GEOTHERMAL DEVELOPMENT

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I. TOTAL KNOWN RESOURCES AND RESERVES

A. Calculated Geothermal Resources

The heat content of the earth is immense. How much, no one knows for sure, but it is not conceivable that man could ever exhaust it, assuming he could find a way to make it all available. Much effort has been expended in estimating and guessing at the size of the geothermal resource. Many assumptions have to be made and one is never quite sure what mix of theoretical, practical and promotional elements may be contained in the estimates.

Some of the calculations of geothermal potential are reminiscent of an old high school chemistry exercise which calculated the weight of the gold in the sea. The calculation shows 56 pounds of gold per cubic mile of seawater which would be worth about $130,000 at today's prices. With the sea containing over 320,000,000 cubic miles, its gold content is worth over $41 trillion.

The real question, of course, is what can be extracted in a practical and economic manner. While there is probably little gold likely to be extracted from seawater, we do know that of the vast geothermal resource, the small part that can practicably be used will be important. Calculations of the total resource within defined paramters do serve a useful purpose in furthering our understanding of the enormous base of energy with which we are dealing. But, these estimates should never be confused with what may be realistically obtainable. D. E. White* estimates the resource in the top ten kilometers of the earth at 3×10^{26} calories. Under the United States alone, his estimate indicates 6×10^{24} calories. This is many orders of magnitude above what can be considered as a recoverable resource base.

Our real challenge, then, is to learn more about the nature of geothermal energy, to find where it is accessible, and then to learn how to develop and use it at reasonable cost. Only then can this resource be mined in a competitive, commercial manner.

B. Practical Resources

Making estimates of the practical or economically recoverable geothermal resources is a relatively easy task. Supporting those estimates with solid data and proven technology is not only infinitely more

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* Geothermal Energy; edited by Kruger and Otte

difficult but actually impossible because supporting data and technology are non-existent. Consequently, we find estimates all too often severely shaded by the analyst's individual optimism or pessimism. Table 1, following, shows a few of the many estimates that have been made. The table has been included here not to define the size of the recoverable resource, but rather to illustrate the very broad range of thinking which reflects the uncertainty attached to this fledgling industry. Most estimates have some rational basis, and it is generally unfair to criticize them out of hand. Others, unfortunately, have been designed to promote geothermal energy as a kind of exotic and glamorous source, and to thrust aside the need for continuing development of fossil-fueled and nuclear energy production. Those engaged in drilling and utilization tend to arrive at conservative estimates based more on what is proven than what might be projected. The California Geysers development is the most explored and developed geothermal area in the world. Information on the field has been accumulating since the early 1920s and especially since significant utilization began in 1960. Periodic reassessments of the resource have increased confidence and commitment so that over 900 megawatts are scheduled to be in operation by 1977. But, even in this well-studied area, the size of the resource is uncertain. Some wells drilled in the Known Geothermal Resource Area (KGRA) have failed to produce steam while other wells to be drilled outside the defined KGRA are almost sure to produce steam. It is clear that there is more energy that can be developed but that the ultimate size of the resource is not known. It can best be defined through a careful, evolutionary-type drilling program.

From the information now available, it appears highly unlikely that the amount of geothermal energy will ever supply more than 10 percent of the nation's needs. Indeed, it is doubtful that, even with the several attractive geothermal developmental areas in California, geothermally-produced electricity will ever exceed 10 percent of the State's requirements. This does not indicate, by any means, that geothermal energy is an unimportant source. The future electrical energy growth rate in California alone is very large and a 10 percent share is likewise substantial.

II. RESERVES PRESENTLY AVAILABLE AT GIVEN PRICES

A. Status of Geothermal Power Use

For centuries, man has used natural hot waters and steam for heating, bathing and therapeutic purposes. In a few areas, wells have been drilled to produce steam or hot water for space and process heating and electric power production. In Reykyvail, Iceland, geothermal energy is used by about 100,000 people for residential heating. In New Zealand, a pulp and lumber facility uses it for process heating. In a number of places in Europe and Asia, geothermal energy is used to heat greenhouses for year-round crop production. In Klamath Falls, Oregon and in Boise, Idaho, it has long been used for space heating in several hundred buildings.

TABLE 1

PARTIAL TABULATION OF ESTIMATES OF GEOTHERMAL POTENTIAL AT THE CALIFORNIA GEYSERS AND IN THE UNITED STATES

Megawatts of Electrical Generation	Year Corresponding to the Level of Generation	Attributed To	Publication	Date of Publication	Comments
California Geysers - Known Geothermal Resources Area					
2,000	Ultimate	J.P. Finney*	Public Utilities Fortnightly	1/31/74	*Project Engineer for Pacific Gas & Electric Co. Geysers development. Estimate based primarily upon the size of resource exposed by completed drilling, with little extrapolation for unproven areas.
4,800	Ultimate	Geothermal Resources Board of California	Economic Potential of Geothermal Resources in Calif.	1/71	
25,000	Ultimate	Dr. R.W. Rex	USAEC Hearing, Diablo Canyon Nuclear Units, Dockets Nos. 50-275; 323	5/19/72	Corresponds to the production of the entire geothermal area at same rate per acre as the presently developed area.
United States					
3,000 to 19,000	1985	National Petroleum Council	U.S. Energy Outlook	12/72	Range depends on price, technological development, and the degree of institutional and ecological impediment
20,000 to 30,000	1985	Interagency Panel for Geothermal Energy Research	Report to Office of Management & Budget	6/10/74	

TABLE 1 (contd.)

