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ASSESSMENT OF GEOTHERMAL ENERGY
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Dallas L. Peck. 26 Jun 72, 97p*

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ASSESSMENT OF GEOTHERMAL ENERGY RESOURCES

FEDERAL COUNCIL FOR SCIENCE AND TECHNOLOGY

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ASSESSMENT OF GEOTHERMAL ENERGY RESOURCES

Prepared for the
Committee on Energy Research and Development Goals
Federal Council of Science and Technology

June 26, 1972

Panel on Geothermal Energy Resources
Dallas L. Peck, Coordinator
Department of the Interior

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ASSESSMENT OF GEOTHERMAL RESOURCES

CONTENTS

	<u>Page</u>
1. CONCLUSIONS AND RECOMMENDATIONS	1
Introduction	1
Conclusions	4
Recommendations	5
2. NATURE OF GEOTHERMAL ENERGY	12
Local Geothermal Reservoirs	13
Sedimentary Basins	17
Dry Geothermal Reservoirs	17
3. CURRENT UTILIZATION	18
4. CURRENT RESEARCH AND DEVELOPMENT	23
International	23
United States of America	25
U.S. Geological Survey	26
Bureau of Reclamation	29
Office of Saline Water	33
Bureau of Mines	35
Bureau of Land Management	37
National Science Foundation	39
Atomic Energy Commission	42
Department of Defense, Advanced Research Projects Agency	45
National Aeronautics and Space Administration	46
State Organizations	47
Private Industry	48
Relevant Research directed at Other Energy Resources	50
5. ENVIRONMENTAL EFFECTS	51
6. ULTIMATE POTENTIAL	55
7. RESEARCH AND DEVELOPMENT NEEDS	65
Resources Appraisal	65
Exploration Methods	67
Reservoir Development and Production	69
Utilization Technology and Economics	72
Environmental Effects	74
Institutional and Legal Aspects	77
8. REFERENCES	79

TABLES

1. World Geothermal Power Production, 1972	19
2. Three Recent Sets of Geothermal Resource Estimates	58

FIGURES

1. Hot springs, known geothermal areas, and producing geothermal fields in the western United States	16
2. Estimated reserves and resources of geothermal energy	56

ASSESSMENT OF GEOTHERMAL ENERGY RESOURCES

CHAPTER 1

CONCLUSIONS AND RECOMMENDATIONS

Introduction

The Office of Science and Technology, in cooperation with the Federal Council on Science and Technology and appropriate Federal agencies, is carrying out an extensive assessment of energy technologies in response to a request from the President in his message on energy of June 4, 1971. As part of this endeavor, the Office of Science and Technology in December 1971 requested the Department of the Interior to assess the technology of geothermal energy and recommend a program of research and development. The assessment has been carried out by the U.S. Geological Survey in collaboration with two panels of experts. The first, an informal interagency geothermal coordinating committee, which began meeting in September 1971 to promote communication between Federal agencies involved in the geothermal resources field. Members of the following agencies have participated in the meetings held at least once a month since the committee was established: Bureau of Reclamation, Office of Saline Water, Geological Survey, Bureau of Mines, National Science Foundation, Atomic Energy Commission, National Aeronautics and Space Administration, Advanced Research Projects Agency, Bureau of Land Management, and Environmental Protection Agency. The members of this committee contributed to this report and reviewed its conclusions. The second panel of experts was established in May 1972, when the National Science Foundation, RANN Program, approved a research proposal submitted by Walter J. Hickel, Adjunct Professor of the University of Alaska and former Secretary of the Interior, to hold a conference on geothermal resources

research in order "To develop an assessment of the state of the art and to recommend a research program to provide the requisite knowledge for establishing the proper role of geothermal resources in providing (1) additional energy to alleviate the Nation's impending shortage, (2) water to supplement present supplies, and (3) mineral resources." The conference is planned for September 1972 and will include about 60 knowledgeable scientists, engineers, and other experts from industry, universities, and state and Federal agencies. The attendees will be divided into six sub-panels as follows: (1) Resources Evaluation, (2) Resource Exploration, (3) Reservoir Development and Production, (4) Utilization - Technology and Economics, (5) Environmental Effects, and (6) Institutional Problems. The final report from this conference will provide an expanded and detailed list of recommended research and development topics that should provide a useful supplement to this present report.

The co-chairman of the sub-panels,^{1/} all of whom are from industry, universities, and state agencies, met with the principal investigator, Mr. Hickel, and the executive secretary, Dr. Dunlop, in Anchorage, Alaska, on May 8 and 9, 1972. At this meeting they planned the September conference and made preliminary recommendations for research and development that provide a major part of the recommendations of this report.

1/ Official attendees at the May 8 and 9, 1972, conference were as follows:

Mr. Walter J. Hickel
Principal Investigator

Adjunct Professor
University of Alaska

Dr. Donald D. Dunlop
Executive Secretary

Fairfax, Virginia

Prof. L. T. Grose
Co-chairman, Resources
Evaluation Sub-panel

Colorado School of Mines

Prof. Robert W. Rex
Co-chairman, Resources
Evaluation Sub-panel

University of California, Riverside

Prof. Gunnar Bodvarsson
Co-chairman, Resource
Exploration Sub-panel

Oregon State University

Mr. Donald H. Stewart
Co-chairman, Reservoir
Development and Production
Sub-panel

Battelle Northwest

Mr. Herbert Rogers, Jr.
Co-chairman, Utilization
Technology and Economics
Sub-panel

Rogers Engineering Company, Inc.

Mr. John P. Finney
Co-chairman, Utilization
Technology and Economics
Sub-panel

Pacific Gas and Electric Company

Prof. Hamilton Hess
Co-chairman, Environmental
Effects Sub-panel

University of San Francisco

Mr. Richard Bowen
Co-chairman, Environmental
Effects Sub-panel

Oregon Department of Geology and
Mineral Industries

Mr. Joseph W. Aidlin
Co-chairman, Institutional
Problems Sub-panel

General Council, Magma Power Company

Mr. Stewart French
Co-chairman, Institutional
Problems Sub-panel

Private Law Practice, Washington, D. C.
(former Chief Council, Senate Interior
Committee)

Dr. Jesse C. Denton
Observer

National Science Foundation

Dr. Dallas L. Peck
Observer

U.S. Geological Survey

Other contributors to and reviewers of this report not present at the Anchorage conference were:

Dr. Abraham E. Dukler	University of Houston
Dr. Carel Otte	Union Oil Company of California
Dr. H. J. Ramey, Jr.	Stanford University
Dr. Geoffrey R. Robson	United Nations, New York
Dr. Bernardo Grossling	U.S. Geological Survey
Dr. L. J. P. Muffler	U.S. Geological Survey
Dr. Donald E. White	U.S. Geological Survey

Conclusions:

Geothermal resources are a natural source of relatively clean energy, water, and minerals that could have a significant impact in the United States if developed to its full potential. In particular, geothermal steam and hot water could provide a significant part of the Nation's electrical energy needs within the next few decades, especially in the western states, Hawaii, and Alaska. Estimates by knowledgeable experts of the impact of geothermal resources on the Nation's energy needs differ, but it appears that at least 19,000 Mw of generating capacity could be installed by 1985 using technology presently available or underdevelopment, and that more than 75,000 Mw could probably be installed by the year 2000 granted a successful expanded Federal research and development program. A much greater potential exists in the large submarginal resources of hot fluids and rocks that occur beneath the surface of the United States, but their commercial development must await technological breakthroughs. Geothermal resources also have a

significant potential for direct use in industrial processes, space heating, agriculture, refrigeration, the production of fresh water by desalination, and the production of mineral byproducts.

Recommendations:

An expanded 5-year Federal program is needed to assess the magnitude, type, and location of the Nation's geothermal resources and to spur the development of improved technology for discovering, evaluating, and utilizing the resource. Funding needed for the first year of the program, including existing funding, is estimated to be \$25,000,000. Of this total, approximately one third would be directed toward research and development directly applicable not only to geothermal energy but also to other energy sources, particularly the development of better techniques for drilling, borehole logging, power generation, desalting, scale removal, air pollution, and noise reduction. In comparison, funds for research and development in fiscal year 1973, in identified geothermal programs of Federal agencies as requested in the President's budget, total about \$6,385,000. An additional \$475,000 has been requested for the management of the geothermal resources of the public lands. Possible supplementary funding for geothermal programs of the Atomic Energy Commission and other agencies may raise the total funds for Federal geothermal programs in FY 73 to the level of \$10,000,000.

Recommended funding levels for a proposed 5-year program are listed below:

Proposed 5-year Geothermal Research and Development Program

	<u>FY-74</u>	<u>FY-75</u>	<u>FY-76</u>	<u>FY-77</u>	<u>FY-78</u>	<u>Total</u>
Resource Appraisal	\$ 6 M	\$ 9 M	\$15 M	\$10 M	\$ 6 M	\$ 46 M
Exploration Methods	5 M	9 M	9 M	5 M	3 M	31 M
Reservoir Development and Production	5 M	9 M	13 M	22 M	17 M	66 M
Utilization Technology and Economics	6 M	8 M	9 M	11 M	16 M	50 M
Environmental Effects	1.5 M	3 M	1.5 M	1 M	1 M	8 M
Institutional and Legal Aspects	1.5 M	2 M	1.5 M	1.5 M	1.5 M	8 M
	<u>\$25 M</u>	<u>\$40 M</u>	<u>\$49 M</u>	<u>\$50.5 M</u>	<u>\$44.5 M</u>	<u>\$209 M</u>

The proposed 5-year program should result in a number of significant accomplishments, including the following: (1) better knowledge of the nature, magnitude, quality, and location of geothermal resources; (2) better exploration techniques including cheaper drilling technology; (3) reduced costs and time for developing geothermal fields; (4) longer life for fields through recharge methods; (5) determination of the feasibility of stimulating geothermal reservoirs and of recovering thermal energy from hot, relatively dry rocks; (6) improved power-generation technology for use of intermediate- and low-temperature geothermal waters and concentrated brines; (7) technology for desalting geothermal brines; (8) determination of the feasibility of recovering chemicals from geothermal fluids; (9) monitoring of environmental effects of all geothermal developments; (10) improved techniques for removing H_2S from geothermal steam and for reducing noise from drilling; (11) preparation of a model code for geothermal development; (12) better liaison and distribution of geothermal information between Federal, State, and local agencies, the academic community, and the geothermal industry; and (13) establishment of several national geothermal field research laboratories. During the 5-year program, the design, construction, and operation of several pilot plants will have demonstrated the technologies for power conversion and brine desalting so that design and construction of large scale demonstration plants can proceed.

Research and development needs are listed in the sections below not by priority but rather by broad topical areas following the organization of the Geothermal Resources Research Conference. Funding levels for the different

topical areas are recommended only for the first year of the program. As the program develops, funding levels should shift to reflect research and development needs. From the beginning the program should include both activities with short range goals and others with longer range goals. However, several elements of the program need to be pursued at an adequate level early in the program in order to better define the magnitude of the resource and spur its development. These high priority elements include (1) development of improved exploration methods, (2) development of better power-generating technology including binary-fluid systems, (3) development of improved drilling techniques and the drilling of many shallow and deep bore holes, (4) development of better models of geothermal reservoirs by computer simulation, (5) development of improved economic models of geothermal utilization from different types of reservoirs using different power generation techniques, and (6) development of desalination methods for geothermal fluids.

Resources Appraisal:

Better estimates of the magnitude, quality, and distribution of the geothermal resources of the United States are needed to develop a Federal strategy for meeting future energy needs and for the management of the geothermal resources of the public lands. An expanded Federal program of regional reconnaissance, heat flow measurements, and research drilling to depths as great as 3 km is recommended for the definition of the geothermal provinces of the United States, the assessment of their potential, and the identification and evaluation of promising areas. Drilling funded under this

program is essential to its success as well as to the success of the programs on Exploration Methods and Reservoir Development and Production. Funding needed for the first year is estimated to be \$6,000,000. A program of very deep drilling (to 6 km), although not recommended at this time is essential to determining the thermal potential of the deep crust beneath the United States.

Exploration Methods:

Development of geothermal resources is handicapped by insufficient understanding of geothermal reservoirs and relatively primitive exploration techniques. An expanded Federal program is needed (1) to develop better geophysical and other methods of exploration, (2) to develop faster, cheaper drilling techniques for drilling both deep and shallow holes by improvement of existing techniques and development of new methods, and (3) to develop improved techniques for logging wells and sampling fluids from them at the high temperatures involved. Funding needed for the first year is estimated to be \$5,000,000.

Reservoir Development and Production:

An expanded Federal program is needed to reduce the time and costs of developing geothermal fields, to solve problems in producing and reinjecting geothermal fluids, to extend the life of fields, and to enlarge the resource by tapping the heat stored in hot, dry rocks. The program would include the following elements: (1) modeling geothermal reservoirs by computer simulation; (2) investigation of recharge methods; (3) research on the geochemistry of geothermal fluids; (4) development of techniques for detecting and removing scale and preventing its formation; (5) investigation of artificial stimulation

of geothermal reservoirs by hydraulic fracturing, thermal stress fracturing, and fracturing by explosives; and (6) study of the feasibility and economics of recovering heat from hot, relatively dry rock masses by fracturing and introduction of water. Funding needed for the first year is estimated to be \$5,000,000.

