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GEOTHERMAL ENERGY ABSTRACT SETS

SPECIAL REPORT NO. 14

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Compiled and Edited By
Claudia Stone

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This section of Special Report 14 Addendum can be removed and added to previously printed Special Report 14 sections.

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SUMMARY

The twelve abstract categories contained in this set of publications were developed by the staff of the Geothermal Resources Council and twelve volunteer Oversight Committee Members who are experts in their fields. The project management and editing was performed by Claudia Stone and the names of the twelve committee members appear on the front of each Abstract Set.

Basic information on various publications was gained primarily through DIALOG Information Retrival Service of Palo Alto, CA. DIALOG provides an online reference service that lists the basic information needed to identify a specific publication. The following Databases were accessed during the preparation of this document. NTIS, GEOREF, GEOARCHIVE, COMPENDEX, DOE ENERGY, EiENGINEERING, ENERGY LINE, ENVIROLINE, and SCISEARCH. In addition, the Science Citation Index was used to determine if more recent material had been published on various categories.

Each citation contains the title, author(s), publication or publisher, year published, number of pages, volume, and NTIS numbers. In most cases the citations are up-to-date within the last six month period. They were all reviewed by the expert members of the Oversight Committee who deleted those not considered worthy and augmented the sets with citations that they found to be important enough to add. It is felt that these sets of abstracts represent the publications that would make up a basic library on geothermal energy.

As designed, each of the Abstract Sets should be removed from the issue of the Geothermal Resources Council *BULLETIN* in which they were published, and they should be inserted in order in a three ring binder. Organized in this manner, they will be easy to locate and use, with some diligence they can be easily augmented from time to time when worthy papers are produced.

David N. Anderson
Executive Director
Geothermal Resources Council

SPECIAL REPORT NO. 14

Abstract Sets Separate and BULLETIN Issues Printed To Date

Case Histories

1/2

GEOTHERMAL ENERGY ABSTRACT SETS

Exploration Strategies and Case Histories

Abstracts reviewed by Norman E. Goldstein, B. Greider, Paul W. Kasameyer, and Phillip M. Wright

TO MEMBERS AND SUBSCRIBERS:

This abstract set is the first of a series dealing with geothermal exploration, development, and production. The series is the product of a Department of Energy grant to the GRC that includes the development of 12 timely topics and compilation and publication of an abstract set on each. Abstract sets have been reviewed by specialists in the topic area for relevance and importance.

Abstracts have been reproduced exactly as published or reproduced by the computer reference service, DIALOG, except for correction of obvious spelling and typographical errors. However, we have noticed that some abstracts retrieved from DIALOG have been abridged. We have abridged (and so noted) a few abstracts that contain nonessential information.

CANADA

Fairbank, B.D., R.E. Openshaw, J.G. Souther, and J.J. Stauder, 1981, Meager Creek geothermal project — An exploration case history: Geothermal Resources Council Bulletin, v. 10, no. 7, p. 3-7.

————1981, Geothermal potential of the Cascade Mountain range: Exploration and development: Geothermal Resources Council Special Report No. 10, p. 15-19.

ABSTRACT — The South Reservoir in the Meager Creek Geothermal Area is within crystalline basement rocks on the southern flank of the Pliocene to Recent Meager Mountain Volcanic Complex. Geological, geochemical and resistivity surveys were used to determine targets for temperature gradient diamond drilling. Temperature profiles indicate anomously high temperature gradients in drill holes M2, M3, M4, M6, M7, M8, M10, M11 and M12. Heat flow values of 105-620 mWm^2 (2.5- 14.8 HFU) have been calculated for drill holes M2, M3, M7, M8, M11 and M12; these values are up to seven times the regional heat flow for the Garibaldi Volcanic Belt. The main South Reservoir thermal anomaly has been defined over an area about 3 km by 1 km in the Meager Creek valley and is open to the north and southeast. Deep drilling and production testing to assess the reservoir as a potential power source will be initiated during 1981.

CHINA

Kuide, Xin, and Yang Qilong, 1983, Geothermal energy development in China: Ninth Workshop on Geothermal Reservoir Engineering, Stanford University.

NO ABSTRACT. Note from Introduction: China's geothermal resources are mainly of low - medium temperature. More than 30 geothermal areas have been or are being explorated. According to the geology, economy and technology of geothermal energy development main efforts are concentrated in some places with better conditions and can be exploited effectively in the near future, such as low temperature geothermal fields in Beijing and Tianjin, Yangbajain and Dengchong high temperature geothermal fields respectively in Tibet and Yunnan province.

In Beijing and Tianjin the geothermal water is used for space heating, bathing, medical treatment, greenhouse, raising tropical fish, industry and so on. In Beijing now more than 200 thousand sq. m. of indoor floor is being heated with geothermal water and about 50 thousand persons per day use it to take bath. In future, the low temperature geothermal water utilization in these big cities would flourish.

In 1970 the first experimental geothermal power plant using the flashing method was built in Dengwu, Guangdong province. In 1977 one MW experimental wet steam power plant was built in Yangbajain, Tibet, and a 6 MW power plant in 1981 (Photo 1). And another 3 MW generator is expected to complete in 1985.

This paper is intended to summarize some important results of exploration, particularly in the geothermal reservoir engineering.

COSTA RICA

Koenig, J.B., 1980, Exploration and discovery of the Miravalles geothermal field, Costa Rica: A case history: Geothermal Resources Council Special Report No. 9, p. 59-62.

NO ABSTRACT. This report discusses geologic, geochemical, and geophysical exploration studies and drilling.

EL SALVADOR

Cuellar, Gustavo, Mario Choussy, and David Escobar, 1981, Extraction-reinjection at Ahuachapan geothermal field, El Salvador, in Rybach, L., and Muffler, L.J.P. (eds.), Geothermal Systems; Principles and Case Histories: John Wiley & Sons, p. 321-336.

NO ABSTRACT. The main sections in this paper are Introduction, Geological Setting, Hydrogeology, Characteristics of the Ahuachapan Wells, Reinjection Program, Effects of the Reinjection-Extraction Rate, and Conclusions.

HUNGARY

Ottlik, Peter, Janos Galfi, Ferenc Horvath, Karoly Korim, and Lajos Stegena, 1981, The low enthalpy geothermal resource of the Pannonian Basin, Hungary, in Rybach, L., and Muffler, L.J.P. (eds.), Geothermal Systems; Principles and Case Histories: John Wiley & Sons, p. 221-245.

NO ABSTRACT. The main sections in this paper are Introduction, Geological Framework, Geothermics, Hydrogeology (including chemistry), and The Recovery and Utilization of the Geothermal Energy.

ICELAND

Arnorsson, Stefan, Axel Bjornsson, Gestur Gislason, and Gudmundur Gudmundsson, 1976, Systematic exploration of the Krisuvik high-temperature area, Reykjanes peninsula, Iceland: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 853-864.

ABSTRACT — The exploration program consisted of two phases, (1) a surface exploration by means of geophysical, geochemical, and geological methods, and (2) drilling of slim, 800 to 1000 m deep exploratory wells.

Surface thermal manifestations are scattered over an area of 10 to 20 km^2. Schlumberger soundings indicate a continuous hydrothermal reservoir under this area at depths of less than 1000 m. The size of the area is about 40 km^2 as determined by the 30 ohm-m isoline at 600 m depth. Drilling of slim wells proved difficult for many technical reasons and not so inexpensive as expected.

All five deep wells in the area display inverse thermal gradients. Possible explanations are: (1) narrow upflow zone or zones and horizontal hot-water movement at shallow depth, and (2) weakening of an intrusive complex heat-source without much decrease in the flow rate of water through the system. Maximum temperature in each well ranges from 180 to 260°C. There is a positive relationship between maximum temperatures and the depth to this maximum. This variation can be explained by mixing of rather saline hot deep water with fresh warm water in the upflow zones. The distribution of the hydrothermal mineral assemblages does not fit well with the present-day underground temperature distribution. Average porosity in selected samples of core is 11%. The rocks at depths of 3 to 5 km appear to be relatively porous as inferred from magnetotelluric (MT) measurements. All the exploratory wells penetrated several permeable aquifers. For better understanding of the inverse gradients, a 2000 m deep exploratory well is needed.

