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GEOTHERMAL RESOURCE INVESTIGATIONS[a]

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(Paper of the Technical Council on Water Resources Planning and Management)

INTRODUCTION

The Bureau of Reclamation is presently involved in a cooperative geothermal investigation program with the Office of Saline Water to evaluate the potential for development of this important resource as a possible source of supply for augmenting the flow of the Colorado River. Other agencies involved include the Geological Survey, State of California, and the University of California at Riverside.

The Colorado River Compact allocates more water per year for consumptive use by the seven basin states than the runoff records of recent decades indicate are available. The supplies in the entire basin have been taxed by expanding agricultural demands and by an expanding population which is using water at an increasing per capita rate. To add to the problems of the area, ground water, an important source of supply, is being depleted rapidly in many parts of the basin. With the forthcoming construction of the Central Arizona Project and with continued expansion of the basin uses, the day will be upon us when essentially the entire runoff of the Colorado River will be utilized.

In addition, there is an obligation to deliver 1,500,000 acre-ft ($1,900 \times 10^6$ m^3) of water annually to satisfy the requirements of the Mexican Water Treaty.

Compounding the deficient water supply problem is the fact that the river is increasing in salinity. If allowed to continue, the Colorado River could become unsuitable for many present uses.

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To help solve these problems, the Congress passed the Colorado River Basin Act in 1968 (Public Law 90-537). One of the prime objectives of this Act is "for the provision of additional and adequate water supplies for the Colorado River Basin." A promising source of augmentation is desalted water from the geothermal resources in Imperial Valley, California.

Exploration within the last few years indicates the presence of a large volume of water in the sediments of Imperial Valley, California. The water has been heated to high temperatures by abnormal heat flow beneath the earth's crust.

Geological History

In order to get an understanding of heat flow in the earth's crust and the formation of geothermal reservoirs, it is necessary to go back hundreds of millions of years when the continents were not separated by large oceans. Recent crustal studies of the ocean floor and continental land masses show that the outer shell of the earth is a series of oceanic and continental plates that are being rafted about on the more or less plastic mantle of the interior.

If a modern-day Moses could be called upon to remove the water from the Pacific Ocean, then the floor would look something like Fig. 1. Submarine soundings and geophysical mapping show the location of oceanic ridges with central rift valleys. The ridges were built during a span of considerable geologic time as magma welled upward into a central rift where it cooled and was fractured as more intruded. Geologists believe that the ridges are spreading centers that mark the alinements where continents split and began to drift. All along the ridges, earth-shaking forces are at work. Geophysicists say that on the thin sea bottom, the earth's crust is being pulled apart and new crust added by injection of molten rock from the underlying mantle. Thus, from the crack, the ocean floors are now known to be moving outward several inches per year.

Geologists believe that most of the constant change in the Pacific's floor starts at the East Pacific Rise, a primal crack which cleaves northeastward from the South Seas for some 9,000 miles (15,000 km) before disappearing beneath the North American continent at the head of the Gulf of California.

About 4,000,000 yr ago, spreading began astride this part of the rise, and is continuing at about 2 in. or 3 in. (50 mm or 76 mm) per yr. Baja California, and that part of California that is west of the San Andreas fault are drifting slowly to the northwest with respect to the North American continent. This action has created a large structural feature in southern California called the "Salton Trough." Fig. 2 gives a conception of the crustal forces at work.

Following the formation of the trough and bordering mountain ranges, there has been a gradual settling of the central portion of the area now occupied by Imperial Valley. As this was occurring, the Colorado River was disgorging its load of sand, silt, and clay, with occasional sheets of gravel, onto deltas. The vast quantity of sediments that now occupy the Salton trough were carved out of the landscape of the Southwest, leaving many miles of deep scenic canyons.

One needs only to view the Grand Canyon in Arizona to get a perspective of the tremendous quantity of material that has been eroded by the river during past ages. This vast quantity of displaced material forms the present day Colorado River delta and also a prism of sediments in the Salton trough. Both are saturated

and constitute one of the largest untapped water supplies in the Southwest. Admittedly, it is mineralized and lies underground, but it contains a vast supply