Utilization Technology and Economics:

Improvements in utilization technology of geothermal fluids could greatly expand the recoverable resource, particularly (1) power generation techniques using geothermal waters of intermediate temperatures ($< 180^{\circ}\text{C}$, 356°F) or with abundant dissolved salts, and (2) multiple use of the resource. An expanded Federal program is needed (1) to conduct research and demonstration programs on techniques of electrical power production using a variety of power cycles including binary-fluid conversion systems; (2) to develop and demonstrate the technology for desalting geothermal brines, and (3) to conduct research and development on the recovery of minerals and gases from geothermal fluids. All these elements, as well as the development of better drilling and borehole logging technology, will require development of improved heat and corrosion resistant materials, and should be accompanied by economic analysis of geothermal utilization of different types of fields using different technology. Funding needed for the first year is estimated to be \$6,000,000.

Environmental Effects:

An expanded Federal program is needed to assure that geothermal development is accomplished in an environmentally sound manner. The program should include monitoring of environmental effects of geothermal developments, including

where relevant, quality of surface water and ground water, land subsidence, and seismic activity. Research and development under the program would be focused on improving techniques for removing H₂S and other toxic gases from geothermal steam and for reducing the noise from drilling, well cleanout, and well bleeding. Funding needed for the first year is estimated to be \$1,500,000.

Institutional and Legal Aspects:

An expanded Federal program is needed: (1) to manage the geothermal resources of the public lands; (2) to investigate several legal aspects of geothermal developments, including the preparation of a model code, (3) to establish and maintain better liaison between Federal, State, and local agencies, the academic community, and the geothermal industry, (4) to aid local agencies in the preparation of plans for the orderly development of local geothermal resources, (5) to establish a central Federal facility for gathering and distributing information on geothermal resources, and (6) to evaluate the need for geothermal field research laboratories. Funding needed for FY 1974 is estimated to be \$1,500,000, of which \$1,000,000 would be directed toward management of the public lands.

CHAPTER 2

NATURE OF GEOTHERMAL ENERGY

Geothermal energy is, in the broadest sense, the natural heat of the earth. Measurements in wells and mines demonstrate that temperatures overall increase with depth, and generally accepted views about the composition of the earth indicate that temperatures continue to rise to 200°C to 1000°C (392°F to 1832°F) at the base of the continental crust (a depth of 25 to 50 km) and to perhaps 3500°C to 4500°C (6332°F to 8132°F) at the center of the earth. Most of the heat stored in the earth is at too great a depth or too diffuse to be considered as a potential resource with technology of the near future. However, economically significant concentrations of geothermal energy are present in several different types of occurrences. Elevated temperatures (40°C to 380°C, 104°F to 716°F) are found in local "hot spots" in permeable rocks at shallow depths (less than 3 km). The thermal energy is stored both in solid rock and in water and steam filling pores and fractures, and the water and steam serve to transfer the heat from the rock to a well and thence to the ground surface. Almost all the presently utilized geothermal systems are of this type. Geothermal reservoirs that contain too little mobile fluid because of impermeable reservoir rocks are not economic reservoirs at the present time, even though they may be of sufficiently high temperature. If suitable technology is developed to tap these reservoirs, they may in the future constitute a very large resource. Another type of geothermal resource is the heat contained in hot interstitial waters in sedimentary basins such as the Gulf Coast geosyncline (Jones, 1970). The magnitude of the heat stored in sedimentary basins in the United States is large, but as yet the resource remains untapped.

Local Geothermal Reservoirs:

Local geothermal reservoirs occur in the upflowing parts of major water convection systems. Water serves as the medium by which heat is transferred from a deep source, presumably a molten igneous intrusion, to a geothermal reservoir at depths shallow enough to be tapped by drill holes. Water percolating underground from an area of tens to thousands of square kilometers is heated by contact with hot rock at depths of 2 to 6 km, expands upon heating, and moves buoyantly upward in a thin column of relatively restricted cross-sectional area (1-50 km²) (White, 1968; Muffler and White, 1972). If the rocks have a high permeability, the heated water rises rapidly to the surface and is dissipated. If, however, the upward movement is impeded by overlying rocks of low permeability, the geothermal energy may be stored in a reservoir beneath the cap.

The fluid in most geothermal systems is water, which may be at temperatures above surface boiling but in a liquid state because of the confining pressure. The water in most of these "hot-water" or "wet-steam" geothermal systems is a dilute solution containing mostly sodium, potassium, chloride, bicarbonate, sulfate, borate, and silica. The silica content and the ratio of potassium to sodium and calcium are dependent on the temperature in the geothermal reservoir, thus the prediction of subsurface temperature from chemical analysis of hot springs is possible (Fournier and Rowe, 1966; Ellis, 1970). Decrease in pressure upon withdrawal of the water to the surface through a well or natural fracture causes steam to be formed by boiling and a mixture of steam and water is produced at the surface. With present technology only the steam can be used to generate electricity.

The major known hot-water geothermal fields are Wairakei and Broadlands in New Zealand, Cerro Prieto in Mexico, the Salton Sea field in California, and the Yellowstone geyser basins in Wyoming.

A small proportion of the known local geothermal systems produces superheated steam with minor amounts of other gases (CO_2 , H_2S , NH_3), but little or no water. Thus all the fluid from these "vapor-dominated" or "dry-steam" geothermal systems can be piped directly to the turbine. Within the vapor-dominated reservoir, saturated steam and water co-exist, but with decrease in pressure upon production, heat contained in the rocks dries the fluid first to saturated steam and then to steam with as much as 55°C superheat. Hot brines probably exist below vapor-dominated reservoirs (James, 1968), but bore holes have not been drilled deep enough to confirm their presence. Larderello, Italy; The Geysers, California; and Matsukawa, Japan, are the major known vapor-dominated systems.

Local geothermal reservoirs are found in regions of the world where the flow of heat from depth in the earth is $1\frac{1}{2}$ to 5 times greater than the world-wide average of 1.5×10^{-6} calories per square cm per second. Such regions of high heat flow commonly are zones of young volcanism, igneous intrusion, and mountain building, and most are located along the margins of the major crustal plates of the earth. Geothermal fields are absent from the stable continental shields, which are characterized by lower-than-average heat flow. Local geothermal reservoirs have not been found at shallow depth in the non-volcanic continental areas bordering the shields, but hot water has been found to occur as interstitial fluids in sedimentary

basins at greater depth (3 to 6 km). In the United States the distribution, extent, and magnitude of geothermal reservoirs are, at present, poorly known. The general extent of the resource can be inferred from distribution of hot springs (fig. 1; from Waring, 1965), and in a more general way from the distribution of young volcanic rocks and areas of high heat flow. The potential within the United States involves primarily the western states, particularly California, Nevada, Oregon, southern Idaho, Utah, New Mexico, Wyoming, Arizona, Colorado, Hawaii and Alaska. In the past, geothermal exploration has been primarily on sites identified by hot springs, an exploration method analogous to the primitive oil exploration methods of the previous century when oil fields could be located only by finding surface oil seeps. Available geologic and geochemical techniques have not been used adequately in discovering and evaluating new fields, and geophysical principles and techniques are only now beginning to be adapted to geothermal exploration.

Knowledge of the character and parameters of individual geothermal systems has come from exploratory drilling, from limited developmental drilling (mainly at The Geysers of northern California and at the Salton Sea in southern California), and from limited studies of major thermal-spring areas, supplemented by shallow research drilling. Extrapolation of knowledge from other countries, mainly New Zealand, has proved useful, but techniques for estimating the size and power potential of geothermal sites prior to drilling are only beginning to be developed.

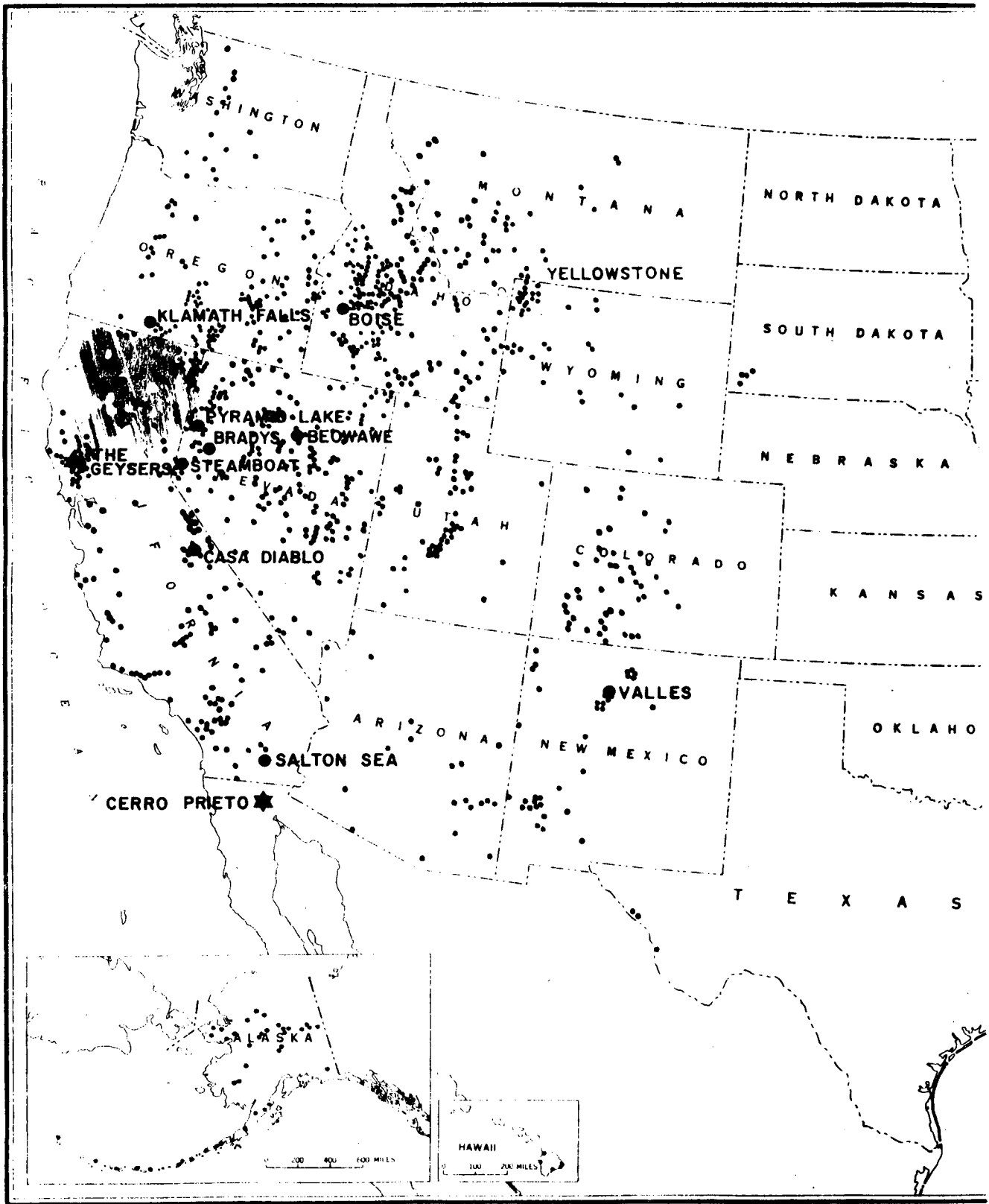


Figure 1. Hot Springs (small dots), known geothermal areas (large dots), and producing geothermal fields (star), in the western United States (from Waring, 1965).

Sedimentary Basins:

Hot interstitial waters in deep sedimentary basins of normal or slightly greater than normal geothermal gradients represent a large geothermal potential. In Hungary 15×10^8 Btu/hour of thermal energy in hot water is being produced from 80 wells and used mainly for space heating (Boldiszar, 1970). In the Gulf Coast area, hot over-pressured water is present at depth beneath large areas (Jones, 1970). Many thousands of wells there now produce fluid hydrocarbons and water at temperatures far above the boiling point of water at atmospheric pressure. Many test wells have produced water-steam mixtures, some yielding more than a million barrels of brine hot enough to be self distilling. Lower-temperature interstitial waters at shallower depths in sedimentary basins contain an even larger amount of heat (Grossling, 1972), but are far less attractive economically.

Dry Geothermal Reservoirs:

Under present technology, a rock mass with too few pores or fractures, or with pores that are not interconnected, does not comprise an economic reservoir, however hot it may be. The abundance of hot but relatively dry geothermal reservoirs is not known but may be very large. If the technology could be developed to economically recover thermal energy from such reservoirs by artificial formation of fractures and by the introduction of fluids if necessary, the magnitude of geothermal resources could be greatly increased. Furthermore, if drilling technology is also improved significantly, the technology for tapping the thermal energy of dry but hot geothermal reservoirs could conceivably be applied in areas of normal heat flow, thus introducing the possibility of tapping the enormous geothermal resource base of the earth's crust.