Megawatts of Electrical Generation	Year Corresponding to the Level of Generation	Attributed To	Publication	Date of Publication	Comments
132,000	1985	Walter J. Hickel	Geothermal Energy, from estimates reported at the 1972 Geothermal Resources Conference	1972	Assumes development of hydrothermal, geopressured, hot rock, and magma systems
6,000	2000	Dr. Chauncey Starr**	Energy and Power Scientific American	9/71	**President of the Electric Power Research Institute
200,000	2000	Interagency Panel for Geothermal Energy Research	Report to Office of Management & Budget	6/10/74	
395,000	2000	Walter J. Hickel	Geothermal Energy, from estimates reported at the 1972 Geothermal Resources Conference	1972	Assumes development of hydrothermal geopressured, hot rock, and magna systems
2,850***	Ultimate	D.E. White	Geothermal Energy; Edited by Kruger and Otte	1973	Includes proved, probable, reserves at 1972 prices and technology
9,500 to 19,000***	Ultimate	D.E. White	Geothermal Energy; Edited by Kruger and Otte	1973	Hydrothermal systems only, Assumes 50% increase in price
4,750 to 190,000,000***	Ultimate	R.W. Rex and D.J. Howell	Geothermal Energy; Edited by Kruger and Otte	1973	High figure based on undiscovered hot rock systems at much higher prices than present

*** Original estimates were given in the form of megawatt-centuries. For comparison purposes, they have been converted to megawatts of installation based upon a 30-year life of plant operating at 70% capacity factor.

The most dynamic use, however, is conversion of geothermal energy into electrical form. In that form, it can be moved great distances and put to innumerable uses. Table 2, following, summarizes the world development of geothermal electric generation. The summary shows that geothermal power, however important it may be locally, still represents only a very small percentage of the total electric power generation of any nation

The first production of electric power from natural steam occurred at Lardarello, Italy in 1904. This area now produces 365 megawatts from a dry-steam or vapor-dominated geothermal reservoir. The Wairakei and Kawerau fields of New Zealand are liquid-dominated resources from which 202 megawatts have been developed using steam flashed from hot water wells. In Northern Mexico, the 75 megawatt Cerro Prieto plant was recently commissioned for use of steam flashed from hot brine having about the same salinity as seawater. Geothermal power installations in Russia, Japan and Iceland are relatively small.

The most rapidly expanding development is at The Geysers field in California. (This is not truly a geysers, but rather a fumarole area.) Technology for utilization of dry steam at this location has been reported upon in considerable detail.

Those who have worked with geothermal resources recognize fully that geothermal steam, hot waters and brines represent valuable and important resources for the future development of electrical power, as well as other potential uses. However, these resources must be developed in a rational and practical manner. Pacific Gas and Electric Company has been deeply involved and is enthusiastically pursuing the development of geothermal energy for production of electricity. At the same time, it rejects the fallacy that geothermal energy is the panacea for all of the world's energy problems, its pollution problems, and, above all, that it is available today simply for the taking.

No one can hope to be completely objective in areas where he is individually involved. Nevertheless, the following comments on geothermal electric generation review the case in a fair manner from the utility perspective. It is hoped that these comments will contribute constructively to a timely and economic development of the resource.

B. The Geysers

In the 1920s, a number of test steam wells were drilled in the Imperial Valley and at The Geysers in California. However, relatively inexpensive hydroelectric power was then abundant, and the potential for generating power from geothermal sources was not economically attractive. Furthermore, there also were some unknown, untested problems associated with the use of geothermal steam. The resource was in a remote area which would not justify expensive transmission installations for the relatively small size of units that would have been practical in that era. Nevertheless, developers continued to pursue its possibilities.

In the late 1950s, following the commendable drilling and developmental effort at The Geysers by the pioneering Magma and Thermal Power companies,

TABLE 2

WORLDWIDE STATUS OF GEOTHERMAL POWER DEVELOPMENTS

Country	Approximate 1973 Geothermal Electric Capacity (Megawatts)*		Reservoir Fluid*	Power Cycle F, Flashed Steam D, Dry Steam B, Binary	1972 Total Electric Installation Megawatts**	Geothermal As a Percent of Total Electric Installation
Iceland						
Namafjall		3	Hot Water	F	400	0.76
Italy						
Lardarello	365		Steam	D		
Monte Amiata	25		Steam	D		
Total		390			36,000	1.1
Japan						
Matsukawa	20		Steam	D		
Otake	13		Hot Water	F		
Total		33			76,000	0.043
Mexico						
Cerro Prieto		75	Hot Water	F	8,000	0.95
New Zealand						
Wairakei	192****		Hot Water	F		
Kawerau	10		Hot Water	F		
Total		202			4,000	4.15
U.S.A.						
Geysers		396***	Dry Steam	D	419,000***	0.095
U.S.S.R.						
Pauzhetsk	5		Hot Water	F		
Paratunka	1			B		
Total		6			175,000	0.003
Total World		1,105				

* Geothermal Energy, by P. Kruger and C. Otte, 1973
** UN Statistical Yearbook, 1973
*** 1973 Figures
**** Wairakei Geothermal Project; New Zealand Ministry of Works, March 1972

Pacific Gas and Electric Company became interested in testing the feasibility of geothermal electric generation. The resource appeared promising, and contracts between the utility and the steam developers were signed to cover a program of continuing installation of geothermal electric generation. Expansion was geared to further exploration and successful production of additional steam. These contracts led to the first commercial production of electricity from geothermal energy in the Western hemisphere. This 1960 event initiated an ever-increasing interest in the future potential of geothermal resources.

