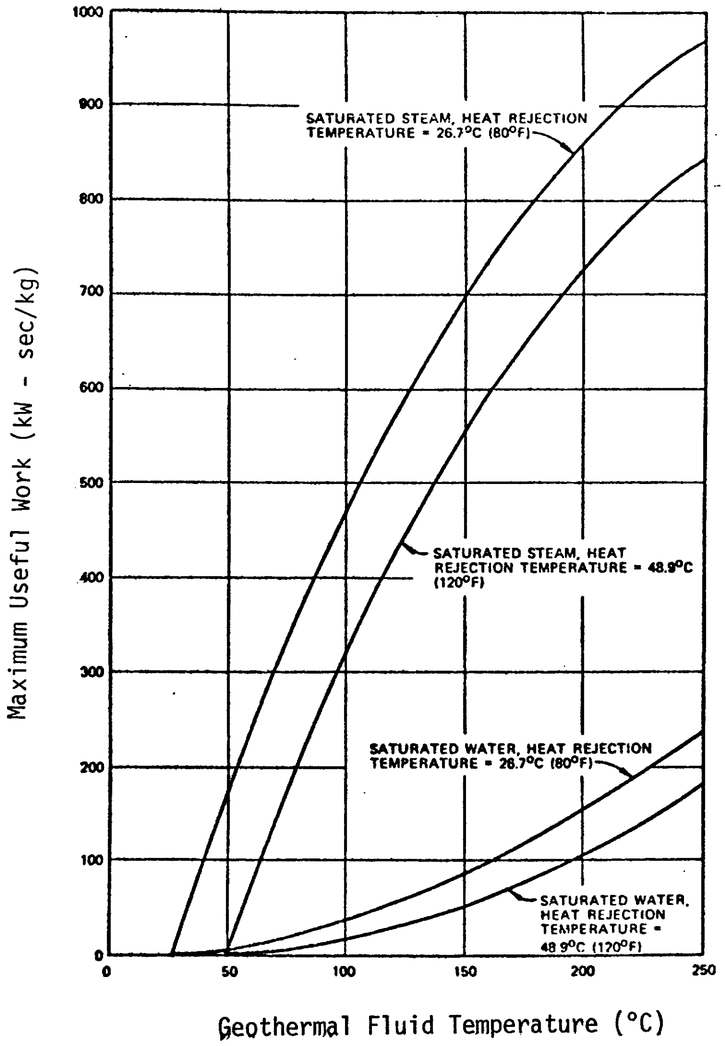
Several observations should be made. First, we can increase our theoretical efficiency by either lowering the engine's final temperature or by raising the input temperature. To raise the input temperature involves obtaining a higher temperature source of steam or water, i.e., drilling deeper. Lowering the final temperature involves a cooling system condenser with an associated heat sink. This could be a body of water or cooling towers (used at the Geysers). The cooling system will have to dispose of four to six units of energy for every one converted to electricity. Second, for a fixed final temperature (henceforth called the reinjection temperature, assuming that the condensed fluids will be reinjected), the theoretical maximum useful work obtainable from a mass of geothermal fluid is a function only of the fluid's initial temperature (Figure 2.7) (Milora and Tester, 1976, p. 17). Any real process will have losses and nonreversible steps which prevent the attainment of these values. Finally, the simplicity of these curves conceals a multitude of practical problems in utilizing the geothermal fluids in conventional electrical generating equipment.

2.5.2 Candidate Cycles

Four basic thermodynamic cycles exist for converting geothermal energy to electricity (Figure 2.8): direct steam flashing cycle, single cycle, dual cycle, and topping/bottoming cycle. As can be seem from Figure 2.8, common elements of each cycle are the turbine, pumps, and condenser. The turbine converts the energy of steam (or other gases) into rotational energy for driving the shaft of the electrical generator (not shown). Pumps circulate liquids and gases through the system. The condenser is a heat exchanger which effectively reduces T_1, the reinjection temperature, and reduces the back pressure at the turbine exit by condensing the exhaust steam from the turbine.

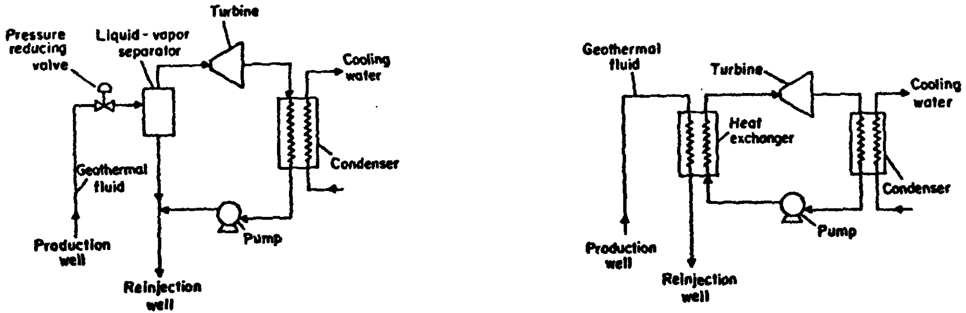
Figure 2.7

Maximum useful work or availability ($\Delta\beta$) plotted as a function of geothermal fluid temperature for saturated steam and saturated water sources.



