A Decade of Geothermal Development in the United States 1974 — 1984: A Federal Perspective

— Part 1 —

EDITOR'S NOTE: This article was prepared and published in the Progress Monitor by the Meridian Corporation of Falls Church, VA under a contract with the U.S. Department of Energy (DOE). It recaps and underscores the positive development that has taken place in both research and field development in the U.S. Geothermal Community from 1974 to 1984. Because of the size of the volume, it will be run in the BULLETIN in three parts. This is part one.

1974 was a banner year for geothermal energy in the United States. Three events of major significance took place that in 1984 provided the baseline for measuring progress in the development of this resource.

The Geothermal Energy Research, Development, and Demonstration Act (RD&D) was enacted by the U.S. Congress on 3 September 1974, establishing a formal federal geothermal research and development program. In August of that year, the first competitive geothermal leases were issued pursuant to the Geothermal Steam Act of 1970. And in the same year, the U.S. Geological Survey initiated the first comprehensive assessment of the geothermal resources of the United States.

These actions did not result in an oversight success story. To the contrary, progress has been slow over the 10 years in both technology development and leasing of the federal lands available for geothermal exploitation, the pace retarded by many direct and indirect influences. In addition, a large portion of the Nation's resource base has yet to be identified. Nevertheless, in 1984 real progress arrived in geothermal development, a product of the efforts of industry and government.

Geothermal Research, Development and Demonstration Act

In 1974, memories of the long lines of gasoline service stations, created by the 1973 embargo on shipments of foreign oil, were very fresh in the minds of the American public. Prices of energy in all forms were soaring. As a result, public pressure for federal support of the development of alternative forms of energy grew to a ground swell. It was in this climate that the Geothermal RD&D Act was passed.

The Atomic Energy Commission had been given an earlier mandate from Congress to conduct geothermal research and development, as had the National Science Foundation. While some of the major geothermal programs still ongoing today had their origins within those agencies, the RD&D Act made the first "national commitment ... to dedicate the necessary financial resources and enlist the cooperation of the private and public sectors in developing geothermal resources..."

Responsibility for coordinating and managing the federal geothermal R&D program was placed in a Geothermal Energy Coordination and Management Project, known today as the Interagency Geothermal Coordinating Council. However, when the Energy Research and Development Administration (ERDA) was created in January 1975, it was given responsibility for the federal R&D program. The responsibility was subsequently passed to the Depatment of Energy (DOE) when it was created in 1977.

The Geothermal "Industry" in 1974

If the term "industry" is defined here as a group of for-profit enterprises, the geothermal industry in 1974 consisted of:

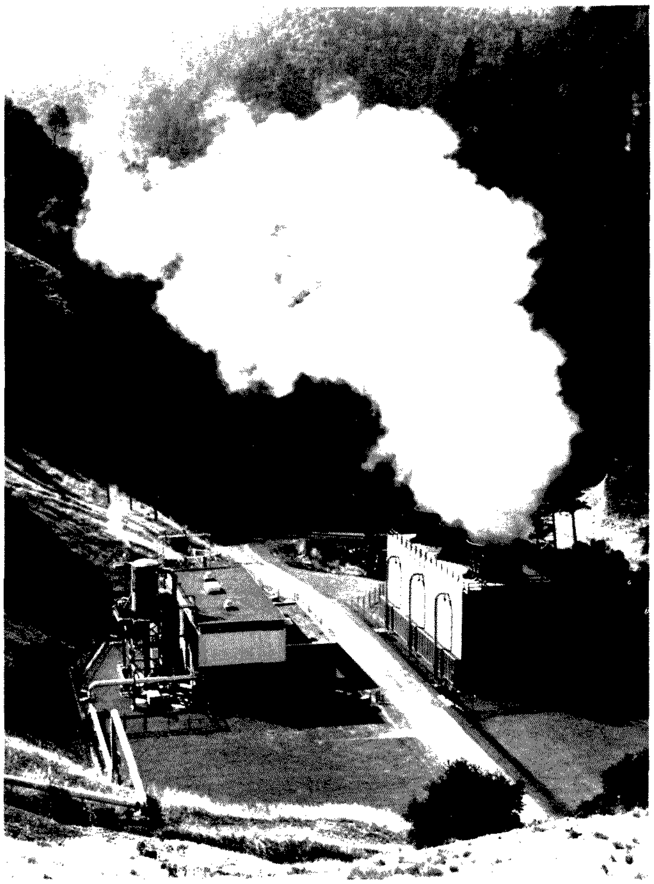
- the power generating plants at The Geysers and the wellfield providing steam
- the Boise, Idaho, district heating system
- a few small commercial greenhouses
- their suppliers of energineering services, equipment, and materials.

The only other uses of record were other direct heat applications by both the public and private sectors.

The generating capacity at The Geysers was 396 MWe. Ten Pacific Gas and Electric Co. (PG&E) units were on-line, and the operation was second in size only to the geothermal installations at Larderello, Italy. Six modern 50 MWe plants accounted for the bulk of the capacity, a giant step from the first 11 MWe plant build in 1960.

