## **GEOTHERMAL ENERGY**

# A NATIONAL PROPOSAL FOR GEOTHERMAL RESOURCES RESEARCH

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Final report of the Geothermal Resources Research Conference, Battelle Seattle Research Center, Seattle, Washington, September 18-20, 1972

## UNIVERSITY OF ALASKA

Sponsored by the National Science Foundation Research Applied to National Needs

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### **PREFACE**

The Nation urgently needs new energy sources. One of the most exciting possibilities lies in the heat beneath the crust of the earth itself.

Our earth is a great furnace. We can tap that furnace to meet the needs of our people. This great power source, known as geothermal energy, should be given high priority by both government and industry.

As we evaluate fuels for the future, we must look at a variety of values. Fuels cannot be only efficient and cheap to be acceptable. They must be readily available, clean and abundant.

There is no question that in these categories geothermal power has tremendous potential. To say that the heat of the earth is infinite would be unscientific, but to say that it is much less than infinite is to underestimate its potential relative to human use.

The questions are when it will be used and how.

The fifty scientists, engineers and environmentalists who contributed their expertise to this report share my optimism. We do not see geothermal energy as the *only* answer to the future, nor necessarily as the *best* answer. We don't yet know.

But we do know that a major research program at the Federal level is vitally important. With the investment of \$684.7 million and ten years, we can probe the engineering and production unknowns and learn to understand and utilize this tremendous resource.

From our current perspective, geothermal energy promises to be perhaps the most acceptable of all new energy sources from an environmental standpoint. Much of the credit for this goes to the fact that, unlike most other forms of energy, geothermal is entirely site dependent.

To the general public the most familiar expressions of geothermal power are geysers, hot springs and volcanoes. These obvious surface forms are only a tiny fraction of the resource base. They should be compared to the oil seeps which, when first found on the surface, were thought to be the sole source of petroleum. Much larger geothermal reserves lie in great subterranean regions of hot dry rocks, volcanic molten rock, and geopressured systems.

Though we are already producing geothermally generated electricity on a small scale, a whole new energy frontier lies ahead of us. With the research and development recommended in this report, I am confident that the United States could be producing from its geothermal resources at least 132,000 megawatts in 1985 and 395,000 MW by the year 2000.

This would be electricity generated without a hidden cost in the balance of payments and would have a major impact on U.S. self-sufficiency.

It would be a mistake, however, to look to electric power alone as the sole benefit from this unusual resource. Electricity, fresh water, minerals, natural gas—they are all there. There is great potential for contributing to the Nation's supply of

fresh water. By 1985 we expect geothermal resources to provide up to 31.5 million acre feet of water to augment our national supplies. And geopressured reservoirs in the Gulf of Mexico will extract, in addition to enormous amounts of water for power generation, perhaps a million standard cubic feet of natural gas per day per well.

Direct use of the heat itself will also be a valuable application. This will include the heating and cooling of residential and commercial buildings, as well as uses for farming and paper and pulp manufacturing.

There exists today no less an urgency for an early solution of the impending national energy shortage than existed in the areas of nuclear research in the 1940's, or space exploration and space communication in the 1960's. The overall potential of geothermal energy to help meet this shortage is of great significance to the Nation.

Respectfully submitted,

Walter Hickl

Walter J. Hickel

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## . INTRODUCTION AND BACKGROUND

The ever-increasing demand for energy and the recent pressures brought to bear through concern for the environment have led the Nation to consider energy alternatives to the conventional sources.

One of the new alternatives is geothermal energy. There is a great scarcity of reliable data on the geothermal resources of the Nation and this has led planners to ignore geothermal energy in comparison to other, more adequately explored, energy resources.

Nevertheless, other countries, including Italy, Iceland and New Zealand, have utilized geothermal power for some years, and Pacific Gas and Electric has built and is operating geothermal power generation equipment in Northern California.

The natural heat of the Earth is thought to be derived from the natural decay of radioactive core materials and frictional forces resulting from solar and lunar tides as well as the relative motion of crustal plates. Temperature measurements in drill-holes, mines, etc. confirm that, on the average, temperatures increase with increasing depth, reaching values in excess of 1000°C (1832°F) in the molten interior of the Earth.

Theoretically, this energy source can be tapped from any point on earth simply by drilling deep enough holes, providing a passage for heat transfer fluid, and extracting the heat. Practically speaking, this hot mass is much too deep to tap in large areas of the world with existing drilling capability. Yet in other areas the resource is much closer to the surface.

The base of the continental crust, where the temperature is perhaps 1000°C or higher, varies from a depth of 25 to 50 kilometers. When a structural fault reaches deep into the crust and relieves crustal

pressures, molten and partially molten mantle materials can move upward toward the surface with great rapidity.

Nevertheless, it is not necessary that the magma break through and flow onto the surface. It may spread out at some depth and mix with rocks of lower freezing points at that level and crystallize. In this way rocks derived from magma of varying composition and varying freezing points may be produced.

The present state of knowledge indicates that such deposits of thermal energy are found at relatively shallow depths in zones of geologically recent volcanism and crustal shifting in areas of above-normal heat flow.

The areas of greatest prospective geothermal resources seem to lie along the tensional environments of the oceanic rises and continental rift systems, and along the compressional environments where mountains are rising and island arcs are forming.

In some areas, surface phenomena, such as geysers and hot springs, suggest that the source of energy is quite near the surface. The United States, particularly in its western region, has an enormous extent of volcanic rocks of recent origin and an abundance of dormant volcanos as well as several active ones. The potential geothermal resources appear to be very large.

It was in this context, in response to a proposal submitted by the University of Alaska with Mr. Walter J. Hickel as principal investigator, that the National Science Foundation, through its RANN Energy Research and Technology Program, granted funds in support of a geothermal resources research conference to be held in September, 1972.

The objective of the conference was to develop an

assessment of the state-of-the-art of geothermal science and technology and to recommend a research program to provide the requisite knowledge for establishing the proper role of geothermal resources in providing additional energy to alleviate the Nation's impending shortage. A further objective was to investigate the potential of geothermal water to supplement present national fresh water supplies.

The conference was a working conference, as contrasted to one for the presentation of scientific papers, and attendance was by invitation only. The setting for the conference was the Battelle Seattle Research Center in Seattle, Washington, an installation designed for just this type of working conference.

For convenience, the conference was organized into six substantive panels with co-chairmen of each panel responsible for assembling panel members who could speak authoritatively on the substance of the panel.

The panel topics selected were: resource exploration, resource assessment, reservoir development and production, utilization technology and economics, environmental effects and institutional considerations.

Both industrial and university viewpoints were represented among the co-chairmen. Federal scientists were invited to contribute to each of the panels.

In order to complete the planning for the conference, Mr. Hickel held a workshop in Anchorage which was attended by almost all of the co-chairmen. At the Anchorage meeting the co-chairmen discussed the state-of-the-art of geothermal science and technology, specified the topics which were to be explored in each panel, and compiled lists of experts

who might be invited to participate.

A preliminary view of a national geothermal research program was also discussed and was subsequently used as one input to the preparation of the report, "Assessment of Geothermal Energy Resources." The main task of the September conference was to amplify and finalize recommendations for a national geothermal resources research program. The conference drew upon the Anchorage workshop and the report, "Assessments of Geothermal Energy Resources," as resource material.

The objective of this report is to present the results of the Geothermal Resources Research Conference which was held September 18-20, 1972. The sequence of chapters includes one for each of the substantive panels of the Conference.

Inevitably, when concurrent panel meetings are held, there is some degree of overlap between the topical research recommended by each panel. It was not possible to make sharp delineations of the area of responsibility for each panel and this accounted for some of the overlap. In other cases, consideration of a given topic, for example reinjection to maintain reservoir pressure, led naturally into conclusions with regard to another panel, for example environmental effects.

In writing the report, every effort has been made to avoid the overlaps. Thus it has been necessary to rearrange the panel reports to present a consistent program.

For rapid reference purposes, however, each chapter has been written as an individual entity. The repetitive language permits each section to stand on its own.

The national geothermal resources research program was to be presented without regard to the appropriate sector for carrying out the research. In certain cases there is an obvious wisdom in selecting a particular sector to perform, or be responsible for, the proposed research. Clearly the U.S.A.E.C. should be responsible for any nuclear fracturing research. In the same sense it is traditional that industry will be responsible for almost all demonstration plant work.

Nevertheless, it was felt that the Conference, and its report, should address the question of total research and development needed to provide a basis for application of geothermal resources. Thus, it has been necessary to add to some of the panel reports, notably the Utilization Technology and Economics report, in

order to assure that each report is presented on the same basis. A substantial part of the additions were covered, at least in part, by duplicate considerations in other panels.

The Geothermal Resources Research Conference attempted to draw together a cross-section of the very best geothermal resources expertise in the country; from industry, government, and universities. Attendance was limited. This report is based on the panel reports which present their findings.

It has been necessary to rearrange, to interpret, and to supplement the panel reports. It is hoped that the rearrangements and interpretations are faithful to the intent of the experts. Any errors are the responsibility of the editor.

## JII. IMPORTANCE TO THE NATION OF GEOTHERMAL RESOURCES

The potential importance of geothermal resources for contributing to the Nation's supply of energy and fresh water is enormous.

It can be comprehended best when contrasted to some familiar examples of man's outstanding achievements. Grand Coulee will provide 9,771 megawatts of electric power when the third power plant comes on line. The entire electrical power supply system of New England is approximately 15,000 MW. By way of contrast, it has been estimated that geothermal resources have the potential of providing electrical generating capacity ranging from 750 MW in 1975 to 395,000 MW in 2000. These estimates and others that are natural consequences are shown in Table 1.

Using a 90 per cent load factor, which is normal for geothermal plants, the potential electrical energy generated will range from 5.9 million megawatt-hours in 1975 to 3,114 million megawatt-hours in 2000. This amount of energy should be contrasted with the production from Grand Coulee which, utilizing a 60 per cent load factor, in 1975 will be 51.4 million megawatt-hours but in 2000 will still be 51.4 million megawatt-hours. Another view of the significance of the geothermal contribution can be obtained by noting that the present demand for electrical energy in New England is less than 60 million megawatt-hours.

Table I also points out that the amount of oil required to generate these amounts of electrical energy, using a 40 per cent conversion efficiency, ranges from 24 thousand barrels per day in 1975 to 12.6 million barrels per day in 2000. The 1985 figure is 4.2 million barrels per day, which is almost 30 per cent of the anticipated oil imports of 14.8 million barrels per day<sup>2</sup> in 1985. Geothermal energy, therefore, can have a major impact on U.S. national self-sufficiency.

It also follows that geothermal energy can have a major impact on improving our balance of payments posture. Table I shows that the value of oil equivalent to the geothermal capacity is 8.9 billion dollars in 1985 which is over one-third of the anticipated 25 billion dollar deficit<sup>3</sup> in our balance of payments in 1985. In addition it may be possible to enhance our balance of payments posture even further by exporting geothermal energy conversion equipment.

The Bureau of Reclamation has formulated extensive concepts<sup>4</sup> for development of the geothermal resources of the Imperial Valley of California. These concepts include the development of geothermal resources to provide both water and energy, 2.5 million acre-feet per year with 10,500 megawatts (including 2000 MW for use on site.)

Most of the potential geothermal developments which can be brought into operation by 1985 will probably be based on hot-water systems. Thus, in 1985, geothermal resources can provide up to 31.5 million acre-feet of water to augment natural supplies. This is over 15 times the present amount of water for municipal, industrial, and other non-agricultural uses supplied by the Bureau of Reclamation and over 25 per cent larger than the amount delivered for irrigation purposes (25.4 million acre-feet)<sup>5</sup>.

Geothermal resources are now and are expected to remain economically competitive with conventional sources of water and energy. The Bureau of Reclamation estimates geothermal water costs in the Imperial Valley to be as low as \$85 per acre-foot and to increase to a possible high of \$150 per acre-foot, depending upon point of delivery and source of

replacement fluids. The cost of electrical energy from geothermal resources was 5.25 mills per kilowatt-hour in 19706 for the Pacific Gas and Electric installation at The Geysers in California. The energy costs are expected to be higher for hot water dominated systems and other new systems but are still expected to be competitive because of steadily rising fuel costs as conventional sources grow more inaccessible and suppliers take into account necessary environmental protection.

Comparatively, it is estimated that geothermal resources can be developed to supply power in less time than more conventional power supplies. Measured from the time when the selection of power supply type is final, geothermal power plants should be operative in about two years, whereas fossil fuel power plants may require up to five years and nuclear plants up to ten. These differences result from the smaller scale of the

geothermal plants and the different complexities in gaining permits and licenses for the different types of plants.

In summary, geothermal resources, by approximately 1985, can have a potentially enormous impact in supplying the nation's need for energy and augmenting the supply of water in regions with insufficient natural water. These resources promise to be economically competitive and able to be brought on-line rapidly. The development of geothermal resources could substantially increase national energy self-sufficiency and provide a dramatic improvement in the U.S. balance of payments posture.

A vigorous research and development program is urged to assure the timely realization of these advantages to the Nation.

## TABLE I. GEOTHERMAL ENERGY RESOURCES POTENTIAL

	1975	1985	2000
Power (thousands of MW)	0.75	132 .	395
Electrical Energy <sup>1</sup> (millions of MWH)	5.913	1,041	3,114
Oil Equivalent <sup>2</sup> (millions of Bbls/day)	0.024	4.213	12.60
Foreign Trade Impact <sup>3</sup> (billions of dollars)	0.051	8.919	26.67

<sup>1. 90</sup> per cent load factor

<sup>2. 3,412</sup> BTU/KWH and 5,800,000 BTU/Bbl of oil used at 40 per cent conversion efficiency.

<sup>3. \$5.80</sup> per barrel (\$1.00 per million BTU)

### III. BUDGET RECOMMENDATIONS

Chapters V through X present the detailed research recommendations derived from the panel discussions. The panel discussions constituted the assessment of the state-of-the-art of geothermal science and technology as a necessary preliminary to the derivation of a geothermal resources research program.

Table II presents the budget requirements for the proposed ten-year geothermal resources research program.

The estimation of research budgets is a difficult task at best. By its very nature, research connotes the unknown. If the precise program needed to answer all of the research questions involved were known, much of the research might be unnecessary.

An additional complication arises when one attempts to project a research budget for a period of ten years. Research done in any given year could be significantly influenced by the results of research done the previous year. This influence could be to increase or decrease the subsequent research funds needed. Experience indicates that unforeseen tasks that are revealed by later research tend to increase the total cost. However, it was felt necessary to project a ten-year budget in order to arrive at a present best estimate of the funds necessary to effect a significant energy contribution from geothermal resources.

TABLE II.

PROPOSED GEOTHERMAL RESOURCES RESEARCH PROGRAM

(Millions of Dollars)

•	1974	1975	1976	1977
Resource Exploration	5.0	8.0	11.0	9.5
Resource Assessment	15.6	23.4	27.8	29.4
Reservoir Development and Production	<b>5.</b> 0	13.5	27.0	44.0
Utilization Technology and Economics	9.9	9.9	11.9	11.8
Environmental Effects	4.2	4.2	3.8	3.6
Institutional Considerations	2.0	2.0	1.5	1.5
Totals	41.7	61.0	83.0	99.8

## Fiscal Year

1978	1979	1980	1981	1982	1983	Total
6.0	3.5	2.0	1.5	1.5	1.5	49.5
31.2	30.4	30.3	31.3	30.3	24.0	273.7
.*						
48.0	21.5	23.0	13.0	10.5	10.0	215.5
10.5	9.1	9.1	9.1	9.1	9.1	99.5
3,5	3.3	3.3	3.4	3.4	3,3	36.0
						en e
1.0	0.5	0.5	0.5	0.5	0.5	10.5
100.2	68.3	68.2	58.8	55.3	48.4	684.7

## IV. OVERVIEW OF GEOTHERMAL RESOURCES

#### A. POTENTIAL OF RESOURCES

Estimates of the amount of geothermal power that may be produced in the form of electrical power differ by several orders of magnitude.

The large differences result from a lack of factual knowledge of the resource itself. There are also differing assumptions about the impacts of future research-derived resource knowledge and technological developments on the probable exploitation of geothermal resources of all types.

The estimate which has withstood the scrutiny of the largest range of expertise is presented in "Assessment of Geothermal Energy Resources." This estimate is that the Nation's geothermal resources could be supplying 132,000 MW in 1985 and 395,000 by 2000.

The basic assumptions behind this estimate are that a comprehensive research program such as presented herein will have three results. It will provide the requisite factual knowledge of the classes of resources described below. It will result in technological developments satisfactory for the exploitation of geothermal resources along the lines described below. And it will improve sufficiently the competitive position of geothermal resources for the different temperature regimes vis-a-vis the more conventional energy sources.

There is little that can be said about these assumptions. Only time and research funding can validate or invalidate them. Nevertheless, they have been subjected to the scrutiny and criticism of a large number of scientists and engineers who are knowledgeable in the many facets of this field.

All projections of geothermal resource utilization must relate back to the resource base. The resource base is all of a given resource in the earth's crust whether its location is known or unknown and regardless of cost considerations. Thus, in the case of geothermal resources, the resource base is all of the heat in the earth's crust at temperatures above the mean surface temperature (about 15°C).

Donald E. White<sup>11</sup> estimates that the thermal energy stored under the United States to a depth of 10 kilometers is about  $6\times10^{24}$  calories which is equivalent to the energy content of almost one quadrillion short tons of coal. A large portion of this thermal energy is in areas of normal temperature gradient and is a very low grade source of energy. White<sup>11</sup> also provides a very rough estimate of  $2\times10^{21}$  calories for the total stored energy of all convective hydrothermal systems to a depth of 3 kilometers and  $10^{22}$  calories to a depth of 10 kilometers of which probably 5 to 10 per cent is in the United States.

Muffler and White<sup>7</sup> point out that these estimates do not include magma deposits, impermeable rock formations, and geopressured resources which for the world are at least 10 times greater than the resources of the hydrothermal systems. If production from all these geothermal reservoirs were feasible, the potential geothermal resource would be at least 10<sup>23</sup> calories, which is approximately equivalent to the energy

represented by the world's potential resources of coal.

Exactly what proportion of the geothermal resource base can be considered a resource depends upon a number of factors, such as depth of extraction and temperature at that depth; effective porosity, specific yield, and permeability of the reservoir rocks; physical state of the fluid (water or steam); available technology; economics of various uses; environmental constraints, and government policy. The function of the proposed research program is to provide the information which will increase the proportion of the geothermal resource base which is considered to be a resource.

#### **B. CLASSES OF RESOURCES**

Geothermal resources consist of the thermal energy and the fluids (water plus dissolved minerals) which are found in the earth where the temperature of the formation and fluids significantly exceeds that which is to be anticipated on the basis of normal vertical temperature gradients, say, 30°C per kilometer, and normal vertical heat flow, 1.5 microcalories per square centimeter per second.

Geothermal resources are conveniently classified in accordance with the presence or absence of fluids. Under each classification, there are several distinctions which are necessary to define adequately the different types of geothermal resources. These distinctions are based on the physical properties of the resource, convective versus non-convective systems, permeable versus non-permeable formations, etc.

In the case of utilization technology and economics it is also necessary to distinguish between several

temperature regimes because the energy conversion cycle is heavily dependent on this characteristic.

Table III shows the classification system which is used in this report.