CHAPTER 3

CURRENT UTILIZATION

The primary use of geothermal resources to date is for the generation of electricity. For this purpose, under existing technology, the geothermal reservoir must have a temperature of at least 180°C (356°F), and preferably 200°C (392°F), and lie at shallow enough depths (3 km or less) to be developed economically. In "dry-steam" fields, the steam is fed directly from well-head to turbine after removal of abrasive particles. In "wet-steam" fields, on the other hand, boiling of hot water at depth yields a mixture of steam and water at the surface. Water at 250°C (482°F) will produce only about 20 weight percent steam when the confining pressure is reduced to 6 Kg per square cm, the approximate well-head pressure in geothermal installations. The steam and water are mechanically separated at the well-head and the steam fed to a turbine. In both types of fields the steam is at a much lower pressure compared to that used in fossil fuel or nuclear-powered generating plants, so that specially designed turbines are used in geothermal plants to drive the conventional generators. World electrical capacity from geothermal energy in 1971 was approximately 800 megawatts (table 1), or about 0.08 percent of the total world electrical capacity from

Table 1 near here

all generating modes. The production of geothermal power is obviously restricted to areas where geothermal energy is found in sufficient quantity. Unlike coal, oil, gas, or uranium, geothermal steam cannot be transported long distances to an electric power generating plant located near the existing load centers.

Table 1

World Geothermal Power Capacity 1972

<u>Country</u>	<u>Field</u>	<u>Electrical Capacity, MW</u>	
		<u>Operating</u>	<u>Under Construction</u>
Italy	Larderello	358.6	
	Mt. Amiata	25.5	
U.S A.	The Geysers	192	220
New Zealand	Wairakei	160	
	Kawerau	10	
Japan	Matsukawa	20	
	Otake	13	
Mexico	Pathe	3.5	
	Cerro Prieto		75
U.S.S.R	Pauzhetka	5	
	Paratunka*	0.7	
Iceland	Namafjall	2.5	
		<hr/>	<hr/>
		790.8	295
			Total = 1085.8

* Freon plant

Power from favorable geothermal systems is competitive in cost with either fossil-fuel or nuclear power. The current unit cost of developing geothermal production from dry-steam fields in the United States based on experience at The Geysers and using a load factor of 85 percent (U.S. Energy Outlook, 1972), is about 0.525¢ per kwh. This cost can be broken down into 2.66 mills for the steam delivered to the plant, 0.45 mills for operating costs, and 2.14 mills for capital costs. Such costs are cheaper than power from fossil-fuel steam plants and current nuclear plants. The cost of generating power from the more abundant hot-water reservoirs should be somewhat greater because of the more complex equipment involved, and higher reinjection costs if brine reinjection is required.

With present technology, geothermal steam is separated from entrained water at the well head and only the steam is used to generate electricity. Some of the thermal energy of the hot water can be utilized by multiple flashing of steam from the water at successively lower pressures. Attention is being directed currently both by private industry in this country and by the U.S.S.R. government towards developing other generating systems that would utilize some of the thermal energy stored in the hot water. In these systems, the hot water is piped under pressure to a heat exchanger where the heat^{is} transferred to a low boiling point fluid, such as isobutane or freon, which in turn is fed into the turbine. The spent water, still under pressure, is then reinjected. Successful development of other generating methods including this binary-fluid generating technology would allow more complete extraction of heat from geothermal fluids and allow use of hot-water reservoirs of lower temperature than presently required, greatly expanding our usable geothermal resources.

Geothermal resources have other uses, but to date they have been minor. Geothermal waters as low as 40°C (104°F) are used locally for space heating and horticulture. Much of Reykjavik, the capital of Iceland, is heated by geothermal water, as are parts of Rotorua (New Zealand), Boise (Idaho), Klamath Falls (Oregon), and various towns in Hungary and the U.S S R. Geothermal steam is also used in paper manufacturing at Kawerau, New Zealand, and has potential use for refrigeration and air conditioning. Some geothermal waters contain potentially valuable by-products such as potassium, lithium, calcium, and other chemicals. Use of geothermal energy to desalt geothermal water itself has been proposed, and the U.S. Bureau of Reclamation and Office of Saline Water are presently developing a pilot operation for producing fresh water from the geothermal waters of the Imperial Valley, southern California.

Generation of electricity from natural steam in the United States at the present time is limited to The Geysers, California, which has an installed capacity of 192 Mw, with an additional 220 Mw under construction. Geothermal resource utilization, however, is receiving increasing attention from private industry, public utilities, and county, state, and Federal agencies because of the likely future energy shortage (and increased prices for electrical power) throughout the United States and the consequent need to evaluate and develop new sources for electrical production other than fossil fuel, nuclear, and hydroelectric. Furthermore, passage of the Geothermal Steam Act of 1970 (P.L. 91-581) gave the Secretary of the Interior the authority to issue leases for the development and utilization of geothermal steam and

associated geothermal resources on Federal lands, where many of the most promising areas are located. Leasing of Federal land for geothermal exploration, however, has been delayed pending satisfaction of the requirements of section 102 (2)(c) of the National Environmental Policy Act of 1969, as interpreted in recent court decisions. The first leasing of Federal lands under the "grandfather clause" is anticipated for September 1972, with subsequent lease sales at approximately six-month intervals. Industry interest and activity in geothermal exploration and development has burgeoned in 1971 and 1972. An active development drilling program at The Geysers has added materially to the reserves. Deep exploratory drilling has taken place in the Jemez Mountains, New Mexico, at Clear Lake, California, at Mono Lake, California, and in the Imperial Valley, California. The great interest in geothermal exploration is illustrated by the attendance of 650 people at a meeting of the Geothermal Resources Council in El Centro, February 16-17, 1972. The interest in geothermal developments is not limited to vapor-dominated reservoirs, such as The Geysers, but is directed in part towards finding hot-water reservoirs.

CHAPTER 4

CURRENT RESEARCH AND DEVELOPMENT

International

Geothermal resources exploration and development programs have been conducted for many years by agencies of the Italian, Icelandic, and New Zealand governments. The first power generating station to use natural steam for electricity was established at Larderello, Italy, in 1904, and since that time the Italian government has expanded the development of the field and carried out exploration for other geothermal fields. Iceland started heating homes and industries in Reykjavik in 1930, and has for several decades carried out a program of exploration to evaluate the island's geothermal resources. The New Zealand government developed the Wairakei geothermal field for electric power generation after World War II, and has also carried out an exploration program for other geothermal resources, resulting in successful discovery of the Kawerau and Broadlands fields. Scientists, engineers, and technicians largely from these countries, the United States, and Japan have staffed a vigorous geothermal exploration and development program in underdeveloped countries by the United Nations. The UN has sponsored several international conferences that have spurred development of the field, a conference on "New Sources of Energy" at Rome in 1961, and in cooperation with the Italian government a "Symposium on the Development and Utilization of Geothermal Resources" at Pisa, Italy, in 1970. The UN has sent technical assistance missions to advise on the potential of geothermal resources to Argentina, Cameroon, Chile, China (Taiwan), Costa Rica, El Salvador, Ethiopia, Greece, Guatemala, India, Israel, Jordan, Kenya, Mali,

Mexico, Nicaragua, the Philippines, Tunisia, and Turkey, and to the Dominica and St. Lucia Islands (West Indies Associated States). Larger scale projects, which include geological, geophysical, and geochemical surveys as well as exploratory drilling, have been carried to the field development stage in Chile, El Salvador, and Turkey, and are currently in the exploration stage in Ethiopia and Kenya. As the result of these efforts, the decision has been made to construct a 30 Mw plant in El Salvadore (the engineering design is now in progress) and decisions are imminent regarding the construction of a small geothermal power facility at a field discovered in Turkey (Koenig, 1972). In the last decade Russia, Japan, and Mexico have carried out successful exploration and development programs for geothermal energy. An effort by the U.S.S.R. government that is of particular interest is the construction of a binary-fluid generating unit using intake water of 81°C (178°F) at Paratunka, Kamchatka. Other exploration and development programs have been carried out by the French government in Guadeloupe, the Republic of China in Taiwan, and the Philippine government, and surveys for geothermal resources have been conducted in Greece, Costa Rica, Israel, Rwanda, Canary Islands (Spain), Tanzania, Colombia, Uganda, and Morocco. In Nicaragua and Indonesia geothermal exploration has been conducted partly with loan funds from the U.S. Department of State Aid for International Development Program. Emphasis in all these programs has been on exploration and development, but they have also yielded, particularly in New Zealand, Iceland, and Italy, noteworthy advances in our understanding of the geothermal resources and how to develop and utilize them. Current research and development,

excluding field development and plant construction, by other countries and the United Nations engages several hundred scientists, engineers, and technicians at a cost of several tens of millions of dollars.

United States of America:

Research and development programs in geothermal resources have been carried out in the United States by several Federal agencies, state agencies in most of the western states, and private industry. The following descriptions of Federal agency programs were prepared from material supplied by the agencies. At the time of this writing (June 1972), fiscal year 1973 programs have been submitted to Congress by the agencies but funds have not yet been appropriated and allotted. Fiscal year 1974 programs for all agencies are still in the planning stage.

U.S. Geological Survey

Prior to 1971, the U.S. Geological Survey had no specially funded geothermal resources program, although modest investigations of hot springs and geothermal phenomena were carried out as part of the Geologic Division investigations of energy and mineral resources. Modern Geological Survey hot-spring studies were begun by Donald E. White in 1945 at Steamboat Springs; the initial emphasis was on mechanisms of ore transportation and deposition, but the results of a decade of study proved to have important application to the understanding of geothermal resources. Beginning in 1963, the focus of Geological Survey geothermal research shifted to the Salton Sea geothermal field, in particular, to cooperative studies with private industry focused on the geochemistry and petrology of the hydrothermal system. In 1966, the Geological Survey began a major investigation of all aspects of the geology of Yellowstone National Park, including intensive studies of the hot-spring areas. Studies included geologic mapping, geophysical surveys, sampling and analysis of hot springs, and the drilling of 13 research holes to depths as great as 1100 feet. Several other hot-spring systems in the western United States have been investigated by the Geological Survey, including Sulphur Bank on Clear Lake, California, and the Lake City area. A very useful source of information for geothermal exploration is the Geological Survey compilation of temperature and other data on thermal springs (Waring, 1965). In addition, other studies by the Geological Survey have proved important to geothermal resources, including heat-flow studies, determination of silica solubility, development of the silica, Na/K, and Na-K-Ca geothermometers, and experimental studies of rock alteration.

In August of 1971 the 92nd Congress appropriated an increase of \$500,000 to the Geological Survey for an expanded geothermal program. As a result (1) the staff for classifying Federal lands for geothermal resources was increased and preparations were made for lease management; (2) projects were started at The Geysers/Clear Lake and Long Valley, California, using detailed geologic, geophysical, geochemical, and hydrologic techniques; (3) reconnaissance geologic, geochemical, and hydrologic surveys were started in northwestern Nevada and southeastern Oregon; (4) a program was started for developing and testing new geophysical techniques (electrical, electromagnetic, passive seismic, and thermal infrared); and (5) laboratory studies were started on hydrologic modeling, solution chemistry, and geochemical indicators of reservoir temperatures.

A \$1,800,000 increase in the Geological Survey geothermal program has been proposed to Congress for FY 1973 to support an augmented program including a number of new research projects, supervision of operations on geothermal leases, and the classification of additional geothermal resource areas. New hydrologic studies will be undertaken on the Island of Hawaii and in the Jemez Mountains, New Mexico. Geophysical studies of these and other areas will be broadened to include microseismic and telluric methods as well as heat flow at shallow to moderate depths. The physics, temperatures, and hydrology of several geothermal areas will be modeled using computer technology. Subsurface temperatures and hydrologic parameters

in the Gulf Coast area will be studied. Reconnaissance surveys will be started in Alaska and expanded in the western states, and chemical analyses of water and rock samples will be supplemented with isotopic analyses. Environmental effects of geothermal developments--such as ground subsidence and earthquake activity--will be monitored with initial emphasis on the Imperial Valley, California.

The Geological Survey has planned an expanded 5-year program starting in FY 1974 to be carried out if funds are made available. The program would include (1) classification and lease supervision, (2) environmental monitoring and evaluation, (3) pre-lease evaluation of geothermal areas and development of better exploration techniques through detailed field studies including research drilling, (4) regional reconnaissance studies, and (5) brine disposal studies.

Bureau of Reclamation

The Colorado River Basin Act (Public Law 90-537) requires the Secretary of the Interior to make reconnaissance studies for the purpose of developing a general plan to meet future water needs of the Western United States and to determine the most economical method of augmenting the flow of the Colorado River by 2,500,000 acre-feet per year. This work has been delegated to the Bureau of Reclamation. A promising source to meet both of the above requirements is the geothermal resources in the Imperial Valley of California, by desalting the hot geothermal brines underlying the Reclamation withdrawn lands. Reclamation and the University of California, Riverside, began a joint exploratory program to evaluate the geothermal potential of these lands in 1968.