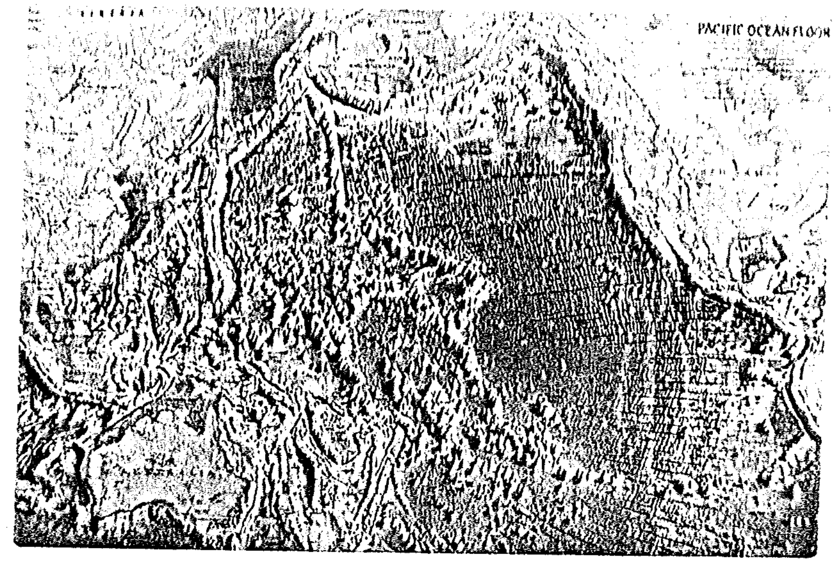

FIG. 1.—Map of Pacific Ocean Floor Showing East Pacific Rise, Primal Crack Which Cleaves Northeastward from South Seas for 9,000 Miles Before Disappearing at Head of Gulf of California

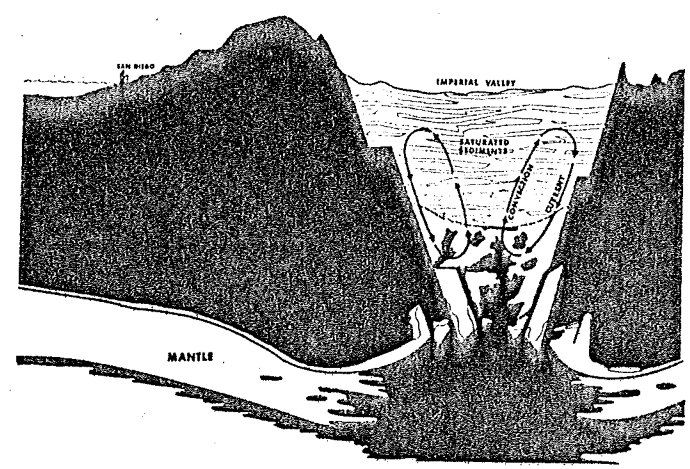

FIG. 2.—Generalized Section Through Salton Trough

of stored heat which can be translated into energy through steam powerplants. The United States Bureau of Reclamation has a mandate to study the feasibility of reclaiming a large part of this supply and putting it to beneficial use.

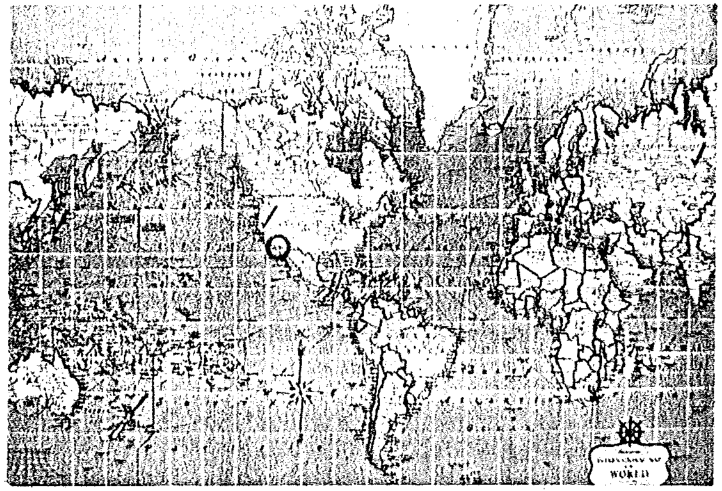

FIG. 3.—World Map Showing Countries Where Major Geothermal Developments Have Occurred

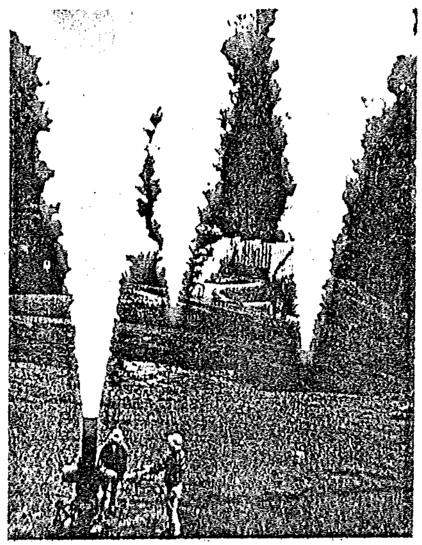

FIG. 4.—Geysers Well Field North of San Francisco, Calif.; Blowing Wells for Testing

Geothermal Resources

It is possible to tap the heat in saturated rocks by drilling geothermal wells. Geothermal wells are drilled routinely by qualified drillers in areas of high heat flow in many parts of the world. Geothermal reservoir engineering technology is presently in its infancy. Techniques for the exploration of geothermal resources are now being improved upon constantly.