The first small unit (11 megawatts) provided the basic economic and technological data for using this local dry steam resource. As confidence grew, the size of the units also grew. The largest now in operation is 53 megawatts, the largest under construction is 106 megawatts, and the largest planned is 135 megawatts. With the installation of the ninth and tenth units in 1973, The Geysers project became the largest geothermal power installation in the world with an output of 396 megawatts. Thus, in less than 15 years, the use of geothermal energy for electric power production in Northern California has progressed from the status of an R&D project to that of an important supplemental power source.

Five additional power units are scheduled to become operational in the years 1974 through 1977. This will raise the output of The Geysers project--still the only commercial geothermal-electric development in the United States--to more than 900 megawatts. Beyond that, about 110 megawatts of additional capacity are planned for installation each year through 1983. Annual reappraisals of the potential of the steam field probably will justify continuing the development many years beyond 1983. Addition of new generation at a rate greater than 110 megawatts a year is possible if the steam suppliers accelerate their resource development program.

The combined investment of the steam developers and Pacific Gas and Electric Company in this project is now about $100 million.

Because of the relatively low pressure and temperature of the natural steam, the physical size of equipment per megawatt of generation is relatively large. The secondary-class access roads into the mountainous area impose limits on the weight and dimension of equipment which can be transported to the steam field. Fortunately, the economic unit size and road limitations are closely compatible. Relatively small units provide a reasonable economic balance between the cost of delivering steam from distant wells and the lower cost per megawatt of installing larger generating units.

C. The Economics of Geothermal Power

There is little information upon which to base a price-availability relationship for geothermal energy except from The Geysers development. The price paid for steam at The Geysers is adjusted in relation to the cost of alternative sources of thermal power. These price adjustments apply to all the steam whether delivered to old or new generating units.

Precipitous increases in steam price, therefore, follow the dramatic increases in cost of fuel oils which soon will become the primary alternative heat sources for electrical generation in this area. The price paid for steam initially was 2 mills for each kilowatt-hour of electricity generated. Under the contract price formula, it is estimated that in 1977 when Unit No. 15 goes into service, steam will cost over 7 mills per kilowatt-hour ($8.00/barrel for fuel oil).

Obviously, the cost of geothermal power will depend to a considerable degree upon the quality of the energy. Ideally, it would be in the form of dry steam under very high temperature and very high pressure, but nature has not offered it in this form. Developers willing to accept what nature does offer see no insurmountable technological problems with using superheated waters or low-quality steam. It must be recognized, however, that The Geysers area is unique. Development of the field has been singularly successful because the steam was dry and the technology for utilization was available at the time the development began. The first unit installed at The Geysers applied the turbine and generator technology of the early 1920s through the installation of used equipment of 1923 vintage which was moved from a retired, inoperative plant. Furthermore, much of the early steam was found relatively near the surface and was developed at relatively low cost. The technology and economics of The Geysers development must never be used as a measure for evaluating other locations having even modestly different characteristics.

Table 3, following, summarizes data on The Geysers development including the utility capital investment.

Table 4 details the estimated capital investment for Unit No. 15, and Table 5 details the estimated power costs for that unit.

In appraising the economics of geothermal electric generation, one must distinguish between cost and price. The steam developers seldom expose their costs, but utilities, through state regulatory control, are normally required to show theirs. Consequently, the mix between the price paid for the steam and the cost to the utility does not really tell the actual overall cost. It merely shows the cost of power to the utility.

TABLE 3

GEYSERS DEVELOPMENT

Unit	Year	MW	Cumulative Megawatts	Steam Producer	Date Certified For Construction By California Public Utilities Commission	Date of Commercial Operation	Electric Utility Capital Investment	Cumulative Electric Utility Capital Investment
1	1960	11	11	U-M-T	4/7/59	9/25/60	$ 4,010,000	$ 4,010,000
2	1963	13	24	U-M-T	7/11/61	3/19/63		
3	1967	27	51	U-M-T	9/22/64	4/82/67	7,610,000	11,620,000
4	1968	27	78	U-M-T	7/12/66	3/02/68		
5	1971	53	131	U-M-T	1/23/68	12/15/71	12,756,000	24,376,000
6	1971	53	184	U-M-T	11/12/68	12/15/71		
7	1972	53	237	U-M-T	11/23/71	8/18/72	10,982,000	35,358,000
8	1972	53	290	U-M-T	11/23/71	11/23/72		
9	1973	53	343	U-M-T	11/23/71	10/25/73	13,520,000*	48,878,000*
10	1973	53	396	U-M-T	11/23/71	11/30/73		
11**	1974	106	502	U-M-T	9/12/72	1/01/75	14,404,000*	63,282,000*
12	1976	106	608	U-M-T	9/01/74*	9/01/76	14,727,000*	78,009,000*
14	1976	110	718	U-M-T	11/01/74*	11/01/76	16,350,000*	94,359,000*
15***	1977	55	773	PEC	3/01/75*	1/01/77	11,303,000*	105,662,000*
13****	1977	135	908	Signal	3/01/75*	3/01/77	$20,717,000*	$126,879,000*

U-M-T Union Oil, Magma Power and Thermal Power
PEC Pacific Energy Corporation
* Estimated
** Under Construction
*** Proposed Unit
**** Lake County