Contrary to the ascendancy of The Geysers operations, the oldest geothermal district heating system in this country was in decline. At its peak, the Warm Springs Avenue system in Boise, Idaho, served 400 homes and business establishments. By 1974, the distribution system, built in 1890, had become antiquated, badly in need of a major capital outlay for renovation, and only marginally profitable for the Boise Water System. A citizens group, independently incorporated and privately financed, had taken over the operation to serve the remaining 170 customers.

By 1974, most of the eastern portion of the City of Klamath Falls, Oregon, was heated by hot water in a unique application that is, to a large extent, a one-well-one-structure approach, with approximately 400 wells supplying about 500 structures in 1974. Since at least the turn of the century, users had installed their own wells, typically using a downhole heat exchanger to heat city water circulating in a closed system. Space heat users in 1974 included residences, city schools, and the Oregon Institute of Technology. Other users included milk pasterurizaion and commercial laundering.



Pacific Gas and Electric Unit No. 1 at The Geysers, the first commercial power plant in the U.S. *(Courtesy of Pacific Gas and Electric Company).*

At this time, the Bureau of Reclamation was operating a demonstration of desalting geothermal brines at East Mesa in the Imperial Valley to study the feasibility of augmenting the water supply to the Colorado River from sources within the Basin. It was determined, however, that all desalting processes tried were far too expensive, including a multistage flash desalting plant combined with a binary power plant for the concurrent production of water and power.

Perhaps the best known geothermal greenhouses in the mid 1970s were those near Susanville, California, used for growing tomatoes by the soilless hydroponic method. The hot water from a surface hot spring — no wells were drilled — was used to heat the greenhouses and, with the addition of nutrients, to irrigate the plants which were grown in gravel. By mid 1974, six greenhouses had been completed in this facility.

The Geothermal Industry in 1984

Despite several factors working against it, a geothermal industry is emerging today beyond the realm of The Geysers. The hot water resource has reached commercial status notwithstanding: 1) reduced power plant construction of all types; 2) low competing fuel prices; 3) very high geothermal drilling costs; and 4) relatively new power conversion technologies.

The total megawatt capacity of all the hot water plants in operation, under construction, and planned in the U.S. is only a fraction of that of the established fossil and nuclear power industries. Nevertheless, the number of plants is significant in today's market of lower than expected power demand, and their size is a plus factor in satisfying today's smaller increments of growth. They will also provide the experience needed to attract others to the use of this resource.

Development also continues at The Geysers, by newcomers as well as the established steam producers and utility. This area embraces the greatest amount of geothermal power generation capacity of any site in the world despite some large developments abroad.

A number of new direct uses of geothermal heat have been installed, beyond a group of such projects partially funded by DOE as field experiments.

Hydrothermal Power Generation

As indicated by the above discussion, the geothermal industry today is confined to the use of *Hydrothermal* fluids, and, except for a small, pilot-scale geothermal generating unit in Hawaii and another operated briefly in Idaho, California was the scene of all U.S. geothermal power development until 1984. Today, there are plants, some of them small-scale units, operating in Nevada, New Mexico, and Utah. Additional geothermal capacity is planned for these three states and Oregon.

California will remain the leader for the foreseeable future, however. This is true even when the capacities of plants under construction or planned to utilize liquid-dominated resources are tabulated alone, uninflated by the large capacity at The Geysers.

At this writing, contracts are in place for the purchase of the power output of about 250 MW_e from nine "hot water" plants in California existing or under construction. Approximately 80 percent of this capacity is in Imperial Valley. Expansion is planned for several of the plants e.g., the capacity of the China Lake Naval Weapons Center facility is to be increased in increments from the initial 25 MW_e currently under construction.

1974 geothermal greenhouse in Raft River Valley, Idaho.
The heat exchanger (shown here) was a tub of hot geothermal water (180°F).

In addition to the "boost" given to geothermal development by the new plant construction, considerable encouragement for the future of this resource is offered by the performance of the existing hot water demonstration plants. While both the Magma Power Co. 10 MWe binary plant at East Mesa and the Union Oil Co. of California/Southern California Edison (UNOCAL)/(SCE) flash plant of the same size at Brawley suffered some initial difficulties after they came on-line in 1980, the performance of the binary plant is now reliable and consistent. Similarly, although all problems are not completely solved, the UNOCAL/SCE 10 MWe plant near the Salton Sea, which began operation in 1982, is performing well. In addition, the Utah Power and Light Co. was sufficiently impressed with the efficiency of a small (1.6 MWe) Biphase generating unit subjected to long-term performance tests that it is using this total flow technology to increase the output of both its 20 MWe plant near Milford and the new 14 MWe plant under construction (Figure 1). More information on the individual hot water plants under construction and planned is included below.

The scene at The Geysers has changed markedly since 1974. PG&E's generating capacity has increased from less than 400 MWe to over 1100 MWe, and the number of plants has grown from 10 to 17. An additional 262 MWe is generated by newcomers to The Geysers. Owners of these include the Northern California Power Agency (NCPA), Sacramento Municipal Utility District (SMUD), and Santa Fe International. The Santa Fe plant, built by Occidental Geothermal, is the first at The Geysers to be owned by a non-utility field developer.

Occidental was only one of several new field developers operating in the area. Once the sole domain of the Union/Magma/Thermal consortium that originally supplied all of PG&E's suppliers now include UNOCAL, Thermal Power Co., Geysers Geothermal, MCR Geothermal and Geothermal Resources International.