Remarkable developments in the use of geothermal resources is to be expected worldwide in years to come. Countries in which geothermal developments are underway include the United States, Japan, Russia, Iceland, New Zealand, Italy, and Mexico (see Fig. 3). Geothermal power generation throughout the world amounts to about 800 Mw. Of that total, Italian geothermal power plants produce about one-half. The Imperial Valley area of southern California has one of the greatest known potentials for a successful geothermal development in this country.

In Mexico, the Cerro Prieto well field, about 20 miles (32 km) south of the Border, has been successfully developed for geothermal power production. This field is in the Mexicali Valley which is geologically contiguous with the Imperial Valley of the United States.

An exploratory well was drilled in 1964 about 2 miles (3.2 km) southeast of the Cerro Prieto volcano. Commercial production of steam with temperatures ranging from 400° F to 600° F (480° K–590° K) has been obtained at the 4,500-ft (1,400-m) depth. Several steam wells have been drilled and placed in full production. These wells supply steam to a 75-Mw power plant. The results at the Cerro Prieto field were so encouraging that plans are underway to extend the field southward and develop steam to generate additional power.

The Electrical Commission of Mexico has initiated a preliminary survey of all the important hot springs in Mexico, as well as a detailed study in the volcanic belt of central and northwest Mexico.

North of San Francisco, Calif., the Geysers dry steam well field is presently being successfully developed for power production. At the present time, about 192 Mw of electricity are being generated and plans are to provide an additional 110 Mw per yr to the system. Fig. 4 shows the Geysers steam field blowing off wells for testing.

Development of geothermal resources in the western United States was given a boost by the Geothermal Steam Act of 1970 signed into law by President Nixon. It is estimated that there are close to 1,500,000 acres (6×10^9 m^2) of Known Geothermal Resources Areas (KGRA) on public domain in the western United States. These areas are mainly in structural basins involving crustal distention and geologically young volcanism. Structural basins in the southern half of California, southern Nevada, western New Mexico, and much of Arizona are of interest to the Lower Colorado Region.

Bureau of Reclamation Investigations

The Bureau of Reclamation began active geothermal resource investigations in 1968. In June of that year, it began providing financial aid to the University of California at Riverside (UCR) which had been conducting geothermal studies in the Imperial Valley since 1964 (4). Contracts covering this financial aid have

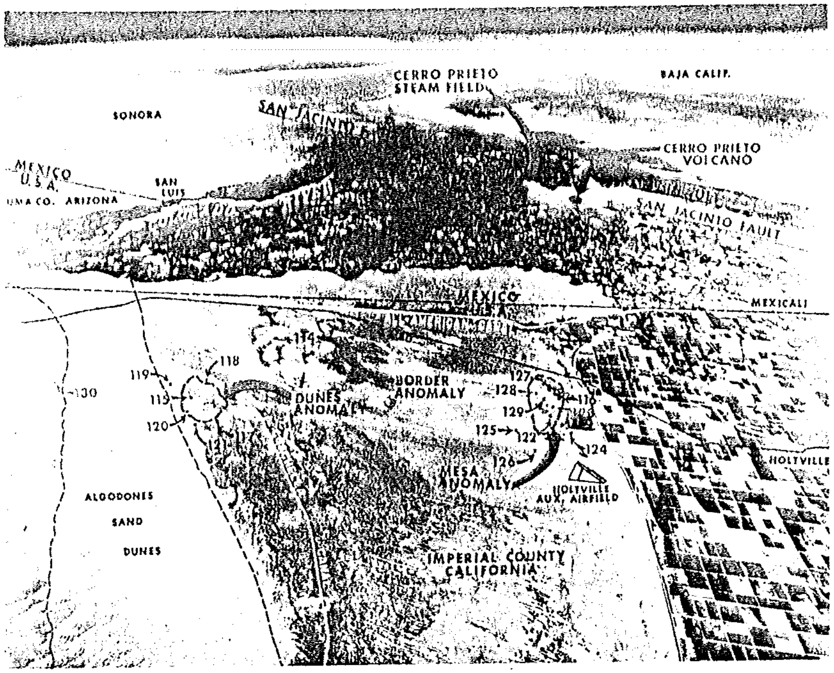

FIG. 5.—Aerial View Over Imperial Valley, Looking South, Shows: Location of Three Anomalies Investigated; Cerro Prieto Steam Field in Mexico