TABLE 4

ESTIMATED CAPITAL COST
OF
THE GEYSERS POWER PLANT UNIT 15
AND
NECESSARY STEP-UP SUBSTATION AND
TRANSMISSION FACILITIES

Item	Estimated Cost (1973 Price Level)
Production	
Land and Land Rights	
Structures and Improvements	$ 1,569,000
Structures and Improvements (Equip.)	115,000
Boiler Plant Equipment	1,005,000
Turbine-generator Equipment	3,999,000
Accessory Electric Equipment	582,000
Miscellaneous Power Plant Equipment	85,000
Communications Equipment	36,000
Engineering and Other Allocable Costs	734,000
Overhead Construction Costs	1,462,000
Total Production	$ 9,587,000
Step-Up Substation	
Station Equipment and Transformers	$ 463,000
Engineering and Other Allocable Costs	46,000
Overhead Construction Costs	92,000
Total Substation At Plant	$ 601,000
Transmission	
Towers and Fixtures	$ 2,000
Overhead Conductors and Devices	2,000
Engineering and Other Allocable Costs	1,000
Overhead Construction Costs	2,000
Total Transmission	$ 7,000
TOTAL PROJECT	$10,195,000
Estimated Additional Cost for Escalation to Date of Completion:	$ 1,108,000

TABLE 5

ESTIMATED COST
(ESCALATED TO DATE OF COMMERCIAL OPERATION; 1977)
OF POWER FROM
THE GEYSERS POWER PLANT UNIT 15

	Steam Production	Step-Up Sub.	Transmission	Summary
Estimated Construction Cost, Thous.$	10,590	705	8	
Total Project, Thous.$		11,303		
Estimated Annual Cost (Excl. Fuel)				
Fixed Charges, Percent of Capital				
Return and Depreciation	10.23	9.96	9.93	
Taxes on Income	2.43	2.19	1.83	
Property Taxes	1.69	1.69	1.69	
Insurance	0.09	0.09	0.09	
Total	14.44	13.93	13.54	
Annual Cost, Thus.$				
Fixed Charges	1,529	98	1	
Operation	66	3	0	
Maintenance	47	3	1	
General Expense	34	2	0	
Total Excl. Fuel	1,676	106	2	
Total Project				1,784
Fuel Requirements and Power Costs				
Basic Data				
Net Capacity, Megawatts				55
Unit Steam Cost, mills/kW-hr (Includes 0.5 mill for Effluent Disposal				7.40
Transmission Losses on Energy Percent				6.00

	Capacity Factor Operation (Percent)		
	70	80	90
Net Annual Energy Production, Million kW-hr	337	385	434
Net Energy at End of Lines, Million kW-hr	317	362	408
Annual Fuel (steam and effluent disposal) Cost, Thous.$	2,494	2,849	3,212
Other Annual Costs, Thous.$	1,784	1,784	1,784
Total Annual Costs, Thous.$	4,278	4,633	4,996
AVERAGE DELIVERED TO SYSTEM COST,MILLS/KW-HR	13.50	12.79	12.26

III. RESERVES AVAILABLE WITH GIVEN ENVIRONMENTAL CONSTRAINTS AND THE EFFECT OF RELAXATION OF THOSE RESTRAINTS

Geothermal energy generally enjoys the reputation of being environmentally pure. Many people who oppose construction of fossil or nuclear generating projects therefore urge geothermal generation as the ideal environmental alternative.

Unfortunately, geothermal power is not without environmental problems. On the positive side, we can note that these problems seem manageable, even though costly. So long as environmental constraints are imposed within reasonable and responsible bounds, development can proceed.

Most natural hydro-thermal systems contain non-condensable gases in varying amounts. Hydrogen sulfide is only a small portion of such gases but is readily detected through its characteristic rotten-egg odor. If the geothermal steam development is located in a relatively unpopulated area, the presence of hydrogen sulfide may, in terms of environmental effect, be quite unimportant. However, regulatory limits seldom recognize the location or unique circumstances and can be unrealistically restrictive. In addition to natural release of hydrogen sulfide through fumaroles at The Geysers project, some hydrogen sulfide is released to the atmosphere from the plant condenser vents and cooling towers. To comply with the applicable air quality standards, a major research effort has developed a process for abating the release of hydrogen sulfide gas from the power units. The process results in the production of elemental sulfur in the form of a wet sludge having no commercial value. It is planned to dispose of this in a controlled land fill.

Initially, at The Geysers, the unevaporated condensate from the power cycle was released to the natural drainage channels, and no problems were detected. However, as development grew, the ammonia content and the quantity of effluent increased to the point where there was potential for an adverse effect upon the local fish life. Further, small concentrations of boron in the condensate created concern because it was known that boron in small quantities could be harmful to certain types of vegetation. Both the ammonia and boron questions were resolved by reinjecting the unevaporated condensate into the underlying steam-producing formations, where it is believed to be reheated by the hot rock and flashed to steam, thereby extending the productivity of the reservoir. For development in other areas where brines or even relatively pure waters are to be released in drainage channels or into bays or the ocean, the impact of those liquids upon the aquatic environment must be considered carefully.

Characteristically, geothermal resources are found in areas of seismic activity. One of the techniques for locating potential geothermal resources is through measurement of micro-earthquakes. Although there have been some questions raised about the possibility of wells being offset in a seismic break, the probability is so remote as to be ignored, and structural designs of surface facilities to resist earthquakes are quite manageable.

Land subsidence has been reported at the Wairakei project in New Zealand and the Cerro Prieto project in Northern Mexico. It is believed that this problem will generally be associated with withdrawal of hot water from geothermal reservoirs, particularly in sedimentary formations. In rock formations such as those at The Geysers, subsidence is not expected.