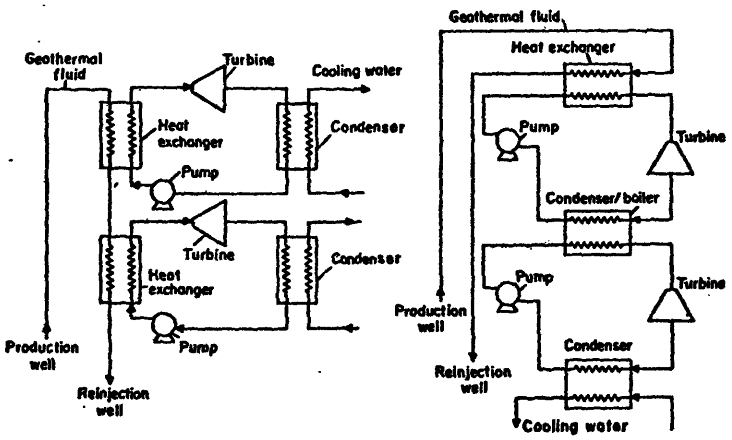
from (Milora and Tester, 1976, p. 17)

Figure 2.8



a. Direct steam flashing cycle

b. Single fluid cycle



c. Dual cycle

d. Topping/bottoming cycle

Schematic of cycle configurations for geothermal power production.

from (Milora and Tester, 1976, p. 5)

2.5.2.1 Direct Steam (Flashing) Cycle

Turbines work best with gases. Liquids in the gases reduce efficiency and eventually can destroy high-speed turbine blades. Consequently, dry steam (containing no liquid water) is the easiest geothermal resource to use. It is also the most scarce resource. Wet steam resources have only 10 to 20% steam in their reservoirs. At present, only the steam portion is used, as in the Wairakei fields of New Zealand (192 MWe). The remaining hot water is reinjected. Figure 2.8a could represent either the dry or the wet steam resources. With dry steam, no separation device to eliminate liquid is needed. With wet steam, the liquid-vapor separation directs the steam to the turbine and the water to reinjection.

This same cycle represents a method of using liquid dominated systems with superheated water ($T > 100°C$). Superheated water exists as a liquid instead of a gas while it is under pressure in the ground at depth. When the pressure is released (as it comes to the surface) the water "flashes" to steam. If the remaining liquid is removed, the cycle operates as if there were a dry steam supply. Efficiency can be improved by having several stages in each of which only a portion of the water is allowed to flash to steam. About 10% of the steam is optimally produced in each multiple flashing stage, causing complex turbine designs. Also, as the water flashes to steam, any dissolved minerals are deposited from the steam. These deposits reduce heat transfer capabilities and eventually foul the system to the point that maintenance is required. Direct steam cycles are the only cycles which have commercial geothermal experience.

2.5.2.2 Single Fluid Cycle

For most liquid dominated systems, the temperature of the extracted water is too low for flashing to steam. In order to produce a gas for driving the turbine, another "working fluid" (typically commercial refrigerants) having a low boiling point must be used (Figure 2.8b) (Table 2.3). A heat exchanger transfers the heat from the geothermal fluid to the working fluid, which in turn vaporizes and drives the turbine. The condenser converts the working fluid back to a liquid and the cycle is repeated. If the resources has a sufficiently high temperature, a closed single-cycle system can even use water as its working fluid. A single fluid cycle can potentially provide more energy per unit of geothermal fluid than can a direct steam cycle (Shitbeck, 1975, p. ii).

Table 2.3

Working Fluid Properties

WORKING FLUID PROPERTIES

Compound	Formula	M g/gmole	T_c K	T_c °F	P_c bar[a]	P_c psia	v_c cm^3/g	v_c ft^3/lb	Z_c
R-11 trichlorofluoromethane	CCl_3F	137.38	471.2	388.4	44.13	640.0	1.804	0.0289	0.279
R-22 chlorodifluoromethane	$CHClF_2$	86.48	369.2	204.8	49.77	721.9	1.9060	0.03053	0.267
R-32 difluoromethane	CH_2F_2	52.03	351.56	173.1	58.30	845.6	2.3277	0.03729	0.242
R-113 trichlorotrifluoroethane	$C_2Cl_3F_3$	187.39	487.3	417.4	34.40	498.9	1.734	0.02778	0.276
R-114 dichlorotetrafluoroethane	$C_2Cl_2F_4$	170.94	418.9	294.3	32.61	473.0	1.7198	0.02753	0.275
R-115 chloropentafluoroethane	C_2ClF_5	154.5	353.1	175.9	31.57	458.0	1.6310	0.02613	0.271
R-13B1 bromotrifluoromethane	$CBrF_3$	148.93	340.2	152.6	39.64	575.0	1.3426	0.02151	0.280
R-600a isobutane	C_4H_{10}	58.12	408.1	275.0	36.48	529.1	4.5220	0.07244	0.283
R-717 ammonia	NH_3	17.03	405.4	270.1	112.78	1635.7	4.2470	0.06803	0.242
RC-318 octafluorocyclobutane	C_4F_8	200.04	388.5	239.6	27.83	403.6	1.6130	0.02584	0.278
R-744 carbon dioxide	CO_2	44.01	304.2	87.9	73.77	1070.0	2.1372	0.03424	0.274
R-290 propane	C_3H_8	44.10	370.0	206.3	42.57	617.4	4.5437	0.07278	0.277
Water	H_2O	18.02	647.3	705.5	221.18	3208.0	3.1077	0.04978	0.230

[a] 1bar = 10^5 Pa

2.5.2.3 Dual Cycle

Under certain geothermal fluid temperature conditions, multiple cycles may produce better efficiency than single cycle fluids. After leaving the first heat exchanger (Figure 2.8c) the geothermal fluid in a dual cycle has given up part of its heat content to the working fluid and is now at a lower temperature. A second cycle, with a different working fluid (having a lower boiling point than the first) can be used to extract additional energy. The economic benefits of higher efficiencies with multiple cycles are quickly lost as larger heat exchange surfaces and extra equipment produce diminishing returns. The Los Alamos Scientific Laboratory uses a dual cycle system in its hot dry rock experiments. Water is used in the first cycle and isobutane in the second.