Bjornsson, Axel, 1981, Exploration and exploitation of low-temperature geothermal fields for district heating in Akureyri, north Iceland: Geothermal Resources Council, Transactions, v. 5, p. 495-498.

ABSTRACT — The Tertiary basalt formations in the vicinity of the town of Akureyri in central northern Iceland are characterized by low permeability, except for thin interlayer and narrow fissures along dykes. Although several thermal springs are found in the area, decades of geothermal exploration brought no success.

A renewed geothermal exploration was started in 1975. Geological and geophysical reconnaissance survey revealed three geothermal prospects. Drilling of the Eyjafjordur area 12 km south of Akureyri, was successful and some 150 l/s of 80-96 °C hot water is now produced from 6 wells. The water is low in dissolved solids and is used direct for cooking and space heating. About 85% of the town is now supplied with 70-80°C hot water from a district heating service. The total cost savings for the people of Akureyri, by using geothermal instead of imported oil, are some $5 million per year. Research and drilling is continuing for further utilization of thermal water.

Georgsson, L.S., Haukur Johannesson, and Einar Gunnlaugsson, 1981, The Baer thermal area in western Iceland: Exploration and exploitation: Geothermal Resources Council, Transactions, v. 5, p. 511-514.

ABSTRACT — The hot springs in the Baer thermal area are distributed in 4 groups on a 2 km long line striking N10°W. Natural discharge is 8 l/s and maximum temperature 94°C. Evidence indicates that the linearity originates from a fracture. The fracture is intersected by NE-SW trending dykes and faults which coincide with the groups of hot springs. The fracture opens the way up for fluid flowing along the dykes and faults.

Nine wells have been drilled in the area of which two are productive and yield 60 l/s of 95°C hot water by downhole pumping. This may be increased to 110 l/s with further drilling and a drawdown of the water level to 110 m depth.

The water will be used for a district heating system in the small towns of Borgarnes and Akranes (6500 inhabitants together). The hot water will be transported 60 km in an insulated pipeline which will be completed in late 1981.

Stefansson, V., 1981, The Krafla geothermal field, northeast Iceland, in Rybach, L., and Muffler, L.J.P. (eds.), Geothermal Systems; Principles and Case Histories: John Wiley & Sons, p. 273-294.

NO ABSTRACT. The main sections in this paper are Introduction, Geological Framework, Exploration History and the Model of the Field, Production Characteristics of the Field, Experience with Utilization, and Current and Future Developments.

INDIA

Shanker, Ravi, R.N. Padhi, C.L. Arora, Gyan Prakash, J.L. Thussu, and K.J.S. Dua, 1976, Geothermal exploration of the Puga and Chumathang geothermal fields, Ladakh, India: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 1, p. 245-258.

ABSTRACT — Puga and Chumathang geothermal fields are situated near the collided junction of the Indian and Asian crustal plates, and thermal activity in these fields is attributed to the widespread igneous activity of Upper Cretaceous to late Tertiary age. A deep suture zone, recognized between these two fields and the associated faults, provides channels for the upward migration of the thermal fluids. High concentrations of Cl, F, B, SiO_2, Na, Li, Rb, Cs in thermal fluids signify contribution of magmatic bodies toward heat and fluid supply.

These fluids are characterized by high heat flow conditions (13 HFU), abnormal shallow geothermal gradients (0.7 to 2.5°C/m), high base temperature (220 to 270°C) as obtained by alkali and Na-K-Ca geothermometry, and low resistivity values (2-20 ohm-m). Low resistivity zones occupy areas of 3 and 1 sq km, respectively, and extend down to maximum depths of 300 m and 130 m at Puga and Chumathang.

Shallow drilling (28-130 m) has established the existence of wet steam reservoirs under moderate pressure (2 to 4.5 kg/cm^2). Hot fluid (90 to 135°C/km) discharges from eight flowing wells ranging from 7.5 to 30 tons/hr.

These thermal fluids are stored in the partly consolidated fluvioglacial deposits of Quaternary to Recent age. The occurrence of a limestone layer in the country rock at Puga brightens the prospects of getting good reservoir at depth. In both these fields two aquifers have been recognized, each having sizeable potential for retaining ground water. The ground water recharge is mainly through snow melt from glaciers in the case of the Puga field and principally from the Indus River in the Chumathang field.

INDONESIA

Radja, Vincent, 1976, Overview of geothermal energy studies in Indonesia: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 1, p. 233-240.

ABSTRACT — The ever-increasing demand for electricity in Indonesia has led to investigation of the possibility of using new sources of energy. One such effort has been directed toward the development of geothermal energy resources.

From the point of view of volcanology, Indonesia is a country potentially rich in geothermal power. Studies have been conducted by government agencies, Indonesian and foreign, as well as by private agencies, to obtain as much data as possible on these potentials.

Since the steam drilling at the Kawah Kamojang (West Java) fumaroles fields in 1928, several attempts have been made to discover new geothermal fields throughout the Indonesian archipelago.

This paper describes geothermal energy exploration carried out at the Dieng Mountains in central Java. This includes airborne and geological surveys, geochemical investigations, geophysical prospecting and determination of geothermal gradients in shallow holes. The paper also discusses a similar study at Kawah Kamojang and other geothermal resources in Indonesia.

ITALY

Baldi, Plinio, G.M. Cameli, Enzo Locardi, Jean Mouton, and Fabio Scandellari, 1976, Geology and geophysics of the Cesano geothermal field: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 871-881.

ABSTRACT — In the Monti Sabatini region, geologic, volcanologic, hydrogeologic, geochemical, and geophysical investigations were carried out for geothermal exploration.

Geologic and geochemical surveys indicate that two aquifers can be singled out: the unconfined one, which is a fresh water aquifer, and the confined one, which bears thermal saline water. Volcanology evidences that a rift volcanism is present in the area. Gravity data show a strong positive Bouguer anomaly (>30 mgal) east of Lake Bracciano, marking the presence of a main structural high trending northwest-southeast. The geoelectric survey confirms this high by the detection of a resistant substratum uplifted feature under a conductive cover complex. This substratum is cut by some northwest-southeast discontinuities into a series of blocks at different depths. Some of these discontinuities match with anomalous conductive bands and with magnetic anomalies. Temperature gradient and heat flow maps show an area of maxima near Cesano.

The overlap of all the data acquired from these investigations evidenced a preferential area north of Cesano where the first exploratory well was sited.

Cameli, G.M., Michele Rendina, Mariano Puxeddu, Aristide Rossi, Paolo Squarci, and Learco Taffi, 1976, Geothermal research in western Campania (southern Italy): Geological and geophysical results: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 1, p. 315-328.

ABSTRACT — A CNR-ENEL research program, begun in 1969, re-examined the Phlegraean Fields area (Naples), where research from 1939 to 1955 had revealed: (1)temperatures in the order of 300°C at 1800 m below sea level; (2) low permeability of the drilled volcanics; and (3) hypersaline waters (up to 35 g/l TDS).

This new research program has involved an area of about 4000 km^2, lying between the Volturno valley to the north, the Naples-Phlegraean Fields coastal belt to the south, the Campanian Apennines to the east and the Tyrrhenian Sea to the west, with the aim of identifying exploitable geothermal reservoirs at a technically and economically accessible depth.

Photogeological, petrological, gravitational, electrical, magnetotelluric, and geothermal surveys revealed an uplifted feature, probably in the buried Mesozoic carbonate formations. This feature is characterized by a southwest-northeast trend and by a mainly clay-sand sedimentary caprock overlain by outcropping volcanics.