The plants scheduled to come on-line in 1985 included the Bottle Rock plant of the California Department of Water Resources, the second NCPA plant and PG&E's Units 16 and 20.

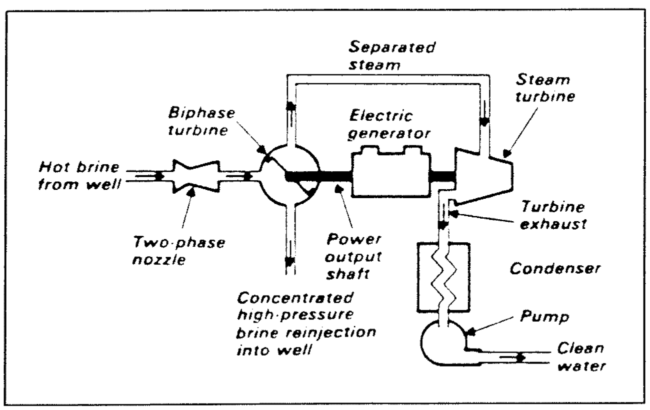
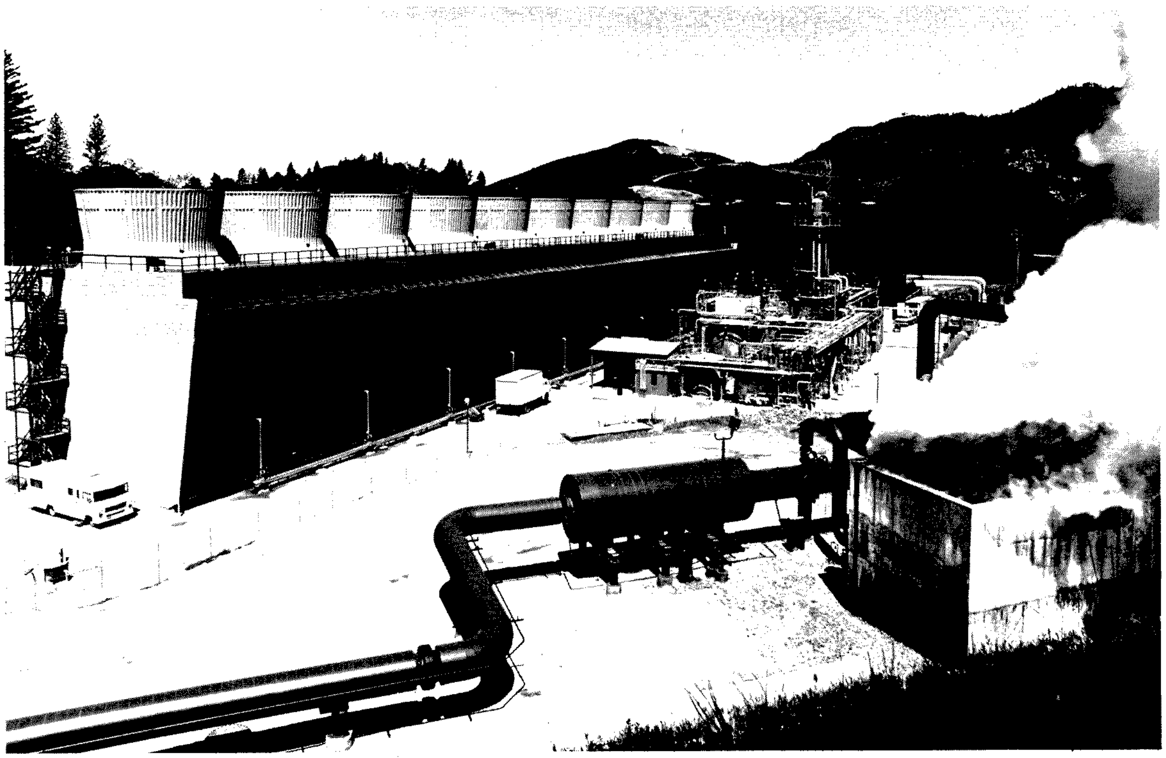


Figure 1. The BiPhase rotary-separator turbine converts kinetic and pressure energy in the geothermal brine to shaft power. It is a valuable adjunct to flash steam turbine installations.



At 135 MWe, this Pacific Gas and Electric plant at The Geysers is the largest geothermal power plant in the world.

Large modern geothermal greenhouse at Bluffdale, Utah. The entire geothermal system, including production and injection wells, cost less than one year's natural gas requirement. Operation and maintenance costs are minimal. *(Courtesy of Utah Roses.)*

Direct Use

The annual thermal energy use of a total of over 260 geothermal direct use projects, either on-line or under construction, has been estimated to be over 1861 billion Btu's. A recent survey by the Meridian Corporation found that of the total annual direct utilization, space and water conditioning projects (473 billion Btu) account for approximately 25 percent; district heating projects (426 billion Btu) are estimated to account for 23 percent; commercial fish farms (396 billion Btu) comprise 21 percent; commercial greenhouses (328 billion Btu) contributed 18 percent; while projects involving small resorts (120 billion Btu) and industrial process heat (118 billion Btu) combine to make up the remainder. All but one of the identified active projects are located in states west of the Mississippi River, with the bulk of the geothermal energy direct heat utilization occurring in California, Idaho, Oregon, Nevada, and New Mexico.