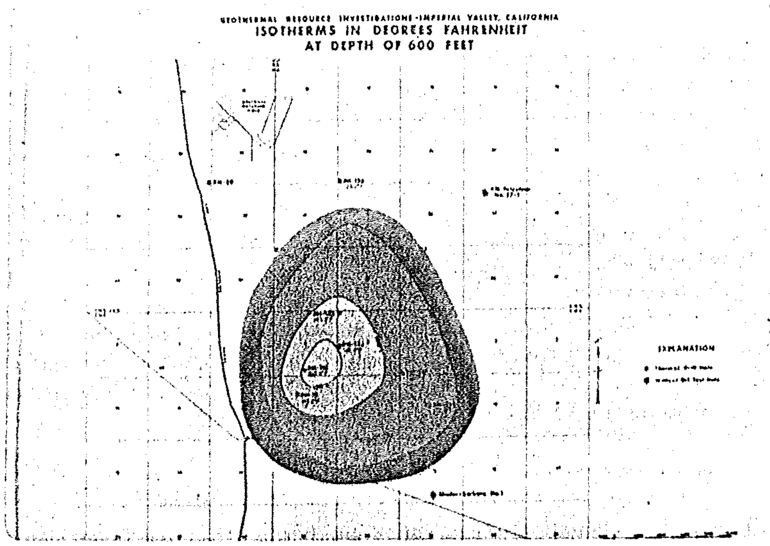

FIG. 6.—Distribution of Isotherms at 600 ft Depth on Mesa Anomaly

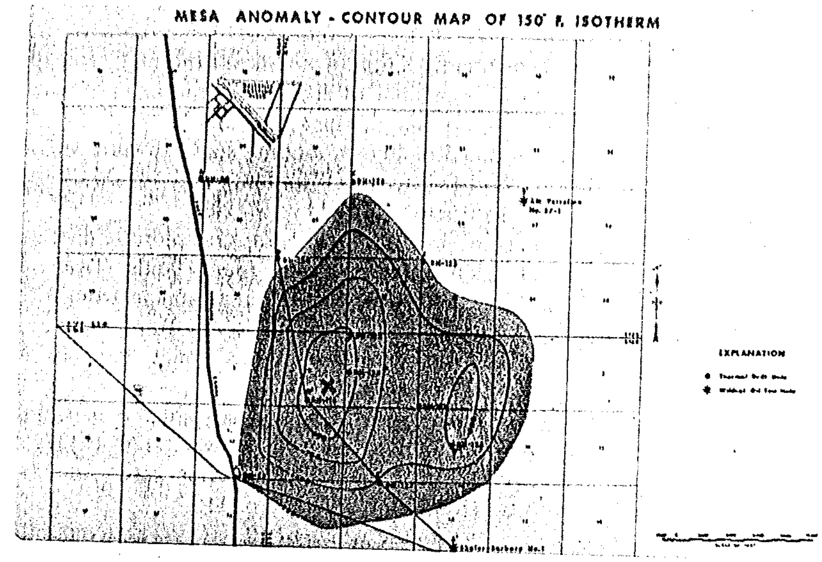

FIG. 7.—Contour Map of Elevations at Which 150° F Temperatures Are Encountered at Mesa Anomaly

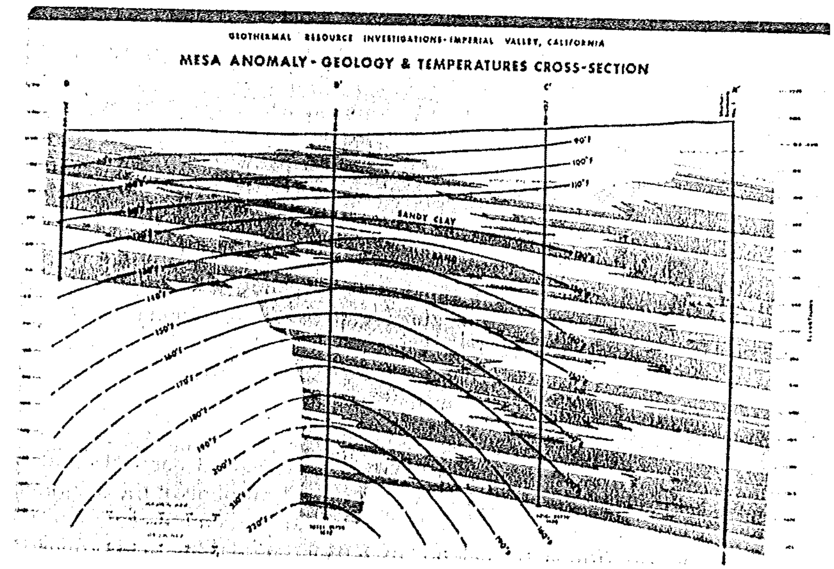

FIG. 8.—Generalized Stratification of Sand and Clay Along Section D-A on Mesa Anomaly; Isotherms Throughout Depth Tested

amounted to about $500,000 in the last 5 yr (1,2).