2.5.2.4 Topping/Bottoming Cycle

This cycle (Figure 2.8d) is similar to the dual cycle in that it attempts to extract energy that would otherwise be lost. In this case, instead of rejecting the heat of condensation from the first working fluid to cooling water, it is exchanged to a second working fluid in what is called a bottoming cycle, a name taken from the condenser's being at the "bottom" of the first cycle. Multiple bottoming cycles are possible, but produce rapidly diminishing economic returns.
A more efficient energy use (although not a source of electricity) applies the "waste" condenser heat to low-temperature needs, such as process or space heating (Swink, 1976, p. 8).

2.5.2.5 Other Systems

Several innovative systems for converting geothermal energy to electricity have been proposed. These may have applications in central conversion plants or at a single well, but will not be commercially available without considerable development. Included in this group are impact turbines, helical screw expanders and bladeless turbines (Kruger, 1975, p. 5) (Austin, 1975, p. 13).

2.5.3 System Design

Basic equipment components are commercially available for electricity production from dry steam and natural high temperature sources (vapor and liquid dominated, $\Delta T > 100°C$). Medium-temperature sources ($15°C < \Delta T < 100°C$) are exploitable with technology such as dual cycles or topping/bottoming cycles which have seen limited use in commercial applications. Commercial use of non-water working fluids in large turbines is very limited. The manner in which these known technologies are combined to form a geothermal energy system design is a complex engineering optimization problem which requires considerable site-specific knowledge. Significant tradeoffs exist between extraction technologies and conversion technologies (Table 2.4) requiring optimization of designs. Dual cycles and topping/bottoming cycles are much harder to optimize than single fluid and flashing cycles. The more complex cycles offer cycle efficiencies which are close to single fluid cycles (15-18%) (Milora and Tester, 1976, p. 52). Lead times for geothermal plant construction have been estimated as at least 8.5 years from initial exploration until operation (Mukhopadhyay, 1976, p. 1).

Table 2.4

Comparison of Optimized Performance of 100 MWe Binary and Two-Stage Flashing Plants

Geothermal fluid temperature = 200°C
Heat rejection temperature = 26.7°C

Working Fluid	Well Flow Rate (kg/sec)	Efficiency η_{cycle} (%)	Net Turbine Power MW(e)	Feed Pump Power MW(e)
R-114	940	16.5	123	23
R-600a (isobutane)	949	17.5	134	34
R-22	951	17.4	134	34
R-32	974	17.0	127	27
R-115	1020	15.1	143	43
RC-318	1090	14.8	123	23
R-717 (ammonia)	1160	18.0	107	7
Dual flash[a]	1093	---	100	0
Dual flash[b]	1250	---	100	0

[a] Heat rejection temperature = 26.7°C

[b] Heat rejection temperature = 37.8°C

from (Milora and Tester, 1976, p. 50)

The distinctive characteristics of geothermal power generation can be summarized as follows: [CEQ, 1975, p. 8-21 (items 1-11)]

1. No combustion of any fuel occurs in a geothermal plant.
2. Low efficiencies result from the low temperature and pressure of the steam. The temperature of the steam entering the turbines at the Geysers is 350°F at 100 psi (75 psi in a hot water field), while inlet temperatures for a modern fossil-fueled plant are 1,000°F at 3,500 psi. The turbine at the Geysers is about 22 percent efficient.
3. The overall plant efficiency for geothermal power production is approximately 15 percent, compared to 35 to 38 percent for a fossil-fueled plant. This means that a geothermal plant requires 22,000 Btu's to generate one kilowatt-hour (kwh) while a modern fossil-fueled plant requires 9,000 to 10,000 Btu's.
4. Due to long, complicated start-up procedures, geothermal units should operate as base-load units rather than peak-load units.
5. Since steam cannot be transported over long distances, geothermal generating plants are relatively small and located in the resources field. At the Geysers, each plant has a 110-MWe capacity and consists of two 55-MWe generators.
6. A 110-Mwe station requires two million pounds of steam per hour or the output of 14 wells at 150,000 pounds per hour each.
7. Direct contact condensers are used in which the steam and cooling water mix directly.
8. No external makeup water for cooling is required. The steam flow to the turbines exceeds the cooling tower evaporation rate; thus, condensed exhaust is used as cooling tower makeup water.
9. In the power generation step, noncondensable gases are released into the air from the condenser and from the cooling tower.
10. In hot water systems, the water or brine is passed through a separator, which draws off steam to drive the turbine, then routed to reinjection wells. Additional water from the cooling tower may also need reinjection.
11. The minerals in the steam cause corrosion and erosion in the turbine, requiring continuous and extensive maintenance.
12. Hot dry rock systems are still in an experimental stage. When operational methods for fracturing rock are available, hot dry rock systems will resemble hot water systems.
13. Hot dry rock systems will have lower efficiencies than natural hot water fields due to pumping losses. Water loss can be a problem.