Under the narrow difinition of a "district heating system" used in the survey — a public utility system — there are eleven such systems in operation in the U.S. and six under construction. Other multiple-structure geothermal heating systems, such as those of college campuses, other institutions, and large resort complexes, were counted in the "space and water conditioning projects," the largest of the utilization categories.

Of the nine aquaculture projects identified, three large fish farms in Buhl, Idaho; Wabuska, Nevada; and Mecca, California, account for nearly 80 percent of the total energy consumption. Twenty-eight commercial geothermally-heated greenhouses are in operation, many with very attractive payback periods. Products produced include decorative flowers, potted plants, and hydroponically grown vegetables.

Geothermal heat for industrial processing, although potentially very attractive, is used at only a handful of locations in the U.S. due to some extent to difficulties in relocating a commercial enterprise to a geothermal site. The total estimated value for direct heat geothermal utilization through industrial processing was derived from a sewage digestion plant in San Bernardino, California, a vegetable drying facility at Brady Hot Springs, Nevada, and copper processing at Hurley, New Mexico. The mushroom growing facility at Vale, Oregon, was considered as a greenhouse.

The future growth of direct use applications have been impacted by the expiration of both the residential and business energy tax credits at the end of 1985. The maximum credit for residential was 40 percent of the first $10,000 of expenditures, or $4,000, and the business credit is 15 percent.

Contributions to the Emergence of the "Hot Water" Industry

How has an industry to utilize liquid-dominated geothermal reservoirs for power generation and direct use applications emerged in spite of all of the technological and instutional barriers of its development? It has resulted from the interacting contributions of a number of forces at work to make it happen:

- the interest and perserverance of many individuals and companies in the private sector
- the industry-guided R&D and commercialization programs of DOE and its predecessors
- the U.S. Geological Survey assessments of the size and locations of the Nation's geothermal resource base
- the efforts of the Departments of the Interior and Agriculture to overcome the obstacles to geothermal leasing and permitting on federal lands
- more favorable federal tax treatment of geothermal production (depletion allowance and deductions for intangible drilling costs) and use (energy investment tax credits for non-utility investors)
- state and local government actions to foster geothermal development.

Success of Industry Exploration

Industry initiated geothermal exploration long before government interest in the use of the resource developed. From a historical perspective, the wells drilled at The Geysers in the 1920s are the earliest identified in the literature, although modern exploration appears to begin in 1955 with the Magma Power Co. exploratory work at The Geysers. Data compiled for the 1982 DOE report *Hydrothermal Industrialization: Electric Power Systems Development* on exploration in the major geothermal areas of interest show that Magma was also the first company to explore in Nevada — at Beowawe and Brady Hot Springs areas in 1959 and 1960 respectively. As identified by the study, the subsequent participants in geothermal exploration in the major areas have been about equally divided between oil companies, or their subsidiaries, and companies organized specifically for geothermal development.

Of the 27 hot-water areas listed by the report as having high and moderate levels of development activity, 15 are the sites of existing power plants, plants under construction, or planned plants.

Area	Operation in 1982
California	
No. Brawley	UNOCAL
Coso Hot Sprints	California Energy
East Mesa	Magma, Republic
Heber	Chevron
Mono-Long Valley	Chevron, Union
Salton Sea/Niland	Union, Magma, Republic
Westmorland	Republic
Nevada	
Beowawe	Chevron, Vulcan Thermal
Brady Hot Springs	Magma
Desert Peak	Phillips
Dixie Hot Springs	Sunedco
Steamboat Springs	Nevada Thermal
Oregon	
Vale Hot Springs	Republic, AMAX
Utah	
Cove Fort/Sulphurdale	Union, Mother Earth
Roosevelt Hot Springs	Phillips

Vale Hot Springs is also the sight of a large mushroom-growing facility utilizing the geothermal resource; the wells at Raft River, Idaho, and at the Valles Caldera, New Mexico, were drilled as DOE experimental wells; and development is inhibited by environmental considerations at Lassen, California.

The other areas on the list not currently scheduled for power development include:

Surprise Valley, CA
Crane Creek/Cove Creek, ID
Humboldt House, NV
San Emedio, NV
Soda Lake, NV
Stillwater, NV
Alvord, OR
Crump Hot Springs, OR

Accurate Resource Assessment

In the 10-year period preceding the initiation of direct government involvement in geothermal energy, various organizations and individuals produced estimates of the geothermal resources of the United States. These estimates tended to vary widely, partially due to the differing assumptions and parameters that were chosen, but mostly because of an inadequate understanding of the nature and occurrence of geothermal resources.

In 1974, the U.S. Geological Survey initiated a comprehensive assessment of the geothermal resources of the United States which was published in 1975 as U.S. Geological Survey Circular 726. This was the first systematic effort to estimate the geothermal resource potential of the U.S., and to create methodology and framework for directing long-term energy policy and strategy.

In 1978, the USGS reevaluated the geothermal resources of the United States in light of new available nonproprietary data and refinements in geothermometry (U.S. Geological Survey Circular 790). The estimate for the number of hydrothermal systems with temperatures over 90°C (excluding those in national parks) dropped from 283 in 1974 to 215 in 1978 (Table 1).