University of California investigations included geophysical surveys and measurement of temperature gradients in wells and test holes. The temperature data were processed and correlated with available geophysical data from all sources. These studies led to the identification of important thermal anomalies. A thermal anomaly is defined as "an area of high temperature at relatively shallow depths and is shown by contouring thermal gradients."

Three major anomalies are outlined in Fig. 5, looking south toward Mexico. The anomalies are referred to as the "Mesa," "Border," and "Dunes." Also shown is the location of the Cerro Prieto well field in Mexico.

In January, 1971, the Bureau started a drilling program to explore temperature gradients to a depth of about 1,500 ft (460 m) on Federal lands. Test wells were drilled on the three thermal anomalies, with depths ranging from 375 ft (114 m) at the Dunes anomaly to 1,463 ft (446 m) at the Border anomaly. A temperature of 231° F (384° K) was measured at the Dunes anomaly at a depth of 375 ft (114 m).

Fig. 6 shows the location of test holes on the Mesa anomaly and the distribution of isotherms at a 600-ft (180-m) depth, varying from between 120° F (322° K) at the outer edge to 160° F (344° K) near the center. A temperature of 221° F (378° K) was reached at 1,365 ft (416 m) in test hole No. 116.

Fig. 7 is a contour map of the elevations at which a 150° F (339° K) temperature is encountered in the Mesa anomaly area.

The generalized stratification of sand and clay at the Mesa anomaly can be visualized in Fig. 8. Also shown are the isotherms throughout the depth tested.

Measurements of heat flow involve a determination of the thermal gradient and the conductivity of the rock through which the heat is flowing. Temperature gradients in the upper 1,500 ft (460 m) of the saturated sediments were measured in existing water wells and test holes.

In comparison to a normal geologic environment where gradients are usually around 1° F (256° K) per 100 ft (31 m) of depth, the temperature gradients at the three anomalies ranged from 8° F to 10° F (260° K–261° K) per 100 ft (31 m) of depth.

The Border anomaly was found to be the coolest and the Dunes anomaly was the hottest. The Mesa anomaly has the greatest areal extent and the most uniform thermal gradients. Projection of the measured gradient in hole No. 116 indicated that high temperature zones capable of producing steam could be expected at depths ranging up to 8,000 ft (2,440 m) (6).

Mesa 6-1 Investigation

A contract for drilling of a deep geothermal well about 8 miles (13 km) east of Holtville, Calif., was awarded on May 25, 1972. The drilling of the exploratory well (Mesa 6-1) commenced on June 23, 1972, and was completed August 14, 1972. The well was drilled to a depth of 8,030 ft (2,448 m). On August 27, hot brine was jetting 75 ft (23 m) into the air as seen in Fig. 9. Several bore hole tests were made to determine the best completion methods for this well. The strata penetrated were logged by geophysical scanning and visual examination of the drill cuttings. Table 1 lists the logs that were run to measure geophysical parameters.

These logs were then utilized to prepare a Saraband log of porosities, permeabilities, and salinity. The Saraband computer program solves the interpretation, cross verifies the input data and results, and determines automatically the sand-clay ratios and other parameters.

Three coring runs were made to obtain cores for petrographic study and laboratory study of rock conductivity. Four drill-stem tests were run by sealing off sections of the bore hole with inflatable packers and allowing the formation fluid to percolate into the bore hole and into the testing tool and up the drill pipe. Formation pressure and temperatures were recorded in the zone tested for use in assessing the stratigraphic interval as to its fluid production potential.