Vapor-dominated convective hydrothermal resources.<sup>7</sup> Vapor-dominated geothermal systems produce superheated steam with minor amounts of other gases (CO<sub>2</sub>, H<sub>2</sub>S, NH<sub>3</sub>) but little or no water. Thus all of the fluid can be piped directly to the turbine.

Within the vapor-dominated geothermal reservoir, saturated steam and water coexist, with steam being the phase that controls the pressure. With decrease in pressure upon drilling and production, heat contained in the rocks dries the fluid first to saturated steam and then to supersaturated steam, with as much as 55°C superheat at a well-head pressure range of five to seven kilograms per square centimeter.

Pressures larger than about 34 kilograms per square centimeter and temperatures above 240°C in vapor-dominated reservoirs are unlikely because of thermodynamic conditions and the flow dynamics of steam and water in porous media. Hot brine probably exists below the vapor-dominated reservoirs at depth but the reservoirs have not yet been drilled deep enough to confirm the presence of such brine. The steam reservoir may be a "cap" for the upflowing part of a major liquid-dominated convective hydrothermal system.

Drilling has demonstrated, so far, only five vapordominated systems, of which only three are really commercial: Larderello, Italy; The Geysers, California; and Matsukawa, Japan. Two small fields in the Monte Amiata region of Italy are marginally commercial. The Valles Caldera region of New Mexico has been recently discovered.

Larderello, Italy was the first geothermal field to be exploited (1904) and is still the largest geothermal generating capacity (358 MW) in the world. The Geysers, California at present produces 247 MW, but plants under construction will boost capacity to 302 MW by the end of 1972. Ultimate potential of The Geysers field has been estimated up to 1000 MW.8

Liquid-dominated convective hydrothermal resources. These are thermally-driven convective systems of meteoric water in the upper part of the earth's crust which transfer heat from a deep igneous source to a depth sufficiently shallow to be tapped by drill holes. The exploration target is a reservoir located in the upflowing part of the convective system. The thermal energy is stored both in the solid rock and in the water and steam which fill the pores and fractures.

Geothermal systems of this type are the "hot spots" within larger than the world-wide average of 1.5 microcalories per square centimeter per second. Such regions are commonly found in zones of young volcanism and mountain-building. Among geothermal systems discovered to date, hot liquid-dominated systems are perhaps twenty times as common as vapor-dominated systems.9

Hot liquid geothermal systems contain water at temperatures that may exceed surface boiling temperatures substantially because of the effect of the higher pressure in elevating the boiling temperature. In major zones of upflow, coexisting steam and water may extend to the surface and result in geysers and hot boiling springs. Such zones are relatively easy to find

but it is not known what fraction of liquid-dominated systems produce such surface expression.

Water in most hot liquid geothermal systems is a dilute aqueous solution (1,000 to 30,000 milligrams per liter) containing sodium, potassium, lithium, chloride, bicarbonate, sulfate, borate, and silica predominantly. The silica content and the ratio of potassium to sodium are dependent on the temperature of the geothermal reservoir, thus allowing prediction of subsurface temperatures from chemical analysis of hot fluids.

The major known hot-liquid geothermal fields are Wairakai (160 MW) and Broadlands (100 MW proposed) in New Zealand, Cerro Prieto (75 MW, 200 MW proposed) in Mexico, Salton Sea field in California, and the Yellowstone geyser basins in Wyoming. The Yellowstone area, the world's most intensive display of hot spring and geyser phenomena, is permanently set aside as a National Park and will never be exploited for its energy.

Geopressured resources.<sup>10</sup> Deep sedimentary basins filled with sand and clay or shale of Tertiary Age (less than 80 million years) are generally undercompacted below depths of 2 to 3 kilometers and, therefore, the interstitial fluid pressure carries a part of the overburden load. Such regions are said to be geopressured.

Geopressured geothermal systems occur in regions where the normal heat flow of the earth is trapped by insulating impermeable clay beds in a rapidly subsiding geosyncline or downward bend of the crust. Pressures at depth are significantly in excess of hydrostatic and may approach lithostatic. Waters in the geopressured zones are not meteoric but are produced by

compaction and dehydration of the marine sediments themselves.

Aquifer systems within the geopressured section are compartmentalized by regional faults into blocks of horizontal extent ranging from tens to thousands of square miles. The interbedded clay or shale commonly has a porosity which is 6 to 8 per cent greater than it would have if fully compacted at its depth of occurrence.

Geopressured deposits are hotter than normally pressured deposits because upward loss of the included water has been essentially stopped for millions of years. Water is a poor conductor of heat compared to the associated minerals, and undercompacted clay is an excellent thermal insulator. The specific heat of water is about five times that of the associated minerals. Thus, geopressured deposits reduce the thermal flux above them compared to that below and store geothermal energy until a steady temperature is reached. The temperature gradient is sharply increased at the top of the geopressured zone.

In this setting, the heat-caused changing of expandable clays liberates bound and intracrystalline water and the free pore water thus formed may be as much as 30 per cent of the volume of the unaltered clay. This new free pore water is fresh and, as it drains into the adjacent sand-bed aquifers, it flushes the more saline water upwards toward the top of the geopressured zone.

Aquifers a few thousand feet below the top of a geopressured zone commonly contain water having less than 10,000 milligrams per liter of dissolved solids. In some places the water is even potable (less than 1,000 milligrams per liter).

Because the solubility of hydrocarbon gases in water increases rapidly with decreasing dissolved solids, and because the high temperatures and pressures have resulted in a natural cracking of the petroleum hydrocarbons, the geopressured reservoir fluids commonly contain 10 to 16 standard cubic feet of natural gas per barrel of fluid. These dissolved hydrocarbon gases would be a valuable by-product of fluid production.

Temperatures of produced water would range from 150 to 180°C. Well-head pressures would range from 4,000 to 6,000 pounds per square inch.

Production rates could be several million gallons of fluid per day per well and perhaps a million standard cubic feet of natural gas per day per well.

Geopressured deposits occur in continuous belts, are commonly bounded by regional faults, and extend for hundreds of miles. The belt in the Northern Gulf of Mexico basin is about 750 miles long, from the Rio Grande of Texas to the Mississippi Sound. It underlies the Coastal Plain inland for a distance of 60 to 100 miles, and underlies the Continental Shelf wherever drilled up to 150 miles offshore. The geopressured zones are not continuous over the entire region but are thought to exist in lenses, blocks, and partitioned volumes as a the complex geological result of processes accompanying the rapid (geologically) subsidence of the geosyncline.

The search for oil and gas has uncovered geopressured reservoirs in many countries of the world. In the United States, geopressures have been encountered in the Gulf Coast, California, and Wyoming. Other sites have been found in Mexico,

South America, Far East, Middle East, Africa, Europe, and in the U.S.S.R.

Impermeable dry rock. Hot impermeable rock systems are those geothermal regions where the heat is contained almost entirely in impermeable rock of very low porosity. Interactions of the large plates of the earth's surface along the west coast of North America have resulted in volcanism, tectonic activity, and high heat flow affecting much or perhaps all of the western United States. The heat generated by those interactions has been in part responsible for the presence of large, once-molten masses of granite forming the core of the Sierras and various other once-molten masses called batholiths.

Areas such as Craters of the Moon, Idaho, are surface manifestations of the recent presence of similar ages of intrusive rocks. Thus the western U.S. holds excellent prospects for finding enormous amounts of hot impermeable dry rock formations.

As an indication of the magnitude of the energy stored in these systems, it has been estimated that the thermal energy released by cooling one cubic mile of rock from an initial temperature of 350°C to 177°C would be equivalent to that available from 300 million barrels of oil.

Once the technologies are available to recover economically the thermal energy from dry anomalies as discussed above, and once deep drilling technologies are available, geothermal energy sources might be extended to areas of normal heat flow, thereby producing a truly immense energy source.

Magma systems. Magma geothermal systems are those systems where the thermal energy is contained in liquid

or near-liquid rock at temperatuaes ranging from 600°C to perhaps 1,500°C. In the Hawaiian Islands a continuing history of magmatic activities presents some unique potentialities for recovering usable energy from volcanic areas. The other live volcanoes of the U.S., including Alaska, offer potential also. In many instances, very deep drilling may be required to reach these resources.

#### C. TEMPERATURE REGIMES

In the case of utilization technology and economics, it is necessary to distinguish among the several temperature regimes because the energy conversion cycle and the economic feasibility of exploiting a geothermal source depends heavily on this characeristic. This section will not dwell on the details of utilization technology but, instead, will employ a descriptive approach to the utilization of geothermal resources to produce electrical energy, desalinated water, recovered minerals, and process heat.

Superheated steam. This category applies to the vapordominated convective hydrothermal resource, magma systems, and the very hot impermeable dry rock formations. The present approach is that of drilling steam supply wells into the formation to withdraw steam. The steam is directed through a separator to remove any abrasive particles that it may carry. From the separator the steam proceeds directly to a turbine which drives an electric generator. Upon issuing from the turbine, for efficiency reasons, the steam is directed through a condenser where it is returned to the liquid state. Part of the cool liquid may be used later as the coolant for the condenser and the remainder may be reinjected into the formation.

In the case of vapor-dominated systems, no pretreatment to improve impermeability of the formation is necessary. In the case of magma systems, no substantial approaches to pretreatment have been identified. There are two approaches which have been discussed for pretreatment of the impermeable rock formations.

Techniques proposed entail nuclear explosive fracturing or hydraulic fracturing followed by thermal fracturing as the thermal energy is withdrawn from the fractured region. If the steam is generated in the formation and is withdrawn as steam, none of these types of resources are appropriate for multiple-use development. The vapor phase of water carries very few mineral impurities and the condensed water remaining after the demands of the cooling system are met is not large.

Above 180°C. This category applies to high-temperature liquid - dominated convective hydrothermal resources, magma systems, and high temperature impermeable rock formations.

It is assumed that the energy will be withdrawn from the formation as contained in liquid water. Depending on the developer's choice, the water may be brought to the surface under pressure without any flashing to steam or it may be allowed to flash partially to steam upon leaving the formation and entering the drill hole.

In either case the surface equipment would commonly consist of flash separators (possibly several stages) in which the water is flashed to steam and the water and steam separated from each other. The steam is then directed to turbines which drive electrical generators. The treatment of the steam following its passage through the turbines is conceptually the same as described above except that the equipment is different.

The water leaving the separators is available for further processing depending upon its mineral content. The water may be reinjected into the formation, it may be desalinated for further use or prior to reinjection (if minerals leached from the formation are economically producible), and the concentrated brines treated for mineral recovery prior to disposal.

Multiple use development of these resources is probably limited to electrical energy production and possibly mineral recovery in the case of magma systems and impermeable rock formations. In the case of liquid-dominated convective hydrothermal resources, production of desalinated water in conjunction with electrical energy production is to be expected.

Pretreatment of the formation is not necessary for development of the liquid-dominated convective hydrothermal resources but will be required, as described previously, for the other formations.

Under existing technology, the geothermal resource must produce a fluid having a temperature of at least 180°C if electrical generation is contemplated by the flashed steam approach. This lower limit results from the fact that the fraction of the original fluid that can be flashed to steam is very low (10 weight per cent or less depending upon pressure)

From 100°C to 200°C. This category applies to intermediate - temperature liquid - dominated convective hydrothermal resources, geopressured

geothermal resources, and perhaps impermeable rock systems. The formation pretreatment required here for the impermeable rock case may preclude its exploitation.

In this temperature regime the hot liquid is brought to the surface and passed through a heat exchanger where its heat is transferred to a low boiling point fluid, such as freon or isobutane, which is subsequently used in a closed cycle energy conversion system to produce electrical energy. The formation fluid in its entirety is then available for reinjection into the formation or subsequent processing such as desalination and/or mineral recovery.

Multiple use development of these resources is to be expected, producing electrical energy, desalinated water, and minerals.

The geopressured resource will require different equipment because of the high pressures but the conceptual development is the same except for one process. Geopressured fluids contain dissolved hydrocarbon gases and it will be advantageous to reclaim this natural gas. No pretreatment of these formations is contemplated.

Below 120°C. This category applies to the low-temperature liquid dominated resources, both convective hydrothermal and geopressured. These resources are predominantly useful for process heat although recorded history contains many references to their use for therapeutic purposes.

The development of these resources can follow two approaches. Either the fluid is piped to the process under consideration or the heat is extracted and conveyed via another medium to the process. Process heat applications include residential and commercial building heating and cooling, horticulture, paper and pulp manufacturing, etc. Clearly the process heat application requires proximity of the process and the geothermal resource since geothermal heat cannot be transported any significant distance.

Multiple use development in this regime may be possible under different sets of conditions. Mineral recovery may be feasible under certain conditions and, at the higher end of the temperature regime, water desalination may be appropriate.

## TABLE III. CLASSIFICATION SYSTEM FOR GEOTHERMAL RESOURCES

### A. Wet Formation

- 1. Convective hydrothermal resources
  - a. Vapor dominated
  - b. Liquid dominated
- 2. Geopressured resources
  - a. Liquid dominated
- **B.** Dry Formations
  - 1. Impermeable rock
  - 2. Magma systems
- C. Temperature Regimes
  - 1. Superheated steam temperatures
  - 2. Above 180°C
  - 3. From 100°C to 200°C
  - 4. Below 120°C

### RESOURCE EXPLORATION

### A. OBJECTIVE AND SUMMARY

The objectives of the resource exploration panel were to identify the research programs necessary to develop, improve, and refine geothermal exploration techniques. These techniques are used to locate areas underlain by high temperature heat sources; to estimate the reservoir volume, temperature, porosity, and permeability at depth; and to determine the nature of any fluids producible from the geothermal resource.

Even though there are several different classes of geothermal resources, as indicated in Table III above, with each having different physical properties, the panel directed its attention to the individual techniques. The combination of techniques which will be most useful in specific explorations is different for each category of resource. Deep drilling technology is not considered as a part of exploration and, therefore, will be considered in the following chapters.

The geothermal exploration techniques reviewed by the panel are: geological, geochemical, electrical, seismic, gravity, magnetic, and thermal methods. In addition, some possibly fruitful areas of basic research were considered, and some research projects concerned with present drilling technology improvement presented.

Some important geological research problems are concerned with determinations of: age, size, and magmatic type of igneous occurrences related to convective hydrothermal and permeable rock systems; and the relationship of convective hydrothermal systems to broad regions of elevated heat flow.

Geochemical research is needed in: chemical,

physical, and thermodynamic properties of aqueous solutions at temperatures ranging from 100°C to 400°C; determination of chemical compositions of in-situ geothermal fluids as a function of in-situ temperature; and isotopic relations among water and various dissolved constituents, particularly gases.

Electrical resistivity research should be directed toward: understanding the variation of porosity, water salinity, and temperature in actual geothermal reservoirs; improving electric field techniques and procedures for extracting true resistivity values from field data; and developing complementary exploration techniques which will improve the interpretation of resistivity data. Other electrical exploration research should include further work on DC resistivity, self-potential, electromagnetic, telluric, and magnetotelluric techniques.

Active seismic methods should be studied to characterize energy absorption and attenuation, and frequency shifts in known high temperature systems. Seismic noise studies should be undertaken to evaluate: temporal and spatial noise variations; characteristics of recognized noise sources, noise spectra, noise coherency, location of source, and cause of noise; and direction of noise propagation and apparent velocity.

Additional research is needed to determine the source of the gravity and magnetic anomalies associated with known geothermal areas and to decide whether these anomalies can be used as indicators of the internal temperature of the system.

Thermal research is needed to determine the relationships between temperature gradients,

subsurface distribution of isotherms, and the geometry of geothermal systems. Laboratory temperature experimentation on model geothermal systems is needed.

Hydrologic studies are required to understand more fully the effect of ground water movement on local geothermal gradients. Basic research should be pursued on physical properties of geothermal watersteam mixtures, thermal geophysics and hydrology, modern geoscience theories and geothermal anomalies, data processing and general interpretation theory, and computer modeling.

Present drilling technology needs improvement in techniques for: isolating tested intervals in unconsolidated sands and in fractured reservoirs; inexpensive core recovery with reservoir fluid in place; logging at temperatures above 180°C; and transmission of information from the bore hole face to the surface. Development of cheap, low density, low viscosity, nonthermally sensitive, high thermal conductivity, and high surface tension drilling fluids would lower drilling costs and leave the bore-hole face in a more nearly undisturbed state.

#### **B. RESEARCH AREAS**

At the present time, the most reliable exploration technique for new geothermal reservoirs is to find areas containing hot springs, a situation similar to that in the petroleum industry in the early 1900's when petroleum exploration consisted of finding areas of surface oil seeps. A great deal of research is needed to develop, improve, and refine geothermal exploration

techniques. Several pertinent research areas are discussed below.

Geological Techniques. Geological techniques are used throughout all phases of geothermal exploration, from reconnaissance to site evaluation to detailed interpretation of drilling data and drill logs. Geological considerations provide the framework in which the various geochemical and geophysical techniques are interpreted, and, as such, are an integral part of all phases of geothermal exploration.

Geological research required to provide the framework for interpretation of data from other exploration techniques includes: determination of the age, size, and magmatic type of igneous occurrences related to convective hydrothermal systems; the nature and cause of structural features controlling the location of convective hydrothermal systems and impermeable rock systems; and the relationship of convective hydrothermal systems to broad regions of elevated conductive heat flow.

Geochemical Techniques. Geochemical exploration for geothermal resources involves sampling waters and gases from hot and cold springs, steam vents, shallow drill holes, and surface streams. The resultant data are used to: determine the state of the fluid at depth; estimate the minimum temperature expected at depth; estimate the homogeneity of water supply; infer the chemical character of water expected at depth; and determine the source of recharge water. Geochemical data collected during exploration is also valuable in the production and utilization phases of geothermal development and therefore should be carefully preserved for future use.

Although several hydrogeochemical indicators have had considerable use and success in geothermal exploration, others can be used only qualitatively at present or are not interpretable in the present theoretical and experimental framework. Research is needed in: chemical, physical, and thermodynamic properties of aqueous solutions at temperatures of 100°C to 400°C; chemical compositions of in-situ geothermal fluids as a function of original (pre-drilling) rock temperatures; and isotopic relations among water and various dissolved constituents (particularly gases).

Electrical Methods. Up to the present time electrical resistivity surveys have been one of the primary geophysical means used for discovering geothermal fields. Geothermal systems are characterized by thermally induced changes in electrical resistivity. Evaluation of the actual temperature and volume of a system is complicated in many cases by resistivity variations associated with changes in porosity, water salinity, rock texture and partial boiling.

It is most important that research be directed to understanding how porosity, water salinity and pressure vary in actual geothermal reservoirs so that interpretation of electrical surveys can be made more certain. In addition, research to improve electrical field techniques and procedures for extracting true resistivity values from field data is needed. Research on the use of other exploration techniques to provide input for improving interpretation of resistivity data may be particularly fruitful.

Electrical exploration methods which should be evaluated or further developed include DC resistivity,

self-potential, electromagnetic methods, telluric and magnetotelluric techniques; airborne methods may be of special interest in large scale reconnaissance.

Seismic Methods. Reflection and refraction studies can be used to determine the structural setting of potential geothermal areas. In addition to these classical arrival time studies additional work should be done in the area of energy absorption and attenuation, and the effects on frequency in known high temperature systems. Geothermal areas do exhibit high attenuation and a shift to lower frequency for transmitted seismic waves. Perhaps these data can be used as a monitor of the internal reservoir temperature.