The Bureau of Reclamation and the Office of Saline Water have recently undertaken a joint 7-year research and development program with an estimated cost of \$16 million (\$9.7 million for the Bureau of Reclamation) to determine the feasibility of multi-purpose development of electric power and desalted water from the geothermal resources of Imperial Valley. This program was begun in FY 1972 with an appropriation of \$800,000. An increase of \$400,000 in the Reclamation geothermal program has been proposed to Congress for FY 1973 to accelerate the program, which is designed to determine the quantity and quality of hot geothermal brines underlying Reclamation withdrawn lands, to develop the technology for total development of the geothermal resources, to demonstrate the feasibility of developing large quantities of desalted water, and to determine on the best plan for delivery of desalted water to the Colorado River. This effort is and will continue to be coordinated with other

investigations aimed at determining the potential of the resource for power generation and recovery of chemicals and gases.

An additional \$5.7 million effort is needed by the Bureau to explore in areas of critical water shortages, other promising geothermal areas having a potential for producing low-cost water supplies in the western States. This exploration is necessary to assure that all potential alternatives for water supplies have been evaluated. In the early stages, this program would concentrate on the exploration and the evaluation of the resource for water production rather than on research and development similar to that presently being carried out in the Imperial Valley. To meet the requirements of Public Law 90-537, this evaluation must be completed no later than 1977.

The components of the Bureau of Reclamation geothermal program are listed below:

1. Exploration-- The exploration program is designed to secure a reasonable appraisal of the quantity and quality of geothermal resources on Reclamation withdrawn lands in the Imperial Valley in the shortest practical time. Methods employed will be geologic and geophysical investigations combined with relatively shallow (1,500 feet or less) temperature gradient drill holes and a limited number of production wells to production depths of 5,000 to 7,000 feet. Verification of water quality will be necessary to assure that desalting and electric power generation techniques will be applicable to the entire production area.

A reasonably reliable estimate of the quantity of the geothermal resources on Federal lands in the Imperial Valley (almost all of which are Reclamation withdrawn lands) will be needed at an early date for a decision on the source of replacement water to prevent subsidence due to fluid withdrawal. If the resource proves to be large, the most economical source is the ocean. If the resource is moderate or small, local replacement water from such sources as near surface ground water, the Salton Sea, and the Wellton-Mohawk Drain would be used. If the total quantity of the resource in the Imperial Valley is of sufficient size to permit large-scale importation of replacement water from the ocean, then the entire resource could be developed as a joint venture by Federal and non-Federal interests to develop water and power at the lowest cost.

2. Production and injection wells.--Sufficient production wells must be drilled in the research and development stage to verify the results of the exploration program. The production wells must also be operated in conjunction with injection wells for a sufficient period of time to determine the best well spacing and well diameter. Environmental effects such as seismic activity, subsidence, and air pollution will be monitored in conjunction with the operation.

3. Research and development.--Research and development activities will be required in various fields in order to support the desalting efforts. The best size and spacing of both production and injection wells will be analyzed. Injection techniques including disposal of byproducts will be studied. The

integration of electric power production and desalting will be studied with the goal of optimizing benefits from both these products and possible mineral byproduct recovery. Subsidence, seismic activity, and other environmental impacts that could result from geothermal resource development will be investigated and procedures developed to modify or eliminate adverse effects. The answer to these problems should be applicable in whole or in part to the nationwide development of geothermal resources.

4. Appraisal.--The results of the research and development program must be carefully analyzed and appraised to provide answers to environmental problems and the character and magnitude of the resource and the economics of desalting appraised to assure that the total potential is realized in the national interest.

Office of Saline Water

The Office of Saline Water started a \$6,300,000 7-year geothermal program in FY 1972 aimed at developing the technology necessary to the desalting of geothermal brines. The program objective is to develop economical and technically feasible processes for the production of high quality water. In addition, the desalting processes must be made compatible with other processes based on the geothermal resource, such as power production and mineral producing processes, to permit an optimal and comprehensive geothermal development. The studies are centered on the geothermal brines in the Imperial Valley, California, and are carried out in close collaboration with the Bureau of Reclamation. A large part of the technology developed there should be applicable to the desalting of other geothermal brines.

In FY 1973, the program will be carried out at a level of \$800,000, subject to congressional approval of appropriation, and will include research on brine chemistry, materials of construction, process analysis and testing, environmental effects of the desalting processes, and effluent disposal techniques. Efforts in brine chemistry will include research on the composition of geothermal brine and its reactions within the desalting plants and the effluent disposal system, determination of the extent of scaling of process equipment and research on means to reduce the effects of scaling to a minimum, and research on the chemical nature of the deep-well disposal system and related chemical reactions. Attention will be directed towards finding economical and reliable materials of construction for the potentially corrosive geothermal fluid--a hot, acidic brine containing sulfide and carbonic gases.

Process parameters, including heat-transfer coefficients and flashing characteristics, will be determined, as well as the effective design of equipment components. Methods will be developed to permit the inclusion of the desalting plant into an integrated power-water-mineral geothermal utilization system. The 7-year program will include the design and construction of a 200,000 to 500,000 gpd pilot desalting plant in FY 74 and a 2 to 3 million gpd prototype plant in FY 76.

Bureau of Mines

The Bureau of Mines has for many years carried out programs that relate generally to geothermal resources research needs, such as extraction, processing, use, reuse, and disposal of minerals and mineral fuels, but has not carried out an identified geothermal program until the present. In FY 1973, the Bureau will undertake a \$160,000 geothermal effort aimed at developing improved drilling muds and improved cements for use in drilling and casing geothermal wells at temperatures as high as 350°C (662°F). Starting in FY 1974, the Bureau of Mines proposes to begin a 5-year expanded program principally aimed toward the recovery of minerals and gases dissolved in geothermal fluids. Reject brines from a water desalting plant would constitute the feed material for mineral recovery processes; non-condensable gases probably would be delivered from a separate power plant. Research investigations would concentrate on the geothermal fluids of the Imperial Valley in addition to other promising geothermal resource areas. If research indicates the presence of mineral and gas constituents of sufficient economic value in the brines, a pilot plant for their recovery could be built in close proximity to a desalination plant in order to receive and process the plant effluents.

The Bureau of Mines geothermal program has the following six goals:

- (1) to develop a system for the evaluation of brines, determining constituents of potential economic value,
- (2) to develop methods for recovering constituents so determined,
- (3) to develop methods for separating non-commercial constituents and disposing of them,
- (4) to determine criteria

for selecting materials of engineering construction needed in the handling of hot commercial brines, (5) to find new metallurgical processing uses for residual brines, and (6) to improve drilling muds and cements so as to lower costs of tapping geothermal resources.

Bureau of Land Management

As manager of the Public Lands, the Bureau of Land Management is responsible for leasing of Federally-owned geothermal resources in compliance with the spirit and objectives of the Geothermal Steam Act of 1970, the National Environmental Policy Act of 1969, other legislation, and supporting Executive Orders and regulations. The Bureau's geothermal leasing program will be at a level of \$200,000 in FY 1973, subject to Congressional approval of appropriation, and the Bureau has proposed an expanded 5-year program beginning in FY 1974.

Initially, the Bureau's geothermal leasing program will be directed primarily at adjudicating conversion rights established by Sec. 4 of the Act, and to leasing of lands of known or potential value for geothermal resources. Competitive lease offerings will result for lands confirmed to be of value for geothermal resources. Other lands will be available for non-competitive leasing, which will proceed concurrently with the competitive leasing program. The expanded program would consist of the following components: (1) identification of potential geothermal leasing tracts based on Geological Survey, Bureau of Mines, and Bureau of Land Management data and evaluation; (2) development of a tentative leasing schedule; (3) consideration of environmental factors and land-use plans for each lease tract; (4) evaluation of resource, cost, and market data including the refinement of Geological Survey estimates of bonus bids for each leasing tract; (5) post-sale evaluation of tracts; (6) development and maintenance of professional competence; (7) development and maintenance of a computer system including all available resource and

land-use data on areas identified for geothermal leasing; and (8) conduct of a study program to update and refine leasing regulations and procedures, pre- and post-sale evaluation procedures, and environmental considerations.

National Science Foundation

The Research Applications Directorate of the National Science Foundation began a careful consideration of the need for geothermal energy research at the end of Fiscal Year 1971 but did not sponsor any projects until FY 1972. Four projects have been sponsored in FY 1972, and several others are under serious consideration. The sponsored projects are described below:

1. "Investigation of the Thermal Regime of the Rio Grande Rift System of New Mexico" by Marshall Reiter of the New Mexico Institute of Mining and Technology (\$24,900/24 months). A geophysical investigation of the thermal regime of the Rio Grande rift system of New Mexico is being conducted in order to help assess the rift's possible potential as a large scale source of geothermal power. The Rio Grande rift displays many geological and geophysical characteristics indicative of both the mid-oceanic ridges and presently producing geothermal sites. Heat flow data are being acquired over the extent of the rift in New Mexico and several profiles normal to the rift will be sought.
2. "Geothermal Resources Research Conference" by Walter J. Hickel of the University of Alaska (\$56,500/8 months). The objective of the conference on geothermal resources research is to develop an assessment of the state-of-the-art and to recommend a research program to provide the requisite knowledge for establishing the proper role of geothermal resources in providing (1) additional energy to alleviate the Nation's impending shortage, (2) water to supplement present supplies, (3) and mineral resources.
3. "Stimulation of Geothermal Aquifers" by Paul Kruger and Henry Ramey of Stanford University (\$141,500/12 months). The research has three major objectives: (1) development of experimental and numerical data to evaluate

the optimum performance of explosion-stimulated geothermal aquifers, (2) development of a geothermal steam reservoir model to evaluate the thermophysical, hydrodynamic, and chemical parameters involved, (3) development of a laboratory model of an explosion-produced chimney to obtain experimental data on the processes of in-place boiling, moving flash fronts, and two-phase flow in hot porous media, as well as chemical and radiochemical data for the fluids produced.

4. "Investigation of Hydrothermal Systems at Kilauea Volcano, Hawaii" by George Keller of the Colorado School of Mines (\$462,500/12 months). Kilauea volcano, Hawaii will be used as a geothermal field research laboratory to evaluate groundwater movement in the vicinity of a magma chamber. Kilauea volcano can provide a means for testing some of the physical concepts that have developed about the characteristics of hydrothermal systems. The project goal is to provide positive evidence about groundwater dynamics in a hydrothermal system and to provide a model for other geothermal systems so that efficient exploration approaches can be developed. The major part of the program will be the drilling of a test hole at a site selected to provide the best chance of intersecting a hydrothermal convection cell above the Kilauea magma-chamber, but the program would also include supplementary geophysical studies of the summit area of the volcano, physical tests in the drill hole, and measurements on recovered samples.

The NSF Research Applications Directorate estimates (Congress willing) in FY 1973 that it will provide approximately \$1,500,000 in the Energy

Conversion section of the Energy Research and Technology program and \$500,000 in the Energy Resources section. The Energy Conversion portion will concentrate on the science and technology of utilizing geothermal resources whereas the Energy Resources portion will emphasize evaluation, exploration, etc., for the resource.

Atomic Energy Commission

Until the present time, the Atomic Energy Commission has not had a formal geothermal resources program, but several investigations carried out under AEC's auspices during the last few years relate directly to research and development needs of geothermal energy. In 1970 and 1971 a detailed study was conducted by a team from Battelle Northwest, American Oil Shale Co., Westinghouse, Inc., AEC. and the Lawrence Livermore Laboratory of the technical and economic feasibility of extracting thermal energy from relatively dry geothermal reservoirs through the use of nuclear explosives to fracture the rocks and the subsequent injection of water to provide a carrier for the heat. At the Los Alamos Scientific Laboratory another project involves the development of a thermal drill using heat generated electrically. A prototype of the drill has been successfully tested in the laboratory and in the field. Preliminary studies have been conducted at the same laboratory of the feasibility of the use of hydraulic and thermal fracture techniques to expose large heat transfer surfaces in a hot but relatively dry geothermal reservoir in order to recover the energy for power generation. In addition, Battelle Northwest has conducted laboratory studies of silica and radio-nuclide leaching from rock melted by underground nuclear explosions.