3.0 ECONOMICS OF GEOTHERMAL ENERGY

3.1 General Considerations

Assessing the economics of geothermal energy presents a difficult problem. Not only are the results dependent on assumptions about economic, financial, and tax issues, but they also vary with reservoir characteristics, extraction and conversion technology, and environmental constraints (Towse, 1975, p. 16). To facilitate systematic projections of geothermal energy costs, researchers have developed computer programs which perform cost calculations for any given set of economic and engineering assumptions (Bloomster, I, 1975) (Bloomster, II, 1975 (Milora and Tester, 1976). Computer output sometimes implies more credibility than its underlying model deserves, and the details of any such models should be verified before using them in a design decision process.

For our purposes, the computerized models form a sufficiently rigorous attempt at identifying and calculating the components of geothermal energy cost. We will look at their structure as much as their output. These models also have been supported by research efforts to identify the range of likely costs for the various components.

In comparing the numerical results of these models, or economic analyses performed by other researchers, we are faced with another problem. Final costs of energy are heavily dependent on economic parameters which tend to vary from researcher to researcher. Comparison between the results of different researchers can be misleading since they are not based on the same assumptions. The safest course is to consider the geothermal-conventional power cost comparisons found in each study, since this is the real issue of interest.

On a historical basis, geothermal costs (1972 dollars) at the most favorable natural locations ranged from 2.5 to 8.0 mills/ KWh (Table 3.1). Using similar assumptions, coal, oil. or gas prices were in the 7.0 - 8.0 mills/KWh range. Of course, fossil fuel prices have risen significantly in recent years so these existing applications have remained attractive.

Table 3.1
COSTS OF GEOTHERMAL POWER GENERATION SYSTEMS
1972 Dollars
(CEQ, 1975, p. 8-18)

Type	Cost (mills per kwh)
Vapor dominated	
Geysers	5.0
Lardarello, Italy	4.8 - 6.0
Matsukawa, Japan	4.6
Hot water dominated	
Wairakei, New Zealand	5.14
Namafjall, Iceland	2.5 - 3.5
Cerro Prieto, Mexico	4.1 - 4.9
Pauzhetsk, USSR	7.2

Projections of geothermal cost show that under favorable reservoir conditions (T > 150°C, flow rates > 45 kg/sec), costs of 20-40 mills/KWh (1976 dollars) are possible, which should make geothermal competitive with conventional base loaded generation (Bloomster, 1975, p. 15), (Milora and Tester, 1976, p. 108). The uncertainty in such estimates must be recognized since the estimates depend on a large number of assumptions about systems with little field experience.

3.2 Cost Components

The costs of geothermal systems can be broken into two broad categories: extraction and conversion. Extraction includes the acquisition of land, exploration, drilling, and maintenance of wells and transmission systems. Conversion includes all of the plant equipment used to produce electricity, such as piping, buildings, and structures, heat exchangers, and turbines, pumps, instrumentation, and controls.

The relationships among the components of geothermal energy costs can be seen in the structure of one of the computerized geothermal cost models (Figure 3.1) (Bloomster, 1975, p. 5). Typically these components can be optimized to yield a design curve (Figure 3.2). Table 3.2 presents the design parameters of the curve. In effect, the minimum point tells us how deep to drill in hot rock systems. In natural hydrothermal reservoirs there is no control over the fluid temperature, and the design of other equipment must compensate for this problem.

Table 3.3 shows the optimized (1986 dollars) cost of several geothermal systems for 18% fixed charges, 100 MW, and 85% load factor based on 1976 estimates (Milora and Tester, 1976, p. 105). A simple escalation rate of 5% per year is assumed. By far, the most critical design parameter is the number of wells and their depths. Well cost estimates are shown in Figure 3.3. Generalizing the results of Table 3.3 to other reservoir conditions, cost variation can be shown as a function of fluid temperature and mass flow rate (Figure 3.4).

A second computer model has projected geothermal costs as shown in Table 3.5. It was found in those computations that for a variety of conversion cycles economies of scale stopped above 100 MWe capacity as transmission costs of steam or water from the wells to the plant offset plant savings. The economics were very sensitive to load factor since so many of geothermal costs are fixed (Figure 3.5).