Detailed studies in Iceland, El Salvador and California have shown the existence of earthquake activity in close association with geothermal fields. The earthquakes occur at shallow depths (6km) and are small in magnitude. Accurate determination of the earthquake pattern delineates faults that may channel hot fluids to drillable depths.

Although most authorities agree that relieving geothermal pressure will diminish earthquake potential rather than stimulate it, the causes of these tremors should be understood, and the effects of fluid and high temperature on fault strength and slip characteristics evaluated. Additional potential and developing geothermal areas should be studied in this regard.

Areas of high background ground motion (seismic noise) have been correlated with geothermal areas in New Zealand and in the Imperial Valley of Southern California. Seismic noise surveys are being conducted in potential geothermal areas in many countries. Studies should be undertaken to evaluate: temporal and spatial

noise variations; characteristics of recognized noise sources, noise spectra, and noise coherency; direction of noise propagation and apparent velocity; location of noise sources; and cause of noise.

Gravity and Magnetic Techniques. The gravity and magnetic signatures of geothermal systems vary tremendously from one geologic province to another. There is no simple answer to the question of what type of anomaly should be expected from a geothermal reservoir. However, these methods have been very useful in the exploration of known geothermal reservoirs for determining gross structural features and in the location of potential geothermal systems. They should be routinely evaluated as a reconnaissance exploration method in outlining suspected geothermal areas.

Additional studies should be made to determine the source of the gravity and magnetic anomalies associated with known geothermal areas and if these anomalies can be used as indicators of the internal temperature of the system.

Thermal Techniques. Thermal exploration techniques provide a direct method of assessing the size and potential of a geothermal system. The thermal techniques can be ordered in terms of increasing cost and usefulness as follows: surface temperature measurements, geothermal gradient surveys, and heat flow determinations.

Additional regional heat flow determinations are needed in order to refine estimates of available geothermal resources. Much research is needed to determine relationships between temperature

gradients, subsurface distribution of isotherms, and the geometry of geothermal systems. Research in the area of laboratory temperature experimentation on model geothermal systems is also required.

Hydrologic studies must be made in order to more fully understand the effect of ground water movement on local geothermal gradients.

Drilling. Drilling techniques are developed in the United States to a point of high reliability for depths from a few hundred feet to 25,000 feet and for temperatures up to 400°F. Temperature gradient holes are drilled by adapting seismic shot hole drilling methods. Wells required are shallow and of small diameter. Current methods are effective and inexpensive. No research is indicated. Heat flow measurement holes are drilled with techniques used in mineral exploration. These methods are reliable though more costly than the temperature gradient holes. The number of heat flow holes which must be drilled is not judged of such magnitude that research to lower the cost should be funded, rather, it is recommended that heat flow holes be drilled using present technology.

Formation testing in uncased holes can provide useful input to the exploration for geothermal fluid reservoirs. Problems of isolating tested intervals in unconsolidated sands and in fractured reservoirs have not been solved. Research effort in this area would benefit geothermal, oil, gas, and water development projects.

Inexpensive core recovery with reservoir fluid in place would aid in model definition of a geothermal cell.

Instrumentation for logging devices now available

is not satisfactory at temperatures above 400°F. Research on methods of transmission of information from the bore hole face to the surface is imperative. The development of low density, low viscosity non-thermally sensitive, high thermal conductivity and high surface tension drilling fluids would improve drilling times thus lowering costs and at the same time leaving the bore hole face in as nearly an undrilled state as possible.

Documentation of data recovered is necessary for future programs. The preservation and storage of drill cuttings, cores and logging data will require funds that are not a research item but are necessary for the effective prosecution of research on geothermal systems.

Basic Research. There is urgent need for studies of the physical properties of water-steam fluid mixtures typical of those found in geothermal systems. This information is necessary to improve the interpretation of geophysical exploration results and to assist in determining optimum production practice.

Research is needed in thermal geophysics and hydrology to obtain a better understanding of the nature of the ultimate sources of energy in developable geothermal systems, and of the main modes of energy transport (conduction, convection, radiation) in the crust and the upper mantle. Moreover, the mode of energy transport within individual geothermal systems (conduction, one- and two-phase convection) is of considerable interest.

The setting of the exploitable geothermal systems within the framework of the modern geoscience theories (sea-floor spreading and plate tectonic models) should be investigated in order to establish global patterns of distribution of geothermal anomalies.

Research efforts should be directed to the solution of the many mathematical problems encountered in the exploration and utilization of geothermal systems. Of particular interest are the problems arising in thermal geophysics, hydrology, data processing, and general interpretation theory. This will involve research in applied mathematical analysis, numerical analysis and computer modeling.

New techniques of geothermal exploration such as in the fields of seismology, potential field and elastic strain should be researched and developed.

Development of theory for optimization of exploration methodology and techniques should be undertaken.

#### C. BUDGET

The panel as a group, feels that the proposed 10-year geothermal exploration research program which was presented in "Assessment of Geothermal Energy Resources" is adequate. Therefore, a 10-year research effort of 49.5 million dollars for resource exploration is recommended. The funds would be programmed as follows.

Fiscal Year 74 75 76 77 78 79 80 81 82 83 Total

Budget 5.0 8.0 11.0 9.5 6.0 3.5 2.0 1.5 1.5 1.5 49.5 (millions)

### VI. RESOURCE ASSESSMENT

## A. OBJECTIVE AND SUMMARY

The objectives of the resource assessment panel were to identify the research programs which are prerequisite to assessing adequately the quantitative characteristics of geothermal resources of all types and, in addition, to assess the magnitude of the resource which underlies the entire United States. These programs do not include research on exploration techniques, and stop short of research on development and production techniques.

The process of estimating the quantitative characteristics of the resource includes the geographical distribution of known reserves, probable reserves, and potential reserves under specified conditions for each different type of geothermal system. Assessment research involves the development of the requisite theory and mathematical models which constitute the assessment methodology. These models must be based on the geological, geophysical, geochemical, and thermal characteristics which can be expected to be available from exploration work preceding the assessment.

In order to assess all different types of geothermal resources it will be necessary to drill into the formations. For this reason, the improvement of present drilling technology as well as research on new drilling technologies for great depths is considered a part of resource assessment research.

A primary research objective is to define the extent of the resource. During the progress of the resource assessment program a national inventory of geothermal resources should be established, and all geothermal resources should be assessed with respect to multiple use: the production of energy, desalinated water, minerals, and process heat.

In order to assess the hydrothermal convection systems, the dynamics of representative convection systems and geological, geochemical, hydrologic, and geophysical characteristics of geothermal systems must be studied. The objective of the first topic is to understand the size, life, origin, and dynamics of natural hot water geothermal systems, whereas the second is to provide the basic data on which the assessment model must be founded.

Three forms of energy are available in the produced fluid from geopressured aquifers. These are the intrinsic thermal energy, the mechanical energy available from the high pressure, and the methane contained in the formation fluid.

A regional resource study should identify three suitable sites for field research leading to a determination of the size and total energy content of typical geopressured reservoirs. This study should be conducted to compile data on temperature, structure, salinity, sedimentary characteristics, pressure potential distribution, and possible waste water disposal methods. In order to validate the geopressured resource model it will be necessary to drill and test the formations selected. This approach should lead to adequate assessments as well as assessment methodology.

Adequate assessment of the impermeable rock resources will draw upon explorations to establish the occurrences, age, volume, temperature, and permeability of the igneous intrusions under consideration. This will require study and modeling of

rock mechanics and fracture systems, and greater understanding of the hydrology and the energy transfer characteristics of fracture systems.

The geochemistry of fractured hot impermeable rock systems is not well understood. Research will have to be conducted on geochemical kinetics to provide key characeristics of the heat transfer medium which brings the energy to the surface.

In order to determine the three-dimensional characteristics of representative geothermal areas, it will be necessary to undertake a deep drilling program into geothermal formations. A minimum of four wells must be drilled to depths in excess of 20,000 feet.

The difficulty and great expense involved in drilling to these depths in hot formations makes it imperative that new innovative approaches to drilling receive high priority in the research program. Erosion drills, electric melting drills, turbine drills, and other techniques should be explored.

#### **B. RESEARCH AREAS**

The program envisioned includes actual assessment studies as well as research on assessment methodology. In all cases, the assessments must consider energy, water, and minerals. During the resource assessment research program a national inventory of geothermal resources should be established. A deep drilling research program is vital to the adequate evaluation of many geothermal resources. The several research areas directed toward resource assessment are discussed briefly below.

Hydrothermal Convection Systems. Present geothermal resource utilization depends entirely on hydrothermal convection systems, in which most energy is transferred upward in deeply circulating fluids. These systems thus provide high temperatures relatively near the surface and also natural fluids for transferring thermal energy to a power plant, desalination plant, or mineral production plant.

Two major types of convection systems are recognized. The relatively rare vapor-dominated (dry steam) systems account for most present world-wide geothermal power production. The much more abundant hot water systems must account for most of the near-future increases. The problems that must be solved to assess the hydrothermal convection systems of the Nation are described briefly below.

In order to understand the dynamics of hydrothermal convection systems it is necessary to determine the size, natural life and circulation rates, origin, and flow patterns of several representative natural hot water geothermal systems. This information establishes the constraints and the main outlines of a comprehensive hydrothermal convection system model which must be validated on fields previously not included in the determinations. Once the modeling methodology is developed and validated, it can be applied to the assessment of such resources and the actual assessments can be supplied to the national inventory.

The modeling effort and the actual assessments referred to above are based on the geological, geochemical, geophysical, hydrologic, and thermal characteristics of the hydrothermal convection systems. Because of the diversity and geological

complexity of hydrothermal convection systems, the assessments require the collection of a great deal of data which will be very useful in the subsequent development of these resources. Thus all of the data should be retained in the national inventory.

Funding in the amount of \$115 million over a period of ten years is recommended for this research and assessment program. The recommended budget schedule is shown in Table IV.

Geopressured Resources. Abnormally high fluid pressures in the northern Gulf of Mexico basin are associated with high porosity deposits in which the confined water has stored geothermal heat for millions of years. These deposits extend in a 750-mile belt beneath the coastal region and underlie the coastal plain and adjacent continental shelf. The aquifers are discontinuous, occurring in partitio ed volumes bounded by faults generally paralleling the coastline. Similar aquifers have been found in Wyoming and in California.

A reservoir suitable for power production would contain a large volume of permeable sandstone. Since formation water is saturated with methane, three forms of energy are available in the produced water. These are the intrinsic heat, the obtained gas, and the mechanical energy available from the high pressure of the discharged water. The research and assessment program for these resources is discussed below.

The first step in assessing the geopressured resource is to conduct regional resource studies based upon data which presently exist in petroleum company files. Because of the proprietary nature of the petroleum company files, even though the data on the

geopressured resource itself is normally not considered proprietary, it will be necessary to derive these data through a cooperative endeavor in which each company extracts the information from its own files and provides it to the resource assessment group.

A neutral part, in respect to the petroleum companies, will be required to carry out the resource study.

The objective is to compile the available data concerning temperature, geological structure, salinity, sedimentary facies, pressure potential distribution and methane content for the geopressured resource.

Regions of interest are the Gulf Coast, Wyoming, and California.

Funding in the amount of \$1 million is recommended for the regional resource studies. The work should be completed in two years with equal funding in each year. The first year would probably concentrate on the Gulf Coast, whereas the second year would cover the remainder of the U.S.

As with hydrothermal convection systems, it will be necessary to develop models to characterize the dynamics of the geopressured reservoir, and then apply these models to assess the resources of this type. The geological setting of geopressured resources appears somewhat simpler than that of the typical hydrothermal convection system and therefore the work necessary to assess them is less extensive.

The models will need to relate to the size, recharge rates from neighboring formations, origin, natural life, and flow mechanics of representative geopressured resources. The actual assessments must be added to the national inventory.

The modeling effort and the actual assessments are

based on the geological, geochemical, geophysical, hydrologic and thermal characteristics of the geopressured resources. It is expected that a significant amount of data must be collected from field tests even though companies' files are thought to contain much of the required data.

Funds are recommended in the amount of \$29 million for a ten year research program for assessing geopressured resourced.

Hot Impermeable Rock. The thermal energy in the crust, mantle, and core of the earth constitutes an immense energy resource base.

The minute fraction of this energy which is actually being used by man is only that delivered to the earth's surface, or at least to shallow depths, by the convective processes represented by natural steam and by hydrothermal convection systems. The rest is not yet established as an accessible resource because the means to deliver it to the surface as usable energy have not yet been developed and demonstrated.

Various approaches have been proposed to develop this new major source of energy, all involving the creation of an artificial circulation system by drilling two holes into the formation and fracturing the rock between these holes. Several fracturing techniques have been discussed, such as hydraulic, chemical explosive, acid treatment, nuclear explosive, and thermal fracturing.

The research discussed below is directed at developing the methodology to assess and actually assessing these resources. No assumption is made with regard to the viability of one approach relative to another.

The hot impermeable rock can occur in two substantially different configurations. First, in a reasonably uniform sense, it is expected that hot impermeable rock underlies the entire United States, even in regions of sub-normal heat flow. This expectation rests upon the idea that meteoric water will only descend to some rather consistent depth in the earth, and that the rocks at great depth have either crystallized from a magma or are so highly recrystallized that they have little or no permeability.

Secondly, during geologic time, magma has forced its way up into the earth's mantle and outer crust as a result of geological processes that are not well understood. Essentially the magma was trapped and either has crystallized or is crystallizing in place as a magmatic intrusive. The development of assessment methodology and the actual assessment of the intrusive resources is the object of this portion of the research program.

It is anticipated that the resource assessment for the very deep resource can be accomplished without further research or field work once the deep drilling technology is developed. Such a development would truly make geothermal energy available to all sectors of the United States. In areas of average temperature gradient (20°C/km) a temperature of 200°C is expected at a depth of 10 kilometers (about 33,000 feet).

In order to determine the methodology which is necessary to assess the hot impermeable rock resource, several research tasks must be completed: studies of rock mechanics, modeling of hydrodynamics of a fracture system, studies of site and bore-hole hydrology, studies of nature of allowable injection fluids, selection of test sites, and drilling and fracturing of formation (both injection and extraction wells). Assessment must include the intermediate grade (older) eastern deposits as well as the western ones.

Funds in the amount of \$41.5 million are recommended for assessment research and assessment of the the hot impermeable rock resources.

Magma Systems. A continuing history of magmatic activities in the Hawaiian islands is surface evidence of the continuing intrusion of magma into the earth's mantle and upper crust. These very large sources of energy at quite high temperatures present some unique problems and opportunities concerning new approaches to derive useful energy from magma.

Including Hawaii and Alaska, there are fifty or more live volcanoes in the United States. Unobserved intrusives at depth, however, probably outnumber the live volcanoes.

In order to assess the magmatic resources it will be necessary to conduct geological, geophysical, geochemical, hydrologic, and thermal tests on typical deposits. Drilling into the formation surrounding the magma chamber will be necessary. The information gained in this manner will be used to establish a model for assessing magmatic geothermal energy resources.

Funding in the amount of \$6.2 million for ten years is recommended in support of assessment research projects and actual assessment of the magmatic geothermal resources.

National Inventory of Geothermal Resources. Several times previously, it has been stated that all of the assessments actually performed in the nation's geothermal resources research program should be

retained in a central depository for subsequent use in the reservoir dvelopment and production phases of exploitation of the geothermal resources. In addition, all of the data used as input to the assessment models should be retained. Not only should the data be retained, but key core samples should be stored for subsequent analysis from different viewpoints. Although this type of activity is not normally considered research, the national inventory is perhaps one of the most vital keys to making the more inaccessible parts of the geothermal resource base available as a true resource.

In support of the national inventory of geothermal resources, funds in the amount of \$2 million, distributed evenly over the total period, are recommended.

Deep Drilling. Deep drilling into hot formations is essential to the determiation of the three-dimensional properties of geothermal resources. The deep drilling phase of the geothermal resource assessment program will involve a minimum of four wells to depths in excess of 20,000 feet and into extraordinarily hot formations.

The data acquired will provide an understanding of the three-dimensional characteristics of representative geothermal areas to depths previously unattainable. The frontier of geothermal science and technology will be pushed into entirely unexplored regions which will probably provide indispensable guidelines for further exploration and expansion of the general energy resource base of the country. It may open up a much larger reserve of geothermal energy for future development.

The difficulty and great expense involved in drilling to these depths in hot formations makes it

imperative that new innovative approaches to drilling receive high priority in the research program. Erosion drills, electric melting drills, turbine drills, nd other techniques should be explored.

Funds in the amount of \$75 million over a period of ten years is recommended in support of deep drilling for assessment purposes and for research on deep drilling technology.

## C. BUDGET

The recommended ten-year resource assessment research budget is shown in Table IV below. Separate budget categories are shown for hydrothermal convection systems, geopressured resources, hot

impermeable rock, magma systems, national inventory of geothermal resources, and deep drilling technology.

It will be noted that the recommended budget for hydrothermal convection systems is almost half of the entire resource assessment budget. Two factors dictate this distribution of funds. First, the hydrothermal convection systems are expected to yield an earlier impact than the other types of resources. Secondly, the diversity and geologic complexity of hydrothermal convection systems is such that their adequate assessment requires more extensive work.

Funds in the amount of \$273.7 million are recommended for the support of resource assessment studies over the ten-year period.

TABLE IV:
RESOURCE ASSESSMENT RESEARCH BUDGET

(Millions of Dollars)							
	1974	1975	1976	1977			
Hydrothermal Convection	8.0	11.0	14.0	14.0			
Geopressured Resources	3.0	4.0	5.0	5.0			
Hot Impermeable Rock	3.4	4.0	4.0	3.7			
Magma Systems	0.5	2.7	1.6	0.5			
National Inventory	0.2	0.2	0.2	0.2			
Deep Drilling	0.5	1.5	3.0	6.0			
Totals	15.6	23.4	27.8	29.4			

# Fiscal Year

1978	<u>1979</u>	1980	1981	1982	1983	Total
14.0	12.0	12.0	12.0	10.0	8.0	115.0
5.0	4.0	3.0	2.0	2.0	1.0	34.0
3.7	4.0	4.0	5.0	5.0	4.7	41.5
0.3	0.2	0.1	0.1	0.1	0.1	6.2
0.2	0.2	0.2	0.2	0.2	0.2	2.0
8.0	10.0	11.0	12.0	13.0	10.0	75.0
31.2	30.4	30.3	31.3	30.3	24.0	273.7

# RESERVOIR DEVELOPMENT AND PRODUCTION

# A. OBJECTIVE AND SUMMARY

The objectives of the reservoir development and production panel were to describe the research programs which are necessary prerequisites to the optimal development of a geothermal reservoir and production of the resource in its several manifestations: energy, desalinated water, minerals, and process heat.

The data gained from resource exploration and the models and data used for resource assessment form the starting point for reservoir development and production. However, the models will need to be extensively modified to encompass the behavior of the reservoir under different distributions of withdrawal and injection sites and schedules of production.

The models must address the problem of the probable life of the reservoir under these distributions and schedules. In addition, the data gained from exploration and assessment will need to be supplemented by further reservoir data gained from exploratory and test drilling. For this reason some research on drilling techniques is in the province of reservoir development and production.