The top of this feature is 1500 m deep, underlying the towns of Qualiano and Parete (about 20 km northeast of the Phlegraean Fields).

The highest geothermal gradient (1.5°C/10 m) was determined near Parete. Research will continue with the drilling of deep exploratory wells located in the structural high.

JAPAN

Nakamura, Hisayoshi, and Kiyoshi Sumi, 1981, Exploration and development at Takinoue, Japan, in Rybach, L., and Muffler, L.J.P. (eds.), Geothermal Systems; Principles and Case Histories: John Wiley & Sons, p. 247-272.

NO ABSTRACT. The main sections in this paper are Introduction, Geological Framework, History of Exploration, Production Characteristics, Effectiveness and Economics, and Future Development.

Sumi, Kiyoshi, 1978, Geothermal resources of Japan: Energy Developments in Japan, v. 1, p. 3-32.

ABSTRACT — Characteristics of geothermal resources of Japan are summarized with special attention given to their geological distributions. Potentially, there are four types of geothermal resources in Japan, i.e., natural dry steam, high enthalpy thermal water in volcanic areas; low enthalpy thermal water in sedimentary basins in non-volcanic regions; hot dry rock; and volcanic heat. Among these, the high enthalpy thermal water in the volcanic areas is of the greatest interest at present. This results from the fact that most of Japanese geothermal resources are distributed in a big volcano-tectonic depressed region which was formed

in the Miocene period. The depressed region is filled mainly with Neogene Tertiary volcanic rocks in thicknesses of one or two kilometers and overlain by the clusters of volcanic cones of Quaternary age. Such a structure is apparently conducive to the formation of high enthalpy thermal water which requires a reservoir structure and a sufficient supply of heat and water. national reserves of the natural dry steam and high enthalpy thermal water which may be utilized for commercial power generation are calculated to be more than ten million kW for a thousand years at least, taking into account only production wells not deeper than 1.5 kilometers. It is demonstrated that prospecting hereafter should be focused on the deeply seated geothermal resources which may occur in pre-Miocene fractured sedimentary rocks hidden beneath the Miocene volcanic rocks of the Neogene volcano-tectonic depressed area in Japan.

MEXICO

Lippman, M.J., 1983, Overview of Cerro Prieto studies: Geothermics, v. 12, p. 265-289.

ABSTRACT — The studies performed on the Cerro Prieto geothermal field, Mexico, since the late 1950s are summarized. Emphasis is given to those activities leading to the identification of the sources of heat and mass, the fluid flow paths, and the phenomena occurring in the field in its natural state and under exploitation.

Lippman, M.J., N.E. Goldstein, S.E. Halfman, and P.A. Witherspoon, 1984, Exploration and development of the Cerro Prieto geothermal field: Journal of Petroleum Technology (in press).

ABSTRACT — A multidisciplinary effort to locate, delineate, and characterize the geothermal system at Cerro Prieto, Baja California, Mexico, began about 25 years ago. It led to the identification of an important high-temperature, liquid-dominated geothermal system which went into production in 1973. Initially, the effort was undertaken principally by the Mexican electric power agency, the Comision Federal de Electricidad (CFE). Starting in 1977 a group of U.S. organizations sponsored by the U.S. Department of Energy, joined CFE in this endeavor.

An evaluation of the different studies carried out at Cerro Prieto has shown that: 1) surface electrical resistivity and seismic reflection surveys are useful in defining targets for exploratory drilling, 2) the mineralogical studies of cores and cuttings and the analysis of well logs are important in designing the completion of wells, identifying geological controls on fluid movement, determining thermal effects and inferring the thermal history of the field, 3) geochemical surveys help to define zones of recharge and paths of fluid migration, and 4) reservoir engineering studies are necessary in establishing the characteristics of the reservoir and in predicting its response to fluid production.

NEW ZEALAND

Prichett, J.W., L.F. Rice, and S.K. Garg, 1979, Summary of reservoir engineering data: Wairakei geothermal field, New Zealand: Lawrence Berkeley Laboratory, Report No. LBL 8669, 25 p.

ABSTRACT — This is an abbreviated summary of the final project report on an extensive collection of fundamental field information concerning the history of the Wairakei geothermal field in New Zealand. The purpose of the effort was to accumulate any and all pertinent data so that various theoretical reservoir simulation studies may be carried out in the future in a meaningful way. Categories of data considered include electrical resistivity measurements, magnetic force surveys, surface heat flow data and a catalog of surface manifestations of geothermal activity, geological and stratigraphic information, residual gravity anomaly surveys, laboratory measurements of formation properties, seismic velocity data, measurements of fluid chemical composition, monthly well-by-well mass and heat production histories for 1953 through 1976, reservoir pressure and temperature data and measurements of subsidence and horizontal ground deformation. The information is presented in three forms. A review of all the data is contained in the final project report. The present report summarizes that information. In addition, a magnetic tape suitable for use on a computer has been prepared. The magnetic tape contains a bank of information for each well in the field, on a well-by-well basis. For each well, the tape contains the completion depth, the surface altitude, the bottomhole depth, the geographic location, the slotted and perforated interval locations, the bottomhole diameter, locations of known casing breaks, the geologic drilling log, fault intersections, shut-in pressure measurements, and month-by-month production totals of both mass and heat for each month from January 1953 through December 1976.

NICARAGUA

Moore, J.L., Erik Osbun, and P.V. Storm, 1981, Geology and temperature distribution of Momotombo geothermal field, Nicaragua, in Halbouty, M.T. (ed.), Energy resources of the Pacific region: Tulsa, AAPG Studies in Geology No. 12, p. 33-54.

__________1982, Geology and temperature distribution of Momotombo geothermal field, Nicaragua: Geothermal Resources Council Special Report No. 12, p. 130-151.

ABSTRACT — The Momotombo geothermal field, located approximately 50 km northeast of the city of Managua on the southern flank of Momotombo Volcano, was discovered in 1970. Subsequent field confirmation and development did not occur until 1974 at which time a field drilling program was initiated. Since then, 33 wells have been drilled within the field, with a combined wellhead energy capacity greater than 100 MW.

Detailed lithologic correlation between wells has provided the basis for a preliminary structural interpretation. Sub-

surface temperature data have been utilized to determine temperature distribution within the field area. Subsequent integration of these data with surface geologic data has resulted in the generation of a basic working model of the Momotombo field.

PHILIPPINES

Sanyal, S.K., M. Che, J.R. McNitt, C.W. Klein, B.S. Tolentino, A. Alcaraz, and R. Datuin, 1982, Definition of a fractured geothermal reservoir. A case history from the Philippines: Geothermal Resources Council Special Report No. 12, p. 98-110.

ABSTRACT — A case history of definition of a fractured, high temperature, liquid-dominated geothermal reservoir is presented. The reservoir considered is located at Palimpinon, Southern Negros, the Philippines. It is shows how a combined interpretation of geological, geochemical, geophysical and well test data could be used to decipher the reservoir geometry and hydrology, as well as the distribution of rock and fluid properties.

Studt, F.E., 1979, Summary of Tongonan exploration case study, Leyte, Philippines: Geothermal Resources Council, Transactions, v. 3, p. 687-688.

NO ABSTRACT. This report discusses geologic, geochemical, and geophysical exploration, as well as drilling results.

SWITZERLAND

Bodmer, P., L. Rybach, D. Werner, F. Jaffe, F. Vuataz, J.F. Schneider, and J.P. Tripet, 1982, Geothermal exploration in the hot spring area Baden-Schinznach, Switzerland, in Cermak, V., and Haenel, R. (eds.), Geothermics and geothermal energy: Stuttgart, Schweizerbart'sche Verlagsbuchhandlung, p. 241-248.