TABLE 1.—Geophysical Logs Run on Geothermal Test Well Mesa 6-1

Logging method (1)	Paramotor measured (2)
Dual induction laterlog	Formation resistivity and self potential
Sonic	Rock velocities
Density (gamma gamma)	Rock densities
Density (neutron)	Density porosity and neutron porosity
Gamma ray	Gamma radiation intensity

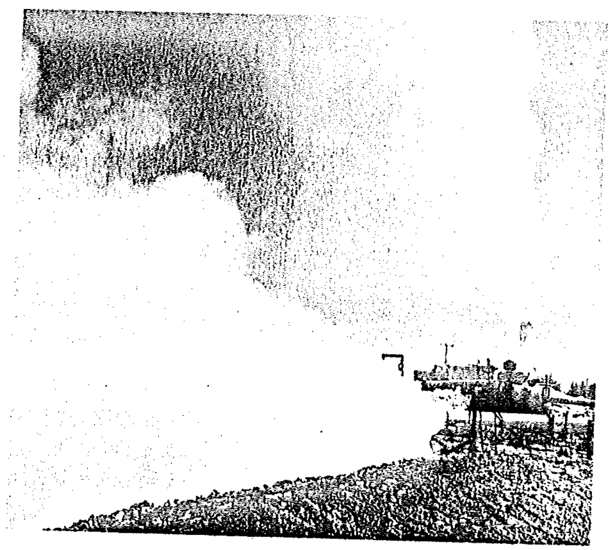

FIG. 9.—View of Hot Brine Jetting into Air from Mesa 6-1 Exploratory Test Well

Temperature surveys were conducted both during drilling and after completion of the well. Temperature runs are plotted in Fig. 10. The first six plots recorded in July and August show temperatures which were measured before completion of the well and reflect the colder temperatures brought about by the thermal effect of the cooling mud and water during drilling. The September plot was measured less than 24 hr after production was shut down and reflects the high temperature effect of production. The October plot was from data collected 6 days after the well was shut down and represents quasi-equilibrium conditions.

Mesa 6-1 was completed with three casing strings and a slotted liner as shown in Fig. 11.

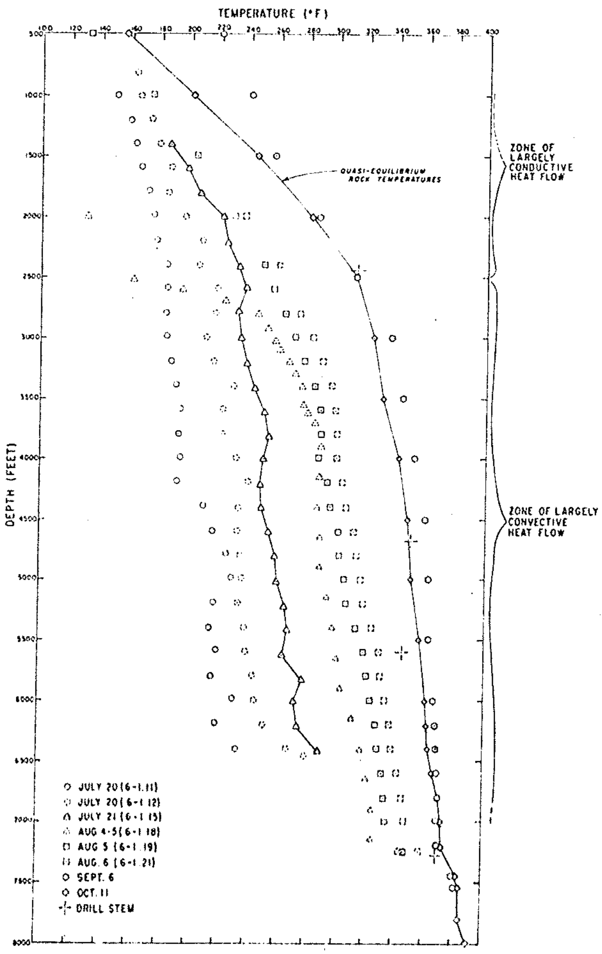

FIG. 10.—Temperatures in Deep Geothermal Test Well Mesa 6-1

Mesa 6-1 has sufficient pressure and temperature to produce steam and mineralized water. Temperature data combined with permeability and porosity measurements show the advisability of opening additional producing sands and sandstone between 2,500 ft (760 m) and 6,000 ft (1,800 m) to obtain additional production of thermal energy and fluid. Detailed temperature surveys are being made to locate the hottest producing sands or sandstones.

The facilities to start research desalting operations were completed recently.