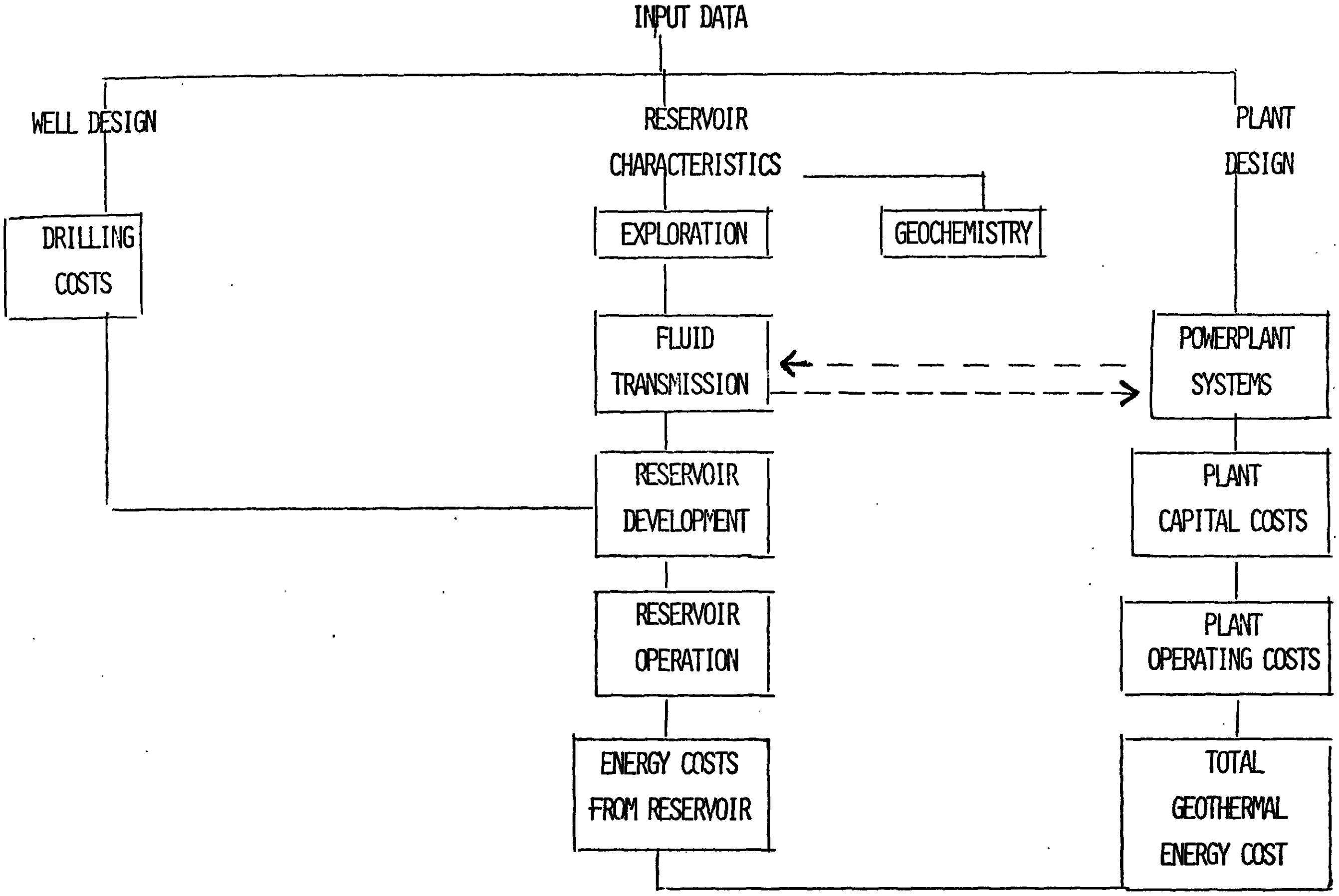
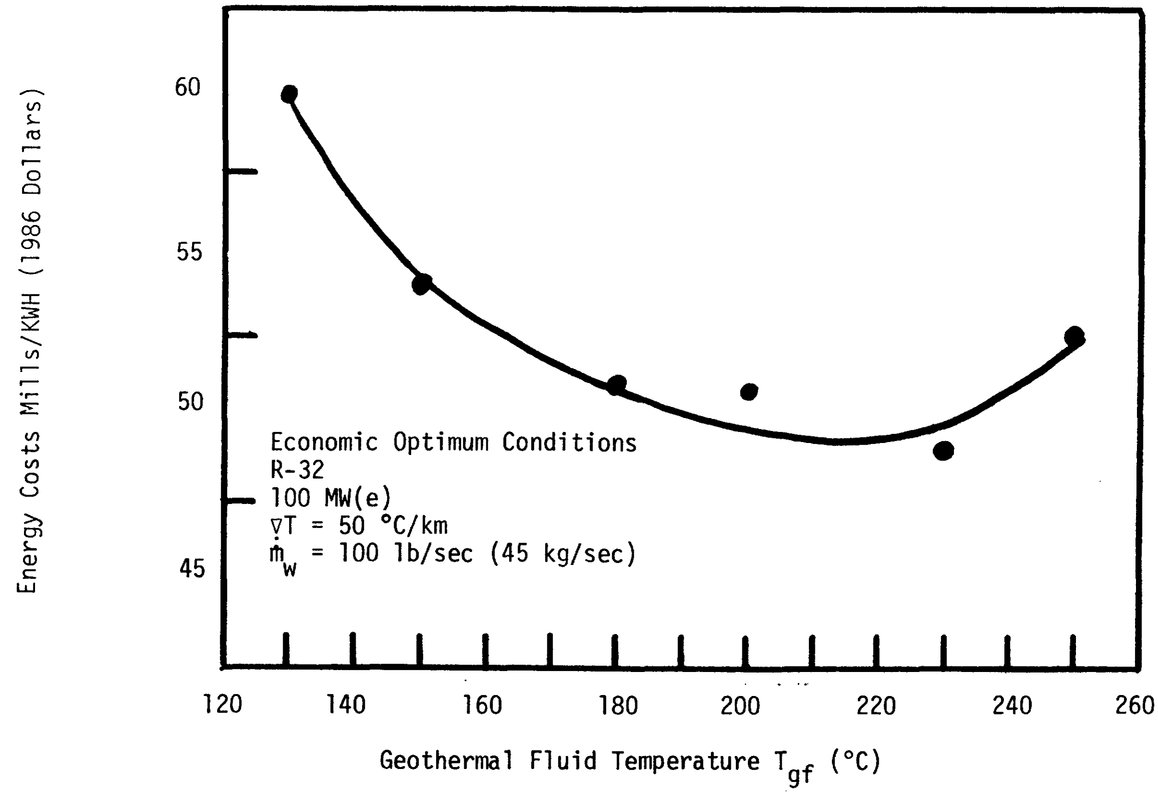