Geothermal projects have been affected by increasing concern over possible effects on the environment. Regulatory agencies now require submittal of extensive environmental statements, which are both time-consuming and expensive. Unfortunately, as presently implemented these requirements are imposed upon each new increment to the development, and because the geothermal generating units have relatively small capacity, new units are added at fairly frequent intervals with the associated requirement for new environmental reports. In California, it is presently necessary to prepare detailed environmental data statements for each addition, even though the individual geothermal area may have been discussed in detail in several earlier data statements. The burden and cost to the utility of preparing statements may be manageable, but the cost and delay are compounded immensely because regulatory bodies must prepare their own environmental statements after reviewing those of the steam developer and the utility. Acceptance of a single environmental report for each specific geothermal resource area would be helpful. The value of such a concept has been recognized at the state level in California and currently there are legislative efforts to streamline the regulatory review, reduce costs, and advance the rate of geothermal development.

In some areas, land use compatibility of geothermal development could be a problem. Construction and operation of geothermal plants are basically industrial activities. Roads must be constructed to individual well sites, wells must be drilled, and piping systems must be installed to carry the steam or hot water to the generating or process plants. The plants themselves and associated electric transmission lines must be constructed. Even at The Geysers, located in an area having relatively few other uses, matters of land use compatibility must be addressed and resolved.

Aside from the possibility of institutional restraints, it is believed that the environmental problems of geothermal development in most places can be solved through applied technology. There is no reason to believe geothermal energy will be attended by any more serious problems than energy from fossil-fuel sources. With a growing realization of the importance of conservation and early development of domestic energy resources, there is every reason to develop and impose environmental constraints in a reasonable manner. If, however, additional layers of "unnecessary" environmental requirements are imposed, costs will get excessive and projects cancelled due to the problem of meeting such requirements. In our striving towards energy self-sufficiency, it would appear counter-productive to preclude the use of this valuable natural resource by unnecessary or punitive regulatory requirements.

IV. STATE OF THE ART

A. The Origin of Geothermal Energy

A widespread view on the source of geothermal heat is that it arises largely from the decay of radioactive material. In addition, exothermic chemical reactions and frictional sources within the earth undoubtedly contribute some of the heat. This heat is transmitted to the earth's surface everywhere. In most regions, however, it is too diffuse to be noticed. In other regions, it is found in dramatic volcanic lava flows and in geyser displays such as "Old Faithful" in Yellowstone Park.

In some regions of recent volcanism, generally associated with tectonic plate boundaries, large amounts of heat are contained in solidified magma at relatively shallow depths. In some of these areas, surface water percolates into the formations. When the water comes into contact with the hot rock, convective cells are formed causing hot water or steam to rise toward the surface. If this water penetrates the surface, geysers, hot springs or fumaroles appear. In the United States, such areas are found predominantly in the West.

It is convenient to separate geothermal resources into major types and sub-types:

(1) Hydro-thermal systems:
   - (a) Dry steam (vapor-dominated) systems
   - (b) Hot water (liquid-dominated) systems, mildly mineralized
   - (c) Hot water (liquid-dominated) systems, highly mineralized.

(2) Geopressure systems.

(3) Hot, dry rock systems:
   - (a) Hot, dry rock without added heat
   - (b) Hot, dry rock with nuclear heat added.

(4) Magma

Following is a brief discussion of each of the types:

1. Hydro-thermal systems

The systems which produce steam, either directly from vapor-dominated fields or flashed from liquid-dominated fields, provide all of the geothermal resources used for electric power generation today. Proven technology now exists for these systems and they are, therefore, the easiest to develop.

a. Dry steam (vapor-dominated) systems

The Geysers steam field in the United States and the Lardarello development in Italy are the major fields which produce dry steam for electric generation. Power installations using dry steam at Monte Amiata, Italy and Matsukawa, Japan are small. The potential for added development at these locations is not known. White* suggests that the higher-temperature vapor-dominated sub-types such as Lardarello and The Geysers probably require a discharge area with recognizable surface manifestations and, therefore, we probably are already aware of all such systems. Other vapor-dominated systems at relatively low temperatures such as that at Monte Amiata will be harder to find because surface manifestations will not be readily observed. Fields like Lardarello and The Geysers are commercially attractive, but it must always be kept in mind that the economics and technology for their utilization cannot be transferred directly to the liquid-dominated or other types of geothermal resources.

b. Hot water (liquid-dominated) systems, mildly mineralized

Because liquid-dominated systems are much more abundant, techniques for utilizing this source of heat are currently receiving increasing attention. Much of the exploration throughout the Western United States in recent years has located hot water sources. The Wairakei and Kawerau installations in New Zealand, the Cerro Prieto plant just south of the United States border in Mexico, and an installation in Japan all utilize heat from hot water systems by allowing the superheated water to flash to steam. While this process of obtaining steam for power production is simple, it does leave large quantities of residual water, sometimes of high mineral content, that must be disposed of.

An alternative method for extracting heat from hot water or brines is through the use of heat exchangers. The Magma Power Company has been particularly active in developing and promoting its Magmamax binary system, in which even fairly low-temperature hot water or hot brine from liquid-dominated systems can be circulated through a heat exchanger and transferred to an organic liquid such as isobutane or freon. Such liquids have low boiling points (14^{o}F at one atmosphere for isobutane) and can be converted into gaseous form, just as we convert water to steam. The expanding gas then acts as the driving medium to turn the turbine. Such a system will be important if we are to extract much electrical energy from the more abundant but relatively low-grade geothermal heat sources. The very small binary system installed on the Kamchatka peninsula of Russia, with freon acting as the working fluid, seems too small for commercial extrapolation. Commercial development of the more abundant, low-grade, liquid-dominated heat sources, therefore, awaits demonstrated heat exchange technology and demonstrated economic feasibility.