The first quantitative assessment of thermal energy contained within low- and moderate-temperature systems (less than 90°C and 150°C respectively) was completed by the USGS in 1982 (U.S. Geological Survey Circular 892). Data for the assessment were generated by "Resource Assessment" (RA) teams through cooperative Department of Energy and State direct use program agencies. The results of these data gathering activities were published as a series of reports and state geothermal maps for prospective direct heat users.

This information, in addition to that generated by the USGS Geothermal Research Program and the Regional Aquifer System Analysis Program, was entered into the computer-based GEOTHERM system maintained by USGS. Data on more than 2500 individual geothermal systems were evaluated.

The results of the USGS geothermal assessments are summarized in Table 1.

Extended Geothermal Data Base

When interest in geothermal utilization mounted in the 1970s, a working data base for geothermal resources did not exist. Energy companies, in order to protect land and resource positions, tended to guard exploratory and development data as proprietary, and there were no other sources of data due to the "newness" of interest in the resource.

In response to this problem, a number of programs were initiated by DOE's predecessor, ERDA, in the mid-1970s. The Industry-Coupled Cost-Shared Program was

TABLE 1

COMPARISONS OF USGS ESTIMATES OF IDENTIFIED GEOTHERMAL RESOURCES WITHIN THE UNITED STATES FROM 1975 TO 1982

Resource Category			Number of Systems Evaluated			Accessible Resource Base (10^{18}J)*			Accessible Fluid Resource Base (10^{18}J)*			Resource (10^{18}J)*		
			1975	1978	1982	1975	1978	1982	1975	1978	1982	1975	1978	1982
Hydrothermal	Convection Systems	Vapor Dominated	1	1	—	79	100	—	—	—	—	8	9.3	—
Hydrothermal	Convection Systems	Hot Water >150°C	61	51	—	1000	850	—	—	—	—	250	210	—
Hydrothermal	Convection Systems	Hot Water 90°-150°C	221	163	—	1440	700	—	—	—	—	360	176	—
Hydrothermal	Convection Systems	Warm Water <90°C	—	—	1119	—	—	200	—	—	—	—	—	31
Hydrothermal	Conduction Dominated	Warm Water <90°C	—	—	*42*	—	—	*27,000*	—	—	—	—	—	56
Geopressured			—	—	—	—	—	—	71,000	170,000	—	360 to 2300	430 to 4400	—
Igneous Related			48	55	—	105,000	63,000	—	—	—	—	—	—	—

(NOTE: Values reported exclude National Parks)

* 10^{18} J = APPROXIMATELY 1 QUAD

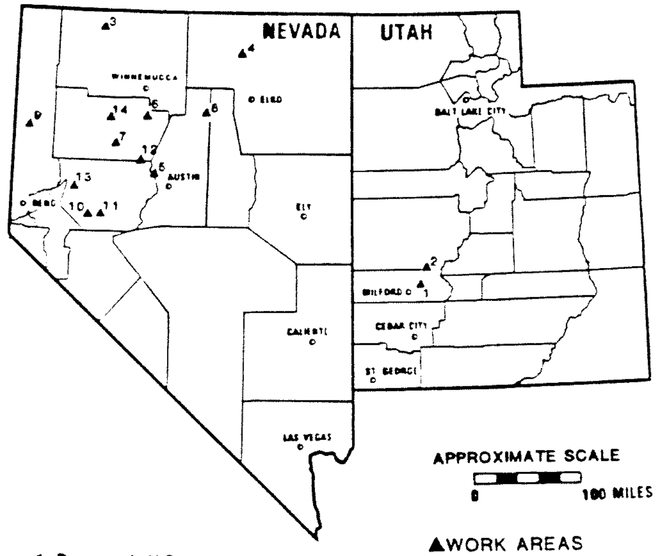
organized to evaluate selected high-temperature geothermal systems; the State-Coupled Resource Assessment (RA) Program undertook to compile regional geothermal data; and the User-Coupled Confirmation Drilling Program provided a means of cost-sharing the high frontend risk portion of direct use exploratory drilling.

The INDUSTRY-COUPLED PROGRAM was initiated to accelerate the commercialization of geothermal energy by (1) stimulating industry exploration efforts through cost (and thereby risk) sharing, (2) making data generated from the program available for unrestricted use, (3) developing case histories of geothermal exploration techniques, and (4) confirming resource potential at selected geothermal sites. The program included 21 deep exploratory wells with an average depth of about 7000 feet, numerous shallow thermal gradient test holes, and geoscience investigative surveys (Figure 2 and Table 2).

Nine major data packages with details of these results may be studied free-of-charge at the University of Utah Research Institute, Earth Science Library in Salt Lake City, or may be purchased by mail. A geothermal sample library containing cuttings and core samples from various DOE-sponsored programs is also maintained at UURI/ESL for study.