Figure 3.1
Structure of GEOCOST Computer Program for Geothermal Cost Calculations
(Bloomster, 1976, p. 5)



Generating costs versus geothermal fluid temperature for an R-32 binary fluid cycle. Well depths correspond to a geothermal gradient of 50°C/km with heat rejection at 26.7°C. Cost estimates based on 1986 dollars, extrapolated from 1976 data at simple 5% annual escalation.

Figure 3.2

adapted from (Milora and Tester, 1976, p. 108)

Table 3.2

Economic Optimum Conditions for a 100 MWe R-32 Cycle (1976 Dollars)

$\dot{m}_w$ = 45 kg/sec (100 lb/sec) ∇T = 50°C/km

Geothermal Fluid Temp. T_{gf} (°C)	Well Depth (m)	Number[a] of Wells	η_{cycle} (%)	$/KW Installed	1975 ¢/KWH	1986 Dollars[b] Mills/KWH
130	2100	132	12.0	1618	3.83	59.4
150	2500	88	12.9	1463	3.48	53.9
180	3100	54	15.4	1388	3.30	51.2
200	3500	44	15.9	1378	3.28	50.8
230	4100	35	16.5	1333	3.18	49.3
250	4500	29	18.6	1420	3.38	52.4

---

[a] Includes production and reinjection wells.

[b] Assumes 5% simple inflation - MIT

from (Milora and Tester, 1976, p. 109) [Last column added by MIT].

Table 3.3

Cost Summary for a 100 MWe Power Plant (1986 Dollars)

	150°C Geothermal Resource			250°C Geothermal Resource
	R-32 Binary Fluid Cycle 10^6\$	Direct Flashing $T_o = 26.7°C$ 10^6\$	Direct Flashing $T_o = 48.9°C$ 10^6\$	R-717 (NH_3) Binary Fluid Cycle 10^6\$
Equipment	85.3	182.1	60.1	59.0
Wells	134.3	147.4	222.7	34.7
Total Capital Investment	219.6	329.5	282.8	93.7
(1986 \$/KW installed)	2196	3295	2828	937
Annual Costs				
Fixed Charges (18%)	39.5	59.3	50.9	16.9
Operating	0.6	0.6	0.6	0.6
Maintenance	0.9	0.9	0.9	0.9
Power Costs (mills/KWH)	55.2	81.8	70.6	24.7

Simple escalation at 5% per year; 85% load factor.

adapted from (Melora and Tester, 1976, pp. 105-106)

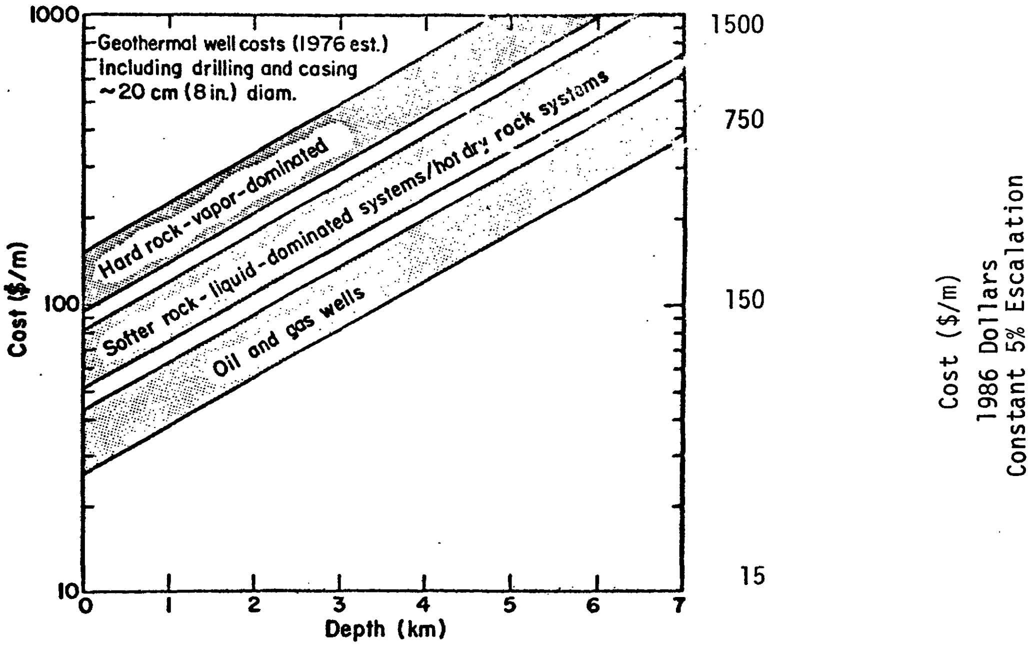
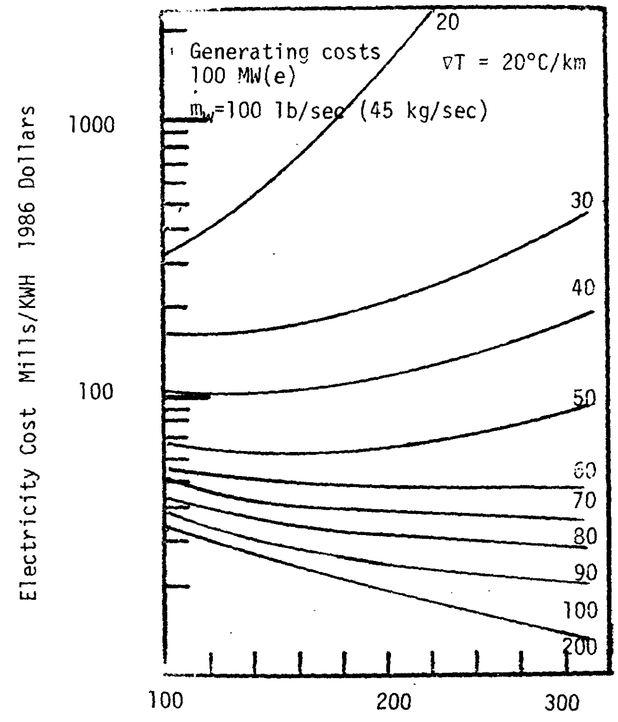