In most cases, it is contemplated that the "spent" hot water from binary systems would be reinjected into wells to avoid environmental problems stemming from surface disposal.

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* <u>Geothermal Energy</u>; edited by Kruger and Otte

c. Hot water (liquid-dominated) systems, highly mineralized

A notable example of a highly mineralized water system is that in the Imperial Valley of California near the Mexican border. Tremendous quantities of heat are found in the hot water underlying large areas of the Valley. Numerous wells have been drilled and the potential of the area has been under study for many years by the University of California at Riverside, by steam developers which include some of the oil companies, and by Southern California utilities.

A major effort is under way to use the heat for electrical generation and for extracting potable water. Most of the problems in extracting the heat relate to the very high mineral content of the hot water, as much as 10 times the mineral content of seawater in some areas. Special technology will have to be applied to overcome problems of corrosion and scaling in plant equipment, particularly heat transfer equipment. The best prospect for using this heat to generate electricity is thought to be through the use of a binary system similar to that described under 1(b) above. An experimental module of such a system has been installed through the joint efforts of the Magma Power Company and San Diego Gas and Electric Company. Some interest has been exhibited in obtaining valuable chemicals from the brines, but it is clear that all of the chemicals could not be removed economically. Reinjection of "spent" brines into wells appears to be the only environmentall acceptable method of disposal for this area.

2. Geopressure systems

A rather fascinating potential resource exists along the Gulf Coast in geopressure systems. While exploring for oil, drillers have encountered "geopressure" areas between the Continental Shelf and about 100 miles inland in an area extending from Texas to Florida. These zones are believed to result from the entrapment of water along geologic faults. Subsequent subsidence and compaction of material above the faults has occurred until the entrapped water itself has become the load-bearing substance creating a "geopressure" reservoir. In some of these reservoirs that water is quite hot, it has an extremely high-flowing wellhead pressure, and contains up to 30 cubic feet of dissolved methane gas per barrel of water.

These systems have potentially great energy capability because of three physical characteristics: (i) the water is at such pressure that it could be run through hydraulic turbines to extract energy; (ii) there is enough heat in the water that energy could be extracted through a binary-cycle system; and (iii) very importantly, the methane gas could be extracted from the fluid and its energy utilized.

C. S. Matthews* of Shell Oil Company has stated: "The problem of locating large, hot, highly productive geopressured reservoirs will be a very difficult exploration problem. Its solution will require both skill and luck". A. T. Maasberg and O. Osborn* of the Dow Chemical Company have made this succinct assessment: "The economics of power production from Gulf Coast geopressured waters appear very attractive, and the potential returns are high. However, the risk is also high, and the development costs will be large."

3. Hot, dry rock systems

The hot, dry rock systems offer theoretically the greatest amount of potential energy; but to date they have not been exploited beyond preliminary research. Hot rock underlies all of the earth's surface. However, due to economic and physical limits for deep drilling, it is only where the higher temperatures are relatively close to the surface that we might expect to extract their energy.

Currently, the Subterrene draws considerable interest because it offers the possibility of overcoming some of the depth limitations. The Subterrene is a system invented and patented by the scientists at the Los Alamos Scientific Laboratory for making vertical or horizontal holes in the earth by melting rock and soils. The penetrator which acts as the drill bit would be heated either electrically or with a specially-designed nuclear fission reactor. Practical development of the Subterrene would provide substantial advantages over conventional methods of deep drilling, not only for geothermal energy exploitation but for other purposes as well.

a. Hot, dry rock without added heat

An over-simplification of the concept for extracting heat from hot, dry rock requires two or more holes to be drilled into a high-temperature rock system. In the absence of natural permeability, hydro-fracturing processes would be used to open the formations between holes. Water, or perhaps another fluid, would then be injected from the surface into one or more of the holes. The fluid would circulate through the reservoir and return to the surface through the other holes at an elevated temperature, either as a liquid or as steam. The fluid in this manner would "mine" the heat of the dry rock system. Drilling and experiments for utilizing this resource are under way in Montana and New Mexico.

b. Hot, dry rock with nuclear heat added

Battelle-Northwest Laboratory, working with the American Oil Shale Company and others, in 1971 prepared a comprehensive study

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* Hearing before Committee of Science and Astronautics, Subcommittee on Energy, H.R. 11212, The Geothermal Energy Research, Development and Commercial Demonstration Act of 1973.

of a potential utilization of hot, dry rock. It was proposed to drill into hot, dry rock and create a permeable pocket at depth through an atomic detonation. The atomic detonation would add heat to that naturally present. A water injection hole and a separate heat extraction hole would then be drilled into the permeable pocket. The combination of both heat sources was indicated as necessary to achieving overall economic feasibility.

There are two readily-apparent problems associated with this type of geothermal development: (i) The detonations would be required at fairly frequent intervals in order to maintain enough energy for continued operation of a power plant. Detonations would require hardening the plant against shocks or designing the plant so that it could be moved temporarily away from the area of detonation in a canal or on rails. While technologically possible, the complications of dealing with the explosive shocks seriously erode the economics. (ii) Although the proposed procedure responsibly considered all the features required to make it radiologically safe, the concept is still hampered by the public's reluctance to accept atomic detonations in any form.

While this plow-share type project has not been abandoned, it is definitely on the back burner.