The STATE-COUPLED RESOURCE ASSESSMENT program was organized around geoscience expertise from state geological surveys, universities, and state water resource agencies (Figure 3). Phase I centered on the

LOCATIONS OF INDUSTRY-COUPLED PROGRAM AREAS



1. Roosevelt H.S.
2. Cove Fort
3. Baltazor
4. Tuscarora
5. McCoy
6. Leach H.S.
7. Colado
8. Beowawe
9. San Emidio
10. Soda Lake
11. Stillwater
12. Dixie Valley
13. Desert Peak
14. Humbolt House

Figure 2

Table 2

SUMMARY OF INDUSTRY-COUPLED PROGRAM EFFORTS

AREA	ROOSEVELT H.S.	ROOSEVELT H.S.	ROOSEVELT H.S.	ROOSEVELT H.S.	ROOSEVELT H.S.	COVE FORT	BALTAZOR	TUSCARORA	McCOY	LEACH H.S.	COLADO	BEOWAWE	BEOWAWE	SAN EMIDO	SODA LAKE	STILLWATER	DIXIE VALLEY	DESERT PEAK	HUMBOLDT HOUSE
COMPANY	TPC	SEI	UD	G	GPC	U	EPP	AM	AM	AO	G	G	C	C	C	U	SR	P	P
DATA																			
GRAVITY						•	•	•	•	•	•	•		•		•	•	•	•
GROUND MAG											•	•					•	•	
AERO MAG						•	•	•	•				•				•		
ELECTRICAL RESISTIVITY				•		•	•	•			•	•	•	•	•	•			
MT/AMT								•	•	•	•	•	•		•	•	•	•	•
SELF POTENTIAL							•	•	•				•	•					
SEISMIC EMISSIONS		•		•		•							•	•					
MICRO-EARTHQUAKE							•	•	•				•						
SEISMIC REFLECTION						•			•	•			•	•	•	•	•		
GEOCHEMISTRY					•	•	•	•		•			•				•		
SHALLOW THERMAL GRADIENT					•	•	•	•	•	•	•	•	•	•	•	•	•		
DEEP THERMAL GRADIENT					•		•	•	•	•	•	•			•		•	•	
EXPLORATORY WELLS	•		•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•
GEOLOGIC STUDIES					•	•	•			•				•			•	•	•

COMPANY ABBREVIATIONS

TPC: Thermal Power Co.
SEI: Seismic Exploration, Inc.
UD: University of Denver
G: Getty Oil Co.
GPC: Geothermal Power Corp.
U: Union Oil Co.
EPP: Earth Power Production
AM: Amax Exploration, Inc.
AO: Aminoil USA, Inc.
C: Chevron Oil Co.
SR: Southland Royalty
P: Phillips Petroleum Co.

gathering of temperature, chemical, and productivity data from known thermal springs and wells in order to define and prioritize new low- to moderate-temperature geothermal exploration targets. Data compiled were contributed to GEOTHERM. In Phase II, regional reconnaissance involved a more detailed look at the geothermal data gathered in Phase I in order to refine exploration target models and to outline optimum geothermal environments.

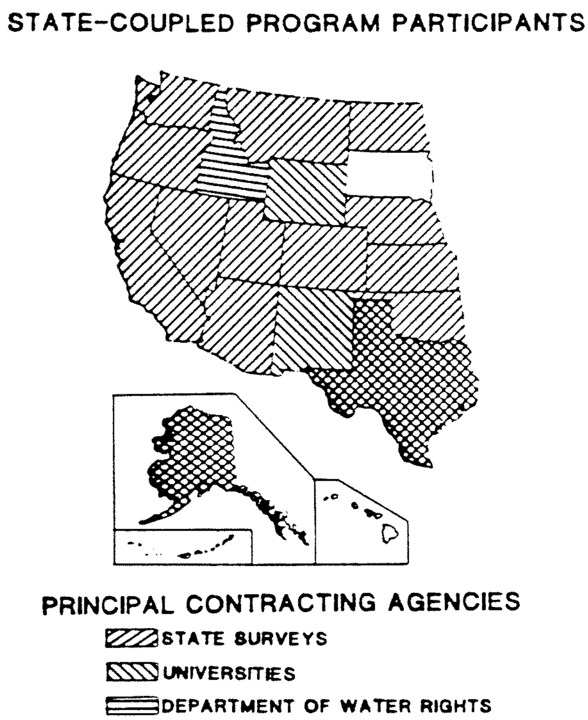


FIGURE 3

Publication of 18 state maps depicting thermal springs and wells (temperature, flow, depth, and TDS), areas potentially favorable for new discovery, and the outline of federal and state KGRAs was an important part of the State-Coupled Program. They are available through the National Oceanic and Atmospheric Administration. More technical maps for New Mexico and California were also produced. During the course of the program, over 150 detailed studies were performed at selected sites in the states identified in Figure 3.

The effect of these programs on the success of geothermal commercialization will not be fully realized for a number of years. Data developed from the Industry-Coupled program, however, are undoubtedly aiding geothermal electric power development in the Basin and Range.

The USER-COUPLED CONFIRMATION DRILLING PROGRAM was initiated in 1980 to promote direct uses of geothermal energy by establishing a predetermined cost-share schedule with an industry participant based upon the degree of success of the project. It was modified, however, by a shift in DOE policy away from direct financial incentives to promote the adoption of specific technologies. From an initial submission of 25 proposals, nine were selected for participation. This number was later reduced to four, and subsequent problems with prosper financing reduced the final number of projects to two, one at Alamosa, Colorado, and the other in the Wendel-Amedee area near Honey Lake in northern California. A production well at Alamosa was shut-in and abandoned after testing. The well at Honey Lake may be used to provide low-temperature fluids for a hybrid binary power plant under development by GeoProducts Co.