There is a great deal of research required to form a sound basis for optimal reservoir development and production methods. This research is required in: geological formation evaluation methods, reservoir engineering, production engineering and production management, well stimulation technology and techniques, and drilling technology and techniques.

Formation evaluation tools include electrical, acoustic, and nuclear logging devices, bore-hole

samplers, sidewall and conventional coring devices, bore-hole flow metering, and measurement of chemical properties of components and chemical behavior of fluid-solid systems. Improved evaluation tools, especially for high temperatures, are badly needed.

In order to support the practice of reservoir engineering for geothermal applications, fundamental research is needed into the physical, chemical, and thermal behavior of multi-phase aqueous systems (steam-liquid solution-solid) in porous rock. Once these physical principles are established, meaningful physical and mathematical models of geothermal fluid systems can be constructed. These studies would include thorough transport phenomena studies.

There is a severe need for field reservoir engineering studies to establish requirements for constructing mathematical models for optimization studies of the effects of well spacing, liquid recharge from aquifers, reinjection of condensate and cooled liquids, cooling due to in-situ boiling of liquids, changes in pore space and fluid conductivity due to precipitation of salts and solids, and other important parameters. Field geothermal research sites are necessary to get this information and to validate reservoir engineering and hydrologic theory.

The problems of concern in production engineering and management are those of well workovers, well stimulation, corrosion and scaling, geothermal fluid separation and metering, critical velocity of flow in pipes and valves, deep well pumps, and other similar problems. The impact of these problems varies with the use of the resource, whether for production of electrical energy, desalinated water, minerals, or process heat.

The well stimulation techniques of interest included hydrofracturing, high explosive, acid treatments, thermal fracturing, and nuclear explosive applications to improve the permeability of the formation. The large void volumes produced by nuclear explosives could provide space for mineral deposition to collect from flashing hot water. Nuclear explosives might dry up a wet flashing system by providing space for the flashing to occur underground.

Research and drilling technology and techniques embraces improvements in current technology for application at higher temperatures. Problems are encountered with rubber seals, valves, cements, drilling muds, heat shields, sound mufflers, etc. Better high temperature instrumentation is needed to measure temperature and pressure and to sample geothermal fluids. Further efforts should be expended to improve the rotary drill.

#### **B. RESEARCH AREAS**

There is much research required to establish firmly an adequate basis for geothermal reservoir development and production. This research is prerequisite to a final evaluation of the potential contribution of geothermal resources to the Nation. The research needs outlined below are broad in scope. In some cases, it is not possible to be completely specific about the details of the research.

Formation Evaluation. There is a strong need for research aimed at development of tools and techniques for geothermal formation evaluation. Conventional formation evaluation tools include wire-line electrical logging devices, bore-hole samplers, temperature and pressure measuring devices, sidewall and conventional coring devices, bore-hole flow metering, radioactivity and acoustic property measurement, and measurement of chemical properties of components and chemical behavior of fluid-solid systems.

Conventional tools are available for temperatures less than 350°F. Extended temperature range devices which are reportedly good to 500°F are sometimes available, but are not reliable.

In addition, there is a need for funding of formation evaluation measurements. Drilling objectives are often at odds with formation evaluation objectives. Because drilling costs are often in excess of 60% of total field development costs, it is important to drill a well rapidly. Formation evaluation data acquisition takes drill rig time that must be funded. Further, the need for research information may not be apparent to a private steam producer. In some cases, it may be necessary to drill special slim holes purely for formation evaluation purposes.

Commercial firms which are presently involved in developing formation evaluation tools and techniques should be encouraged to expand their efforts to development programs which are presently not feasible due to limited markets. Additional institutions with appropriate expertise should be funded to expand formation evaluation research.

Although existing physical laws govern geothermal systems, it should be recognized that measurement of many important physical, chemical, and thermal properties of components of geothermal systems have never been conducted at elevated temperatures. It

should also be recognized that unknown physical mechanisms might be at work in geothermal systems. Thus, basic research in this area should be conducted.

Reservoir Engineering. Reservoir engineering involves evaluation of the size and deliverability of the geothermal resource, and planning for the optimum development of the resource. As such, this field is inextricably coupled with utilization technology and economics, and with environmental concerns. A proper reservoir engineering development plan cannot be obtained without a utilization plan, which in turn determines environmental effects which must be considered in the reservoir engineering plan. Nevertheless, the following will deal with only the reservoir engineering problems which must be solved to facilitate development of geothermal fluid production.

Basic research must be done in the field of reservoir engineering in order to get the most use from the resource, and to insure that apparently marginal resources will not be overlooked. Fundamental studies of the physical, thermal, and chemical behavior of multiphase aqueous systems (steam-liquid solutionsolid) in porous media are needed to establish the physical principles for constructing meaningful physical and mathematcal models of geothermal fluid systems. These studies would include thorough transport phenomena studies. There is a definite need for field reseroir engineering studies to establish the field requirements for constructing mathematical models. These models should include sufficient detail to permit optimization studies of the effects of well spacing, liquid recharge from aquifers, reinjection of

condensate and cooled liquids, cooling due to in-place boiling of liquids, changes in pore space and fluid conductivity due to precipitation of salts and solids, and other important parameters.

Proper field studies require careful, detailed plans for data acquisition, and realistic banking of useful reservoir data (in the national inventory mentioned previously) to permit development of reservoir engineering procedures without unnecessary duplication. To this end, there is a need for development of field pilot geothermal reservoirs operated to acquire such information and to test reservoir engineering and hydrologic theory. This approach would permit performance forecasting from actual performance matches with mathematical models.

Production Engineering and Production Management. Sound production engineering and management must be based upon resource use. Electrical power generation is considered most important currently, with space heating, mineral production, and water desalination recognized as other important uses. problems not involving Current production equipment, but nevertheless requiring study include: land use planning (surface and groundwater, mineral rights); legal regulation of geothermal fluid production; numerous environmental issues (sound, chemicals, seismic activity, subsidence, etc.); and reinjection of cooled liquids. Many other, more conventional problems exist concerning well workovers, well stimulation, corrosion and scaling, geothermal fluid separation and metering, and critical velocity of flow in pipes and valves.

One important problem impeding geothermal production development is the time lag between completion of a well and successful siting of the power plant and associated transmission lines and construction. Because of the likelihood of damage to wells with reduced flow as well as the waste of resources, interim operation of power plants should be considered to provide a market for this sort of developed steam production.

Well Stimulation Technology and Techniques. The effectiveness of well stimulation techniques has been demonstrated in the oil and gas industry, and many of these same techniques could prove effective in geothermal fields. Marginal wells might be brought to a level of economic production.

Hydrofracturing, high explosive, acid treatments, thermal fracturing and nuclear explosives should all be considered. They all have potential for improving the permeability of the formation and should prove equally effective in both production and reinjection wells. The large void volumes produced by nuclear explosives could yield additional advantages. They might provide space for mineral deposition to collect from flashing hot water and/or dry up a wet flashing system by providing space for the flashing to take place underground.

Large geothermal areas are known which are not economically productive and where scientific studies might yield a wealth of information. Some of these might benefit from field stimulation experiments.

The potential energy available from hot dry rock is apparently very large, although the existence of these resources near the surface is yet to be proved. One area near Marysville, Montana is expected to be over 500°C at a depth of 2 km. Correlation of heat flow measurements and gravity maps define an area which is estimated to contain billions of dollars worth of energy above 5 km in depth if the rock could be cooled by only 300°C. If this proves true it is important to tackle the problem of economic production of this energy.

Two methods have been proposed for extracting energy from hot dry rock. Both involve injecting water into the rock through fractures artifically produced. One proposal is to develop a reservoir by hydrofracturing the rock probably enhancing the fractured area by thermal stress cracking. The other proposal uses nuclear devices to produce the fractures required for heat removal. Field experiments are required on both these systems.

In addition to conventional hot, dry rock, the obvious thermal energy in lava from volcanoes and in magma are intriguing potential sources of energy. Long-range study of energy production techniques to convert these potential resources to actual ones is warranted.

Drilling Technology and Techniques. The drilling research contemplated in this section is directed at improvement in current technology. Such a small market exists for special geothermal equipment that the manufacturer simply cannot recover his research and development costs. Most conventional equipment will not stand up to the temperatures encountered. Some critical areas include rubber seals, valves, cements, muds, heat shields, sound mufflers, etc. Federal funding of research and development contracts on these types of problems with private industry could

make a major contribution to the safety and efficiency of the drilling operations. Research in Federal laboratories could also undertake this work.

Drilling technology and cost is important to the discovery and utilization of almost all natural resources and further efforts should be expended in improving the rotary drill. Erosion drills, electric melting drills, and other techniques should be explored. These are recommended under resource assessment studies. A breakthrough in drilling techniques would be a giant step in resource assessment and reservoir development.

A similar situation exists in regard to logging equipment. Better high temperature instrumentation is required to measure temperature and pressure and to sample geothermal wells. Much standard well logging

equipment is not satisfactory for geothermal applications. Until good measurements are readily available, reservoir analysis will continue to be very difficult.

#### C. BUDGET

The panel, as a group, feels that the proposed ten-year geothermal reservoir development and production research which was presented in "Assessment of Geothermal Energy Resources" is appropriate. Therefore, a ten-year research effort of \$215.5 million for reservoir development and production is recommended. The funds would be programmed as follows:

Fiscal Year 74 75 76 77 78 79 80 81 82 83 Total

Budget 5.0 13.5 27.0 44.0 48.0 21.5 23.0 13.0 10.5 10.0 215.5 (millions)

# VIII. UTILIZATION TECHNOLOGY AND ECONOMICS

## A. OBJECTIVE AND SUMMARY

The objectives of the utilization technology and economics panel were to identify the research and development programs, including demonstration projects where appropriate, which are needed to develop, improve, and demonstrate the technology to exploit the different categories of geothermal resources over the different temperature regimes indicated in Table III.

The technology discussed in this section is principally the surface technology for utilizing the resource. In those cases where deep well pumps may be needed to lift the resource to the surface, such equipment is a logical topic for research on utilization technology.

A very important category for research is the technology for the best utilization of the different types of geothermal resources. For the vapor-dominated systems and the higher temperature (above 180°C) hot liquid-dominated convective hydrothermal resource, the technology for economic production of power appears well developed.

In the case of vapor-dominated systems, such as The Geysers field, steam is available at the well head in a slightly superheated state. After filtering, it is fed to low pressure turbines which drive the generator.

In the liquid-dominated systems, the liquid in the reservoir flashes into a mixture of steam and liquid upon reduction of pressure by the well. After separating the liquid from the steam, the steam is fed to a low pressure turbine. If the reservoir temperature is sufficiently high it may be possible to employ multiple

stages of flashing and lower pressure turbines. It appears that there is no significant need for research on surface technology in these two cases.

In the case of hot dry rock systems, the same may be said if the temperature of the formation is high enough to heat the fluids sufficiently. However, it is necessary to conduct research on gaseous emissions, particulate removel, noise control, removal of dissolved salts such as silica and boron, and disposal of brine, condensate, and solids.

There are many geothermal reservoirs (perhaps 80% of all hydrothermal reservoirs) in which the temperature is not high enough to provide fluids that may be used with existing technology to produce economic power. Successful demonstration that these intermediate-temperature and low temperature reservoirs can be utilized economically for generating electric power and for multiple uses would expand the recoverable geothermal resources many fold.

For the generation of power from such reservoirs, U.S. industry has made some progress in developing the technology of binary fluid systems in which the heat is transferred to a low boiling point fluid (such as freon or isobutane) which is then used as the working fluid in a closed cycle system. Further research on a variety of binary fluid systems as well as other power cycles deriving energy from hot concentrated brines is needed and demonstration plants should be built. Thermodynamic data is needed on the applicability of various working fluids for geothermal applications.

A great deal of effort must be expended to develop multiple uses of the resource. Desalination pilot plants using geothermal energy are in order. Mineral production will require pilot plants. Many of the utilization problems would be better understood if the physical and chemical properties of brines were better known. Corrosion rates of construction materials exposed to geothermal brines are required.

Immiscible heat transfer systems for extracting teothermal energy should be studied. These systems involve injecting a fluid which will not mix with water into the formation and then producing the combined fluids. Mechanical separation at the surface would provide a clean hot working fluid.

In the case of geopressured resources, research is needed to remove methane from the formation fluid. Direct conversion of geothermal energy to electrical energy, as by thermoelectric techniques, should be studied. As more data become available to support utilization design studies, a great deal of system modeling and analysis work will be necessary as a prerequisite to the design and construction of the several pilot plants.

#### **B. RESEARCH AREAS**

The research recommended by the utilization technology and economics panel is discussed under the following areas: vapor-dominated systems, liquid-dominated systems, geopressured systems, thermoelectric systems, artifically fractured systems, economics, and demonstration plants.

It should be recorded that the panel specifically did not recommend that the Federal program include demonstration plants. This topic was added to the discussion of utilization technology in preparing the final report. The information was derived from other panel reports (assessment) and supplemented by the editor.

Vapor-Dominated Systems. The technology of utilizing these steam sources, such as at Larderello, Italy and The Geysers, California, is reasonably well advanced. In these systems, the dry steam flows directly from the reservoir and is used as the working fluid in a turbine which drives an electric generator. It is unlikely that this type of resource lends itself to water production.

The non-condensible gases in the steam can vary widely in consistency and quantity. Their removal is necessary to maximize plant efficiency, to minimize corrosion of plant equipment, and for ecological considerations. The Pacific Gas and Electric Company has had a program under way for some time to abate the release of hydrogen sulfide from its plants, and this program should succeed. In other areas, ammonia, or other gases will require attention.

Particulates in steam cause erosion of turbine blading and valves. In order to minimize erosion and to maintain good performance from transfer equipment, it is very desirable to remove as much particulate matter as possible from the steam before it reaches the utilization plant.

Noise control has been a problem in geothermal plants. Considerable improvement has been made in the control of noise from the release of steam during well venting, during release of overpressures in the steam collection system, and during general in-plant operations. Currently, there is technology available to minimize this problem.

Dissolved salts may be carried into the utilization equipment when any wet steam is present. Silica can cause fouling of turbines and decrease their performance; it can restrict the flow in pipes. Boron can be detrimental to plant life. Research should be conducted on preventing dissolved salts from entering the equipment.

Research funds are recommended in the amount of \$6.0 million over a ten year period for support of research on utilization of vapor-dominated systems. The funding should be distributed over the ten years in accordance with Table V.

Liquid-Dominated Systems. These reservoirs produce hot liquid (largely water) in which a number of dissolved salts exist. Heat is extracted for power generation by either partly flashing the liquid into steam or transferring its heat to a secondary working fluid. Pure water can also be produced by condensing and collecting the steam. Still another use is space heating by conducting the liquid to residences and other buildings such as is done in Iceland. A fourth potential use is the extraction of minerals. Combinations of tthese uses are sometimes possible and may be more economical than single purpose use.

Non-condensible gases are entrained in the reservoir fluids as they are in vapor-dominated systems. Differences in quantity will exist but the basic techniques for removing and disposing of these gases will be essentially the same as for the vapor-dominated systems.

The noise control problem in the case of liquiddominated systems is complicated by the fact that flashing produces a two-phase mixture at the exit of the well vent. More energy must be dissipated in the well vent which means that larger and more costly devices are used than on vapor wells. Better muffling is required to solve this problem.

The hot reservoir fluid often contains an abundance of dissolved salts. When the liquid is partially flashed to steam, the dissolved salts remain in the liquid phase which therefore becomes supersaturated with them. Precipitation of the dissolved salts naturally follows.

Identification of the types and concentrations of solutes in a number of reservoirs is necessary to provide design information. Problems of equipment fouling because of precipitates will be serious. These precipitates act to plug the flow passages in the reservoir if flashing occurs underground.

In certain areas which contain geothermal brines, it will be necessary to recharge the reservoirs artificially. The fluids used for recharge generally will have to be treated to make them compatible with the prior formation fluids. Equipment will have to be developed for these tasks.

Environmental considerations may require that the produced brine and the steam condensate from the power plant not be reinjected as a recharge fluid. Alternative disposal schemes will be required which do not cause a nuisance and do not create any dangers to the environment.

Precipitates and separated solids derived from geothermal fluids may contain useful minerals. However, there will be large quantities of minerals which will have little or no value and will simply have to be removed. Burial, sluicing, and injection below ground are potential solutions which require research.

The use of secondary fluid power systems would make it possible to have an isolated working fluid with its characeristics selected for equipment, pressure and temperature requirements of the energy conversion cycle. This would require the transfer of heat from the hot geothermal fluid to the secondary fluid by use of heat exchangers. Research is required on the thermodynamic properties of various appropriate working fluids.

It will be necessary to match the characteristics of the working fluid (perhaps even synthesize a new fluid chemically) to the requirements of the utilization system as revealed by a thorough techno-economic analysis and preliminary design studies.

Turbines will probably have to increase in size and horsepower rating but manufacturers are capable of meeting these research and development requirements and have historically done so out of their own funds as markets developed.

Further research on special fouling problems of heat exchangers utilizing geothermal brines will have to be conducted. As with turbines manufacturers of this equipment have traditionally met these needs using their own funds.

The physical and chemical properties — both static and kinetic — of the geothermal brines are the starting point for the design of utilization equipment. Geothermal brines produced by flowing wells, and their subsequent concentration of solutes in the liquid phase due to flash chamber production of steam, require a study of the chemical kinetics of geothermal brines.

It is anticipated that, in certain cases, multi-

purpose development of geothermal resources may be more economically advantageous than single-purpose development. Careful study of the potential interface problems for multi-purpose development to produce energy, desalinated water, minerals, and low-grade heat is indicated. The development, design, and construction of pilot plants for the desalination of water using geothermal energy is urged.

The extraction of geothermal energy by means of injecting fluids other than water into a geothermal reservoir is possibly feasible. If this fluid is immiscible with the geothermal brine, mechanical separation at the surface will provide a clean, hot working fluid without the necessity for surface heat exchangers.

The severe corrosiveness of geothermal fluids will require investigation of the ability of a number of alloys to withstand, or at least to mitigate, their effect. Design information on rates of corrosion and deposit build-up on materials of construction for turbines, heat exchangers, pipes, valves, and other plant components is required.

The use of geothermal energy for space heating and cooling will be expanded as more geothermal sources are developed. The proximity of the user to the source of supply is very important because of the difficulty of transporting the low-grade energy. Application technology for space heating and cooling, using hot water, have been in existence for many years and no further research is indicated.

Funds in the amount of \$21.5 million is recommended over a period of ten years in support of research on utilization of liquid-dominated systems. The recommended distribution of funding is shown in Table V.

Geopressured Systems. Much of the technology that is available, or that will become available as a result of the research directed toward utilization of the liquid-dominated system, will be directly applicable to the utilization of geopressured resources.

Technology exists today to pump large quantities of water up to pressures of 3,500 to 4,000 pounds per square inch for supercritical boilers in fossil-fueled steam power plants. This pump experience can be applied to develop a high pressure water turbine which would extract the pressure energy from the geopressured fluid and discharge the fluid at conditions of pressure and temperature such that its thermal energy could be extracted just as if the fluid had originated in the liquid-dominated system discussed above. A demonstration plant will be necessary and is considered below.

Geopressured fluids are normally saturated with methane. At the pressures and temperatures encountered, substantial quantities of methane could be associated with the fluid. This resource would provide an additional incentive for development of geopressured resources. Research is needed to extract the methane from the fluid.