4. Magma

Solidified magma might be tapped as an energy source through the hot, dry rock concepts described under 3 above. Tapping the energy of molten magma or lava systems would require totally different technology. Such molten systems do contain immense amounts of energy in spectacularly evident form, but these are found only in a few places in the world and on a somewhat unreliable, intermittent basis. In any event, such systems may defy practicable technology to harness the energy.

V. RESEARCH AND DEVELOPMENT GOALS

A. Major Problems and Their Solutions

Once a geothermal resource is brought to the earth's surface, most of the technology already developed for the utilization of other kinds of heat sources will be applicable to the conversion of geothermal energy for man's use. The technology for the use of dry steam such as that found at The Geysers is basically the same technology that has been used for decades in electrical generation. Nature has merely provided the boiler and the steam is run through low-pressure, low-temperature turbines of a design not too different from that of 50 or more years ago. Because of the chemical content of the steam at The Geysers project, there are turbine blade deposits which require additional maintenance. Surfaces in contact with the steam or condensate require special treatment and certain sensitive electrical gear is confined to special rooms away from the corrosive effects of hydrogen sulfide. Rock and dust that get past the centrifugal separators and screens can create serious turbine blade problems. However, when one considers that the steam used in fossil or nuclear units is extremely pure, it is remarkable that these geothermal units operate at and above a 70% capacity factor. Most of the design and operational problems are now well understood and efforts are being made to push output of the project substantially above 70% capacity factor.

The more hostile forms of geothermal resources such as heavy brines will require use of special materials. Scaling of conduits and heat exchangers through which the brines will move may be a serious problem.

Certainly, there needs to be a demonstration of the workability and reliability of heat exchangers and of energy conversion machinery to be used with working fluids such as isobutane and freon.

The only long-term experience with reinjection of geothermal effluents is at The Geysers. Similar experience will be needed in other areas.

Probably the most pressing technical problems associated with accelerating expansion of geothermal energy use lie in the areas of resource exploration, assessment and development. Too little is presently known about the location and potential of this resource, assessment techniques are limited, and less expensive ways of drilling for and producing the resources are needed. We must learn much more about all these subjects.

Also, we must clear away certain non-technical problems which tend to inhibit geothermal development:

1. Institutional Problems

   Sixty percent of the identified potential geothermal property is on federal land. Bids totaling about $6.8 million were opened in January 1974 for geothermal leases on 53,000 acres of federal land in California. This implementation of the Geothermal Leasing Act of 1970 was long overdue, and further leasing should be expedited to stimulate development of this nation's geothermal reserves. The ownership of steam on large acreages in the West where mineral rights are reserved to the federal government is still being argued in the federal courts. Adjudication of these questions should be accelerated.

2. Scarcity of Tubular Goods

   Limited supply of tubular goods such as well casings has been reported recently as a limiting factor in the development of oil and gas resources. Competition for supplies of this kind poses a serious problem for a large-scale geothermal development program. Expansion of mill capacity for producing these goods should be encouraged.

3. Availability of Drilling Rigs

Drilling rigs are specialized, expensive, large pieces of equipment which take a long time to manufacture and put into operation. It would take about half of all the rotary drill rigs in the United States today working until the end of this century to develop the resource suggested in the Hickel report. And this assumes that every well would be successful and that the wells would produce for nearly a century without the necessity for redrilling or developing fill-in wells. Advancing the rate of development of geothermal resources, therefore, will have to be accompanied by a significant increase in availability of drill rigs.

4. Availability of Electrical Generating Equipment

There is no question of the manufacturers' ability to produce equipment for the utilization of geothermal steam for generation of electricity. There is doubt, however, how far the geothermal electric industry must be developed before manufacturers will see sufficient potential profit to commit the necessary plant for manufacture of the specialized equipment at other than custom-made prices. Manufacturers need a large enough assured base to justify entering the market competitively and economically. Since The Geysers-type equipment will not be usable at most other areas which call for different technology, convincing suppliers to dedicate their resources to making standardized equipment for other types of geothermal energy may be a slow process.

5. Availability of Capital

The average steam well at The Geysers project currently (1974) costs somewhere between one-quarter and one-half million dollars to complete. The cost of the electric generation and associated facilities is estimated to be about three times the cost of wells and other production facilities. If resources of the expansive magnitude suggested by some should be developed, we would be looking for about $4 billion per year. It can only be with proven economics and an assured supply of heat that industry would ever make such an enormous financial commitment.

B. Necessary R&D Programs Relating to Electrical Generation

The following are major technological areas where R&D seems to require concerted effort. Some were mentioned earlier.

(1) Exploration technology

(2) Deep, hot drilling technology

(3) Geothermal reservoir engineering

(4) Material corrosion and heat transfer scaling investigations

(5) Organic fluid power machinery

Locating oil reserves is a reasonably advanced technology, developed over many years through identification of specific types of geological structures. This is not true with geothermal resources. Generally, we start from surface indications such as hot springs or fumaroles. Heat-flow studies from relatively shallow holes can provide some information. The final test, of course, is in drilling. New and more efficient exploration technology should be a high priority R&D goal.

Present techniques for deep drilling in geothermal areas are those developed in the gas and oil industry. If some of the deep hot rock formations are to be reached and utilized, new methods will be needed. The Subterrne, described earlier, offers one possibility.

After a geothermal resource is located, drilled and tested, it needs careful assessment. In the case of vapor-dominated systems, techniques similar to those used for assessing natural gas reservoirs can be utilized. If, as some believe to be the case, vapor-dominated systems are recharged from liquid reservoirs at great depth, the resource is much greater than would exist with a vapor reservoir alone. Wells about 9,000 feet deep at the California Geysers have not reached an interface. More would be known about the nature of the reservoir if such an interface could be found, and suggestions have been made for drilling holes on the order of 20,000 feet deep to answer this question. Such a hole would be very expensive and evaluation of what benefits might be obtained from such an effort is still under study.