Improvements in Predictive Techniques

In the late 1960s and early 1970s, exploration methods for geothermal energy were adapted from the petroleum and mining industries, or were based upon methods used in historically established geothermal areas (i.e., The Geysers and Larderello, Italy), with only partial success. The need to develop better predictive methods became evident when exploration moved to the liquid-dominated geothermal environments.

A number of programs sponsored by DOE and USGS over the past few years have addressed these problems. Case history development from DOE's Industry-Coupled Program identified the suitability and limitations of various exploration methods and were subsequently modified to account for the nature of geothermal systems.

Improvements in chemical geothermometry by the USGS and others have allowed for the determination of prospective geothermal targets. Early interest in the mid 1960s on silica concentrations of natural water systems evolved through the use of sodium, potassium, and calcium concentrations in empirically-derived equations. Correction factors for these equations using other dissolved constituents (e.g., magnesium) were later introduced to better estimate reservoir equilibration temperature. State-of-the-art methods in chemical geothermometry currently incorporate the use of chemical thermodynamics and kinetics in the development of mixing models.

USGS research efforts have paralleled DOE's by program interaction and ongoing scientific research. Major geoscience accomplishments of the Geothermal Research Program of the USGS include:

- multidisciplinary studies of selected geothermal regions
- geothermometry development
- electrical and electromagnetic technique development
- refinement of passive and active seismic methods
- mathematical modeling of hydrologic systems.

The current DOE emphasis in hydrothermal reservoir research is directed at parameters that individually characterize producing hydrothermal systems. Research is under way for improvements in techniques to predict reservoir behavior under longterm production/injection of geothermal brines and to determine reservoir limits and controlling factors.

Various exploration methods, their usefulness, and present status are summarized in Table 3.

TABLE 3

USEFULNESS AND PRESENT STATUS OF VARIOUS EXPLORATION TECHNIQUES

METHOD	APPLICATION	STATUS
1. Thermal Gradient/Heat Flow	• Direct detection.	• *Currently recognized as most valuable indicator of* thermal anomaly.
2. Gravity	• Low-cost delineation of Shallow Basin Structure.	• Better resolution with improvements in quantitative numerical modeling.
3. Electrical Resistivity	• Low Resistivity Zones related to hot fluid circulation. Best detection of high angle structures.	• Numerical modeling techniques help produce intrinsic resistivity maps to depths of 500M.
4. MT/AMT	• Although used for detection to great depths, can be limited by surficial conductors.	• Research for application still ongoing.
5. Self Potential	• Low-cost detection of Basin Structure. Best in late stage of exploration.	• Utility uncertain.
6. Passive Seismic	• Detection of seismic emissions related to hydrothermal activity.	• Recognition of limitations within areas of thick alluvial cover. Method may not be cost-effective.
7. Reflection Seismic	• Cost-effective delineation of Border Faults and depth of alluvial fill.	• *Improvements in digital processing may reduce* problems associated with near-surface volcanics.
8. Magnetics	• Aeromagnetic surveys useful in determining regional structure.	• Identified limitations include interference from Reversely Polarized volcanic units, prism model development, interaction in complex geologic settings.
9. Geologic Mapping	• Low-cost regional and area studies.	• Currently recognized as important component to site-specific exploration programs, especially where faults intersect.
10. Geochemistry	• Estimating reservoir equilibration temperature.	• State-of-the-art methods include the use of chemical thermodynamics, development of "mixing" models, and studies of isotope fractionation. Isotope ratios give a simple and cheap initial idea of thermal conditions.

Advanced Drilling Techniques

In 1975, a federal program was initiated to improve rotary techniques for geothermal drilling in the hot, corrosive, and hard fractured rock geothermal environment. Since 1977, this program has been managed at Sandia National Laboratories, Albuquerque, New Mexico. The near-term goal of this research is to bring about a 25 percent cost reduction in conventional geothermal drilling. In the long term, a 50 percent cost reduction through the implementation of advanced drilling techniques is targeted.

Drilling Hardware: One of the success stories in the geothermal R&D program is the unique adaptation of *PDC (polycrystalline diamond compact) cutters* to drill bits. By 1981, five percent of all bits sold in the U.S. were PDC bits, and it has been estimated that this share will increase to 50 percent by 1990, with a large percentage used for oil drilling.

The Sandia *bit hydraulics test stand* permits the fluid flow around drill bits to be visualized and has indicated that some cutters in commercial drill bits were poorly situated. Similiar facilities have since been installed by at least one major bit manufacturer for use in improved bit design and cutter placement.

An *unsealed roller cone bit* and the required *high temperature lubricants* for this equipment are now on the market as a result of this program. Currently, the wear resistance of a much less expensive refractory material, niobium carbide, is being tested to determine the suitability of this material as a replacement for tungsten in *bit inserts*.

The use of *cavitating nozzles* has been pioneered to increase the efficiency of conventional drill bits. These nozzles cause bubbles to form in the fluid exiting the drill bit. When the bubbles contact the rock surface, they collapse violently, weakening the rock and aiding the drill bit cutters.