These include a cyclone separator, a steam silencer, surface plumbing, and a brine holding pond. The Office of Saline Water provided a portable desalting plant for installation in connection with research on the desalting process. On June 3, 1973, the first recovery of fresh water from geothermal brine was accomplished. Fluid with salinities of over 20,000 ppm, total dissolved solids, was reduced to less than 50 ppm in a multistage flash unit utilizing geothermal

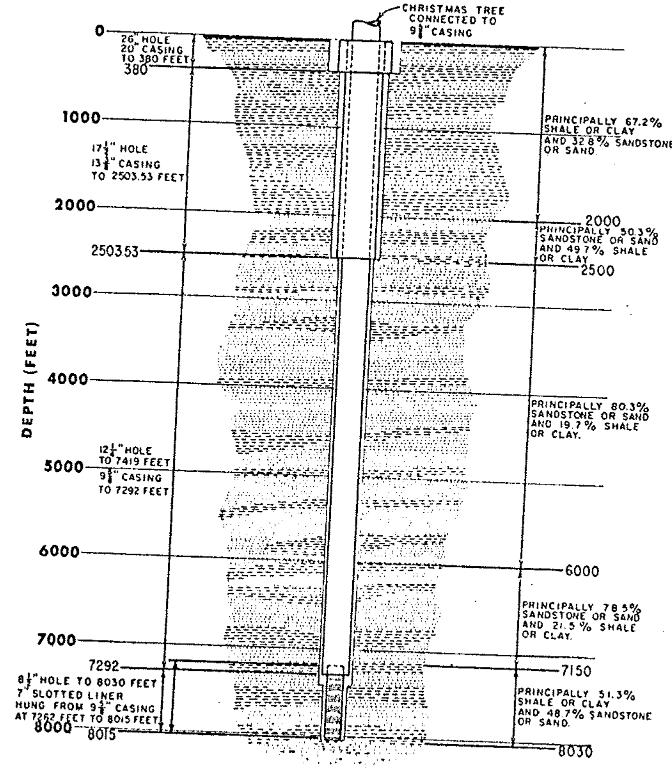

FIG. 11.—Diagram of Deep Geothermal Test Well Mesa 6-1

energy. Fig. 12 shows the desalting unit in operation. A vertical tube evaporator unit has also been installed and is being tested.

A second geothermal well (Mesa 6-2), drilled just to the west of Mesa 6-1 was completed in August, 1973. Pipelines and facilities are being constructed to connect the two wells and injection studies are being planned.

Continuing Research

Many unknowns still exist, e.g., what is the extent of the resource? What desalting process should be used? How should reinjection waters be treated so they will not plug the aquifer? These unknowns dictate careful step-by-step development.

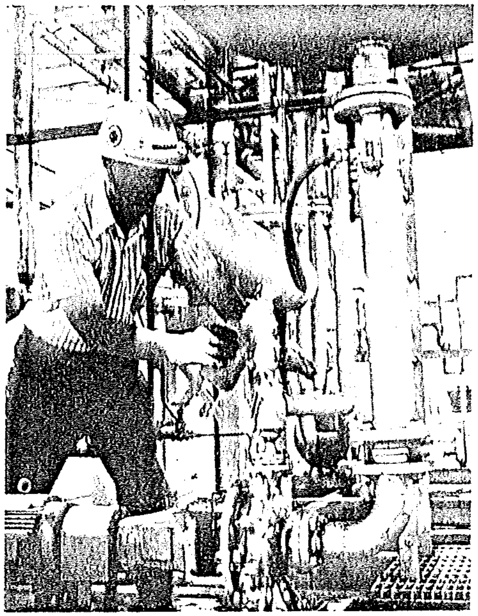

FIG. 12.—View of Multistage Flash Distillation Unit in Operation at Test Well Mesa 6-1

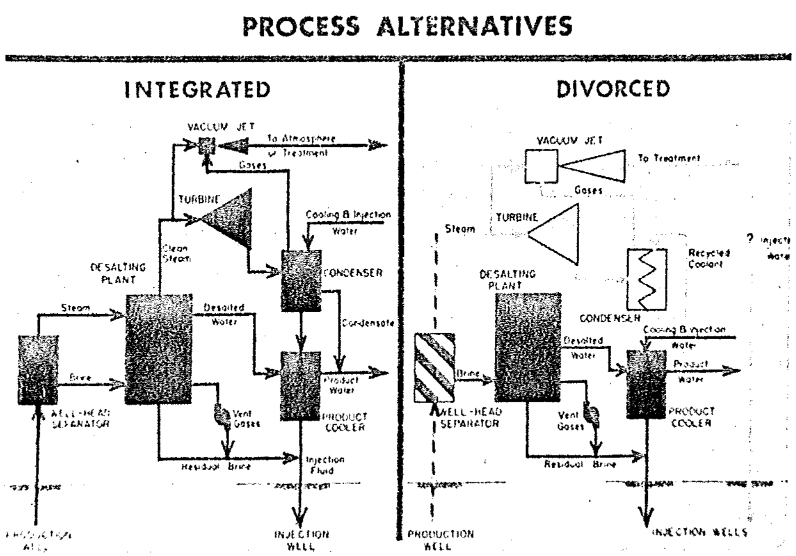

FIG. 13.—Diagrammatic Representation of Integrated and Divorced Process Alternatives

It will be necessary to import makeup water for reinjection into the ground-water reservoir to maintain subsurface pressures and prevent subsidence. In the Imperial Valley, subsidence could not be tolerated. The canals and drains that make this into a highly developed irrigation area slope less than 5 ft (1.5 m) per mile (1.6 km) and any appreciable subsidence would seriously affect the ability of the irrigation system to function.