To the extent that utilization technology still has gaps, research effort should be made on the problems of material corrosion and heat-transfer surface scaling. These gaps are fairly well closed in utilization of the dry steam at The Geysers where research has been completed or is under way, but the gaps are wider for utilization of heat from liquid-dominated systems, especially those having high mineral content. Current research programs to investigate the binary cycle using organic fluid power machinery should be accelerated.

The fact that some research has been undertaken does not mean that parallel research efforts using different techniques should not be started. Both new and backup research programs leading to development of new economic techniques are needed.

VI. MAXIMUM ACCELERATED APPROACH

The rate at which geothermal development occurs will not be controlled by a predetermination of how fast it <u>should</u> proceed, but rather by constraints which now exist and which may build up around it. Such constraints will be both technological and institutional, but, basically, the rate of development will be controlled by the confidence that grows with success in various aspects of research and discovery, and then, finally, through the test of cold economic realities of investment and operation. Electric utilities, which are prospectively the major users of geothermal resources, have been notably cautious in shouldering large, speculative investments because of the regulated nature of their business. The rate of development of such an infant industry as geothermal should, in a utility view, be continued on an evolutionary basis to match the proven resources, rather than presuming that the resource is available and attempting to match the presumption. The rate of development certainly can be accelerated, but the whole concept would be seriously harmed if the rate of commitment to development should overrun the availability of the resource and usable technology.

Even though geothermal energy might develop more slowly utilizing the free marketplace philosophy, it should do better and be stronger if it develops under the test of economic viability. It can then assume an increasing role in the energy mix as a competitive form with other energy sources, as it presently does in Northern California. Large geothermal leasehold positions are being taken in the Western United States by many of the nation's energy companies. These include not only the small venture-capital firms which pioneered the exploration of this resource, but also some of the nation's major oil companies. These firms are necessarily profit oriented and are motivated to accelerate geothermal energy development. Working in concert with the nation's utilities, a balanced development program will evolve. With the proper economic incentives and regulatory climate, these industries will combine their diverse talents to bring this resource to its timely and full economic potential.

VII. SUPPORT OF RESEARCH AND DEVELOPMENT

There is a great body of technology for utilizing geothermal energy that has already been developed by the nation's resource companies, equipment manufacturers and the electric utility industry. Historical precedent gives assurance that these industries can provide the goods and services to develop the resource once it has been found, assuming reasonable economic incentive. Government's historic relationship with the mining and oil and gas industries has generally provided incentive that permitted resources to be developed to the benefit of the country.

A similar relationship should be extended to the geothermal industry in most aspects of resource exploration, evaluation and development. The government should continue to examine prospective areas using existing agencies such as the U.S. Geological Survey. A federally sponsored national or at least a Western geothermal heat-flow study--consisting of study wells on a regular grid pattern--would undoubtedly locate additional resources, and would provide a less speculative appraisal of the nation's geothermal resources. Information of this kind should then be disseminated widely. Industry should be allowed to evaluate the information, determine the location of the most promising geothermal resources, and then be allowed to carry out their development, production and utilization in a competitive manner.

Some research programs such as those relating to the use of dry, hot rock, development of the Subterrene, and potable water production are presently under federal sponsorship and undoubtedly will require substantially more government funding.

VIII. SUPPLY OF GEOTHERMAL ENERGY PROJECTED TO 1975, 1980, 1990, 2000

Many factions want to increase the production of geothermal energy--including environmentalists, drillers and producers of steam, electric utilities, research organizations, geophysicists, geologists, and some politicians who properly understand that the energy crisis is real and long-term. With this support, geothermal energy is likely to be developed to its maximum economic capability. Geothermal energy needs enthusiastic voices to keep its development moving, but that enthusiasm should never lead to irresponsible suggestions, as have been made in the past, that everything should stop while we wait for a full geothermal economy to arrive. The nation should not overreact to geothermal energy's appeal and follow a course of wasting another important resource--our nation's dollars.

While the potential for using geothermal heat in electric generation is quite important, extrapolations of the present, meager information on this resource should not overshadow the need for continuing development of other sources of electrical generation. While pressing very hard for development of geothermal energy as a proper part of the mix of world energy resources, we must continue to use the full range of energy sources available now.

IX. USES AND BENEFITS OF GEOTHERMAL TECHNOLOGY

Two centuries ago, the industrial revolution began with the extensive use of fossil fuels. First coal, and then oil and gas served man's ever-increasing need for energy. In the period to the end of this century, nuclear energy holds promise of becoming a dominant energy source. In fact, it will be essential if we are to meet the nation's need for electric power. Coal will also be an important heat source. In this period, geothermal energy can be expected to become an increasingly important supplemental energy source in a number of regions in the West; but it is now difficult to conceive of geothermal power providing 10 percent of the electric energy needs of the nation or even of one of the more active geothermal areas, California. In some areas, production of potable water is possible through the use of geothermal energy, and in those areas where highly-saline geothermal waters are available, raw materials for the chemical industry could be important.

One utility, Pacific Gas and Electric Company, appreciates fully the great benefit geothermal power bestows in saving valuable fossil-fuel resources. It maintains an aggressive, optimistic view with respect to The Geysers development.

Encouragement is needed for advancement of the technology necessary to assess and develop this resource, wherever it can be found, so that the economic sources will be utilized as rapidly as possible.