Funds in the amount of \$3.0 million for a period of ten years are recommended in support of research directed toward utilization of geopressured geothermal resources. The recommended scheduling of these funds is shown in Table V.

Thermoelectric Systems. Thermoelectric and other approaches to the direct conversion of heat to electrical energy (without using turbines) using geothermal resources should be investigated. It may not even be

necessary to go directly to electrical energy; the heat might be used to produce chemicals (such as hydrogen) which could be applied later to generate electricity. Research should be directed toward any such sound approaches to utilizing geothermal resources directly and thereby avoiding some of the problems mentioned above. Proof of concept should precede significant long-range research projects.

Funds in the amount of \$0.5 million for a period of ten years are recommended in support of research directed toward the development of thermoelectric systems and other direct conversions of geothermal energy to chemical energy, electrical energy, etc. without employing rotating machinery to drive generators.

Artificially Fractured Systems. Hydrofractured systems (possibly enhanced by thermal fracturing during production) do not appear to pose any unique utilization technology problems that have not already been covered above if it is assumed that injected water is the heat transfer medium. No research specifically allocated to this topic seems needed.

Nuclear fracturing does produce radioactive materials in the formation. Research will be required to identify these materials and to assure that technology is available to prevent their occurrence above ground.

Funds in the amount of \$0.5 million for a period of ten years are recommended in support of research directed at the utilization technology for artificially fractured systems.

Economics. The current and impending fuel supply situation for electric power generation is presently serious and deteriorating. Supplementary energy sources for this purpose, such as geothermal, are now

desirable and soon may be necessary for the economic and social health of the Nation. In this context, the economics of producing electric power by geothermal means may be secondary to its availability.

In dealing directly with the economics of geothermal-electric power production, the lack of definitive cost data makes the usual straightforward cost calculation impossible. The panel, therefore, attacked the problem from the standpoint of what can be afforded in the way of cost for a geothermal system. in order for its energy to be economically competitive with the leading anticipated methods of generation.

Apparently nuclear energy will be the least costly form of generation, among the conventional sources, in the remainder of this century. If the known costs of an electric power plant using geothermal energy are compared with the total cost of producing power from a nuclear plant, the difference will be that margin which is allowable for the unknown geothermal costs. These unknown cost items include reservoir exploration, development, and production; flashing chambers; particulate removal; noise reduction; effluent disposal; transmission differentials; environmental controls; etc.

Employing this technique, the panel has estimated that \$200 per kilowatt will be allowable for a 1980 time frame and \$250 per kilowatt for a 2000 time frame to cover these unknown geothermal costs.

There is an urgent requirement for comparison of types of energy cycles with the type of resources. System modeling and analysis studies will be very important in matching these elements. Technoeconomic comparisons will have to be made.

Funds in the amount of \$1.5 million over a period

of ten years are recommended in support of research directed toward the economic problem of utilization of geothermal resources.

Demonstration Systems. Historically, the research and development that is needed to make available power facilities has been accomplished by the electric power industry who then installs these facilities.

It is assumed that the manufacturers will continue to make the necessary investments to develop new equipment and that the utilities will invest in the necessary demonstration plants.

The exception to this assumption is in the case of a desalination demonstration plant which has already been discussed above. The exception arises because of the traditional governmental role in providing water supplies.

In order that this report reflect the anticipated total research and demonstration cost of developing geothermal resources for the benefit of the Nation, this section provides an estimate of the funds which will be required for demonstration plants. The estimate was not compiled by the utilization technology and economics panel nor was their concurrence sought.

The requirements for funds were estimated in two ways. The first approach consisted simply of collecting those portions of utilization technology research that were estimated by other panels (principally the resource assessment panel) and that were appropriate tasks to accomplish by operating demonstration plants. These were estimated to require a total funding of \$64.1 million. The tasks estimated by the other panels would have required the equivalent of a complete set of demonstration plants.

The second approach, which is discussed below, is recommended. The total funding estimated by the second approach is \$66.5 million. The closeness of the two independent estimates lends added assurance that each approach is sound.

New equipment can be developed in a number of ways. The most common and efficient method of improving equipment in a well-established market is through in-house development expenditures by the manufacturers. Their costs are then recovered through volume sales, if the demand develops, or through the high price for one-of-a-kind prototype models. Rather than trying to estimate the specific equipment development costs (the usual approach), it is assumed that these expenses will be reflected in the capital costs of the demonstration plants.

While most geothermal plants can be constructed today for approximately \$150 per kilowatt, it is assumed that the demonstration plants will cost \$500 per kilowatt in present dollars. Making a correction for inflation at 5 per cent per year, these costs would be about \$650 per kilowatt.

The number and size of demonstration plants to be built is very difficult to predict with any great accuracy at this time, but for calculational purposes, it is assumed that seven demonstration plants will be needed, each of 10,000 kilowatts capacity: two hot water, flashing systems (under different conditions); two hot water, binary fluid systems; one hot brine system; one geopressured system; and one demonstration system for a new approach (unknown as yet).

The capital cost of these seven plants would be \$45.5 million. It is assumed that all operating costs of these plants would be covered by power sales even though they were operated at low load factors for experimental purposes.

A test bed laboratory should be installed at a site which has a geothermal fluid supply. This would allow the short term (1-2 years) testing of new equipment as it became available under field conditions without the necessity of building a new plant. Such a laboratory would cost about \$5 million to build and equip plus about \$1 million per year to operate. If this were built in the third and fourth years, it would operate six years in the ten year period being considered. The costs would then total \$11.0 million.

It is most probable that as the dynamics of geothermal fields are better understood, an optimum field management strategy will evolve which will maximize field productivity while meeting demand. To be most effective this should be a fully automated control system which would cost about \$10.0 million over a ten year period to develop.

Funds in the amount of \$66.5 million for a period of ten years are recommended for support of the facilities discussed above to demonstrate the utilization technology for geothermal resources.

#### C. BUDGET

Funds in the amount of \$99.5 million over a period of ten years are recommended for research and development and demonstration of the utilization technology and economic viability of developing the Nation's geothermal resources. The recommended distribution of these funds is shown in Table V below.

TABLE V.

UTILIZATION TECHNOLOGY AND ECONOMICS RESEARCH BUDGET

# (Millions of Dollars)

(TARITIO)	(Minoria of Donata)			
·	1974	1975	1976	1977
Vapor Dominated	0.6	0.6	0.6	0.6
Liquid Dominated	2.8	2.8	2.8	2.8
Geopressure System	0.3	0.3	0.3	0.3
Thermoelectric System	0.1	0.1	0.1	0.1
Artificially Fractured Systems	0.2	0.2	0.1	
Economics	0.2	0.2	0.2	0.2
Demonstration Plants	5.7	5.7	7.8	7.8
Totals	9.9	9.9	11.9	11.8

# Fiscal Year

1978	1979	1980	1981	1982	1983	Total
0.6	0.6	0.6	0.6	0.6	0.6	6.0
2.8	1.5	1.5	1.5	1.5	1.5	21.5
0.3	0.3	0.3	0.3	0.3	0.3	3.0
0.1						0.5
						0.5
0.2	0.1	0.1	0.1	0.1	0.1	0.5
0.2	0.1	0.1	0.1	0.1	0.1	
0.2 6.5	0.1 <u>6.6</u>		0.1 <u>6.6</u>		0.1 <u>6.6</u>	
						1.5

# IX. ENVIRONMENTAL EFFECTS

## A. OBJECTIVE AND SUMMARY

The objectives of the environmental effects panel were to identify the research necessary to define accurately the potential environmental impact which may be associated with the development of the Nation's geothermal resources, and to identify a program of research to alleviate, eliminate, or monitor any possible hazards.

Numerous environmentalists worldwide have reason to believe that geothermal energy may prove to be the "cleanest" source of convertible power readily available to man.

Geothermal developments are unique in that all activities related to resource production are localized to the immediate vicinity of the power plant or other utilization facility. Support operations such as mines, fuel processing, transportation, and other handling facilities do not exist. For this reason, the environmental effects are solely site dependent in origin.

Certain undesirable effects, however, can extend for several miles from the geothermal field itself and thus introduce environmental problems into the surrounding region. These must be studied, and solutions must be found.

Because the early utilization of geothermal resources will be for the generation of electric power, the panel addressed itself to the effects of this type of development. Potential effects on the environment of most immediate concern are gaseous and particulate emissions, land pollution, subsidence potential, seismic considerations, water pollution, biological effects, and

social effects. Research should be directed to an accurate determination and evaluation of their character and magnitude.

Because of the relatively equal weight of the concerns, the panel addressed itself primarily to the problems either known or anticipated to exist in presently operating installations; that is, geothermal plants using dry slightly superheated steam, hot water flashed to steam, and binary fluid systems.

Little consideration was made of multi-purpose developments, geopressured systems, direct use of hot waters for heating and cooling, and extractions of energy from "hot-dry" rock.

Directly concerning the "Plowshare" proposal, it was the consensus of the panel that the environmental hazards of both peaceful nuclear explosives technology and geothermal technology were combined in this approach and that the panel did not have the expertise to make recommendations concerning the environmental effects of the use of peaceful nuclear explosives technology.

#### **B. RESEARCH AREAS**

In order to alleviate, eliminate, or monitor any possibly adverse environmental effects associated with the development of the nation's geothermal resources, a number of possible environmental hazards must be investigated and an accurate determination made of their character, magnitude and control. Several of these are briefly described below.

Gaseous and Particulate Emissions. The most

publicized noxious material creating air pollution from existing geothermal steam power plants is hydrogen sulfide gas. The majority of this emission comes from the non-condensible gas ejected from direct contact condensates. The remainder is absorbed in the circulated cooling water. A portion of the hydrogen sulfide is oxidized to sulfates and elemental sulfur. The unreacted portion is air-stripped at a cooling tower, creating additional air pollution.

Considerable research is being applied to sulfur emissions, both to sulfur dioxide and hydrogen sulfide, and there are commercially proven processes for bringing those discharges into compliance with emission standards. However, research efforts are still required to resolve the problem of atmospheric pollution from hydrogen sulfide discharged at a cooling tower.

One solution would be to use surface condensers and thereby physically separate the steam condensate from the cooling water. This approach would impose the additional cost and burden of providing surface or ground water for make-up water to the cooling tower.

In addition to the hydrogen sulfide, there are undoubtedly other gaseous chemical substances, e.g., mercuric compounds, radioactive materials such as lead-210 and Radon-222, etc., present in some geothermal reservoirs which could adversely affect the environment if allowed free discharge to the atmosphere.

Research must be applied to identify the chemical composition of the non-condensible gas derived from geothermal reservoirs, and to quantify permissible exposure limits. Based on these findings, methods for containment and safe disposal of these materials must

be developed. Concomitant with these research efforts is the need to develop the analytical techniques and instrumentation to monitor and control the discharge of these materials.

Similar research must be directed towards the emission of particulate matter. Particulate emission from an operating geothermal steam plant may not be readily apparent, but it can occur. Plants utilizing direct-contact condensers concentrate the particulates entering with the steam as much as five-fold through evaporation at the cooling tower.

Just as the blowdown from the cooling tower can contain high concentrates of boron, arsenic, fluorides and free ammonia, the entrained water leaving the cooling tower as "drift-losses" will contain equivalent concentrations in the droplets. Atmospheric dispersion and evaporation of these droplets will leave a dust of these materials on the surrounding lands. The composition of the blowdown has so far been such that it must be reinjected to avoid environmental quality degradation.

Research is required to determine the impact of this dust on the environment. Research can be applied also to mechanical designs which would reduce drift losses. Basic needs for research are to identify, quantify, and regulate the disposal of gaseous and particulate matter from geothermal resources.

Funds in the amount of \$4 million over a ten-year period are recommended for expenditure in this area. The major expenditure would come early in the budget period as data is gathered and equipment devised. During the latter part of the period the funds would be used for monitoring emissions. These studies should be immediately applied to those geothermal fields already

shown capable of producing fluids of sufficient temperature for power generation.

Effects on the Land. In relation to the problem of land surface pollution, research is to be directed towards preventing the degradation of usable soil and toward the control of on-site surface deposition of pollutants that may be transported subsequently from the site of production to the surrounding environment. These problems arise in different ways in relation to different resource production processes.

With regard to a vapor dominated system, research is needed to identify and quantify all pollutants (such as Hg, As, Se, Pb<sup>210</sup>) in the vapor phase of a geothermal source and at each site proposed for development. Precipitation mechanisms need to be identified to evaluate and quantify fall-out and rain-out problems arising from such pollutants, and emission control methods need to be developed for use at the well head and at the points of power plant and cooling tower exhaust.

In connection with the water dominated geothermal system, the effects of accidental run-off of geothermal fluids from the production site to surrounding land areas needs to be assessed, with an identification of surface deposited material that may harm plants, cause soil sterility, or be subject to biological magnification and entrance into food-chains.

Blow-out contingency programs to minimize land pollution by chemical deposition and to control possible erosion are needed, so that they can be applied at each development site. Facilities need to be developed for the adequate and safe storage of both liquid and solid wastes.

Funds in the amount of \$3 million are recommended to be expended in this area over the tenyear period.

Subsidence Studies. Experience has shown that subsidence occurs in some areas when a fluid is removed from the ground, while in other areas the removal of equal quantities of fluid has produced no measurable subsidence. Much knowledge has been accumulated on this problem from studies of both petroleum and ground water reservoirs, but very little has been gathered from the production of geothermal fluids.

The tools and techniques for these studies are presently available and consist first of establishing precise close-spaced leveling data in the present fields known to be capable of producing high enthalpy geothermal fluids. Networks of monitor wells presently exist in some of these areas, but in others they should be established.

The tools, techniques and data from subsidence studies are all applicable to other studies requested below which are related to both water dynamics and water quality.

The funding level should be \$4,500,000 over the ten-year period with most coming early in the period to establish the data gathering stations.

Seismic Hazards. A fundamental characteristic of many geothermal resource areas is their close association with regions of high geologic activity, which is manifested most commonly as earthquakes. Studies have shown that, if fluid pressures are changed in regions of tectonic stresses, faults can vary their normal patterns of earthquake activity.

Present research is being directed toward resolving many questions regarding seismic activities and some of this information can be applied to geothermal areas. However, seismic monitoring stations should be established near productive geothermal areas to determine if patterns emerge that appear to be related to the removal or injection of fluids from geothermal reservoirs.

Funds in the amount of \$4.5 million are recommended for expenditure in this area over the tenyear period. This would fund the establishment of monitoring stations to gather seismic data in geothermal areas prior to the onset of the effects of production or injection. The major costs would occur later in the budget period after the effects, if any, of fluid pressure changes are better understood and counter-measures can be developed.

Water Studies. Water studies cover a broad area, but the panel felt the subject should be broken into two major groups; fluid dynamics and fluid contamination.

At this state of the science of fluid dynamics, the capacity to predict the effects on regional ground-water supply and the effect on land subsidence due to the exploration of geothermal fluids is hampered by inability to distinguish and quantify the sources of the water, to measure reservoir properties, and to define flow systems. New data and cheaper isotopic techniques are needed. Computer modeling with these data could greatly add to the understanding of these complex systems.

Funds in the amount of \$7.0 million are recommended to be expended in fluid dynamics research over the ten-year period. The funding should

be at about an equal annual rate with the effort in the first years expended to gather data, and in the later years, to apply it to modeling studies.

A possible risk associated with the development and utilization of geothermal resources is the contamination of surface and ground waters by geothermal fluids. This again is a site dependent phenomenon, since in some regions the high enthalpy fluids carry a heavy load of dissolved solids, while in others the water quality is similar to presently used ground waters.

This is an area where information and tools developed in the related study of subsidence and fluid dynamics could be applied, but specific research is required to identify those chemical constituents which may have a detrimental effect. Sample collection, analysis, and procedures should be developed where they are presently lacking or are too expensive for widespread field application.

With particular reference to injection of geothermal fluids, chemical and isotopic studies should be undertaken to determine if geothermal fluids will indeed return to the reservoir from which they were produced or if they migrate into other reservoirs.

Funds in the amount of \$7.0 million are recommended for water contamination research to be applied in approximately equal amounts over the tenyear period.

Biological Effects. Numerous unknowns exist regarding the probable impact of geothermal operations upon the biota native to prospective resource areas as well as areas presently under exploration or development.

Given the delicate balance of a natural environment, damage to many species of plant and animal life can take place through changes of chemical balance in soil and water, through the use of toxic substances in industrial application, through the destruction of such specialized habitats as thermal pools or alpine meadows, through the interruption of migratory patterns, through long term alterations in humidity, and through the introduction of human presence and activity into formerly unaffected regions.

These and other factors are in critical need of study in representatively selected geothermal resource areas to determine necessary procedures for the adequate protection of plant and animal life in regions of development.

Funding in the amount of \$4.0 million is recommended to be applied to this research area over the ten-year period. Fifty percent of these funds is to be spent in the first three years in intensive studies of sites currently under development. The remainder is to be evenly distributed over the next seven years in additional sites specifically selected with differing characteristics.

Social Effects. Serious social effects arising from geothermal resource development which are needful for research involve the problems of noise and land use.

Many phases in the development of a geothermal field can produce high noise levels. Most of the sources of noise can be controlled by present technology, but the blowing of wells in the cleanout and testing phases of the development of the flashed steam production process in a water dominated system presents unique problems for noise attenuation because of the presence of water droplets in the high pressure steam.

The flashed steam process is now in the experimental stage, and the early development of effective muffling equipment is necessary if this potentially important production process is to achieve the degree of public acceptability which will allow its being brought to perfection.

The research funding recommended for the immediate solution of this problem is \$500,000 over a three-year period.

The land use problems connected with geothermal field development involve both conflicts in land use, long term land utility and the possibilities of multiple use. Geothermal operations are industrial in character and geothermal resources areas normally occur in non-industrial regions. Because of noise, odor and visual impact, geothermal development, under present technology, is not compatible with residential or recreational land use. Problems exist with regard to the possibility of development of known resource areas where different land uses have been previously established.

Sociological, economic and planning studies are greatly needed to determine public policy for the equitable resolution of conflicts of land use arising in these cases. The brief history of geothermal operations in the United States has already generated controversy in this matter, and if it is decided that the development of the resource is to take place at a rate requisite to satisfy the energy demands which it can supply, a means must be found to bring cases of conflict to rapid resolution. Advances in technology which will allow a reduction of the industrialized character of a developed

TABLE VI.

ENVIRONMENTAL EFFECTS RESEARCH BUDGET

(Millions of Dollars)

	1974	1975	1976	1977
Emissions	0.6	0.5	0.5	0.5
Land Effects	0.3	0.3	0.3	0.3
Subsidence	0.7	0.7	0.6	0.5
Seismic Effects	0.3	0.3	0.3	0.4
Water Studies	1.4	1.4	1.4	1.4
Biological Effects	0.7	0.8	0.5	0.3
Social Effects	0.2	0.2	0.2	0.2
Total	4.2	4.2	3.8	3.6

Fiscal Year

1978	1979	1980	1981	1982	1983	Total	
0.4	0.3	0.3	0.3	0.3	0.3	4.0	
0.3	0.3	0.3	0.3	0.3	0.3	3.0	
0.5	0.3	0.3	0.3	0.3	0.3	4.5	
0.4	0.5	0.5	0.6	0.6	0.6	4.5	
1.4	1.4	1.4	1.4	1.4	1.4	14.0	
0.3	0.3	0.3	0.3	0.3	0.2	4.0	
0.2	0.2	0.2	0.2	0.2	0.2	2.0	
3.5	3.3	3.3	3.4	3.4	3.3	36.0	

geothermal field will help reduce the land use conflict problem.