ABSTRACT — Detailed geological, geochemical and geophysical investigations have been carried out in the hot spring area Baden - Schinznach, Switzerland, in order to clarify the origin and the geothermal potential of the thermal water system. All existing springs and boreholes have been observed periodically in order to determine the chemical and physical characteristics of the thermal and nonthermal fluids. The application of different chemical geothermometers indicated the reservoir temperature of different water types. The occurrence of warm water with temperatures up to 48°C and high mineralization up to 4.5 g/l is strongly linked to the intersection of the main Jura overthrust ('Hauptueberschiebung') and a system of subvertical north-south striking faults. Detailed geological and geophysical surveys made it possible to locate 20 shallow and three 70 - 135 m deep drillholes in order to obtain more information about the hydrogeology and the geothermal conditions of the most promising parts of the area under investigation. Geological description, aquifer tests, well logging and water sampling for geochemistry have been performed in those drillholes. One of them was put into commercial production. Computer simulation of the thermal water system together with the interpretation of structural and geochemical data as well as heat flow determinations led to a model of the thermohydraulic conditions in the deep underground and to a yield estimate of the system under study.

Rybach, L., and F.C. Jaffe, 1981, Low enthalpy geothermal energy exploration and development in Switzerland: Geothermal Resources Council, Transactions, v. 5, p. 205-208.

ABSTRACT — The geothermal potential of Switzerland is restricted to low-enthalpy resources related to warm water circulation systems in thermal spring areas and to deep aquifers in sedimentary basins. The two first geothermal exploration projects leading to the exploitation of natural warm water for heating purposes were carried out and completed successfully in the Baden-Schinznach-Zurzach area and in the Lavey spa.

These ventures led to the development of an integrated exploration concept, in which hydrogeochemical methods appear to be particularly useful in the complicated geological conditions prevailing in Switzerland. It is believed that with the available know-how the geothermal exploration can now be extended to the definition and the subsequent development of the hot-water potential of the deep aquifers.

TAIWAN

Hwang, Ke-Kong, and Weng-Tse Cheng, 1981, Exploration and development of geothermal resources in Taiwan, in Halbouty, M.T. (ed.), Energy resources of the Pacific region: Tulsa, AAPG Studies in Geology No. 12, p. 215-221.

ABSTRACT — Although there are many hot-spring areas in Taiwan, only one geothermal area has been explored. Ten of the hot-spring areas were chosen for exploration to see if there were related geothermal prospects.

The Tatun region, 15 km north of Taipei, was first investigated in 1965 because of its intense surface manifestations and easy access. Nineteen exploratory wells were drilled and most tapped steam and hot water. The water was highly acidic and caused serious corrosion, forcing suspension of the field in 1973. However, the dry steam has been tested for multi-uses, and has been successful in a lumber-drying kiln.

The hot water from other hot-spring areas is the sodium bicarbonate type. Three areas that have been studied are the Tuchang, Chingshui, and Lushan areas. Tuchang and Chingshui are within 10 km of each other and are considered to be one system. Deep holes have been drilled and hot water recovered through fractures and fissures. The

steam has been transmitted to a turbo-generator for demonstration purposes.

Although geothermal resources have not been found in connection with Taiwan's hot springs, there are many areas yet to be explored that have potential. Also it is recommended that deep reservoirs of the Tatun area be studied further for possible neutral geothermal fluids.

TURKEY

Alpan, Sadrettin, 1976, Geothermal energy explorations in Turkey: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 1, p. 25-28.

ABSTRACT — In recent years many countries have placed great importance on the exploration and evaluation of their geothermal resources. The presence and location of geothermal energy resources in Turkey is likewise being explored by systematic geological, geophysical, geochemical, and drilling studies carried out by the MTA Institute. The Institute started exploration activities in 1962 by making an inventory of thermal springs. Following this, geological and hydrogeological studies of 1:25,000 scale (in various placed 1:10,000 scale), magnetic maps of 1:25,000 scale, gravity studied of 1:50,000 scale, hydrochemical analysis, gradient drillings, and resistivity and seismic reflection methods were developed. As a result of these studies useful geothermal possibilities have been found in nine areas.

In one of these areas (Denizli-Kizildere), two separate reservoir levels were determined —14 drillings were completed and 12 of these gave geothermal fluids. According to the tests a 10 MW generator with 1000 ton/h production is feasible. In continuation of some of the tests, a small 0.5 MW turbo-generator mounted on one of the wells is being used. A pilot greenhouse set up in this region is heated by air which has been heated by geothermal fluid.

The studies aimed at the heating of domiciles are concentrated around the towns of Ankara and Afyon and are in the drilling phase. Ankara was chosed as a pilot city because of its air pollution problem. If geothermal heating of Ankara is realized, it will have importance far greater than the economic aims.

UNITED STATES

ALASKA

Turner, D.L., R.B. Forbes, E.M. Wescott, Juergen Kienle, Thomas Osterkamp, Samuel Swanson, Daniel Hawkins, William Harrison, Joan Gosink, Jeffrey Kline, Roman Motyka, Richard Reger, and Mary Moorman, 1980, Summary of results of a geological and geophysical investigation of the geothermal energy potential of the Pilgrim Springs KGRA, Alaska: Geothermal Resources Council, Transactions, v. 4, p. 93-95.

ABSTRACT — Reconnaissance-level geologic and geophysical studies indicate that the Pilgrim Springs, Alaska, area is underlain by an intermediate-temperature, liquid-dominated geothermal system of substantial magnitude. Initial exploratory drilling has confirmed the presence of the shallow, 1-1.5 km^2 hot water reservoir delineated by our geophysical surveys. Large artesian flow rates of 200 and 300-400 gallons/minute of 90°C water indicate that at least one good aquifer is present at shallow depths within this reservoir. Resistivity surveys suggest that the reservoir is approximately 50 m thick. Deeper hot water reservoirs may also be contained in the thick sedimentary section identified by seismic and gravity surveys, but they have not as yet been located by our initial resistivity surveys. The power presently being dissipated from the upper 50 m of the system is a minimum of 350 megawatts.

CALIFORNIA

Benson, S. C. Goranson, J. Noble, R. Schroeder, and D. Corrigan, 1980, Evaluation of the Susanville, California geothermal resource: NTIS Report No. LBL-11187, 105 p.

ABSTRACT — Twelve exploratory temperature gradient holes have been drilled (bringing the total number of old and new holes and wells to 23), subsurface geologic and geophysical data have been analyzed, and a well test has been conducted. Interpretation of data obtained from well testing, drillers' and lithologic logs and geophysical surveys suggests the presence of a fault-related reservoir of high permeability, shallow depth, limited thickness and limited lateral extent. Temperature contours and profiles suggest the upwelling of fluids on a northwest-trending fault, from where they are dispersed into the reservoir along a highly permeable, fractured agglomerate-basalt interface and fractured volcanic units. Well tests show a high lateral permeability associated with the fractured interface, and porosity values are low, supporting evidence for a fracture-dominated producing aquifer(s). The areal confinement of the anomaly has been established on three sides (west, south, east) to a depth of 200 m. In the southern portion, temperature reversals below an agglomerate-basaltic interface suggest a vertically confined aquifer. Water samples and petrologic data indicate that in the past, fluids of temperatures between 70°C and 150°C flowed through the fracture system. Computer modeling indicates that a horizontal, regional flow of hot fluids is required to match the observed temperature distribution.

Sorey, M.L., R.E. Lewis, and F.H. Olmsted, 1978, The hydrothermal system of Long Valley caldera, Calfornia: U.S. Geological Survey Professional Paper 1044-A, p. A1-A60.

ABSTRACT — Long Valley caldera, an elliptical depression covering 450 km^2 on the eastern front of the Sierra Nevada in east-central California, contains a hot-water convection system with numerous hot springs and measured and estimated aquifer temperatures at depths of 180°C to 280°C. In this study we have synthesized the results of previous geologic, geophysical, geochemical, and hydrologic investigations of the Long Valley area to develop a generalized conceptual and mathematical model which describes the gross features of heat and fluid flow in the hydrothermal system.