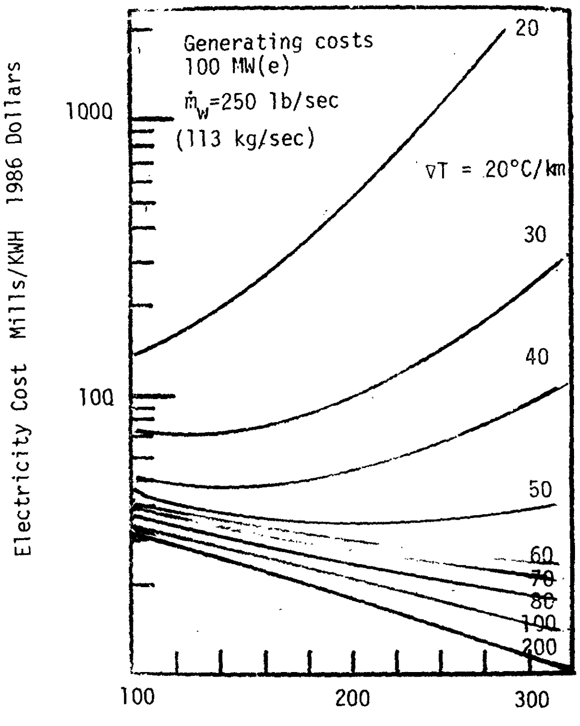
Figure 3.3

Predicted Well Costs as a Function of Depth. Based on 1976 Dollars.



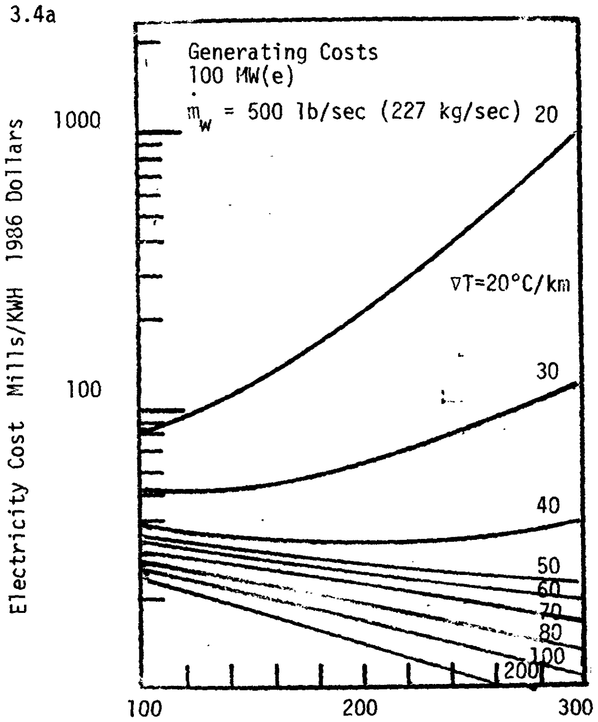
T_{gf} (°C)

Fig. 3.4a



T_{gf} (°C)

Fig. 3.4b



T_{gf} (°C)

Fig. 3.4c

Figure 3.4

Generalized cost model for geothermal systems. Generating costs expressed as a function of well flow rate $\dot{m}_w$, geothermal gradient ∇T, and geothermal fluid temperature T_{gf}. Cost estimates based on 1976 dollars, escalated to 1986 using simple 5% escalation.