In response to inquiries, the AEC stated before the Senate Appropriations Committee that if funds were made available a program of research and development contributing to the wide-scale use of geothermal resources and their conversion into economic electric power could begin at about a level of \$2,000,000 in FY 1973. Primary emphasis would be placed on initial examination of the feasibility of extracting energy from relatively dry geothermal reservoirs

through the injection and recovery of water in a high-pressure system. This effort would include study of the behavior of dry geothermal reservoirs as they are cooled and energy is extracted in order to determine the effect of a hydraulic fracture system and the possible expansion of this system by thermal-stress cracking to expose additional heat transfer surface. Laboratory and preliminary field preparation would be undertaken on the feasibility, methods, and economics of developing dry geothermal reservoirs by circulating cooling water through hot rock exposed by hydraulic fracturing techniques. The geothermal provinces of concern would be those where there is abundant hot rock (about 300°C or more) but where there is little or no mobile ground water because of the low permeability of the rocks. Assessment and evaluation would also be undertaken of methods to stimulate production of geothermal fluids from known geothermal provinces which do not produce steam or hot water of sufficient temperature, quantity, or purity as to be economically usable in power generation. It is believed that stimulation techniques similar to those that have been successful in the oil and gas industry may be of value in these areas. Studies would be undertaken of the mass transport of silica as well as the chemical, hydraulic and thermal characteristics of natural geothermal systems in order to develop methods for removal of impurities and to develop generating plant equipment compatible with geothermal fluids. These studies would provide information leading to the development of models for evaluation of the economic potential of geothermal systems and techniques for power generation as well as the cost-effectiveness of geothermal research and development programs.

Beginning with engineering analysis of existing technology, a program would be undertaken to develop efficient binary-fluid conversion systems for lower temperature or highly corrosive geothermal fluids in order to maximize the electrical generating capacity of the thermal energy and to enlarge the range of productive geothermal fluids.

Department of Defense

Advanced Research Projects Agency

The Advanced Research Projects Agency has started a study to investigate the potential applications of geothermal energy sources to specific military needs. It is possible that a number of power requirements for the Services can be satisfied with geothermal energy sources much smaller than those necessary for commercial power production. Possible military applications of geothermal energy of interest to the Department of Defense include (1) primary source of reliable power at remote locations, (2) an emergency or back-up power source in the event conventional power sources are disrupted, and (3) a self-contained, stand-by power source for hardened underground or underwater facilities capable of providing space heating and cooling, and usable water as well as electric power.

The ARPA effort is limited to the definition of Department of Defense needs, definition of the research and development required to apply geothermal energy technology to a variety of military requirements, and to a pilot study of a specific geothermal reservoir adjacent to an existing military facility to determine the research necessary to develop this type energy source for selected military needs.

National Aeronautics and Space Administration

The National Aeronautics and Space Administration has carried out for several years cooperative research with the U.S. Geological Survey in the remote sensing of thermal areas. In this program, data from Geological Survey field and laboratory studies and aerial photographs were augmented by infrared scanner data and high altitude aerial photographs provided by NASA. This cooperative program will continue into space through Geological Survey proposals selected by NASA for analysis of data from ERTS-A (July 1972 launch) and Skylab (April 1973 launch).

ERTS television and multispectral imagery will contribute indirectly to geothermal studies through analysis of snowmelt and vegetation anomalies. Addition of emitted infrared imagery with Skylab will permit direct observation of thermal anomalies, with anticipated ground resolution of approximately 80 M and 0.4°K temperature sensitivity. In addition to the above, NASA plans to keep abreast of research and development in geothermal resources in order to assist in basic technology wherever possible. In carrying out its responsibilities NASA has developed during the last decade capabilities in many disciplines, technologies, and techniques. The particular problems in the field of geothermal resources to which NASA may be able to make contributions in cooperation with user agencies include material development, heat conversion cycles, and silencers development, pipe flow and compressor design.

State Organizations

Natural resource agencies of many of the western States are carrying out geothermal studies. In California the Division of Mines and Geology as well as the Department of Water Resources and Division of Oil and Gas have conducted noteworthy geothermal programs for many years including appraisal of the State's resources and geologic investigations of the producing field at The Geysers and several promising areas in the State. The Oregon Department of Geology and Mineral Industries and the New Mexico Bureau of Mines and Mineral Resources have also conducted productive geothermal programs for many years, resulting in the cataloguing of hot spring data in both States and the geologic analysis of favorable areas. Useful geothermal resources programs are also being carried out by the Nevada Bureau of Mines and Geology, the Idaho Bureau of Mines and Geology, and natural resource agencies of Alaska, Arizona, Colorado, Montana, Utah, and Washington. Altogether, geothermal research and development studies by State agencies, most of which are aimed at resource appraisal, involve several dozen scientists and engineers at an annual funding level of perhaps half a million dollars.

Private Industry

Significant exploration and development programs for geothermal resources in the United States have been conducted by private industry only for the last two decades. The first plant in the United States to generate electricity from natural steam was put into production in 1960 by Pacific Gas and Electric Company, based on steam produced by Magma Power Company and Thermal Power Company. In the ensuing years these latter companies and Union Oil have carried out successful development of The Geysers field together with exploration of promising areas elsewhere in the western United States. A few other companies, largely petroleum companies, joined in these activities in the 60's, but interest on the part of private industry was not widespread until passage of the Geothermal Steam Act of 1970 opened the possibility of leasing Federal lands for geothermal development.

Private industry has supported geothermal research and development by industry staff, university consultants, and other companies in all the topic areas listed in this report. Because of the general lack of knowledge in the field, each exploration program is a research project. The development of The Geysers field has led to increased knowledge of the resource and the development of new techniques of reservoir development and production. The attempted development of the Salton Sea geothermal field required research and development on power generation and mineral recovery technology using concentrated geothermal brines. Industry has supported engineering design studies of binary-fluid power generating technology, and plans to construct a pilot plant of this nature if sufficient private capital is found.

Some of the knowledge resulting from industry research and development has been made available to other scientists and engineers in the field of geothermal resources through the exchanges at scientific meetings, formal publications, etc., but much remains confidential because of its competitive value. The total current effort in geothermal research and development by private industry in the United States is not known, but it very probably amounts to several tens of millions of dollars per year apart from costs of land purchase, production drilling, and plant construction.

Relevant Research Directed at Other Energy Resources

Some of the research and development needs in the field of geothermal resources are not unique to that field but are the subject of research and development projects under other programs. Noteworthy research and development projects in this regard include: (1) drilling technology (petroleum industry and Federal rapid-excavation programs), (2) well-logging and sampling techniques (petroleum industry), (3) brine-rock interactions (Federal fluid-waste-disposal programs), (4) brine chemistry and desalination technology (Federal desalination programs), (5) binary-fluid power generation (private utilities and Federal programs on bottom cycles), (6) removal of H_2S from steam (private utilities and Federal air pollution control programs), and (7) reduction of noise (private industry). The total funding for relevant research and development and the applicability of such R and D to the needs of geothermal resources is not known, but it should be thoroughly investigated before funding new geothermal programs.

CHAPTER 5
ENVIRONMENTAL EFFECTS

Considerable attention has been drawn to geothermal resources as an electrical generating mode that can have a relatively small adverse effect on the environment. Geothermal energy does not produce atmospheric particulate pollutants as do fossil fuel plants; nor does it require fuel to be mined or transported, handled, or consumed; in addition, there is no production of radioactive waste nor potential for nuclear disaster. Present geothermal generating plants do not require a supplementary source of cooling water, in contrast to other thermal generating plants. The power plant must be located close to the site of the geothermal source, and the environmental effects are therefore local in extent.

Geothermal power, however, is not without adverse impact on the environment. An analysis of the environmental effects of geothermal power was made in the Draft Environmental Impact Statement for the Geothermal Leasing Program issued by the Department of Interior in September 1971. In this analysis, the environmental effects to be expected during the exploration, test drilling, production testing, field development, power plant and power line construction, and full scale production phases are outlined. The environmental effects of vapor-dominated and hot water systems are significantly different and are treated in detail. The major possible problems are thermal effects, land despoilment, contamination of ground- and surface-waters, noxious gases, noise, land subsidence, and supply of cooling water for closed-system generating modes. The remote possibility of increasing seismic frequency or intensity by increases or decreases of fluid pressure

in a tectonically active environment is also a consideration for some fields. With proper management and technology, and at some cost, all adverse environmental effects could be held to acceptable levels.

Geothermal energy has the unfavorable aspect of greater water consumption and waste thermal discharge per unit of electricity than either nuclear or fossil fuel modes because of the lower turbine conversion efficiencies at the low geothermal steam pressures and temperatures. A geothermal field and power plant utilizes more land than would an equivalent nuclear or fossil power plant. Present reservoir development utilizes several wells spaced at about 20 acres each to supply a small central power plant. The field is laced with steam pipes radiating out from power plants connected together by high-voltage power lines. In the present state of technology the visual impact of areas of geothermal development is heavy, and such areas must be classified as industrialized regions. Land use conflicts may be expected frequently to arise on this account. Although the actual space requirement of the field is large compared to that of a fossil fuel or nuclear power plant, the total requirement is in reality smaller than many of these systems when mining of materials and waste disposal are considered. Multiple land use of the field for agricultural and other purposes is possible in many areas.

Vapor-dominated systems, such as The Geysers, yield relatively pure steam low in noxious content. The condensates (about 20% of the feed fluid) are reinjected into the reservoir. Non-condensable gases at The Geysers are less than 1% of the steam and consist predominantly of carbon dioxide with

less abundant ammonia, methane, hydrogen sulfide, nitrogen and hydrogen. Hydrogen sulfide is the most objectionable component because of its unpleasant odor, and there is at the present time no completely suitable technique for its removal from the steam. Although research is currently being conducted into methods of its removal at The Geysers and in other energy resource fields, additional research is needed to solve the problem.

Noise during well-cleanout and well-bleeding stages of geothermal development causes a problem in dry steam fields, and the noise during well drilling is a problem attendant to all geothermal fields (as well as to other energy resources). Better mufflers need to be developed to hold the noise to acceptable levels.

Hot-water systems generally yield large quantities of warm water that commonly is mineralized and presents a chemical pollution hazard to surface and ground waters. Most proposed geothermal developments in the United States, however, plan to dispose of the waste water by reinjection into the geothermal reservoir in which cases contamination of surface waters and useable ground water should not be a problem. In some cases, it may be practical to purify or treat the water for removal of these contaminants, but even so, residual brines will need to be disposed of by reinjection into the producing reservoir. The pilot project planned by the Office of Saline Water for the Imperial Valley will test the practicality of water desalinization treatment.

Another problem posed by removal of large volumes of water and heat from some reservoirs is that of land subsidence (Hunt, 1970). Subsidence may occur in the few geothermal reservoirs that are found in relatively

unconsolidated sedimentary rocks, such as those that fill intermountain basins in the western United States. In some areas such as the Imperial Valley of California, subsidence could cause major problems by the disruption of irrigation canals, pipelines, and so forth. During field development or the production stages in critical geothermal fields, subsidence should be monitored, and if it is greater than an acceptable amount, a program of reinjection should be initiated to control the subsidence.

At those hot-water geothermal fields where the geothermal fluid is extracted from the reservoir, utilized for power generation with a method such as the binary-fluid system, and reinjected back into the reservoir--all in a closed system under pressure--large supplies of cooling water for the power generation cycle will have to be provided from an external source, just as it has to be provided for conventional power generation plants. Supply of large quantities of such cooling water may present a problem in some areas such as the arid Basin and Range provinces of the western United States.

Finally, when large volumes of fluids are removed or injected in a tectonically active environment, there is the remote possibility that the resulting change in fluid pressure could increase the incidence of earthquakes by a mechanism similar to that demonstrated for the Rocky Mountain Arsenal Well (Healy and others, 1968). Provisions should be made to monitor seismicity of those geothermal fields that lie astride faults that could generate major earthquakes.

CHAPTER 6
ULTIMATE POTENTIAL

Estimates of the geothermal resources of the United States and the impact of the utilization of these resources on the Nation's energy needs differ by more than a thousand times. For example, calculations based on D. E. White's (1965) estimate indicate that 5,000 to 10,000 Mw could be generated and maintained for at least 50 years under present economic conditions and technology. Kilkenny (1972), in the course of a study by the "New Energy Forms Task Group" of the National Petroleum Council, estimates that generating capacity based on geothermal fluids in the United States, specifically in California and Nevada, will increase to between 7,000 and 19,000 Mw by 1985. R. W. Rex in testimony before the Senate Interior and Insular Affairs Committee on Fuels and Energy Policy (Congressional Record, June 15, 1972) stated that with a successful augmented Federal research and development program, a generating capacity of 400,000 Mw based on geothermal resources could be developed in the western United States within the next 20 years. The wide variation in resource estimates reflects a number of factors including different assumptions about technological developments and cost factors, preparation of different estimates for different reasons (for example, legal requirements versus program justification), and different uses of the terms "resources" and "reserves", but the major cause of the broad spread in estimates is a lack of factual knowledge of the resource itself.