There are two possible ways in which the development could proceed: (1) Under an integrated system which appears most economical; or (2) under a divorced system (see Fig. 13).

In the integrated system, fluids would come from the ground as a two-phase mixture of water and steam. Behaving similarly to a percolator, they would reach the wellhead about 80% brine and 20% steam, then run through a wellhead separator where the steam and the brine would be separated. Both steam and brine would enter the desalting plant and pass through the distilling process, and the steam would condense to produce water.

Before passing through the power turbines, the steam would have to be cleansed of any hydrogen sulfide, carbon dioxide, and ammonia, permitting the turbine to be built of conventional instead of exotic materials. From the desalting plant, the high temperature desalted water stream would pass into the product water coolers. The residual brine leaving the desalting plant along with imported makeup water would then be reinjected into the ground.

With a divorced system, the power-producing and water-producing facilities would be separated to the extent possible. In the divorced system, however, if the turbine or the desalting plant were inoperative, it would have an effect on the disposition of the brine or the disposition of the steam as it would not be practical to operate one without the other also being on the line.

All of the preceding require a carefully planned program of continuing investigations.

Future Investigations

Geophysical work on the Mesa anomaly is being intensified in order to locate additional exploratory well sites and the best locations for drilling injection wells. This will be accomplished by gravity, resistivity, and seismic ground noise studies, followed by a drilling program and by temperature, water chemistry, and ground-water reservoir studies. Other work in the immediate future includes the drilling of wells to approx 6,000 ft (1,800 m) to study the configuration of the Mesa geothermal system. Brine disposal methods and means of recharging the geothermal fields will also be studied, and the investigation of power generation will be an integral part of the geothermal program. Close coordination will be maintained with the Geological Survey (5) and other agencies in the areas of injection and other methods of brine disposal.

Geothermal Well Potential

It is estimated that a total of 1,800 geothermal wells would be required to form 150 modules for the purpose of producing 2,500,000 acre-ft ($3,100 \times 10^6$ m^3) of desalted water per year (3). Approx 2,400 injection wells would be required to recharge the ground-water basin with injection water imported from the Pacific Ocean and the Salton Sea. The potential electric power development at full operation would be 10,500 Mw annually. Pumping and processing load requirements are estimated to be 2,000 Mw per yr.

Desalted water could be delivered to several points along the Colorado River. The most distant and highest points such as Lake Mead would be the most costly, but would provide the greatest benefits for storage and water quality.

In addition to Reclamation's geothermal investigations, the states are making some studies of this important resource. On June 3, 1972, the California Department of Water Resources started drilling a well in the Dunes geothermal anomaly a few miles east of Reclamation's Mesa 6-1 well. On June 29, 1972, the well was completed to a 2,007-ft (610-m) depth. Highest flowline temperature (temperature of drilling mud coming out of the hole) was 200° F. (370° K). The contractor installed a 4-in. (100-mm) casing and temperature tests were performed. The highest temperature recorded was 222° F (378° K) at the 900-ft (270-m) depth. The University of California at Riverside and California Department of Water Resources will continue testing and sampling flows from this well.

Conclusions

The future holds great promise in the geothermal field, and it is up to the ingenuity and capabilities of the Bureau of Reclamation to develop the best plan possible. Geothermal development in the Lower Colorado Region is one of the more promising programs of water development available to supplement the present supply of the Colorado River System.

Although the drilling and testing of Mesa 6-1 and Mesa 6-2 have yielded substantial information on the nature of the Mesa geothermal anomaly, a geothermal field cannot be characterized on the basis of only two wells, and the data collected to date emphasize the need for further study. The information available is useful in planning additional exploration and testing programs involving the production and utilization of geothermal fluids (7).

The Bureau of Reclamation's near-term efforts will continue to be concentrated on the Mesa anomaly. This will include the installation and testing of pilot desalting units. To maintain continuity of operation of the pilot desalting units, an injection well will be necessary as a means of brine disposal. Exploratory holes will be drilled to further define the extent and character of the anomaly and temperature distribution within the anomaly.

It is important to proceed on an orderly plan of development to meet the water needs of the Lower Colorado River Basin, not only for the immediate future, but for long-range projections as well.

Appendix.—References

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