The problem of long term land utility arises from the extensive alteration of the physical condition of a developed geothermal resource area, such as by excavation, soil distribution and compaction which take place in the construction of drilling pads, access roads and power plant sites.

Research is needed for the development of resource production methods which will reduce this heavy physical impact. Utilizing the advanced techniques of directional drilling already in existence will make possible the location of several wells on a single drilling pad, thereby considerably confining the physical effects of field development. This method would have the additional benefit of reducing the

extensive visual impact arising from the large numbers of drilling pads and piping networks presently utilized in field development.

Funds in the amount of \$2.0 million are recommended to be spent equally over the ten-year period.

# C. BUDGET

The environmental effects panel believes that the research budget recommended in "Assessment of Geothermal Energy Resources" is too low by about \$4.5 million. The total budget recommended by the panel is \$36.0 million. The recommended distribution is shown on the following chart by topic for each year in millions of dollars.

# X. INSTITUTIONAL CONSIDERATIONS

## A. OBJECTIVE AND SUMMARY

The objective of the institutional panel was to identify the scope of institutional studies, including the organizational, legal, and regulatory considerations, which will permit the development of geothermal resources in a safe, economical, environmentally sound, and desirable manner considering the interest of all concerned.

Concerned parties include the general public as ultimate users, industrial and other entities as developers or users, and local, State, and Federal governmental agencies as planners or regulators.

The panel recommends that serious studies to weigh the merits and demerits of different organizational structures be undertaken by a Presidential Study Commission.

The adequacy of the existing body of law should be assessed with the purpose of recommending changes wherever desirable. Governmental planning and regulatory processes should be examined with a clear objective of suggesting amplification, effective coordination, and other improvements. Detailed discussions and recommendations follow.

#### **B. RESEARCH AREAS**

In order to achieve optimum development of geothermal resources, a number of research problems of an institutional and/or legal nature must be solved. Several of these are described briefly below.

Definition, ownership, and rights of geothermal resources. Geothermal steam is a resource peculiar unto itself. One may be interested in it for its energy content,

for the derivative water, or for the minerals it contains. Thus, it cannot simply be classified either as a water resource or as a mineral resource, and in any event its energy value must not be ignored in establishing its legal position.

Like ground water, geothermal steam or hot fluids may cross property boundaries, carrying with them their energy and mineral content. Exploitation of these entities on one side of a line may affect exploitation on the other side. This poses legal questions and, judging from the current complexity of water laws alone, these questions cannot be easily answered.

The fact that some geothermal steam can be viewed simultaneously as a source of energy, water, and minerals, raises further questions regarding the multiple use of the resource and the allocations among the several resources.

Fragmentation of research efforts. Below is a list of the various elements of the Federal, State and private institutions with current interest in some phase of geothermal research, planning, or development. The list reveals the highly fragmented nature of the present national effort.

Although it is possible that wasteful duplication may not be occurring at the present time, duplication almost assuredly is eventually inevitable unless steps are taken to coordinate the national effort. Without effective coordination there can be no realistically achievable programs. In terms of current Federal activity alone, more than a dozen agencies have R&D programs either in the planning stage or already underway.

Some of the questions of the specific responsibilities of the private sector and government

(both Federal and State) will have to be worked out and structured to some degree if the private sector and the government are to be meshed in a program that is both effective and efficient in relation to the national need.

# GEOTHERMAL RESEARCH AND DEVELOPMENT INSTITUTIONS

# **Federal Agencies**

- 1. Department of the Interior —
  U.S. Geological Survey
  Bureau of Land Management
  Bureau of Reclamation
  Bureau of Mines
  Bureau of Outdoor Recreation
  Bureau of Sport Fisheries and Wildlife
  Office of Saline Water
  Office of Water Resources Research
- 2. Atomic Energy Commission —
  Division of Applied Technology
  Division of Research
- 3. National Science Foundation —
  Earth Sciences Section
  Energy Research and Technology Program
- 4. Federal Power Commission
- 5. Department of the Treasury
- Department of Defense —
   Advanced Research Project Agency
   Naval Weapons Center
- 7. National Aeronautics and Space Administration
- 8. Environmental Protection Agency
- 9. Department of State
- 10. Office of Science and Technology

- 11. Office of Management and Budget
- 12. Congress Interior and Insular Affairs Committee (Senate and House)

Joint Committee on Atomic Energy

## State Agencies

1. Variable by state but essentially parallel to those mentioned under Federal Agencies above.

#### **Private Sector**

- Research Organizations —
   Universities
   Industry
   Private research laboratories
- Industry —
   Producers (oil companies)
   Consumers (utilities and others)

Regulatory interfaces. Adequate regulatory jurisdiction for the development of geothermal energy is held by the Federal government and the State and county governments; however, some states and counties with geothermal resources have not as yet developed and promulgated comprehensive regulations. As the geothermal industry develops and each regulatory level becomes more involved, the overlap and, in some cases, the inconsistency of regulations will become very serious. This is an appropriate area for institutional study.

Information collection and dissemination. The need for a coordinated effort for the rapid collection and dissemination of current information on geothermal resources research and development activities is critical to the evolution of a sound national program. The information must be validated and qualified, and it must be made available to the interested public.

International considerations. Several items of international significance should be considered. Among these are the problems of coextensive resources along or near international borders, possible undesirable environmental and exploitational effects resulting from developments near the border, the establishment and implementation of joint international projects, such as is currently proposed under the U.S.-U.S.S.R. Joint Commission on Scientific and Technical Cooperation, and the need for an information exchange to insure that use is made of the latest available information.

The United Nations has done extensive work in this area, and its contributions to the state-of-the-art should be studied thoroughly.

Manpower. Because work on this resource is relatively new in the U.S., most of the people engaged in geothermal research and development have entered it from other fields. There are few institutions of learning where programs in geothermal resources are sufficiently well developed to provide a ready source of new manpower. The desirability of establishing interdisciplinary programs, specialized curricula, or centers of research should be investigated.

Industry problems. The private sector will bear the ultimate responsibility for harnessing geothermal energy to generate electrical power and space heating. In doing so, it is faced with a host of problems and decisions that should be considered in designing and implementing a national program.

Among these are: preparing environmental impact statements and obtaining public utility commission certifications as now required on a unit-by-unit basis; seeking governmental cooperation where assistance is needed to establish an economically viable resource; interacting with government agencies in the development of cooperative programs or appropriate leasing regulations for the resource; forming a beneficial industrial association to represent geothermal interests at the national level; considering the economic impact of the lead times required for development; and establishing the lifetime of the resource.

#### C. INDUSTRY REGULATION

In general, the regulation of the "Geothermal Resource Industry" has been merely a series of prohibitions. This is most natural as the industry is still in its infancy and is little understood. To allow and encourage the development of this resource, within a reasonable time period, many in-depth studies are needed covering the physical, economic and sociological aspects of geothermal resource production.

Land Use. Studies are needed regarding policies for use of geothermal lands. Consideration must be given to beneficial uses other than the dominant one—geothermal resource production (energy, demineralized water, and/or minerals). In the recovery of geothermal resources, regardless of the end product, consideration must be given to regulating well spacing.

For example, should there be a grid system or a clustering of wells in the underground reservoir tapped by slant drilling to minimize surface distance? Should geothermal fluids move in pipelines above ground or in buried ones?

Criteria need to be developed as a basis for forming specific regulations. It will be necessary to reconcile geothermal resource production with other land uses. Studies are needed to formulate policies and methods to reconcile conflicts with grazing, wildlife habitats, watershed, timber production, and so on.

Exploration and Production. Some of the tools of exploration, such as geophysical and geochemical, can have an impact on the land. The impact of such methods and tools must be understood to regulate the exploration for and production of the geothermal resource intelligently.

At the present time, exploration, development, and production of geothermal resources requires some forty permits and/or licenses. When power plants, transmission lines, and chemical plants are required, an even greater number of permits will be needed from agencies of the Federal, State, and local governments. Many of these procedures duplicate one another, at least in part. Technology is not in all cases sufficiently developed to implement the present regulations for all levels of government.

Financing and Construction. Studies are needed regarding methods of financing and the relationships between the producer of the geothermal resource and the electric utility or other user. Concerns arise between the electric utility company, which purchases the steam, and the lessee in the areas of lease rights and assignments of those rights to successors. These concerns are compounded when multiple use development of the resource is planned.

For purposes of amortizing capital investments, studies are needed to estimate realistically the probable life of a geothermal field. In the case of the Magma Power and Union Oil holdings in Sonoma County, California, geothermal steam is considered a gas and entitled to the same tax consideration as natural gas. The applicability of that ruling to other geothermal fields should be determined.

Operating Regulations. Existing Federal, State and local regulations cover operations for private investor-owned power plants and those plants that are joint ventures between two entities. Those plants that are publicly owned are essentially regulated by the local governing body. Inconsistencies in this area should be reconciled.

Transportation of Power. Throughout the United States, as the development of electrical energy took place, complex systems of power transmission grids have evolved. Separate lines on the grids may be owned by one company or jointly owned. In some cases an investor-owned public utility and the Federal government jointly own and operate such a facility.

A possible problem exists where a small publicly owned utility has the ability to develop geothermal power but the site is far distant from the utility's operating area. Power transmission becomes a problem since the construction of transmission lines is a costly item for such a utility. Because certain investor-owned public utilities, for a number of reasons, may be legally prevented or reluctant to share transmission facilities with competing utilities, the power transmission facilities are not available to the smaller publicly owned utilities.

Sales of Power. The regulation of the sale of power varies with the ownership of the power plant. A power plant owned by a local public utility essentially sets its own rates. The sale of power from private investor-

owned plants and those operated under joint ventures is regulated by the Federal, State and local governments. If the power from such plants is sold wholesale to an entity who plans to resell it, the sales are regulated by the Federal Power Commission, or equivalent, and the local municipality. These regulations need review to assure that the rules are consistent and equitable to the geothermal power source, since geothermal energy as such is a non-transportable resource.

Regulation Interface Problems. Adequate regulatory jurisdiction for the development of geothermal energy is held by the Federal Government and the State and County governments; however, some states and counties with geothermal resources have not as yet developed and promulgated comprehensive regulations.

As the geothermal industry develops and each regulatory level becomes more involved, the overlap, and in some cases the duplication, of regulatory duties will become more serious. The county government is the smallest unit and it essentially regulates the land use of the county through zoning. The counties can also regulate those actions which will have an environmental effect, and they can move into those areas where they have not been pre-empted by the State.

The State and Federal governments, as possible land holders in the counties, are faced with the need to comply with county regulations. Where not preempted by Federal regulations, the State government should regulate the geothermal industry statewide, except in those areas that are considered under county control, such as land use planning.

The Federal geothermal regulations for Federal

lands should take into consideration the applicable State regulations where State regulatory programs exist.

#### D. LEGISLATIVE CONSIDERATIONS

The Geothermal Steam Act of 1970 (Public Law 91-581; 84 Stat. 1566) was enacted some 21 months ago, but because of problems growing out of the environmental protection laws and interpretative court decisions, as well as administrative difficulties, as of November 1972 there are no regulations to implement the Geothermal Steam Act. Therefore, no geothermal leases have been issued on any Federal lands and the statute has not been subject to any practical test of workability and effectiveness. However, developments in the industry since the Act was passed and further study and analysis indicate that consideration might well be given to amendatory or new legislation on the following matters, among others.

Application of mineral or water laws. Clarification of whether geothermal steam is, as a matter of law, a mineral resource or a water resource is needed. The Act is not clear on this point and, while it does provide for the leasing of "geothermal steam and associated geothermal resources," as such, the answers to a number of associated problems arising out of geothermal steam development depend upon whether water law or mineral law is applicable.

For example, who has the rights to the water remaining after the energy-producing potential has been exhausted and the by-products extracted? Section 9 of the Geothermal Steam Act provides that State water law shall govern production and use, but does not settle the question of rights to the waters.

The Act itself recognizes that this basic question is unanswered. Section 21 (b) requires that, where the title to geothermal leased lands has passed from Federal ownership, but the minerals have been reserved to the United States, the Attorney-General must bring a quiet title action in Federal Court to determine whether the reservation of minerals to the United States included the geothermal resources. Such action shall be taken upon a report by the Secretary of the Interior when he finds that development of geothermal leasing under the Act is imminent. The action need be taken only once. Also, in Section 22, the uncertainty as to whether geothermal steam is water or mineral is recognized again where provision is made that nothing in the Act shall constitute an express or implied claim or denial on the part of the Federal government as to its exemption from State water laws.

Continuity of resources. Whether geothermal steam is a renewable or depletable resource is of extreme importance with respect to taxation. The Internal Revenue Service as noted above treats geothermal steam from The Geysers field in California as a gas and thus the producers are entitled to the 22½ per cent depletion allowance. However, it would be well to have the eligibility of geothermal steam for such depletion allowance provided by legislation.

Unitization. Section 18 of the Act authorizes voluntary unitization by lessees for conservation, and gives the Secretary of the Interior power to require unitization by provision in the lease. However, such forced unitization applies, of course, only to Federal lands. Unitization of Federal, State, and private lands is authorized, but not compulsory. Required unitization of lands within the

same field appears desirable in some instances for conservation and efficient production. State cooperation will be required.

Incentives to industry. The Geothermal Steam Act of 1970 is based on the concept of the development of the geothermal resources of Federally owned lands by and through private enterprise. However, the industry is a new one, with very little economic data on which to base decisions. Initial investments required are extremely high and the risks great at the present stage of knowledge and experience.

Therefore, it is highly desirable that ways be found to give private industry incentive to engage in development of this gravely needed natural resource. Such incentives might include a sliding scale of royalties, instead of the bonus system.

For competitive bidding, sliding royalties would have the three-fold advantage of requiring less immediate capital outlay by the private investor; it would have the government share in the success of development; and it would enable the so-called "little man," persons of limited capital, to have the opportunity to participate in the publicly-owned wealth of our national lands.

Another incentive might be an arrangement whereby the government guarantees a private entrepreneur up to 50 per cent against loss on his investment.

A third incentive might be a credit for expenditures by the lessee for research and development against royalties, term of use, and acreage limitations.

These and other avenues of providing incentives to private industry to carry out the purpose of the Act should be explored.

#### E. PROGRAM DEVELOPMENT

Prime consideration in getting the nation's geothermal resources research program under way should go to the selection of the institutions required to assess exploration methods, resource appraisal, reservoir development and production, utilization technology and economics, and environmental effects.

There exists today no less an urgency for an early solution of the impending national energy shortage than existed in the areas of nuclear research in the 1940's, or space exploration and space communication in the 1960's, when it was agreed that means to meet these national needs required the establishment of new and unique federal organizational entities.

Organizational structures should be studied and a suitable institution selected which could implement geothermal resources research as its sole or principal mission. It is envisioned that such a mission-oriented organization would be separate from, but function in consonance with, the existing Federal, State, and local regulating bodies.

Currently there are no less than nine executive departments and independent Federal agencies concerned, in some part, with what is developing as the national geothermal program. These organizations should be studied to determine if improvements should be made in institutional and technical competence, intra-agency priorities, planning, budgeting, administration, and coordination of geothermal activities. It is almost trite to observe that in order to realize a coordinated, well-managed and effective national program, a solution to these fragmented responsibilities needs to be found.

While the actual performance of the geothermal resources research effort as outlined in this report may well be carried out by existing competence in private companies, educational institutions, national laboratories, and newly created geothermal field research centers, the funding, direction, management, and support functions may well best be carried out by one, rather than several, Federal department or agency.

A partial listing of such common support functions is as follows: budget and program planning, cost effective analysis, audit and accounting, technical information collection and dissemination, intellectual property arbitration and review, public information and acceptance programs, environmental impact assessment and National Environmental Policy Act compliance, joint Federal-private industry cooperative project policy and administration, Federal-State coordination and cooperation, international information exchange and cooperative projects, manpower development (scientific and technical training programs), legislative programs regulating coordination and advisory functions, Congressional relations, operation of geothermal field research and experimental centers, technical advisory support for regulatory agencies, and coordination with other Federal agencies with related responsibilities.

Varying degrees of centralization are possible to embody these common functions and support services. Consideration should be given to any and all possible institutional opportunities, some of which are listed below:

Geothermal Energy Commission — a new independent agency, established by legislation, reporting to the President and combining the function and

responsibilities of all other Federal agencies presently concerned with geothermal resources research and development. Similar existing Federal agencies are: the Atomic Energy Commission (AEC) and the National Aeronautics and Space Administration (NASA).

Geothermal Resources Corporation — a quasigovernmental corporation, established by legislation and funded jointly by appropriations and private capital or operating revenues. Other generally similar organizations are the Tennessee Valley Authority (TVA), the Communications Satellite Corporation (COMSAT), and the Bonneville Power Administration (BPA).

Joint Office of Geothermal Research and Development — a separate office jointly funded and staffed by participating Federal agencies and existing by formal agreement of these organizations or by executive order. The Office would have all the responsibilities of a separate agency with budgets and funding received through participating agencies. Examples of such offices are: the Space Nuclear Propulsion Office (SNPO), the Office of Naval Reactors, and the Office for International Decade for Ocean Exploration.

National Geothermal Coordinating Council — a council providing a forum for formal coordination of Federal programs which exist by executive order. The Council would have no programmatic nor mission oriented responsibility.

Ad Hoc Interagency Coordinating Committee — The continuation of the existing ad hoc Federal group which assisted in preparation of the report entitled "Assessment of Geothermal Energy Resources". It is a voluntary participation group with no programmatic function nor responsibilities of its own.

National Council for Geothermal Resource Development — a Presidential council to set policy, coordinate and oversee the conduct of a national geothermal resources research program carried out by the several agencies involved. Similar councils have been employed for national security affairs, as well as domestic and foreign affairs.

National Geothermal Field Research Laboratories — a small set of laboratories organized around a small set of different types of geothermal resources. A large number of techniques and different technologies must be employed in finding, appraising, mapping (in three dimensions), and experimenting with each typical geothermal resource in order to develop and validate the methodology and technology for finding, appraising and exploiting similar resources.

If all the research is concentrated on one each of all different types of geothermal resources, then cooperation between research projects will reduce both the time and money required to complete the research. Laboratories would be available for researh and development projects being conducted by industry, government, and university investigators subject to the scientific approval of a Geothermal Resources Advisory Council. Laboratories should be jointly operated by U.S.G.S. and N.S.F.

In addition to a Federal institutional forum for geothermal development, there is a need for a national association of geothermal industries. This would conceptually be a privately sponsored association not to be substituted for any of the above, but highly desirable to provide effective industry representation at the national level and to provide a responsible point of liaison with the Federal geothermal institution or institutions.

### F. RECOMMENDATIONS

It is recommended that a Study Commission be established by, and report directly to the President of the United States. A study group, given a broad scope and composed of highly qualified individuals, is required to establish a Commission of sufficient status to deal effectively with the authorities and jurisdictional prerogatives of cabinet level departments.