Feasibility of Economic Recovery →

← Degree of Certainty

	Identified Reserves	Undiscovered Resources
Recoverable ^{1/}	10 ¹⁶ Btu	6-12x10 ¹⁶ Btu
Paramarginal ^{2/}		4x10 ¹⁸ Btu
Submarginal ^{2/}		> 4x10 ¹⁹ Btu

1/ figures shown are energy at the well head

2/ figures shown are energy in situ

Figure 2. Estimated reserves and resources of geothermal energy

Conservative estimates of geothermal reserves and resources are shown in the diagram of figure 2, which is based on the format of McKelvey (1972). Reserves and resources should be distinguished from the "resource base," which is defined by Schurr and Netschert (1960, p. 297) as all of a given material present in the earth's crust, whether its existence is known or unknown and regardless of cost considerations. For geothermal resources, the resource base is all of the heat in the earth's crust above mean surface temperature (about 15°C). White (1965) estimates the heat in the earth's crust to a depth of 10 Km to be about 10^{24} Btu, equivalent to 2000 times the world's coal reserves. Grossling (1972) estimates that the heat stored in the crust of the United States in cratonic and platform rocks to a depth of 10 Km and in interstitial water in sedimentary basins to be 2×10^{22} Btu. Only a small proportion of the geothermal resource base, however, can be considered a resource. Extraction of all the heat in the crust not only would be uneconomic but also might cause problems such as ground movement and earthquakes caused by the resulting thermal stresses. Exactly what proportion of the geothermal resource base can be considered a resource depends on a number of factors, such as depth of extraction; assumed temperature distribution to 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; and government policy with respect to research and development, leasing, environmental constraints, etc. Different assumptions as to technology, economics, and government policy have caused much of the large variation in published estimates of geothermal resources.

Table 2.-- Three recent sets of geothermal resource estimates.

Estimated Geothermal Reserves and Resources
(L.J. P. Muffler and D.E. White, in Theobald, 1972)

Identified resources	10^{16} Btu (at the well head)
Undiscovered recoverable and submarginal resources to a depth of 10 km	4×10^{19} Btu (<u>in situ</u>)

Forecast of Geothermal Power Generation Capacity in Megawatts
(J. E. Kilkenny, 1972)

<u>Cost per kwh (in mills)</u>	<u>1970</u>	<u>1975</u>	<u>1980</u>	<u>1985</u>
5.25	82	1500	4500	7000
5.75			4000	7000
6.25	<u>82</u>	<u>1500</u>	<u>2000</u>	<u>5000</u>
		1500	10500	19000

Estimated Geothermal Reserves
R. W. Rex (written comm. May 1972)

Megawatt centuries of electricity (in thousands)

<u>Fuel Price mils/kwh ^{1/}</u>	<u>Known Reserves ^{2/}</u>	<u>Probable Reserves ^{2/}</u>	<u>Undiscovered Reserves ^{2/}</u>
2.90 - 3.00	1 ^{3/}	5 ^{3/}	10
3.00 - 4.00	30 ^{4/}	400 ^{5/}	2,000 ^{6/}
4.00 - 5.00	?	600 ^{7/}	12,000 ^{8/}
5.00 - 8.00	?	?	> 20,000 ^{9/}
8.00 - 12.00	?	?	> 40,000 ^{10/}

Footnotes on following page:

1/ A fuel price of 2.90 mils/kwh is equivalent to a power cost (as shown in the estimate by Kilkenny) of 5.25 mil/kwh. Assumptions include the following:

Recovery of 50 percent in in situ thermal energy in the hot water reservoirs
Power conversion efficiencies of 20 percent for vapor-dominated reservoirs and 14 percent for hot-water reservoirs
Present costs and prices inflated by 5% per year for the next 30 years
22 percent depletion allowance for geothermal energy
Energy price in present dollars
Development by tax-paying entities
10 percent royalty to landowner (Federal or State governments, or private land holders)
No severance taxes
State taxes at a level no higher than the California Corporate rate
No increase in Federal corporate taxes
Cost of capital 8.5%
Expensing of intangible drilling expenses
No change in the depreciation rate for amortizing wells

2/ Note that the term reserves as used by Rex differs from the usage by Muffler and White and in the text of this report.

3/ Vapor-dominated reservoirs, primarily The Geysers area, California

4/ Deeper vapor-dominated reservoirs, primarily in the Clear Lake/Geysers area and high-temperature hot-water reservoirs in the Imperial Valley, California

5/ Deeper vapor-dominated reservoirs and high-temperature reservoirs in the above areas plus Jemez mountains, New Mexico, and Long Valley, California

6/ Deeper vapor-dominated reservoirs and high-temperature reservoirs in the above areas plus the remainder of The Basin and Range province, western United States

7/ Intermediate-temperature hot-water reservoirs and deep high-temperature hot-water reservoirs in the above areas plus Hawaii and the over pressured hot brines of the Gulf Coast

8/ Same as above plus hot-water reservoirs in Alaska

9/ Hot dry rock systems at less than 6 km depth over 5 percent of western U.S., development based on hydrofracturing or cost-equivalent technology; cost estimate based on present drilling technology and could be reduced by new low-cost drilling technology

10/ Hot dry rock systems as above between 6 km and 10 km depth

The identified recoverable geothermal resources of the United States (excluding National Parks) are estimated in figure 2 to be 10^{16} Btu, based on the estimate of Muffler and White (1972) of 6×10^{16} Btu in the ground, including measured, indicated, and inferred resources. This estimate includes the vapor-dominated reservoirs at The Geysers as well as several high-temperature hot-water reservoirs elsewhere in the western United States. As only about 15 percent of this is deliverable to the well head with current technology, the total reserves (at the well head) are thus 10^{16} Btu or enough steam to generate 1000 Mw for 50 years at the current generating efficiency of 14 percent. In comparison, R. W. Rex (Table 2) estimates that reserves in the vapor-dominated reservoirs at The Geysers alone would support 1000 Mw for 100 years.

Undiscovered recoverable geothermal resources (defined as those resources recoverable at cost competitive with alternative forms of energy) are estimated in figure 2 to be $6-12 \times 10^{16}$ Btu at well head, based on White's (1965) estimate of geothermal resources recoverable as electricity to a depth of 3 Km in the United States (assuming that 1 percent of the in situ heat is recovered as electricity). This resource would support 3000-6000 Mw generating capacity for 50 years. The estimate is for the generation of electricity using proven and conventional technology, thus the geothermal reservoirs included in the estimate must have temperatures of at least 180°C (356°F), because at lower temperatures the quantity of flash steam is inadequate, and would include vapor-dominated and high-temperature hot-water systems.

In comparison, Rex estimates (Table 2) that there are sufficient vapor-dominated reservoirs, primarily at The Geysers, to support 15,000 Mw generating capacity for 100 years. Kilkenny (Table 2) has not estimated resources explicitly, but his forecast of future geothermal power production implies at least minimum estimates of resources. He has, for example, estimated that there will be 7000 Mw installed capacity by 1985 with costs of 5.25 mills/Kwh (i.e., production based on vapor-dominated systems).

Paramarginal resources are estimated in figure 2 to be 4×10^{18} Btu in situ, sufficient to support 40,000 Mw generating capacity for at least 50 years. These resources would consist largely of high-temperature ($>180^{\circ}\text{C}$, 356°F) hot-water systems that might be developed economically at the present time or in the near future. Critical economic factors will be the cost of reinjecting waste fluids and the successful development of binary-fluid or other efficient generating systems and multipurpose (i.e., power-water-chemicals) utilization technology. Much attention is presently being given to the generation of electricity from geothermal waters, using a system whereby the geothermal heat is used in a heat exchanger to boil a secondary fluid such as isobutane or freon, which drives the turbine. A generating unit based on the heat-exchange principle and using intake water at 81°C (178°F) is reported to be in pilot operation at Paratunka, Kamchatka, U.S.S.R. (Facca, 1970). Industry interest in this generating mode in the United States is high, and engineering design for a pilot plant using isobutane has been completed, although construction of the pilot plant has not been undertaken. Multipurpose developments yielding power, desalted water, and/or recovered chemicals improve the economics of power generation by sharing

a significant part of the costs against other products. Several projects of this type are currently in the development stage, including the El Tatio field, Chile, under UN sponsorship, and the Imperial Valley, California, by the Bureau of Reclamation and the Office of Saline Water. Kilkenny (Table 2) estimates that successful application of these technologies at somewhat higher costs (5.75 - 6.25 mills/kwh) will result in the installation of an additional 6000 Mw generating capacity by 1980 and 12,000 Mw by 1985. Rex (Table 2) includes in known reserves high-temperature hot-water reservoirs of this quality largely in the Imperial Valley, as well as deeper vapor-dominated reservoirs at The Geysers, which are sufficient to support a generating capacity of 30,000 Mw for 100 years. He estimates that additional resources of this type in the western conterminous United States are sufficient to support 2,400,000 Mw generating capacity.

Recoverable geothermal resources could be still further expanded by technological breakthroughs that would permit the economic development of resources that are clearly not economic at the present time. These submarginal resources are estimated to be more than 4×10^{19} Btu by Muffler and White (Table 2) and sufficient to support more than 400,000 Mw generating capacity for 50 years. Such possible developments include the (1) successful application of power generating technology to geothermal reservoirs of intermediate and low temperatures, that is, cooler than 180°C (356°F); (2) development of better methods for recharge of fluids in geothermal reservoirs, thus permitting fuller and longer utilization of the heat stored in both rocks and fluids of the reservoir; (3) development of techniques of artificial stimulation to

increase the productivity of geothermal reservoirs, and in combination with the introduction of fluids, to tap the heat stored in hot dry rocks; (4) improvements in existing drilling techniques as well as the development of new drilling techniques that would allow economical drilling to greater depths; (5) new technology that would favor wider utilization of low-temperature geothermal resources for space heating, product processing, agriculture, etc. As these techniques are successfully developed, the recoverable geothermal resource will expand within the limit set by the U.S. geothermal resource base. R. W. Rex (Table 2) estimates that the resources present in intermediate-temperature hot-water reservoirs and in deep reservoirs of vapor-dominated and hot-water type in the western United States, the Gulf Coast area, Alaska, and Hawaii, could support 12,600,000 Mw for 100 years. In addition, he estimates that the successful development and application of technology for recovering the thermal energy from hot dry rocks could add resources sufficient to support more than 20,000,000 Mw generating capacity at depths of less than 6 Km and an additional 40,000,000 Mw at depths between 6 and 10 Km.

An estimate of the impact of geothermal resources on the Nation's energy needs over the next 30 years can be gained from the following estimates of the magnitude of installed power generation capacity based on geothermal resources:

	<u>Mw</u>
1972	192
1975	1,500
1980	10,500
1985	19,000
1990	35,000
2000	75,000

For the years 1975 through 1985 we have accepted the estimates of John E. Kilkenny (1972) because of his position as an official in one of the very few companies in the United States engaged in the exploration, development, and production of geothermal resources at a profit. The estimates are for power generating capacity at costs of 6.25 mills/kwh and less (at current prices), and are based on the assumption that technologies will be developed for the economic generation of power from hot water reservoirs as well as for the multipurpose utilization of some geothermal resources such as those of the Imperial Valley. A larger Federal research and development program than that assumed by Kilkenny could bring about an earlier application of the technology and result in greater installed capacity in 1985 than that shown. The estimated increase in power generating capacity beyond 1985 to 35,000 Mw in 1990 and 75,000 Mw in 2000 is based on the assumption that an expanded Federal research and development program will result in the identification of more geothermal reservoirs and the development of technologies for generating power from deeper and lower temperature geothermal fluids including the over-pressured geothermal brines of the Gulf Coast. The successful development and application of technologies for the economic recovery of thermal energy from reservoirs with insufficient fluids or permeability might result in an even greater increase in geothermal-based generating capacity.

CHAPTER 7

RESEARCH AND DEVELOPMENT NEEDS

Resources Appraisal

More precise estimates of the magnitude, quality, and distribution of geothermal resources in the United States are essential in developing a Federal strategy for meeting the future energy needs of the Nation. Current estimates by knowledgeable experts of potential geothermal power generation differ by several orders of magnitude, in part because of different assumptions about technology but also in part because of the lack of sufficient data on which to base the estimates. The delineation and evaluation of the different geothermal provinces of the United States, an essential first step in determining the geothermal resources of the Nation, would also provide useful information for planning by public utility districts, and the identification of specific promising areas and evaluation of the approximate magnitude and quality of their geothermal resources would provide useful background information for the ultimate recovery of the thermal fluids and production of power. For promising areas on Federal lands, the information gained under this program will be of considerable value to ^{the} Federal government in classifying and leasing public lands under the Geothermal Steam Act of 1970, as well as for supervising the resulting leases.

In order to determine the magnitude of the geothermal resources within the next few years, an augmented Federal program of regional studies, heat-flow measurements, and research drilling is needed. Part of this effort should be focused in selected regions of high geothermal potential which

could be delineated as National Geothermal Field Laboratories. Regional studies would include geologic mapping and synthesis, geochemical sampling and analysis, and geophysical studies including both ground and airborne methods. The program is closely related to the program of development of improved Exploration Methods. A greatly increased program of heat-flow measurements in moderate depth drill holes (200-300 m) across the country would provide data essential to delineating the major geothermal provinces and should also help in identifying specific favorable target areas. Drilling of deep (mostly >1000 m) drill holes is an essential element of this program, as well as the programs in Exploration Methods and in Reservoir Development and Production. The deep drilling is needed to determine in the third dimension the characteristics of geothermal reservoirs, such as temperature, pressure, rock composition, structure, and fluid composition. Drilling of shallow (<200 m) holes and measurements of temperature gradients will also be a necessary part of the program in detailed study of some areas.