Table 3.5

Distribution of Power Costs (200°C Resource)
55 MW Plant Binary Fluid Cycle

RESERVOIR		1975 Dollars (MILLS/KW-hr)	1986 Dollars (MILLS/KW-hr)
Exploration		0.5	0.8
Field Development		3.5	5.4
Producing wells	(1.7)		
Fluid transmission	(0.6)		
Fluid disposal	(0.9)		
Non-producing wells	(0.3)		
Field Operation		3.5	5.3
Producing wells	(0.7)		
Fluid disposal	(1.1)		
Fluid transmission	(0.6)		
Other	(1.1)		
State Income Tax		0.1	0.2
Federal Income Tax		0.7	1.1
Royalty Payment		1.0	1.6
Bond Interest		0.5	0.8
TOTAL*		9.8	15.2
POWER PLANT			
Initial Plant		2.7	4.2
Interim Capital Replacement		0.1	0.2
Energy Supply		12.0	18.6
Direct	(9.6)		
Excess for internal power consumption	(2.4)		
Operating Expenses		0.3	0.5
Property Taxes and Insurance		0.9	1.4
State Revenue Taxes		0.7	1.1
State Income Tax		0.1	0.2
Federal Income Tax		0.7	1.1
Bond Interest		0.7	1.1
TOTAL *		18.2	28.4
TOTAL POWER COSTS		28.0	43.6

from (Bloomster, 1975, p. 15)

*Total may not add because of rounding.

4.0 ENVIRONMENTAL EFFECTS

Little experience exists for determining the environmental effects associated with geothermal energy extraction, especially for experimental hot dry rock technologies. The effects are likely to depend strongly on the physical, thermodynamic, and chemical properties of the reservoir, and will therefore be site-specific. Impacts can be expected from drilling, reservoir development, surface collection system construction and operation and conversion plant construction and operation. Since reservoirs will continually need replacement or stimulation, reservoir development impacts would continue through the life of the facility.

4.1 Land Use

About an acre of land is required for drilling and reservoir development operations at each well. This land can be compatible with limited other uses (forestry, crops, grazing) once equipment is in place. Land required for the conversion plant is greater than that of a similarly sized fossil plant. On a total fuel-cycle basis (i.e., considering land used for fuels extraction), geothermal plants are comparable to fossil plants; of course, all land use is localized with geothermal energy while fossil fuel extraction would not occur in Maine.

4.2 Noise

Noise problems arise from several oeprations, including drilling and testing of wells and the release of vented steam. Mufflers can be placed on wells to reduce steam discharge noise. For liquid dominated and hot dry rock systems, noise will be caused by drilling operations. Since little or no steam is released, testing of wells and plant operation should be comparable to conventional fossil units.

4.3 Air Pollutants

Hydrothermal reservoirs typically contain a variety of dissolved gases which can be released to the atmosphere when vapor or liquid-dominated sources are utilized. Some of these, such as mercury and radon, could accumulate in the environment of geothermal facilities. Others, such as methane, hydrogen, carbon dioxide, nitrogen, ammonia and hydrogen sulfide, do not accumulate but can be irritating or require removal. It is not known what effluents hot dry rock systems will release, if any.

4.4 Water Pollutants

Water pollutants are naturally dissolved in hydrothermal systems and can be leached by the circulating water of hot dry rock technology. These pollutants pose problems in several ways. During reinjection of fluids, existing groundwater supplies may be contaiminated. If pollutants such as mercury or arsenic are present, a hazard may be created. Scaling and deposition of materials such as silica or calcium carbonate can occur in the geothermal system. When these materials are discarded leaching into the groundwater may occur.

4.5 Heat Discharges

Geothermal plants are less efficient than conventional technologies and therefore reject more heat into the environment per unit of electricity produced. Counteracting this problem is the smaller size of typical geothermal facilities, resulting in wider dispersal of heat discharges. Use of conventional cooling technologies can avoid the need for discharging heat into rivers or lakes, where even relatively small temperature rises can upset the ecosystem. However, cooling towers can require makeup water and cause aesthetic objections because of their size, drift, noise, odor, etc. Hot dry rock systems, which have closed cycle circulation of water may be able to reject some heat by reinjecting cool water. This may even prolong reservoir life.

4.6 Seismic and Subsidence Effects

The removal of water from aquifers for irrigation has been known to produce microearthquakes and surface subsidence. Similarly, open loop (no reinjection) geothermal systems might produce instabilities as water is removed from rock formations and internal pressures are reduced. Such behavior has been observed in New Zealand where the surface has, in places, subsided 12 ft. in 20 years of operation (Milora and Tester, 1976, p. 11). Dry hot rock systems and systems employing reinjection should experience fewer seismic and subsidence effects.

5.0 GEOTHERMAL IN MAINE

No Maine hydrothermal sources have been identified by the geothermal surveys conducted for the U.S. Geological Survey (White and Williams, 1975). Maine appears to have a region (along the Appalachian fold) with somewhat higher average thermal gradients than much of New England (Figure 2.3). This could possibly be a future site for use of hot dry rock technology.

It seems clear that Maine will not be a likely location for even serious geothermal exploration for many decades. The less ambiguous resources of the western states will be developed first, probably followed by the geopressurized resources of Texas and Louisiana (EPRI, 1977, p. 13).

6.0 CONCLUSIONS

- Uncertainty and lack of data have produced widely ranging estimates of the geothermal resources of the U.S. Present electricity production from geothermal energy is only 500 MW.

- Existing production of electricity relies upon scarce dry steam resources. Hot dry rock technology may produce commercial plants in the mid- to late 1980's, but is now experimental.

- Estimates of hydrothermal costs range from 27 to 89 mills/KWH in 1986 dollars, depending on resource characteristics and recovery technology.

- Insufficient data exist to estimate electricity costs from hot dry rock systems.

- Environmental impacts of geothermal systems appear to be manageable and comparable to conventional fossil technologies.

- Geothermal energy will not contribute to Maine's electricity supply until after 2000.

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