Cenozoic volcanism in the Long Valley region began about 3.2 m.y. (million years) ago and has continued intermittently until the present time. The major event that resulted in the formation of the Long Valley caldera took place about 0.7 m.y. ago with the eruption of 600 km^3 or more of Bishop Tuff of Pleistocene age, a rhyolitic ash flow, and subsequent collapse of the roof of the magma chamber along one or more steeply inclined ring fractures. Subsequent intracaldera volcanism and uplift of the west-central part of the caldera floor formed a subcircular resurgent dome about 10 km in diameter surrounded by a moat containing rhyolitic, rhyodacitic, and basaltic rocks ranging in age from 0.06 to 0.05 m.y.

On the basis of gravity and seismic studies, we estimate an average thickness of fill of 2.4 km above the precaldera granitic and metamorphic basement rocks. A continuous layer of densely welded Bishop Tuff overlies the basement rocks, with an average thickness of 1.4 km; the fill above the welded Bishop Tuff consists of intercalated volcanic flows and tuffs and fluvial and lacustrine deposits. Assuming the average grain density of the fill is betwen 2.45 and 2.65 g/cm^3, we calculate the average bulk porosity of the total fill as from 0.11 to 0.21. Comparison of published values of porosity of the welded Bishop Tuff exposed southeast of the caldera with calculated values indicates average bulk porosity for the welded tuff (including fracture porosity) from 0.05 to 0.10. Because of its continuity and depth and the liklihood of significant fracture permeability in the more competent rocks such as the welded tuff, our model of the hydrothermal system assumes the Bishop Tuff provides the principal hot-water reservoir. However, because very little direct information exists from drill holes below 300 m, this assumption must be considered tentative.

Long Valley caldera is drained by the Owens River and several tributaries which flow into Lake Crowley in the southeast end of the caldera. Streamflow and springflow measurements for water years 1964-74 indicate a total inflow to Lake Crowley of about 10,900 L/s. In contrast, the total discharge of hot water from the hydrothermal reservoir is about 300 L/s. For modeling purposes, the groundwater system is considered as comprising a shallow subsystem in the fill above the densely welded Bishop Tuff containing relatively cold ground water, and a deep subsystem or hydrothermal reservoir in the welded tuff containing relatively hot ground water. Hydrologic, isotopic, and thermal data indicate that recharge to the hydrothermal reservoir occurs in the upper Owens River drainage basin along the western periphery of the caldera. Temperature profiles in a 2.11-km-deep test well drilled by private industry in the southeastern part of the caldera suggest that an additional flux of relatively cool ground water recharges the deep subsystem around the northeast rim. Flow in the shallow ground-water subsystem is neglected in the model except in recharge areas and along Hot Creek gorge, where approximately 80 percent of the hot-water discharge from the hydrothermal reservoir moves upward along faults toward springs in the gorge.

Heat-flow data from the Long Valley region indicate that the resurgent dome overlies a residual magma chamber more circular in plan than the original magma chamber that supplied the Bishop Tuff, and lead to the inference that magma beneath the east part of the caldera was exhausted during eruption of the Bishop Tuff. Seismic and teleseismic studies (based on distant earthquakes) also indicate that an anomalously hot or partially molten mass persists below 6-8 km under the west part of the caldera. Other evidence, including an estimate of present-day heat discharge of 6.9×10^7 cal/s, implies that the heat source for the hydrothermal system is related to the main magma chamber rather than to any of the postcaldera eruptive volcanics.

Constraints on modeling the natural conditions of heat and fluid flow in the hydrothermal system are provided by applying chemical mixing models to spring discharges and rates of boron discharge into Lake Crowley to yield estimates of 200-300 kg/s of water at temperatures between 200°C and 280°C leaving the reservoir under the area of hot-spring discharge. We also estimate 6.9×10^7 cal/s for the total heat discharge at the land surface, based on measurements of spring discharges and temperatures, shallow conductive heat flows, and advective heat losses from warm water discharge into Lake Crowley. Unfortunately, the time over which this heat discharge has persisted is uncertain. Evidence of hydrothermal alteration indicates that hydrothermal activity was present and perhaps more extensive at 0.3 m.y. ago than today, although only relatively recent periods of saline discharge (30,000-40,000 years) from Long Valley can be accounted for by analysis of salts in deposits of Searles Lake, downdrainage from the caldera.

The total amounts of various hot-spring constituents—such as B, Cl, Li, and As—which have been contributed to Searles Lake by the Long Valley system could have been supplied by leaching of realistic volumes of reservoir rocks. A direct magmatic source would not be required to supply these elements, even considering that an additional Searles Lake-size deposit from a previous period of hydrothermal activity around 0.3 m.y. ago remains undiscovered.

Our mathematical model of the Long Valley caldera involves a transient, three-dimensional simulation using numerical techniques to solve the appropriate partial differential equations. The model includes five horizontal layers corresponding to the major rock units identified by seismic-refraction and geologic studies. The simulated hydrothermal reservoir is in fractured Bishop Tuff and precaldera basement rocks at depths from 1 to 3 km. Recharge to the reservoir occurs along the caldera ring fault around the west and northeast rims, and discharge occurs at the surface along Hot Creek gorge and at depth through the southeast rim. Estimates of effective reservoir permeability, assuming an equivalent porous-media flow system, were obtained with the model for several variations of reservoir permeability distribution. This was done by assigning pressure-boundary conditions in recharge and discharge areas based on water-table altitudes and then adjusting reservoir permeability to yield a throughflow of 250 kg/s. Intrinsic permeability values from 30 to 50 millidarcys (10^{-15} m^2) were obtained for a 1-km-thick reservoir covering the entire area of the caldera. A permeability of 350 millidarcys was required for the case of a more areally restricted fault zone reservoir. The values obtained are inversely proportional to the simulated reservoir thickness. Comparisons with laboratory results on cores from Long Valley and the Nevada Test Site (NTS), and well tests in fractured, welded tuff at NTS indicate that permeability values obtained from the model analysis represent an integration of the effects of fracture permeability over the volume of the reservoir rock.

Thermal boundary conditions in the model included a constant-temperature distribution at the base, which simulated a magma chamber under the west half of the caldera, and constant temperature at the land surface. Initial temperature conditions were obtained from a steady-state solution with no fluid flow in the reservoir. Simulation of heat and fluid flow for a period of 35,000 years (based on the estimated age of Long Valley salts in Searles Lake) indicates that present-day heat discharge could have been sustained for this period by a magma chamber at 6 km with fluid circulation to depths from 1.5 to 2.5 km in a reservoir which is continuous over the area of the caldera. Simulated reservoir temperatures under the Hot Creek gorge area are close to those estimated geothermetrically (200°C-280°C) after 35,000 years, but are only abut 80°C under the southeastern portion of the caldera as a result of recharge from the northeast rim near Glass Mountain. Cooler temperatures under the eastern caldera are consistent with results from the 2.11-km-deep test well drilled in that area.

To sustain hot-spring discharge with present-day heat flow and reservoir temperatures for periods much greater than 35,000 years, deeper levels of fluid circulation would be required. For a period of 350,000 years, at which time the system would have reached steady-state conditions, fluid circulation to at a least 4-5 km would be necessary. Consideration of cellular convection in addition to horizontal throughflow in the hydrothermal reservoir does not significantly alter these results.

The model simulations and the diverse indications of the age of hot-spring activity are consistent with the concept that hydrothermal system has functioned intermittently with considerable periods of inactivity—possibly related to climatic variations and chemical self-sealing processes. Additional data from deep drilling in the western part of the caldera are needed to more satisfactorily delineate the characteristics of the hydrothermal flow system and the caldera's geothermal history and to evaluate the adequacy of the simplified hydrothermal model considered in this study.

Bureau of Reclamation, 1979, Geothermal resource investigations, East Mesa Test Site, Concluding report: U.S. Department of Interior, Bureau of Reclamation, 140 p.

NO ABSTRACT. This report summarizes the technical aspects of the Bureau of Reclamation research, testing, and design activities at East Mesa.