A program of very deep drilling, to depths as great as 10 Km, is essential for evaluating the geothermal potential of the deep crust beneath the United States. Such a program would require \$10 million to \$20 million per year for the drilling of 1 to 2 boreholes per year. We recommend that this program be deferred until after the development of better, cheaper techniques for deep drilling and the demonstration that hot, relatively dry rocks at depth can be artificially fractured to form a viable geothermal reservoir.

The initial level of funding recommended for this program is \$6 million, of which \$2 million is for reconnaissance studies, \$2 million for heat-flow measurements and related drilling, and \$2 million for other drilling programs.

Exploration Methods

Development of geothermal resources and evaluation of their magnitude are handicapped by the relatively primitive nature of exploration techniques currently in use, by the absence of an adequate understanding of the factors that characterize geothermal systems, by the lack of inexpensive techniques for drilling, and by the need for better borehole logging and sampling techniques. Better methods are needed both to detect geothermal areas during regional reconnaissance and to determine the size and power potential of an area once it has been found. At the present time the most reliable technique for the discovery of new geothermal reservoirs is to search out areas of hot springs--a situation analogous to that in the petroleum industry in the early 1900's when petroleum exploration consisted of drilling surface oil seeps. A variety of geophysical, geochemical, and geologic methods are now being applied to the exploration for geothermal resources. Many of the successful exploration methods used in exploration for mineral and petroleum deposits are also applicable to geothermal exploration although in a different setting, and several new methods show promise. Research is needed on the different techniques and on the methodology of applying them to geothermal exploration. Furthermore, a better understanding of geothermal reservoirs, such as the three-dimensional variation in

temperature, the circulation of geothermal fluids, and the pattern of geochemical alteration of reservoir rocks and deposition of minerals, would lead to better techniques for discovering and developing geothermal fields. Drilling is a large component in exploration, development, and production of geothermal fields, because of the use of (1) shallow (200 meters) temperature-gradient holes in exploration, (2) holes of the same or somewhat greater depth for heat-flow measurements in defining geothermal provinces, (3) deeper drill holes for proving the existence of a geothermal reservoir and determining its extent, and (4) production wells for tapping the reservoir. Faster, safer, and less expensive drilling techniques for both shallow and deep holes and both slim exploration holes and greater-diameter production wells, would aid greatly in the discovery and development of geothermal fields and in the production of steam and hot water from them. Research and development is needed both to improve existing techniques and to develop wholly new techniques. Existing techniques for logging boreholes and sampling fluids from them are not completely satisfactory for geothermal exploration, in part, because of the high temperatures and corrosive fluids of geothermal reservoirs. Development of better techniques would have an immediate practical application in evaluating exploration holes and would also further the effort to gain a better understanding of geothermal reservoirs.

An expanded Federal program to develop better exploration methods is recommended, with initial funding at an annual level of approximately \$5 million. Of this amount, about \$1 million should be allotted to

development of better drilling techniques, \$1 million to better borehole logging techniques, and \$3 million to the development of other exploration methods. Among the latter, geophysical methods, particularly electrical prospecting techniques using both natural and induced currents, show the most promise and should receive the most emphasis. Other methods that deserve attention include the following: electromagnetic, microearthquake and seismic noise monitoring, seismic refraction and reflection, remote sensing using infrared and multispectral techniques, temperature gradient measurements, geochemical methods, particularly analysis of thermal waters, gravity, magnetics, and geologic analysis. Efforts to develop better exploration methods probably should be focused largely on only a few representative geothermal fields in order to avoid scattering the Federal effort. Designation of certain fields as National Geothermal Laboratories could help channel efforts in that direction. The drilling program described under the section on Resources Appraisal is an essential element in the program, and efforts should be made in addition to provide the maximum amount of data from deep holes drilled by private industry.

Reservoir Development and Production

Geothermal fields are currently developed using equipment and methods similar to those used in developing petroleum fields. However, the nature of geothermal reservoirs, particularly the temperature, pressure, state, and composition of the geothermal fluids, and unknown porosity, thickness, and permeability of the host rock introduces some different problems that hinder development of the resource. Furthermore, the lack of experience on the

part of both exploration and utility companies in developing geothermal fields and producing steam from them results in time delays and added costs in developing a field, that is, in drilling production wells and demonstrating that they will yield sufficient steam over a sufficiently long period of time to justify construction of power plants. Part of the problem would be helped by research and development under "Exploration Methods," particularly the development of improved techniques for drilling and for borehole logging and sampling. However, an additional need is for the development of better computer models for geothermal fields (Whiting and Ramey, 1969; White and others, 1971), models that will aid in predicting the life and quality of the field and that can be used to determine the best well spacing and production rate. Development of successful models will depend in part on assembling sufficient data on temperatures, pressures, hydrology, etc., of a field, using data both from industry (see Cady, 1969; Bilhartz, 1971; Cady and others, 1972), and from drilling and research carried out under the Resource Appraisal and Exploration Methods programs. A problem in some geothermal fields is the deposition of carbonate in production or reinjection wells and the deposition of silica is a possible problem in some fields. Research is needed on the geochemistry of geothermal fluids, (White, 1964, 1970, 1971) including fluid-rock interactions and mass transport of silica and carbonate, and development is needed on practical methods of preventing deposition of silica and carbonate and removing scale once it has formed.

Other research and development programs could lead to the extension of the size or life of geothermal reservoirs and to the extension of geothermal resources to a new type of resource. A research and development program on methods of recharge by reinjection (including the modeling of the reservoir under recharge) could lead to longer production from fields. Artificial stimulation of geothermal reservoirs by hydraulic fracturing, thermal-stress fracturing, and fracturing by explosives could extend both the life and size of a field, and could reduce the cost of drilling by producing fractures at shallow depths in a reservoir (Raghavan and others, 1971; Ramey and others, 1972). This investigation should include the development of better and cheaper chemical explosives for use at the high temperatures found in geothermal reservoirs. Geothermal reservoirs have been found which lack sufficient permeability to support geothermal development; other hot rock masses may exist at depth which also lack sufficient fluids, although the existence of such masses has not been demonstrated. Possibly the thermal energy stored in such hot but relatively dry rocks could be tapped by first using the above techniques to form a permeable reservoir and, if necessary, then circulating water through the reservoir (see Kruger and Otte, 1972).

An expanded Federal research and development program is recommended to investigate these subjects. Funding needs for the first year would be about \$5 million. \$2 million is needed for (1) modeling geothermal reservoirs, (2) investigating recharge methods, (3) investigating the

geochemistry of geothermal fluids, and (4) developing techniques for detecting and removing scale and preventing its deposition. Another \$3 million is needed to investigate the artificial stimulation of geothermal reservoirs and the feasibility of tapping the thermal energy stored in hot, relatively dry rocks.

Utilization Technology and Economics

The technology for generating power from dry steam fields such as The Geysers and from certain wet steam fields, such as Cerro Prieto and Wairakei, is well developed. In dry steam fields the steam is available at well head at low pressure compared to that used in conventional fossil fuel or nuclear-powered plants; abrasive particles are removed, the steam is fed to turbines of special design because of the low steam pressure. In wet steam fields, hot water in the geothermal reservoir flashes into a mixture of steam and water upon reduction of pressure by the well; the steam and water are separated at the well head, and the steam, which is also at relatively low pressure, is fed to a turbine; the separated water may be flashed again at lower pressure yielding steam at still lower pressure. No Federal research and development program is needed for power generation technology for these fields--that is, for dry steam fields or for wet steam (hot-water) fields where temperatures exceed 180°C (356°F) and the geothermal brines are dilute.

However, there appear to be abundant geothermal reservoirs that do not meet this criterion, and for these Federal research and development on power generation technology are needed. Furthermore, Federal research and

development is needed on other utilization of geothermal resources, particularly desalination of brines and commercial recovery of chemicals. Possibly 70 to 80 percent of the geothermal reservoirs susceptible to development within the next decade or so contain hot water at insufficient temperature (less than 180°C, 356°F) or have dissolved chemical of such a nature or abundance that they cause problems in power generation. Successful demonstration that these reservoirs can be utilized economically for generating electrical power would greatly expand recoverable geothermal resources. Private industry in the United States, and the U.S.S.R. government, have made some progress toward developing techniques for using these geothermal fluids for generating power; the techniques are based on binary-fluid systems in which the heat is transferred to a low-boiling point fluid (such as isobutane or freon) which is fed to the turbines. Federal research is needed to examine a variety of power generation methods for dilute geothermal brines, including binary-fluid systems as well as other power cycles using hot concentrated brines. Federal development funds may be needed for design and construction of demonstration power plants, although at least one such binary-fluid plant may be constructed by industry using private funds.

A Federal research and development program is also needed to develop and demonstrate the technology for desalting geothermal brines and recovering chemicals and gases from them in combination with power generation. The successful demonstration of multiple use of geothermal fluids would help in expanding the recoverable resource by sharing plant

costs among different uses. In many areas of the world, desalted water might be a far more valuable product than the electric power. The Department of Interior geothermal resources program in the Imperial Valley, California, is aimed at demonstrating the utility of such a multiple use of geothermal fluids.

The research and development described above, as well as the development of drilling and better borehole logging techniques, will require the development of materials (alloys, cements, plastics, etc.) resistant to the high temperatures and corrosive fluids. The economic modeling of both single and multiple use of geothermal fluids and of power generation from different geothermal fluids using different power cycles should be an element in the research program.

The needs for an expanded Federal Research and Development program on Utilization Technology and Economics are estimated to be \$6,000,000 for the first year, including \$3,000,000 for power generation techniques including economic modeling, and \$3,000,000 for techniques of desalination and recovery of chemicals.

Environmental Effects

Although geothermal energy has probably less impact on the environment per kilowatt capacity than other generating modes such as fossil fuel and nuclear power, it is not without adverse environmental effect. Of particular concern in dry steam fields are emission of H_2S and noise from well cleanout and bleeding; in hot-water fields possible deleterious effects include

contamination of surface and ground waters, subsidence, and possible generation of earthquakes and supply of cooling water for closed system generating modes. A Federal program of research, development, and monitoring is needed to insure that adverse environmental effects do not hinder the development of geothermal energy. A priority list of elements of the program follows:

1. Monitoring of quality of surface and ground waters in regions of geothermal developments. Although reinjection of geothermal fluids into the producing zone at most if not all geothermal fields developed in the United States should result in no impairment and perhaps even an improvement in the quality of surface waters and shallow ground waters in each individual field, the quality of the water should be determined before development of the field and monitored periodically thereafter. Research on reinjection of geothermal fluids, listed under the program on Reservoir Development and Production, has obvious applications to this program on environmental effects. Although some data exist on natural emissions from thermal areas and chemical composition of surface and ground waters, an expanded program, including research on sampling techniques, will be required to establish base-level values.

2. Research and development on the technology for removal of hydrogen sulfide gas at the well head, at other points of steam emission, and from power plant exhausts. Hydrogen sulfide, which is easily detected in small concentrations by its offensive odor, is present in many geothermal steam

fields. In highly sensitive individuals, exposure to hydrogen sulfide beyond the threshold of odor can cause nausea or other illness. Although air-pollution control equipment has been developed for other industries and applied to geothermal fields, emission of hydrogen sulfide from geothermal developments is still a problem requiring Federal research and development funds.

3. Development of technology for reducing noise from drilling operations and from well cleanout and bleeding. The development of a geothermal field extends over a period of years, and the machinery noise from drilling operations and roar of steam from wells under development make geothermal operations incompatible with residential or recreational land use. The problem has been reduced somewhat during the last few years by use of mufflers, but further research and development is needed on the reduction of noise by various means of sound baffling and improved mufflers and muffling techniques during all phases of geothermal development and production. Other research should be directed at reducing to a minimum the disruption of the ecologic system of a geothermal area by installations and operations.

4. Monitoring of land subsidence. Geothermal developments that involve removal of large volumes of water from a geothermal reservoir in relatively unconsolidated sedimentary rocks beneath a developed urban or agricultural area may result in undesirable subsidence causing disruption of irrigation canals, changes in local elevation with respect to sea level, etc., unless most of the spent brines are reinjected into the reservoir. The planned Imperial Valley geothermal development is such a project. For such

developments, monitoring of surface elevations by means of repeated leveling surveys is essential and a modified reinjection program may be necessary.

5. Monitoring of seismic activity. Some geothermal fields that will be developed within the next few years may be in areas that have undergone damaging earthquakes in the past. The Imperial Valley field, which lies astride the San Andreas fault system is an example. Changes in the fluid pressure within these fields from withdrawing and reinjecting fluids may change the pattern of strain release in the area. Although the possibility of causing damaging earthquakes by these methods seems to be remote, a modest program of seismic monitoring should be carried out in the few areas that appear hazardous.

The needs for the first year of an Environmental Effects program are estimated to be \$1.5 million, including \$.5 million for research and development of air pollution and noise reduction techniques, and \$1 million for monitoring environmental effects.