The recommended charter is to examine existing Federal structures and missions responsible for aspects of geothermal resources and their development, to assess the capabilities and effectiveness of such components, and to recommend institutional and programmatic solutions to mount a vigorous national geothermal resources program.

The Commission should report its findings to the President on or before January 1, 1974.

## G. BUDGET

The institutional panel endorses the program budget previously recommended in "Assessment of Geothermal Energy Resources". The total ten-year budget was \$10.5 million. It is recommended that \$2.0 million be allocated for support of the Study Commission, with the remainder being used to support specialized investigations in the institutional research areas identified above consistent with the findings of the Study Commission.

Fiscal Year 74 75 76 77 78 79 80 81 82 83 Total

Budget 2.0 2.0 1.5 1.5 1.0 0.5 0.5 0.5 0.5 0.5 (millions)

## XI. SUMMARY OF RESEARCH NEEDS

The key research needs derived from the panel discussions are summarized below.

Resource Exploration. The objectives of geothermal resource exploration are to locate areas underlain by hot rock, to estimate the resource volume, temperature, and permeability at depth, and to determine the nature of any fluids producible from the geothermal resource. For convenience, exploration for geothermal resources is often discussed in terms of different categories, each of which has different physical properties which form the basis for a selection of techniques useful for exploration for that category. Only the individual techniques are discussed herein.

Geological considerations provide the framework in which the geochemical and geophysical techniques must be interpreted. Some important geological research problems are concerned with determinations of age, size, and magmatic types of igneous occurrences; nature and cause of structural features controlling the location of geothermal resource systems; and relationship of convective hydrothermal systems to broad regions of elevated heat flow.

Geochemical data collected during exploration is useful in the subsequent phases of resource evaluation, reservoir development and production, utilization, and environmental studies. Several hydrogeochemical indicators have had considerable success in geothermal exploration while others are still qualitative or difficult to interpret in the present theoretical and experimental framework.

Research is needed in: chemical, physical, and thermodynamic properties of aqueous solutions at

temperatures of 100°C to 400°C; determination of chemical compositions of in-situ geothermal fluids as a function of in-situ rock temperatures; and isotopic relations among water and various dissolved constituents, particularly gases.

Geothermal systems are characterized by thermally induced changes in electrical resistivity. Research should be directed toward: understanding the variation of porosity, water salinity, and temperature in actual geothermal reservoirs; improving electric field techniques and procedures for extracting true resistivity values from field data; and developing complementary exploration techniques which will improve the interpretation of resistivity data. Electrical exploration research should include further research on DC resistivity, self-potential, electromagnetic, telluric, and magnetotelluric techniques. Airborne methods may be of particular interest in large-scale reconnaissance.

Both active and passive seismic techniques are useful in geothermal exploration. Active seismic methods should be studied to characterize energy absorption and attenuation, and frequency shifts in known high temperature systems. Accurate determination of earthquake patterns can help delineate faults that may channel hot fluids to drillable depths.

A greater understanding of the effects of fluid and high temperature on fault strength and slip characteristics is needed. Seismic noise studies should be undertaken to evaluate: temporal and spatial noise variations; characteristics of recognized noise sources, noise spectra, noise coherency, location of source, and cause of noise; and direction of noise propagation and apparent velocity.

The gravity and magnetic signatures of geothermal systems varies greatly from one geologic province to another. Additional research is needed to determine the source of the gravity and magnetic anomalies associated with known geothermal areas and to decide whether the anomalies can be used as indicators of the internal temperature of the system.

Thermal exploration techniques provide a direct method for assessing the size and potential of a geothermal system. More regional heat flow determinations are needed to refine the estimates of available geothermal resources. Research is needed to determine the relationships between temperature gradients, subsurface distribution of isotherms, and the geometry of geothermal systems.

Laboratory temperature experimentation on model geothermal systems is needed. Hydrologic studies are required to understand more fully the effect of ground water movement on local geothermal gradients.

The development of new, less expensive techniques for drilling to depths in excess of 30,000 feet would benefit both geothermal and fossil fuel exploration greatly. (These topics are covered under resource assessment.) In addition, drilling research needed at shallower depths. Formation testing in uncased holes can provide useful input to the exploration for reservoirs.

Problems of isolating tested intervals in unconsolidated sands and in fractured reservoirs have not been solved. Inexpensive core recovery with reservoir fluid in place would assist in defining a model of a geothermal cell. Instrumentation for logging devices at temperatures about 180°C is urgently needed.

Research on methods of transmission of information from the bore hole face to the surface is required. Development of cheap, low density, low viscosity, non-thermally sensitive, high thermal conductivity, and high surface tension drilling fluids would lower drilling costs and leave the bore hole face in a more nearly undisturbed state. Drill cuttings, cores, and logs should be preserved.

In addition to the more applied research, basic research should be pursued on physical properties of geothermal water-steam mixtures, thermal geophysics and hydrology, modern geoscience theories and geothermal anomalies, data processing and general interpretation theory, and computer modeling.

Resource Assessment. Resource assessment research can be approached logically in terms of the research necessary to evaluate three different classes of geothermal resources: hydrothermal convection systems, geo-pressured systems, and hot, dry, impermeable rock resources.

A deep drilling research program is vital to the adequate evaluation of all geothermal resources. During the process of the resource assessment research program a national inventory of geothermal resources should be established. The program envisioned includes actual assessment studies as well as research on assessment methodology. In all cases, energy, water, and minerals are to be considered.

Two major types of hydrothermal convection

systems are recognized. The relatively rare vapordominated systems account for most of the present geothermal power production world-wide, but the much more abundar: liquid-dominated systems are expected to account for most of the increases in power production capacity in the near future.

In order to increase use of hydrothermal convection systems the following two research topics must be pursued: dynamics of representative convective systems; and geological, geochemical, hydrologic, and geophysical characteristics of representative geothermal systems. The objective of the first topic is to understand the size, life, origin, and dynamics of natural hot water geothermal systems whereas the second is directed toward basic data needed for engineering development of geothermal resources. Both topics contribute to the ability to construct models of representative systems using basic data concerning the system as input.

Geopressured aquifers occur in partitioned volumes bounded by faults which generally parallel the Gulf of Mexico coastline. Three forms of energy are available in the produced water. These are the intrinsic thermal energy, the mechanical energy available from the high pressure, and the methane contained in the formation fluid.

In order to assess these resources adequately, the following research program is necessary. A regional resource study, extending well into the coastal plain (750 miles) and out in the adjacent continental shelf, should be conducted to compile data on temperature, structure, salinity, sedimentary characteristics, pressure potential distribution, and possible waste water disposal methods in the Gulf coast region.

This study should identify three suitable sites for subsequent field research leading to a determination of the life, size, and total energy content of typical geopressured reservoirs. It will be necessary to design, drill, and test the formations selected and to instrument and observe the performance of disposal wells. Adequate assessments as well as assessment methodology should result from this approach.

No adequate means has yet been demonstrated to deliver the thermal energy of hot dry impermeable rock as usable energy at the earth's surface. Adequate assessment of these resources will draw upon explorations which will establish the occurrence, age, volume, temperature, and permeability of the igneous intrusions under consideration. Assessment will require study and modeling of rock mechanics and fracture systems.

The hydrology and energy transfer characeristics of fracture systems must be understood before it will be possible to assess adequately the hot dry rock resource. The geochemistry of fractured hot, dry rock systems is not well understood. Research will have to be conducted on geochemical kinetics to provide key characteristics of the heat transfer medium which brings the energy to the surface.

In order to determine the three-dimensional characteristics of representative geothermal areas it will be necessary to undertake a deep drilling program into geothermal formations. Probably a minimum of four wells must be drilled to depths of 20,000 feet or deeper. The difficulty and great expense involved in drilling to these depths in hot formations makes it imperative that new innovative approaches to drilling receive high priority in the research program.

Reservoir Production and Development. There is a great deal of research required to form a sound basis for reservoir development and production methods needed for optimal development of geothermal resources. Research is required in: drilling technology and techniques, geological formation evaluation methods, reservoir engineering, production engineering and production management, and well stimulation technology and techniques.

The research in drilling technology and techniques embraces both improvement in current technology and development of entirely new drilling techniques. The major difficulty with present technology is in its application at high temperatures. Problems are encountered with rubber seals, valves, cements, drilling muds, heat shields, sound mufflers, etc.

Better high temperature instrumentation is needed to measure temperature and pressure, and to sample geothermal fluids. Further efforts should be expended in improving the rotary drill. Erosion drills, electric melting drills, turbine drills and other techniques should be explored.

There is a strong need for research aimed at development of tools and techniques for evaluation of high temperature geothermal formations. Evaluation tools include electrical, acoustic, and nuclear logging devices, bore-hole samplers, sidewall and conventional coring devices, borehole flow metering, and measurement of chemical properties of components and chemical behavior of fluid-solid systems.

Reservoir engineering involves assessment of the size and deliverability of the geothermal resource and planning for the optimum development of the resource. Fundamental research into the physical, chemical, and

thermal behavior of multiphase aqueous systems (steam-liquid solution-solid) in porous media are needed to establish physical principles to construct meaningful physical and mathematical models of geothermal fluid systems. These studies would include thorough transport phenomena studies.

There is a severe need for field reservoir engineering studies to establish requirements for construction of mathematical models. These models should include sufficient detail to permit optimization studies of the effects of well spacing, liquid recharge from aquifers, reinjection of condensate and cooled liquids, cooling due to in situ boiling of liquids, changes in pore space and fluid conductivity due to precipitation of salts and solids, and other important parameters. To this end, field geothermal research sites are necessary for acquiring information and for validating reservoir engineering and hydrologic theory.

Production engineering and management problems vary with the use of the resource. Important uses considered are generation of electric power, space heating, production of chemicals and desalination of fluids. Some of the problems of concern are those of well workovers, well stimulation, corrosion and scaling, geothermal fluid separation and metering, critical velocity of flow in pipes and valves, deep well pumps and other similar problems.

Well stimulation technology and techniques are concerned with improving the permeability of the formation and thus are important in both production and reinjection. Hydrofracturing, high explosive, acid treatments, thermal fracturing, and nuclear explosives should all be considered. The large void volumes produced by nuclear explosives could provide space

for mineral deposition to collect from flashing hot water. Nuclear explosives might also dry up a wet flashing system by providing space for the flashing to occur underground.

Utilization Technology and Economics. Another category for research is the technology for the best utilization of the different types of geothermal resources.

For the vapor-dominated systems and the higher temperature (above 200°C) hot liquid-dominated systems, the technology for the economic production of power appears well developed. In the case of vapor-dominated systems, such as The Geysers field, the steam is available at the well head. After filtering, it is fed to low pressure turbines which drive the generator.

In the higher temperature, hot liquid-dominated systems, the liquid in the reservoir flashes into a mixture of steam and liquid upon reduction of pressure by the well. The mixture is produced and, after separating the liquid from the steam, the steam is fed to a low pressure turbine. If the reservoir temperature and pressure are sufficiently high, it may be possible to employ multiple stages of flashing and lower pressure turbines. It appears that there is no large need for research on surface technology in these two cases.

In the case of hot dry rock systems the same may be said if the temperature of the formation is high enough to heat the fluids sufficiently.

It would be helpful to conduct research on gas emissions, particulate removel, noise control, removal of dissolved salts such as silica and boron, and disposal of brine, condensate, and solids.

It is believed that there are many geothermal

reservoirs (perhaps 80% of all reservoirs) in which the temperature is not high enough to provide fluids that may be used with existing technology to produce economic electricity. For the generation of power from such reservoirs, U.S. industry has made some progress in developing the technology of binary fluid systems in which the heat is transferred to a low-boiling point fluid (such as freon or isobutane) which is then used as the working fluid in a closed cycle system. Further research on a variety of binary fluid systems as well as other power cycles deriving energy from hot concentrated brines is needed and demonstration plants will need to be built. Thermodynamic data is needed on the applicability of various working fluids for geothermal applications.

In addition, technology is needed to expand the application of geothermal resources, particularly desalination of brines and commercial recovery of minerals. Successful demonstration that these reservoirs can be utilized economically for generating electric power and for multiple uses would expand the recoverable geothermal resources many fold.

Desalination pilot plants using geothermal energy are needed, and mineral production may also require pilot plants.

Many of the utilization problems would be better understood if the physical and chemical properties of brines were better known. Corrosion rates of materials of construction exposed to geothermal brines are required.

Immiscible heat transfer systems for extracting geothermal energy should be studied. These systems involve injecting a fluid which does not mix with water into the formation and then producing the combined fluids. Mechanical separation at the surface would provide a hot clean working fluid.

In the case of geopressured resources, research is needed to remove methane from the formation fluid. Direct conversion of geothermal heat to electricity, as by thermoelectric techniques, should be studied. As more data become available to support utilization design studies, a great deal of system modeling and analysis work will be necessary as a prerequisite to the design and construction of the several pilot plants.

Environmental Effects. Geothermal developments are unique in that all activities related to the power production cycle are localized to the immediate vicinity of the power plant. Support operations such as mining, fuel processing, transportation, and other handling facilities do not exist. For this reason, the environmental effects are site dependent in origin. Certain undesirable effects, however, can extend for several miles from the geothermal field itself and thus introduce environmental problems into the surrounding region. For this reason, the environmental effects are site dependent in origin. Certain undesirable effects, however, can extend for several miles from the geothermal field itself and thus introduce environmental problems into the surrounding region.

Possible hazards to the environment which are of most immediate concern are: gaseous and particulate emissions, land pollution, subsidence potential, seismic considerations, surface and ground water pollution, biological effects, noise effects, and social effects. Research should be directed toward an accurate determination and evaluation of the character and magnitude of these factors.

It will be necessary to set up a careful program of monitoring environmental effects as geothermal developments progress in order to gather the requisite data. It will probably be necessary to develop techniques for decreasing some environmental impacts. Reinjection of geothermal fluids into the formation cannot be done without proper regard for ground water quality. More water resources research will be required to guard against contamination.

Institutional Considerations. The objective of considering institutional problems is to define those research studies concerning the organizational, legal, and regulatory considerations which will permit geothermal development in a safe, economical, environmentally - sound, and equitable manner for all concerned parties. The concerned parties consist of the general public as users, private industry as developers, and local, State, and Federal governmental agencies as regulators.

The geothermal industry is an infant one in comparison to the total energy industry. Institutional problems will have to be faced squarely and solved at the highest level if geothermal resources are to become a major supplier of energy. There are questions of law to address as well as questions of the proper role of the Federal government versus industrial research and development. The adequacy of the existing body of law should be assessed.

There are many institutional problems and great opportunities implicit in the development and extensive application of geothermal resources. A great

deal of study and analysis must precede the solutions. Such efforts should include: a compilation of State. Federal, and local laws and regulations governing geothermal developments and an analysis of their functioning. administration, and interactions: preparation of a model code; an analysis of the legal ownership of geothermal resources and the problems of utilization pending final determination of ownership; establishment of effective liaison between all sectors of the field and exploration of mechanisms for cooperation; establishment of a Federal information gathering function to promote systematic gathering and rapid distribution of geothermal resource information; and establishment of a Presidential Study Commission to recommend organizational and mission changes.

Conclusions. All of this research activity will become irrelevant if the economic parameter is not thoroughly researched. An exhaustive economic analysis of the potential of geothermal resources must be undertaken. The first look must use economic parameters which other primary energy producers use so that comparisons may be valid. The subject is debatable since present uses are related to utility economics. Perhaps the only legitimate viewpoint is to focus on the cost to the ultimate consumer. Utilities are a regulated industry and the regulation may need to be changed.

It is apparent that the energy, the water, and perhaps the mineral potentials of geothermal resources are vast. It is also clear that considerable work in other fields suggests that this enormous resource may be tapped using extensions of present technology. Methods of defining the resource per se and optimal methods of locating resources require considerable additional research. Adverse environmental aspects seem controllable and institutional factors need a great deal of study but appear tractable as well. The real crux of the situation is whether or not the bulk of this reserve is available under economically feasible conditions.

From the beginning, the research program should include both short range and long range goals. One of the first tasks is to undertake a research program at an adequate level to better define the magnitude of the resource and accelerate its development. Such a program should include: development of binary fluid power generating systems; development of improved exploration methods; development of desalination methods for geothermal fluids; development of better models of geothermal reservoirs; and development of faster, cheaper methods for deep drilling into hot formations. The establishment of a Presidential Study Commission to study the merits and demerits of different possible organizations and to recommend the best organization is urged.

#### REFERENCES

- 1. Assessment of Geothermal Energy Resources, Panel on Geothermal Energy Resources, Department of the Interior, August 1972.
- 2. U.S. Energy Outlook, an Initial Appraisal 1971-1985, National Petroleum Council, Vol. 1, July 1971.
- 3. Outlook for Energy in the United States to 1985, Energy Economics Division, The Chase Manhattan Bank, June 1972.
- 4. Geothermal Resource Investigations, Imperial Valley, California, Bureau of Reclamation, Department of the Interior, January 1972.
- 5. Summary Report of the Commissioner, Bureau of Reclamation, 1970, Statistical and Financial Appendix, Department of the Interior.
- 6. U.S. Energy Outlook, an Interim Report, an Initial Appraisal by the New Energy Forms Task Group, 1971-1985, National Petroleum Council, July 1972.
- 7. Geothermal Energy, L.J.P. Muffler and D.E. White, The Science Teacher, Vol. 39, No. 3, March 1972.
- 8. The Economics of Geothermal Power in the United States, A. Kaufman, U.N. Symposium on the Development and Utilization of Geothermal Resources, XI/11, Pisa, Italy, September 1970.
- 9. Geochemistry Applied to the Discovery, Evaluation, and Exploitation of Geothermal Energy Resources, D.E. White, U.N. Symposium on the Development and Utilization of Geothermal Resources, Rapporteur's Report, V, Pisa, Italy, September 1970.
  - 10. Unpublished Letter to L.T. Grose from S. Kaufman, August 1972.
  - 11. Geothermal Energy, D.E. White, U.S. Geological Survey Circular 519, 1965.

# Additional references which are not necessarily cited in the text of the report but are significant in the study of geothermal phenomena:

American Oil Shale Corporation, 1971, Battelle-Northwest, Westinghouse Electric Corporation and Lawrence Livermore Laboratory, Feasibility study of plowshare geothermal power plant.

Austin, D.F., 1966, Selection criteria for geothermal prospects, in Papers presented at the AIME Pacific Southwest Mineral Industry Conference, Sparks, Nevada, May 5-7, 1965; Part C, Session on North American Exploration and Mine Development: Nevada Bureau of Mines Report 13, p. 93-125.

Axtell, L.H., 1972, Overview of geothermal exploration and development in California, presented at the Geothermal Resources First National Conference, El Centro, California.

Barnea, J., 1972, Geothermal Power, Scientific American, v. 226, no. 1, p. 70-77.

Barton, D.B., 1970, Current status of geothermal power plants at The Geysers, Sonoma County, California: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Biehler, S., Kovach, R.L., and Allen, C.R., 1964, Geophysical framework of the northern end of the Gulf of California structural province, in Marine Geology and Gulf of California, a symposium: Am. Assoc. Petroleum Geologists Me. 3, p. 126-143.

Biehler, S. and Rex, R.W., 1971, Structural geology and tectonics of the Salton trough, southern California, in Geol. Soc. America Cord. Mtg., Riverside, March, Field Trip Guidebook: Geol. Excur. in So. California p. 30-42.