Non-conventional drilling systems that were developed as far as prototype designs include the *chain bit*, with downhole replaceable cutters, and the *Terra-drill*, a bit that fires ceramic projectiles (bullets) into the formation to weaken it and increase the drilling rate.

In order to improve drill bits and associated tools, Sandia is seeking to increase the knowledge of downhole conditions through *drill string dynamics* modeling. The importance of this project to industry is demonstrated by the fact that there are five industry co-sponsors (NL Baroid, Mobil Oil, Sohio, Conoco, and Arco). Downhole conditions are also simulated by *GEOTEMP*, a computer program that calculates the temperature profile in a well, and downhole drilling mud properties are measured on-site by a *high-temperature, high-pressure viscometer*.

Drilling Fluids: A major contribution of the federal geothermal program is the development of high-temperature geothermal drilling fluids. The temperature range of conventional muds can be increased by using *fibrous clays* developed by the on-going clay studies program, and *aqueous foams* that can survive temperatures up to 260° C (500° F) have been pioneered.

Lost Circulation: Loss of drilling fluid into fractured or high permeability zones is the most costly problem in geothermal drilling overall. Thus, a Lost Circulation Test Facility has been constructed and is used for simulating downhole tests of potential *lost circulation materials*. *Computer models* are also being used to identify the "ideal" lost circulation fluid.

Instrumentation: Significant advances in the development of *high-temperature electronics* have been made. Component development has resulted in a 275° C (527° F) operational amplifier, multiplexor, and hybrid circuitry (voltage regulators, line drivers, pulse stretchers, V/F converters).

Experimental logging tools have also been developed, including the *Wellbore Inertial Navigator* (borehole directional survey accurate to 1 m/1000 m depth) and the prototype *High-Temperature Acoustic Borehole Televiewer* (capable of operating to 275°C (527° F)). The televiewer has been successfully run for the Geothermal Division of Union Oil in the Imperial Valley, yielding valuable information on casing condition and fracture location. Temperature sensors and a variable logging speed capability are being added to the televiewer to modify it for use as a *Lost Circulation Zone Mapping Tool*.

Other ongoing projects include the *High-Temperature Cement Bond Log Tool*, *High-Temperature Mono-Cable Tools* (temperature, pressure, and flow measurements for production/injection logging), and the *Radar Fracture Mapping Tool* (using VHF electromagnetic signals to "see" fractures tens of meters away from the borehole).

Improvements in Materials

Initial geothermal energy projects borrowed materials and fluid engineering techniques from other industrial applications, largely oil production. Short well and equipment life and/or low process efficiency resulted because of the high-temperature, corrosive geothermal environment. In addition, numerous, and occasionally very costly, materials failures were experienced in the field, due to the unavailability of appropriate materials; a lack of awareness of suitable materials already existing; or a lack of knowledge about geochemical characteristics and behavior. Inefficient or ineffective components and systems often prevented the constant monitoring and data analysis required to maintain peak performance and avoid downtime of even a properly designed energy facility. The materials problems faced by the geothermal industry in the 1970s, the DOE R&D response, and the materials breakthroughs that are now available as "off-the-shelf" products and components are identified in Table 4. ☐

Part 2 Developments in Power Conversion Technology will be run in the July 1986 Issue of the *BULLETIN*.

Table 4

MATERIALS PROBLEMS IN GEOTHERMAL DEVELOPMENT — DOE MATERIALS PROGRAMS, SOLUTIONS/IMPROVEMENTS

PROBLEMS	DOE PROGRAM OBJECTIVES	SOLUTIONS/IMPROVEMENTS	
High cost of materials due to: — High temperatures and pressures — Corrosive and erosive fluids — Short lifetime Lack of materials performance data Fouling and scaling Poor understanding of fluid behavior/complex chemistry Unreliable sampling and anaylsis procedures	• Identify alternate high-temperature, corrosion-resistant materials to costly metals for borehole and energy conversion components • Test corrosion inhibitors and monitor • Research cathodic and anodic protection • Develop corrosion data base • Develop improved downwell and power plant instrumentation • Collect, analyze, and document field performance data • Develop solids and scale control methods • Model scale deposition and multi-ion fluids • Develop sensors for monitoring • Chemical and kinetic studies • Measure injectability of brine • Evaluate existing sampling and analysis methods and develop new techniques	• Mathematical model to calculate temperature changes in wells • High temperature equipment and materials: — hybrid electronic circuits — elastomeric seals and o-rings — open hole packer — well completion cement — lubricants, grease, and mud — downhole electric cable and cablehead equipment • Corrosion resistant equipment and materials: — downhole flow meter — well casing materials — polymer concrete — downhole pumps — pressure lubrication system — non-metallic heat exchanger tubing • Steels for improved drill bit life for fluids up to 400°C	• Wear resistant tungsten carbide and Ni-Cr-Si-B line shaft pump coatings • Improved roller cone bits, diamond drill bit • Effective carbonate scale control agent • Flash crystallization/thickening process • Binary system leak detector (e.g., sensors, particle counters) • On-line suspended solids monitor for injection • Summary document on sampling/analysis techniques • Guidelines/handbooks on materials selection, high temperature electronic components, and injection treatment