Institutional and Legal Aspects

A variety of functions and problems have been included in this category even though some are not of a research and development nature. All, however, are essential or desirable for the full development of geothermal resources.

Federal programs directed toward the management of the geothermal resources of the public lands are necessary for the development of the Nation's geothermal resources, many of which underlie public lands. The Bureau of Land Management and the Geological Survey have responsibility

for classifying the Federal lands for geothermal resources, leasing the lands under the Geothermal Steam Act of 1970, and supervising activities on the leased lands.

A variety of efforts aimed at analysis of laws and regulations and development of better communication between all types of organizations involved in the geothermal resources field could help considerably in the development of the field. Such efforts include the following: (1) to compile State, Federal, and county laws and regulations concerning geothermal developments, to review and analyze their functioning and administration, and consider desirable amendments; (2) to prepare a model code; (3) to analyze the legal problems of ownership of geothermal resources and utilization of the resources pending final determination of ownership; (4) to establish and maintain liaison between Federal, State, and local agencies, the academic community, and the geothermal industry and to explore mechanisms of cooperation between these groups that would enhance industrial application of geothermal resources; (5) to aid local agencies in the preparation of plans for the orderly development of local geothermal resources; (6) to establish a central Federal facility for the systematic gathering and rapid distribution of information on geothermal resources; and (7) to evaluate the need for geothermal field research laboratories.

The needs in FY 1974 for the Federal program of management of the geothermal resources of the public lands are estimated to be \$1,000,000. An additional \$500,000 is needed for the other legal and institutional activities listed above.

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A National Geothermal Energy Program Budget

The attached program budget and accompanying illustrations were prepared by an interagency working group composed of representatives from the Geological Survey, the Atomic Energy Commission, the National Science Foundation, the Bureau of Reclamation, the Office of Saline Water, and the Environmental Protection Agency. This group views the program as one involving the cooperative efforts of existing Federal agencies, the university community, and private industry. The Federal government is seen as carrying the major share of the research and development costs until technical and economic feasibilities have been established, at which time industry will begin to assume the principal costs of the completion of, and production from, specific geothermal systems. Industry would also be involved in earlier phases of the research and development program, but largely on a cooperative and/ or contract basis.

The program and its impact are illustrated in Tables 1, 2, and 3 and Figures 1 and 2. The separate list of milestones refer to numbered points in Figure 1. The breakdown followed throughout is that of the 26 June 1972 report entitled Assessment of Geothermal Energy Resources (hereafter referred to as the Peck Report). Table 1 represents the broad budget, by category. Table 2 shows a detailed breakdown of expenditures in the categories of Reservoir Development and Production and Utilization Technology and Economics. The other categories do not lend themselves readily to this type of breakdown, at least with our present state of knowledge. Table 3 presents the range in current estimates of the nation's geothermal energy resources, the probable on-line power capacity resulting from the proposed research and development program, and a first approximation of the effect of the estimated resources on the nation's balance of payments. A simple and inelegant method was used for this last item. The resource was evaluated by comparing it to the cost of another commodity which would produce the same amount of electrical power. The basis was oil, at 68¢/MBtu, generating at a thermal conversion efficiency of 39%. If coal is used instead of oil, the figures would be reduced by approximately one-third. The geothermal resources were evaluated on the basis of the t.c.e.'s listed in the Peck Report.

The basic premises of the Peck Report were accepted as a starting point in preparing the accompanying budget. The budget figures contained in the Peck Report were subjected to further analysis and discussion, modified accordingly, and extended over the life of a 10-year program (Tables 1 and 2 and Figure 1). The 10-year program includes doing several things that the Peck Report noted as significant and important, but which it regarded as lying beyond the scope of a 5-year program. The results of the extended program are seen as providing a potential power capacity estimated at just under 400,000 megawatts by the year 2000 (Table 3 and Figure 2). The total cost of the research and development needed to realize this capacity is seen to be approximately \$650 million.

It should be stressed that these figures, as well as those of the reserve estimates and their equivalent dollar values (Table 3) are not firm figures. The Peck Report (p. 55) lists the various reasons for this, but it is worth re-emphasizing here that the principal basis for uncertainty lies in a lack of factual knowledge about geothermal resources in general. Compared with some of the other energy resources currently under exploitation by the nation (e.g. oil, gas, and coal), we know little about U. S. geothermal reserves. The working group essentially views the country's geothermal resources, along with the energy available from oil shale, tar sands, coal gasification, resource conservation and breeder reactors, as intermediate-range energy sources with which to combat the encroaching energy crisis, while we await the evaluation and development of fusion and solar energy sources to meet the national needs. In order to evaluate geothermal energy in the context of all of the other intermediate range options, however, a vigorous program of Federal research is going to have to be initiated.

The assumptions relating the estimated power yield to the research and development costs should be noted here. The Kilkenny estimates and the Peck Report extrapolation were used as a base. All of the GO-NO GO mileposts were assumed to be GO. All of the energy extracted was assumed to be utilized in the production of electrical power. The various parts of the program are interdependent. The estimated impact of the various parts of the program were crudely proportioned according to their cost.

The interdependency of the various parts of the program essentially precludes achieving a fraction of the estimated power capacity on-line by expenditure of an equivalent fraction of the estimated total cost. The interdependent nature follows from the dependence of success in one phase of the program on feedback from another and from the common threads which run throughout the program and essentially give it its fabric. This can be illustrated by a single theme like drilling. The development of faster and cheaper drilling techniques is, of necessity, a goal of the Exploration Methods part of the program. Initially, however, conventional drilling techniques will be used, while this work is going on. Drilling is needed in order to put down: 1.) shallow holes for thermal gradient measurements; 2.) holes of intermediate depth for heat flow measurements; 3.) deeper holes for determining both the three dimensional nature of a given geothermal system and for artificial stimulation and production tests; and 4.) very deep holes for defining the geothermal resources of the deep crust. Thus, the drilling theme runs across the categories of Resource Appraisal and Reservoir Development, as well as Exploration Methods. Development of specific techniques and materials to cope with the extreme environments of natural geothermal systems constitutes part of the Utilization Technology program. The drilling of reinjection wells and the necessity for subsurface monitoring of producing systems brings drilling into the environmental aspects of the total program, as well. Similar arguments can be made for other physical themes such as reinjection, materials development, etc.

Threads that run across the program fabric in another direction include the various resource types: dry steam, low enthalpy waters, high enthalpy waters, geopressured waters in deep sedimentary basins, hot dry rock, and lava. The working group believes that research on all of these types of systems should go on essentially simultaneously.

A word on the time sequence of various parts of the program is in order. The graphs in Figure 1 show a steady, if irregular, succession of budgetary peaks beginning with Exploration Methods (1976) and running through Resource Appraisal and Utilization Technology (1977), Reservoir Development and Production (1978), Environmental Effects (1979), a second peak in Reservoir Development and Production (1980), and culminating in one in Utilization Technology (1981). The magnitude of these budget peaks and their relative impact creates the waviness seen in the final impact curve (Figure 2). The highest budget peaks represent either massive efforts in development or construction of demonstration power plants and it is our general consensus that at least one such demonstration plant should be built for each type of geothermal system. The time-location and varying slopes of the different impact curves reflect varying lags in impact following major R and D efforts and also the fact that the easiest parts of the program are the cheapest and the ones that will be done first. Thus the curves begin to flatten perceptibly toward the year 2000. They do not, however, tend toward zero slopes (relative to the base curve) except in the instances of Exploration Methods and Resources Appraisal, where massive funding will probably begin to yield less and less in terms of return as the year 2000 is approached.

Table 1.

PROPOSED 10-YEAR GEOTHERMAL RESEARCH PROGRAM\$ in Millions

	FY										Total
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	
I. Resource Appraisal	6.0	11.0	16.0	18.0	16.0	15.0	15.0	15.0	15.0	15.0	142.0
II. Exploration Methods	5.0	8.0	11.0	9.5	6.0	3.5	2.0	1.5	1.5	1.5	49.5
III. Reservoir Development & Production ^{1/}	5.0	13.5	27.0	44.0	48.0	21.5	23.0	13.0	10.5	10.0	215.5
IV. Utilization Technology & Economics ^{1/}	6.0	8.0	13.0	25.0	15.5	15.5	40.0	57.0	16.0	7.5	203.5
V. Environmental Effects	1.5	2.0	2.5	3.0	4.5	5.0	4.0	4.0	3.0	2.0	31.5
VI. Institutional & Legal Aspects	1.5	2.0	1.5	1.5	1.5	0.5	0.5	0.5	0.5	0.5	10.5
TOTALS	25.0	44.5	71.0	101.0	91.5	61.0	84.5	91.0	46.5	36.5	652.5

^{1/} For detailed breakdown by resource type, see Table 2.

Table 2.

DETAILED BREAKDOWN OF PROGRAM CATEGORIES III AND IV BY RESOURCE TYPE\$ in millions

	FY									
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
III. Reservoir Development & Production										
a. Dry Steam	0.25	1.00	5.00	6.00	4.00	1.50	--	--	--	--
b. Hot Water	2.50	7.50	19.00	28.00	35.00	11.00	7.00	7.00	4.50	4.50
c. Dry Hot Rock - Hydro fract.	2.00	4.50	1.50	4.50	3.50	6.50	11.50	4.00	4.00	2.00
- Explosive fract.	0.25	0.50	1.50	5.50	5.50	2.50	4.50	2.00	2.00	3.50
TOTALS	5.00	13.50	27.00	44.00	48.00	21.50	23.00	13.00	10.50	10.00
IV. Utilization Technology & Economics										
a. Dry Steam	1.50	3.00	1.00	1.00	0.50	--	--	--	--	--
b. Hot Water	4.00	4.00	9.00	10.00	12.00	12.00	35.00	40.00	10.00	6.50
c. Dry Hot Rock - Hydro fract.	0.50	0.50	1.00	8.00	2.00	0.50	1.00	16.00	5.00	1.00
- Explosive fract.	--	0.50	2.00	6.00	1.00	3.00	4.00	1.00	1.00	--
TOTALS	6.00	8.00	13.00	25.00	15.50	15.50	40.00	57.00	16.00	7.50

92

Table 3.

Geothermal Resources, Potential Power Installed, and Resource Values

	1975	1980	1985	1990	1995	2000
A. Range of estimated cumulative geothermal energy resources available <u>in thousands of megawatt centuries</u> (low figures are based on estimates by D. E. White and L. J. P. Muffler; high figures are those of R. W. Rex.)	22-2,400	50-7,000	130-20,000	190-29,000	215-33,500	225-35,000
B. Potential power installed resulting from program, <u>in thousands of megawatts</u> .	.75	36	132	242	335	395
C. Value of estimated resource as dollar equivalents of electrical power generated from imported oil, <u>in billions of dollars</u> .	23-2,510	52-7,320	140-20,920	200-30,330	220-35,040	240-36,600

Milestones in 10-year (1977) program budget (Figure 1)

1. Tests of existing, conventional surface geophysical techniques at two EGNA's and experimental field tests of new and promising ones.
2. Beginning of comprehensive geologic investigations in three areas (2 in California and one in Alaska).
3. Initiation of digital reservoir modelling and geochemical studies of geothermal fluids.
4. Initiation of intensive heat-flow drilling program (holes of moderate depth).
5. First hydrofracturing tests: results determine GO or NO-GO.
6. Initiation of monitoring program (noise, noxious gas emission, water pollution, subsidence, earthquakes).
7. Development of management program.
8. Development of high temperature geophysical logging equipment.
9. Demonstration of prototype generating plant for hot dry rock.
10. Binary cycle tests completed for hot water systems.
11. Preparation of a model code and establishment of centralized Federal information facility.
12. Peaking of both geophysical and drilling technology research activities.
13. "Conventional" stimulation and reinjection field tests for dry steam and hot water systems.
14. Development of recovery techniques for minerals and gases in solution in geothermal fluids.
15. Completion of appraisal of a deep sedimentary basin: results determine GO or NO-GO for small prototype plants; maximization of efforts in heat-flow drilling program and delineation of major geothermal provinces.
16. Nuclear stimulation tests for hot water systems: results determine GO or NO-GO; large heat source developed in hot dry rocks.
17. Turbine tests and corrosion treatment program for dry steam systems.
18. Development of air pollution and noise control systems.
19. Construction of prototype generating plant for geopressured waters in a deep sedimentary basin (Gulf of Mexico); aggregate peaking of all other development and production research.
20. Initiation of very deep drilling (5 to 10 km) for determining deep crustal geothermal potential.
21. Development of high salinity heat exchangers for hot water systems.
22. Peaking of monitoring program and installation of control systems.
23. Beginning of routine phase of geothermal management.
24. Large prototype generating plant completed for hot dry rock.
25. Tests of advanced low-temperature water power-conversion system.
26. Advanced flash or binary cycle hot water system tests; Flowshare heat removal tests: results determine GO or NO-GO.
27. Prototype hot dry rock power source developed and tested.