Swanberg, C.A., 1976, The Mesa geothermal anomaly, Imperial Valley, California: A comparison and evaluation of results obtained from surface geophysics and deep drilling: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 1217-1229.

ABSTRACT — To date, a range of geophysical and geochemical surveys and five deep geothermal wells have been completed at the Mesa anomaly. The geophysical surveys all outline the same general area as having abnormally high subsurface temperatures, making the Mesa anomaly an ideal area for comparison and evaluation of geothermal exploration techniques. The origin of the anomaly is an active fault which acts as a conduit for ascending geothermal fluids. Dipmeter logs from the geothermal wells indicate that this fault has been active during the deposition of the most recent 2 km of sediments. The geothermal wells were sited so as to obtain stratigraphic and thermal data from various parts of the anomaly, both for comparison with surface geophysical data, and to determin the ultimate size, shape, and production potential of the geothermal reservoir. The geothermal reservoir is confined beneath a clay cap, roughly 600 m thick and consisting of about 60% clay. This clay cap is an effective seal as there are no surface manifestations of geothermal activity at the Mesa anomaly, and waters collected from shallow wells (<400 m) located within and away from the high heat-flow area yield similar Na-K-Ca estimated temperatures. The stratigraphic interval 600 to 750 m is a transition zone between the clay cap and the geothermal reservoir. Over this interval the clay content drops to abut 25% and the geothermal gradient drops from over 150°C/km to less than 40 °C/km. The reservoir itself is at least 1400 m thick and has a surface manifestation ($q > 5$ hfu) of 40 km^2 and a base temperature of 200°C. The sediments within the reservoir are essentially flay-lying, loosely consolidated continental deposits. The sands (75%) have a mean porosity of 20% and a modal permeability of 100 md. The geothermal fluids are of a sodium chloride type with a total dissolved solids content of 2500 mg/liter or less.

Younker, L.W., P.W. Kassameyer, and J.D. Tewhey, 1982, Geological, geophysical, and thermal characteristics of the Salton Sea geothermal field, California: Journal of Volcanology and Geothermal Research, v. 12, p. 221-258.

ABSTRACT — The Salton Sea Geothermal Field is the largest water-dominated geothermal field in the Salton Trough in Southern California. Within the trough, local zones of extension among active right-stepping right-lateral strike-slip faults allow mantle-derived magmas to intrude the sedimentary sequence. The intrusions serve as heat sources to drive hydrothermal systems.

We can characterize the field in detail because we have an extensive geological and geophysical data base. The sediments are relatively undeformed and can be divided into three categories as a function of depth: (1) low-permeability cap rock, (2) upper reservoir rocks consisting of sandstones, siltstones, and shales that were subject to minor alterations, and (3) lower reservoir rocks that were extensively altered. Because of the alteration, intergranular porosity and permeability are reduced with depth. Field permeability is enhanced by renewable fractures, i.e., fractures that can be reactivated by faulting or natural hydraulic fracturing subsequent to being sealed by mineral deposition.

In the central portion of the field, temperature gradients are high near the surface and lower below 700 m. Surface gradients in this elliptically shaped region are fairly constant and define a thermal cap, which does not necessarily correspond to the lithologic cap. At the margin of the field, a narrow transition region, with a low near-surface gradient and an increasing gradient at greater depths, separates the high temperature resource from areas of normal regional gradient. Geophysical and geochemical evidence suggest that vertical convective motion in the reservoir beneath the thermal cap is confined to small units, and small-scale convection is superimposed on large-scale lateral flow of pore fluid.

Interpretation of magnetic, resistivity, and gravity anomalies help to establish the relationship between the inferred heat source, the hydrothermal system, and the observed alteration patterns. A simple hydrothermal model is supported by interpreting the combined geological, geophysical, and thermal data. In the model, heat is transferred from an area of intrusion by lateral spreading of hot water in a reservoir beneath an impermeable cap rock.

HAWAII

Furumoto, A.S., 1976, A coordinated exploration program for geothermal sources on the Island of Hawaii: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 993-1001.

ABSTRACT — Staff members of the Hawaii Institute of Geophysics carried out an exploration program for geothermal sources on the island of Hawaii by using all relevant geophysical and geochemical methods. Infrared scanning surveys by aircraft followed by reconnaissance-type electrical surveys and ground-noise surveys narrowed down the promising area to the east rift of Kilauea.

The surveys carried out over the east rift included magnetic, gravity, and electrical surveys by various methods; microearthquake surveillance; temperature profiling of wells; and chemical analysis of water samples. Aeromagnetic, regional gravity, and crustal seismic refraction data were available in the published literature.

A model of the thermal structure of the east rift was put together to account for the data. The dike complex through which magma from the central vent of Kilauea travels laterally occupies a zone 3 km wide extending from a depth of 1 to 5 km. On the south side of the dike complex, there may be a self-sealing geothermal reservoir where ground water heated by the dike complex is trapped. Not all of the dike complex is hot; hot sections seem to occur in patches.

Shupe, J.W., and P.C. Yuen, 1981, Geothermal energy in Hawaii — Present and future, in Halbouty, M.T. (ed.), Energy resources of the Pacific region: Tulsa, AAPG Studies in Geology No. 12, p. 99-104.

ABSTRACT — Drilling at geothermal well HGP-A on the Big Island of Hawaii was completed on April 27, 1976 to a depth of 6,450 ft (1,966 m). This culminated a 4-year program of planning, exploratory surveys, related research, and experimental drilling requiring over $2.5 million of federal, state, county, and private funding. Maximum downhole temperature recorded was 358°C (676°F), and initial sampling indicated that the quality of the fluid was excellent—low in chloride content, mercury, and hydrogen sulfide.

Subsequent ERDA and state funding supported a comprehensive well-testing program, which resulted in the following preliminary results:

1. The Kapoho reservoir is liquid-dominated; has a tight formation, permeability thickness of approximately 1,000 md/ft; has high temperatures and formation pressures, 350°C and 2,000 psi; is a potentially large reservoir, possibly 1,000 MWe for 50 years; and contains slightly brackish relatively benign fluid, although high in dissolved silica.

2. HGP-A geothermal well drilled in the Kapoho reservoir probably has severe skin damage, since the flow rate increases with each test. It exhibits wellhead pressure of 160 psi at steam flow rate of 60,000 lb/hr; has a potential power output of 3.5 MWe for at least 30 years; and indicates that flashing occurs in the formation. During flashing, the borehole contains steam and water at saturation. The probable producing zones are at bottomhole and 4,300 ft (1,310 m).

Approval has been obtained from DOE for major funding for a wellhead generator of around 2 MWe capacity—the limit of the existing power line in the area. State and county matching funds will be provided and negotiations are under way. The Big Island utility has agreed to purchase the power and assist with construction.

Deterrents to rapid expansion of geothermal energy on the Big Island are: (1) Limited guaranteed power demand; (2) the only confirmed geothermal resource is in an active volcano rift zone; and (3) state geothermal regulations had not been adopted as of February 1, 1978. Driving forces for geothermal development include: (1) high vulnerability of seaborne petroleum and high energy costs; (2) major potential markets in mineral refining and other energy intensive industry; (3) potential nonelectrical geothermal uses; and (4) a very positive attitude toward geothermal energy use at all levels of government in Hawaii, as well as by the general public.

IDAHO

Dolenc, M.R., L.C. Hull, S.A. Mizell, B.F. Russell, P.A. Skiba, J.A. Strawn, J.A. Tullis, and R. Garber (eds.), 1981, Raft River geoscience case study: NTIS Report No. EGG-2125, 304 p.