Bilhartz, H.L., Jr., 1971, Fluid Production from Geothermal Steam Reservoirs, MS Report, Stanford University, Stanford, California.

Bodvarsson, G.D., 1970, Evaluation of geothermal prospects and the objectives of geothermal exploration: Geoexploration, v. 8, p. 7-17.

Boldizar, T., 1970, Geothermal energy production from porous sediments in Hungary: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Bowen, R.G., 1971, Electricity from geothermal, nuclear, and coal sources. An environmental impact comparison; The Ore Bin, Oregon Dept. of Geol. and Mineral Industries v. 33, no. 11, p. 197-212.

Bowen, R.G., and Peterson, N.V., 1970, Thermal springs and wells in Oregon: Oregon Dept. of Geol. and Mineral Industries Misc. Paper 14.

Bowen, R.G., and Groh, E.A., 1971, Geothermal - earth's primordial energy. Technology Review, p. 42-47, Oct/Nov.

Bowen, R.G., 1972, Overview of geothermal exploration and development in Oregon, presented at the Geothermal Resources First National Conference, El Centro, California.

Bradbury, J.J.G., 1970, The economics of geothermal power (Rapporteur's Report): U.N. Symp. of Dev. and Util. of Geothermal Resources, Pisa, Italy.

Burnham, J.B., and Stewart, D.H., 1970, The economics of geothermal power: Pacific Northwest Laboratories, Battelle Institute, Richland, Wash., 18 p.

Cady, G.V., 1969, Model Studies of Geothermal Fluid Production, Ph.D. Dissertation, Stanford University, Stanford, California.

Cady, G.V., Bilhartz, H.L., Jr. and Ramey, H. J., Jr., Model Studies of Geothermal Fluid Production, Presented at 71st National Meeting, American Institute of Chemical Engineers, Dallas, Texas, Feb. 1972.

California, Department of Water Resources, 1967, Investigations of geothermal waters in the Long Valley area, Mono County.

California Division of Oil and Gas, 1971, California Laws for conservation of geothermal energy.

California Division of Oil and Gas, 1971, Map of The Geysers geothermal field.

California Division of Oil and Gas, 1971, Map of the Salton Sea geothermal field.

California Geothermal Resources, 1967, Report to the 1967 Legislature by the Joint Legislative Committee on Tide Lands, 194 p., 75 p.

Campbell, K.V. and others, 1970, A survey of thermal springs in Washington State: Northwest Science, v. 44, no. 1, p. 1-11.

Clayton, R.N., Muffler, L.J.P., and White, D.E., 1968, Oxygen isotope study of calcite and silicates of the River Ranch No. 1 well, Salton Sea geothermal field, California: Am. Jour. Sci., v. 266, p. 968-979.

Combs, Jim and Muffler, L.J.P., 1972 Exploration for geothermal resources: Trans. Amer. Nuclear Soc., 1972 Annual Mtg., Las Vegas, Nev., June 18-22, 1972. p. 15.

Crosby, J.W., III, 1971, New developments in geothermal exploration: 1st Northwest Conf. on Geothermal Pow Dept. of Natural Resources, Olympia, Washington.

Decker, Edward, 1972, Overview of geothermal exploration and development in Wyoming, presented at the Geothermal Resources First National Conference, El Centro, California.

Decius, L.C., 1964, Geological environmental of hyperthermal areas in continental United States and suggested methods of prospecting them for geothermal power: U.N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 166-177.

Ellis, A.J., 1970, Quantitative interpretation of chemical characteristics of hydrothermal systems: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Facca, G., 1970, General report of the status of world geothermal development (Rapporteur's Report): U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Fournier, R.O. and Rowe, J.J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells: Am. Jour. Sci., v. 264, p. 685-697.

Fournier, R.O. and Truesdell, A.H., 1970, Chemical indicators of subsurface temperature applied to hot spring waters of Yellowstone National Park, Wyoming, U.S.A.: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Garside, L.J., 1972, Overview of geothermal exploration and development in Nevada presented at the Geothermal Resources First National Conference, El Centro, California.

Geothermal Resources Board, California, Compendium of Papers, Imperial Valley - Salton Sea Area Geothermal Hearing, Oct. 22 and 23.

Geothermal Resources Board, California, 1971, Economic Potential of Geothermal Resources in California, 35 p.

Goodwin, L.H., Haigler, L.B., Rioux, R.L., White, D.E., Muffler, L.J.P., and Wayland, R.G., 1971, Classification of public lands valuable for geothermal steam and associated geothermal resources: U.S. Geol. Survey Circ. 647, 18 p.

Goldsmith, M., 1971, Geothermal Resources in California, potentials and problems; California Ins. Tech. Environmental Quality Laboratory report no. 5, 45 p.

Griscom, A., and Muffler, L.J.P., 1971, Aeromagnetic map and interpretation of the Salton Sea geothermal area, California: U.S. Geol. Survey, Geophys. Inv. Map GP-754.

Groh, E.A., 1966, Geothermal energy potential in Oregon: The Ore Bin, Oregon Dept. of Geology and Mineral Industries, v. 28, p. 125-135.

Grose, L.T., 1971, Geothermal Energy: Geology, exploration, and developments, part 1, Colorado School of Mines Mineral Industries Bull. v. 14, no. 6, 14 p.

Gross, L.T., 1971, Geothermal Energy: Geology exploration and developments, part 2, Colorado School of Mines Mineral Ind. Bull. v. 15, no. 1, 16 p.

Grossling, B.F., 1972, An appraisal of the prospects of geothermal energy in the United States, part 1, in chapter 2, Geothermal Energy, of An Initial Appraisal of the New Energy Forms Task Group 1971-1985: Washington, D.C., NATL. Petroleum Council, p. 15-26.

Haigler, L.B., 1969, Mineral and water resources of Arizona: Arizona Bur. Mines Bull. 180.

Harrenstein, Howard, 1972, Overview of geothermal exploration and development in Hawaii, presented at the Geothermal Resources First National Conference, El Centro, California.

Harshbarger, J.W., 1972, Overview of geothermal exploration and development in Arizona, presented at the Geothermal Resources First National Conference, El Centro, California.

Healy, J.H., Rubey, W.W., Griggs, D.T., and Raleigh, C.B., The Denver Earthquakes; Science, v. 161, no. 3848, Sept. 1968, p. 1301-1310.

Hewitt, W.P., 1972, Overview of geothermal exploration and development in Utah, presented at the Geothermal Resources First National Conference, El Centro, California.

Heylmun, R.C., 1966, Geothermal power potential in Utah: Utah Geological and Mineralogical Survey Special Studies 14, 28 p.

Horton, R.C., 1964a, Hot Springs and sinter deposits, and volcanic cinder cones in Nevada: Nevada Bur. Mines Map 25.

Horton, R.C., 1964b, Geothermal power in Mineral and Water Resources of Nevada, Nevada Bur. Mines Bull. 65, p. 267-269.

Hunt, T.M., 1970, Net mass loss from the Wairakei Geothermal Field. New Zealand: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Imperial County Department of Public Works, 1971, Terms, conditions, standards, and application procedures for initial geothermal development, Imperial County, California.

James, Russell, 1968, Wairakei and Larderello: geothermal power systems compared, New Zealand Jour. Science 11, p. 706-719.

Jones, P.H., 1970, Geothermal resources of the northern Gulf of Mexico Basin; U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Kaufman, A., 1970, The economics of geothermal power in the United States: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Kiersch, G.A., 1964, Geothermal steam: Origin, characteristics, occurrence and exploitation: U.S. Air Force Cambridge Research Labs. (AFCRL - 64-898), Washington, D.C., U.S. Dept. of Commerce.

Kilkenney, J.E., 1972, Geothermal Energy, part II, General appraisal of the Earth's prospective energy, in An Initial Appraisal by the New Energy Forms Task Group, 1971-1985; Other Energy Resources Subcommittee of the National Petroleum Councils Committee on U.S. Energy Outlook, p. 27-35.

Koenig, J.B., 1967, The Salton-Mexicali geothermal province: Calif. Div. Mines and Geol., Mineral Information Service, v. 20, p. 75-81.

\_\_\_\_\_\_, 1969, The Geysers geothermal field: California Div. Mines and Geol., Mineral Inf. Service, v. 22, no. 8, p. 123-128.

\_\_\_\_\_\_, 1970, Geothermal exploration in the western United States: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

\_\_\_\_, 1971, Geothermal development: Geotimes, v. 16, no. 3, p. 10-12.

\_\_\_\_\_\_, 1972, The worldwide status of geothermal exploration and development; Trans. Amer. Nuclear Soc. 1972 Annual Mtg., Las Vegas, Nev., June 18-22, 1972, p. 13.

Kruger, Paul, and Otte, C., 1972, Geothermal Energy - Resources, Production, Stimulation, Stanford University Press, Stanford, California, to be published in November, 1972.

Livingston, V.E., 1972, Overview of geothermal exploration and development in Washington, presented at the Geothermal Resources First National Conference, El Centro, California.

McKelvey, V.E., 1972, Mineral Resource Estimates and Public Policy: American Scientist v. 60, no. 1, Jan/Feb. 1972, p. 32-40.

McNitt, J.R., 1963, Exploration and development of geothermal power in California: Cal. Div. of Mines and Geol. Special Report 75, 45 p.

- , 1964, Geology of The Geysers thermal area, California: U.N. Conf. New Sources of Energy, Rome, Proc., v. 2, Geothermal Energy: I, p. 293-302.
- , 1965, Review of geothermal resources, in Lee, W.H.K., ed., Terrestrial heat flow: Am. Geophys., Union Geophys. Mon. Ser. no. 8, p. 240-266.
- , 1970, The geological environment of geothermal fields as a guide to exploration (Rapporteur's Report): U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Mundorff, J.C., 1970, Major thermal springs of Utah: Utah Geol. and Mineralogy Survey, Water Resources Bull. 13, 60 p.

Muffler, L.J.P., and White, D.E., 1972, Geothermal energy: The Science Teacher, v. 39, no. 3.

the Salton Sea geothermal field and Salton Trough, southeastern California: Geol. Soc. American Bull., v. 80. p. 157-182.

Muffler, L.J.P., White, D.E., and Truesdell, A.H., 1971, Hydrothermal explosion craters in Yellowstone National Park; Geol. Soc. America Bull., v. 82, no. 3, p. 723-740.

Pearl, Richard, 1972, Overview of geothermal exploration and development in Colorado, presented at the Geothermal Resources First National Conference, El Centro, California.

Peterson, N.V., and Groh, E.A., 1967, Geothermal potential of the Klamath Falls area, Oregon - A preliminary study: The Ore Bin, Oregon Dept. of Geol. and Mineral Industries, v. 29, p. 209-231.

Peterson, N.V. and McIntyre, J.R., 1970, The reconnaissance geology and mineral resources of eastern Klamath County and Western Lake County, Oregon: Oregon Dept. Geol. and Mineral Industries Bull. 66, 70 p.

Raghavan, R., Ramey, H.J., Jr., and Kruger, P., 1971, Calculation of Steam Extraction from Nuclear-Explosion Fractured Geothermal Aquifers, Trans. Am. Nucl. Soc., v. 14, p. 695.

Ramey, H.J., Jr., 1970, Short Time Well Test Data Interpretation in the Presence of Skin Effect and Wellbore Storage, J. Petro. Tech., v. 22, p. 97-104.

Ramey, H.J., Jr., Kruger, P., and Raghanan, R., 1972, Stimulation Modes of Geothermal Aquifers, Trans. Am. Nucl. Soc., v. 15, p. 20, see also Kruger and Otte, Editors (1972).

Rex, R.W., 1966, Heat flow in the Imperial Valley of California (abs.): Amer. Geophys. Union Trans., v. 47, p. 181.

\_\_\_\_\_, 1968, Investigation of the geothermal potential of the Lower Colorado River Basin: Phase I - The Imperial Valley Project: The Institute of Geophysics and Planetary Physics, University of California at Riverside.

, 1970, Investigation of geothermal resources in the Imperial Valley, and their potential value for desalination of water and electricity production: Riverside, California Univ. Inst. Geophys. and Planetary Phys., 14 p.

picture: Riverside, Calif. Univ. Inst. Geophys. and Planetary Phys., Contribution 72-10, 8 p.

Ross, Sylvia H., 1970, Geothermal potential of Idaho: Idaho Bureau of Mines and Geol. open-file report, 28 p.

Roy, R.F., Decker, E.R., Blackwell, D.D., and Birch, F., 1968, Heat flow in the United States: Jour. Geophys. Research, v. 73, p. 5207-5221.

Sass, J.H., Lachenbruch, A.H., Munroe, R.J., Greene, G.W., and Moses, T.H., Jr., 1971, Heat flow in the western United States: Jour. Geophys. Research, v. 76, no. 26, p. 6376-6413.

Schurr, S.H., and Netschert, 1960, Energy in the American Economy 1850-1975: An Economic Study of Its History and Prospects: Johns Hopkins Press, Baltimore.

Stone, R.T., 1971, Implementing the Federal Geothermal Steam Act of 1970: Northwest Conf. on Geothermal Power, 1st, Dept. of Natural Resources, Olympia, Washington.

Summers, W.K., 1965a, A preliminary report of New Mexico's geothermal energy resources: New Mexico Bur. Mines and Mineral Resources Circ. 80, 41 p.

,1965b, Chemical characteristics of New Mexico's thermal waters - a critique: New Mexico Bureau Mines and Mineral Resources Circ. 83, 27 p.

\_\_\_\_\_\_,1970a, Geothermal prospects of New Mexico: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

\_\_\_\_\_\_,1970b, New Mexico's thermal waters: New Mexico Bur. Mines and Mineral Resources microfilm.

,1971, Annotated and indexed bibliography of geothermal phenomena: New Mexico Bur. Mines and Mineral Resources. s.

Summers, W.K., and Ross, S.H., 1971, Geothermics in North America: present and future: Wyoming Geol. Assoc. Earth Sci. Bull., March, p. 7-22.

Summers, W.K., 1972, Overview of geothermal exploration and development in New Mexico, presented at the Geothermal Resources First National Conference, El Centro, California.

Theobald, P.K., Schweinfurth, S.P., and Duncan, D.C., 1972, Energy resources of the United States: U.S. Geol. Survey Circ. 650, 27 p.

United Nations, 1964, United Nations conference on new sources of energy Proceedings of the conference in Rome, Italy, Aug. 21-31, 1961, v. 2, geothermal energy - 1., 420 p.; v. 3, geothermal energy - II, 516 p.

United Nations, 1970, Report on "United Nations Symposium on the Development and Utilization of Geothermal Resources." Pisa, Italy, Sept. 22-Oct. 1, 1970 (ST/TAD/Ser. C/12b).

U.S. Dept. of Interior, 1971, Draft environmental impact statement for the geothermal leasing program, 97 p.

U.S. Dept. of Interior, 1972, Supplement to Draft Environmental Impact Statement for the geothermal Leasing Program, 55 p.

- U.S. Dept. of Interior, Bureau of Reclamation, 1972, Geothermal Resource Investigations, Imperial Valley, California Developmental Concepts, 58 p.
- U.S. Dept. of Interior, Bureau of Reclamation, 1972, Environmental Statement, final deep geothermal test well, Geothermal Resource Investigation Imperial Valley, Calif., 27 p.
- Waring, G.A., 1965, Thermal springs of the United States and other countries of the world a summary: U.S. Geol. Survey Prof. Paper 492, 383 p.
- White, D.E., 1964, Preliminary evaluation of geothermal areas by geochemistry, geology, and shallow drilling: U.N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 402-408.
- \_\_\_\_\_,1965, Geothermal energy: U.S. Geol. Survey Circ. 519, 17 p.
- \_\_\_\_\_,1968, Environments of generation of some base-metal deposits: Econ. Geology, v. 63, no. 4, p. 301-335.
- \_\_\_\_\_\_,1969b, Thermal and mineral waters of the United States a brief review of possible origins: Internat. Geol. Cong., 23rd, Prague 1969, v. 19, p. 269-282.
- \_\_\_\_\_\_,1970, Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources (Rapporteur's Report): U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.
- White, D.E., McNitt, J.R., 1966, Geothermal energy, in Mineral Resources of California, Calif. Div. Mines Geol. Bull. 191, 174 p.
- White, D.E., Muffler, L.J.P., and Truesdell, A.H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Econ. Geol., v. 66, p. 75-97.
- Whiting, R.L., and Ramey, H.J., Jr., 1969, Application of Material and Energy Balances to Geothermal Steam Production, J. Petro. Tech. v 21, p. 893-900, (1969).

## **APPENDIX**

This report has been edited from the original draft reports which were prepared by the six panels at the Geothermal Resources Research Conference. The opinions expressed are the general concensus of the majority of the participants but are not necessarily endorsed by each contributor.

The conference participants were as follows:

# ANCHORAGE PLANNING CONFERENCE

Mr. Walter J. Hickel Principal Investigator Adjunct Professor University of Alaska

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Prof. Robert W. Rex University of California, Riverside

Prof. Gunnar Bodvarsson Oregon State University

Mr. Donald H. Stewart Battelle Northwest Mr. Herbert Rogers, Jr. Rogers Engineering Company, Inc.

Mr. John P. Finney Pacific Gas and Electric Company

Prof. Hamilton Hess University of San Francisco

Mr. Richard Bowen
Oregon Department of Geology and
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Mr. Joseph W. Aidlin General Counsel, Magma Power Company

Mr. Stewart French Private Law Practice, Washington, D.C. (former Chief Counsel, Senate Interior Committee)

Dr. Jesse C. Denton National Science Foundation

Dr. Dallas L. Peck U.S. Geological Survey

## GEOTHERMAL RESOURCES RESEARCH CONFERENCE

## Panel on Resource Assessment

Dr. L. T. Grose, Professor of Geology (Co-Chairman) Colorado School of Mines

Dr. Robert W. Rex, Exploration Manager (Co-Chairman) Pacific Energy Corporation, Inc.

Mr. Paul H. Jones, Research Geologist U.S. Geological Survey

Dr. Sidney Kaufman, Research Geologist Shell Development Company

Dr. Ralph O. Kehle, Professor of Geology University of Texas

Mr. James B. Koenig, Geologist and Executive Officer California Division of Mines and Geology

Dr. Robert M. Potter, Research Physicist Los Alamos Scientific Laboratories

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#### Panel on Resource Exploration

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Mr. L. Axtell, Geologist Phillips Petroleum Company Dr. S. Biehler, Assistant Professor University of California

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## Panel on Reservoir Development and Production

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Mr. James G. Gist, Vice President for Production and Manager of Western Operations Pacific Energy Corporation

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Mr. Joseph F. Dietz, Manager-Environmental Coordination San Diego Gas & Electric Company

Mr. Robert N. Newkirk, Manager of Engineering and Special Projects The Fluor Corporation Mr. J. Lynn Rasband, Mechanical Engineer Southern California Edison Company

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## Panel on Institutional Problems

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Mr. George W. Nielsen U.S. Bureau of Land Management

Mr. Reid Stone, Geothermal Coordinator U.S. Department of the Interior

Mr. Glenn West Pacific Gas and Electric Company Mr. Joseph W. Aidlin General Counsel Magma Power Company

## Panel on Environmental Effects

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Mr. Michael McCloskey, Executive Director The Sierra Club

Mr. Robert C. Scott, Head San Francisco Regional Office Environmental Protection Agency

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