ABSTRACT — The Raft River Geothermal Site has been evaluated over the past eight years by the United States Geological Survey and the Idaho National Engineering Laboratory as a moderate-temperature geothermal resource. The geoscience data gathered in the drilling and testing of seven geothermal wells suggest that the Raft River thermal reservoir is: (a) produced from fractures found at the contact metamorphic zone, apparently the base of detached normal faulting from the Bridge and Horse Well fault zones of the Jim Sage Mountains; (b) anisotropic, with the major axis of hydraulic conductivity coincident to the Bridge fault zone; (c) hydraulically connected to the shallow thermal fluid of the Cook and BLM wells based upon both geochemistry and pressure response; (d) controlled by a mixture of diluted meteoric water recharging from the northwest and a saline sodium chloride water entering from the southwest. Although the hydrogeologic environment of the Raft River geothermal area is very complex and unique, it is typical of many Basin and Range systems.

MARYLAND

Costain, J.K., 1980, Geothermal exploration methodology in the eastern U.S. and results of first deep test on the Atlantic Coastal Plain at Crisfield, Maryland: Geothermal Resources Council Special Report No. 9, p. 33-38.

NO ABSTRACT. Note from introduction: This paper includes a brief discussion of the geological and geophysical techniques we have used to investigate the geologic framework of geothermal resources on the Atlantic Coastal Plain. Results of the recent geothermal test well at Crisfield, Maryland are discussed.

MONTANA

Blackwell, D.D., and Paul Morgan, 1976, Geological and geophysical exploration of the Marysville geothermal area, Montana, USA: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 895-902.

ABSTRACT — Extensive geological and geophysical surveys have been carried out at the Marysville geothermal area in Montana, USA. The area is characterized by high heat flow (up to 20 μ cal/cm^2 sec), a negative gravity anomaly, high electrical resistivity, low seismic ground noise, and nearby microseismic activity. Significant magnetic and infrared anomalies are not associated with the geothermal area. The geothermal anomaly occupies the axial portion of a dome in Precambrian sedimentary rocks intruded by Cretaceous and Cenozoic granitic rocks. The results from a 2.1-km deep test well indicate that the cause of the geothermal anomaly is hydrothermal convection in a Cenozoic intrusive. The convection is along distributed fracture zones in the intrusive granite porphyry. Maximum temperatures of about 98°C are measured in the test well, although chemical geothermometers predict temperatures of 120 to 180°C somewhere in the system.

NEVADA

Beard, G.A., 1981, Geothermal reservoir assessment case study: Northern Basin and Range province, Leach Hot Springs area, Pershing County, Nevada; Final Report, April 1979—December 1981: NTIS Report No. DOE/ET/27005-1, 143 p.

ABSTRACT — A Geothermal Reservoir Assessment Case Study was conducted in the Leach Hot Springs Known Geothermal Resource Area of Pershing County, Nevada. The case study included the drilling of 23 temperature gradient wells, a magnetotelluric survey, seismic data acquisition and processing, and the drilling of one exploratory well. Existing data from prior investigations, which included water geochemistry, gravity, photogeologic reports and a hydrothermal alteration study, was also provided. The exploratory well was drilled to total depth of 8565' with no significant mud losses or other drilling problems. A maximum temperature of 260°F was recorded at total depth. The relatively low temperature and the lack of permeability (as shown by absence of mud loss) indicated that a current, economic geothermal resource had not been located, and the well was subsequently plugged and abandoned. However, the type and extent of rock alteration found implied that an extensive hot water system had existed in this area at an earlier time. This report is a synopsis of the case study activities and the data obtained from these activities.

Benoit, W.B., J.E. Hiner, and R.T. Forest, 1982, Discovery and geology of the Desert Peak geothermal field: A case history: Reno, Nevada Bureau of Mines and Geology Bulletin 97, 82 p.

NO ABSTRACT. Note from front cover: A case history of the exploration, development (through 1980), and geology of the Desert Peak geothermal field. Contains sections on geochemistry, geophysics, and temperature-gradient drilling.

Denton, J.M., E.J. Bell, and R.L. Jodry, 1980, Geothermal reservoir assessment case study: Northern Dixie Valley, Nevada: NTIS Report No. DOE/ET/27006-1, 517 p.

ABSTRACT — Two 1500 foot temperature gradient holes and two deep exploratory wells were drilled and tested. Hydrologic-hydrochemical, shallow temperature survey, structural-tectonic, petrologic alteration, and solid-sample geochemistry studies were completed. Eighteen miles of high resolution reflection seismic data were gathered over the area. The study indicates that a geothermal regime with temperatures greater than 400°F may exist at a depth of approximately 7500' to 10,000' over an area more than ten miles in length.

Flynn, Thomas, D.T. Trexler, and B.A. Koenig, 1982, The Kemp thermal anomaly: A newly discovered geothermal resource in Pumpernickel Valley, Nevada: Geothermal Resources Council, Transactions, v. 6, p. 121-124.

ABSTRACT — Geophysical, geochemical and shallow-depth drilling surveys were successfully employed in Pumpernickel Valley, Nevada, to identify a previously unrecognized geothermal resource. The study area, located within the 'Battle Mountain Heat Flow High', contains many low-temperature (<100°C) geothermal occurrences and at least one moderate temperature (100-150°C) geothermal well. The newly recognized resource is not spatially associated with any known thermal manifestation, and was first identified on the basis of a 2-m depth temperature-probe survey. Gravity data suggest the thermal anomaly originates from a fault located 1-2 km (.6-1.2 mi.) east of a prominent northeast-trending range-bounding fault. The maximum temperature measured was 70°C at a depth of approximately 100 m (300 ft.). The areal distribution of economically recoverable geothermal fluids associated with this discovery is probably limited to one km^2 or less. Direct temperature measurement techniques were judged to be the most useful in this study.

Hill, D.G., E.B. Layman, C.M. Swift, and S.H. Yungul, 1979, Soda Lake, Nevada, thermal anomaly: Geothermal Resources Council, Transactions, v. 3, p. 305-308.

ABSTRACT — The Soda Lake thermal anomaly is located in the southern part of the extensional Carson Sink in Western Nevada. The shallow thermal regime is well defined, with temperatures in excess of 365°F in exploratory temperature holes. Current interpretation of all available data yields a NE-SW trending fault, NE of Soda Lake. Geochemical base temperature determinations estimate reservoir temperatures in excess of 400°F. Additional work is underway to define and evaluate the potential geothermal reservoir.

Mackelprang, C.E., J.N. Moore, and H.P. Ross, 1980, A summary of the geology and geophysics of the San Emidio KGRA, Washoe County, Nevada: Geothermal Resources Council, Transactions, v. 4, p. 221-224.

ABSTRACT — Geologic mapping, thermal gradient drilling, electrical resistivity surveys, and gravity data interpretation define a north-trending Basin and Range fault which acts as the principal conduit for hydrothermal fluids at San Emidio. There is a possibility that this principal conduit has not been intersected in the drilling to date. The maximum temperature recorded to date is 262°F. The low apparent reservoir temperatures have reduced interest in exploration for an electrical power quality resource. An economic evaluation for using the hydrothermal fluids in industrial processing is now underway.

McManness, David, Bob Quillin, and David Butler, 1981, Granite Mountain, Nevada geothermal prospect — A case history: Geothermal Resources Council, Transactions, v. 5, p. 107-110.

ABSTRACT — A geophysical and geological interpretation was made in the area of Kyle Hot Springs, Pershing County, Nevada. This paper includes a brief description of the geophysical methods used by MicroGeophysics Corp. in the survey area and a presentation of the final interpretation of the prospect.

Parchman, W.L., and J.W. Knox, 1981, Exploration for geothermal resources in Dixie Valley, Nevada — A case history: Geothermal Resources Council Bulletin, v. 10, no. 6, p. 3-6.

NO ABSTRACT. This paper discusses geologic, hydrologic, geochemical, and geophysical exploration studies.

Pilkington, H.D., 1981, Tuscarora area, Nevada: Geothermal reservoir assessment case history, northern Basin and Range. Final report, 1 October 1978—9 September 1980: NTIS Report No. DOE/ET/27011-1, 45 p.

ABSTRACT — The Tuscarora prospect is located at the north end of Independence Valley approximately 90 km north-northwest of Elko, Nevada. Geothermal exploration on the prospect consisted of an integrated program of geologic, hydrogeochemical and soil geochemistry studies. Geophysical exploration included heatflow studies, aeromagnetic, self-potential, gravity, dipole-dipole resistivity and magnetotelluric surveys. Exploration drilling includes 32 shallow thermal gradient holes, six intermediate depth temperature gradient wells and one 5454 foot test for discovery well. Shallow low-temperature reservoirs were encountered in the Tertiary rocks and in the Paleozoic rocks immediately beneath the Tertiary. Drilling problems forced the deep well to be stopped before the high-temperature reservoir was reached.

Trexler, D.T., B.A. Koenig, Thomas Flynn, J.L. Bruce, and George Ghusn, Jr., 1981, Low-to-moderate temperature geothermal resource assessment for Nevada, area specific studies: NTIS Report No. DOE/NV/10039-9, 203 p.

ABSTRACT, Abridged — The Hawthorne study area is located in Mineral County, Nevada and surrounds the municipality of the same name. It encompasses an area of approximately 310 sq. km (120 sq. mi).

A variety of scientific techniques was employed during area-wide resource assessment. General geologic studies demonstrate the lithologic diversity in the area; these studies also indicate possible sources for dissolved fluid constituents. Geophysical investigations include aeromagnetic and gravity surveys which aid in defining the nature of regional, and to a lesser extent, local variations in subsurface configurations. Surface and near-surface structural features are determined using various types of photo imagery including low sun-angle photography. An extensive shallow depth temperature probe survey indicates two zones of elevated temperature on opposite sides of the Walker Lake basin. Temperature-depth profiles from several wells in the study area indicate significant thermal fluid-bearing aquifers. Fluid chemical studies suggest a wide spatial distribution for the resource, and also suggest a meteoric recharge source in the Wassuk Range. Finally, a soil-mercury survey was not a useful technique in this study area.

Two test holes were drilled to conclude the area resource assessment, and thermal fluids were encountered in both wells. The western well has measured temperatures as high as 90°C (194°F) within 150 meters (500 ft) of the surface. Temperature profiles in this well indicate a negative temperature gradient below 180 meters (590 ft). The eastern hole had a bottom hole temperature of 61°C (142°F) at a depth of only 120 meters (395 ft). A positive gradient is observed to a total depth in the well.

Several conclusions are drawn from this study: the resource is distributed over a relatively large area; resource fluid temperatures can exceed 90°C (194°F), but are probably limited to a maximum of 125°C (257°F); recharge to the thermal system is meteoric, and flow of the fluids in the near surface ($<$500 m) is not controlled by faults; heat supplied to the system may be related to a zone of partially melted crustal rocks in the area 25 km (15 mi) south of Hawthorne.

Pilkington, H.D., 1982, McCoy area, Nevada geothermal reservoir assessment case history, northern Basin and Range. Final report, 1 October 1978—30 September 1982: NTIS Report No. DOE/ET/27010-1, 76 p.

ABSTRACT — The McCoy geothermal prospect is located in north-central Nevada at the junction of the Augusta Mountains, Clan Alpine Mountains and the New Pass Range. Geothermal exploration on the prospect consisted of an integrated program of geologic, geochemical and geophysical studies. The geochemical studies included hydrogeochemistry, soil geochemistry, and drill cuttings geochemistry. Geophysical exploration included heatflow studies, aeromagnetic, self-potential, gravity, passive seismic, dipole-dipole resistivity, electromagnetic and magnetotelluric surveys. Exploration drilling includes 52 shallow thermal gradient holes and five intermediate depth temperature gradient wells. Shallow low-temperature geothermal reservoirs were encountered in two areas. In the McCoy Mine area the resource was found in the Permo-Pennsylvanian rocks. In the southern part of the prospect a resource with temperatures of 100°C was encountered in the basal conglomeratic sandstone of the Triassic section.

Trexler, D.T., Thomas Flynn, B.A. Koenig, E.J. Bell, and George Ghusn, Jr., 1982, Low- to moderate-temperature geothermal resource assessment for Nevada: Area specific studies, Pumpernickel Valley, Carlin and Moana: NTIS Report No. DOE/NV/10220-1, 145 p. plus appendix.

ABSTRACT, Abridged — Geological, geophysical and geochemical surveys were used in conjunction with temperature gradient drilling to assess the geothermal resources in Pumpernickel Valley and Carlin, Nevada. The exploration techniques include:

1. Literature search and compilation of existing data.
2. Geologic reconnaissance
3. Chemical sampling of thermal and non-thermal fluids
4. Interpretation of satellite imagery
5. Interpretation of low-sun angle aerial photographs
6. Two-meter depth temperature probe survey
7. Gravity survey
8. Seismic survey
9. Soil-mercury survey
10. Temperature gradient drilling

The work in Pumpernickel Valley demonstrated that the widespread geothermal fluids are likely channelled to the surface by range bounding faults. Temperatures of geothermal fluids have been estimated to be 170°C, based on chemical geothermometers. A previously unrecognized geothermal prospect was discovered on the west side of Pumpernickel Valley where there are no surface manifestations of thermal fluids. The prospect was first identified on the basis of a two-meter depth temperature probe survey. A maximum temperature of 70°C was subsequently measured at a depth of 76 m in a temperature gradient hole. Thermal fluid flow for this prospect is fault controlled and surface discharge is precluded by a thick impermeable clay layer above the geothermal fluids. This area is also coincident with a steep gradient in gravity contours and high soil-mercury values.

In Carlin, two existing hot springs separated by 11 km (7 mi.) were found to represent two distinct hydrothermal circulation systems. Thermal fluid flow is controlled by two unrelated geologic structures; there are also no chemical or isotopic similarities in the fluids. A maximum temperature of 90°C was calculated for thermal fluids in Carlin based on chemical geothermometers.

Whelan, J., C. Halsey, and B. Jackson, 1980, Geothermal evaluation of Range Bravo 19, Naval Air Station, Fallon, Nevada: Geothermal Resources Council, Transactions, v. 4, p. 261-264.

ABSTRACT — The geothermal potential of Range Bravo 19, a bombing range, located 18 miles south of NAS, Fallon, Nevada, has been evaluated as part of an on-going Navy program. Geologic and thermal grdients data were obtained from five, 500 ft. drill holes. Gradients ranged from 7°C/100 m to 10.4°C/100 m. Soil geochemistry located three areas with mercury contents over 20 ppb, with a threshhold of 5 ppb. Water geochemistry using analyses from Lee Hot Springs, two cold springs and one drill hole, using the various geochemical thermometers and models gave reservoir temperatures of from 13 to 240°C.

Combining the data indicates a possible geothermal reservoir in the northwest portion of the range with a probable temperature of about 170°C.

Wright, T.C., 1983, Baltazor KGRA and vicinity, Nevada: Geothermal reservoir assessment case study, northern Basin and Range province. Final report, 1 October 1978—31 January 1983: NTIS Report No. DOE/ET/27007-1, 68 p.

ABSTRACT — The Baltazor KGRA and McGee/Painted Hills geothermal prospects are located in northern Humboldt County, Nevada along the northwestern margin of the Basin and Range province. Exploration work other than drilling has included groundwater sampling, a microearthquake study, a geologic literature search and photogeologic mapping, compilation of aeromagnetic and gravity mapping, soil mercury surveying, electrical resistivity and self-potential surveys and detailed hydrothermal alteration mapping. Exploration drilling included 27 shallow temperature gradient holes, four intermediate-depth gradient wells and one 3703-foot deep test, Baltazor 45-14. The deep test penetrated Miocene rhyolite, andesite, basalt and andesitic basalt flows before excessive hole deviation forced an end of drilling and completion as a deep temperature observation well. A temperature two weeks after completion obtained a 119.7°C (247.4°F) reading at survey total depth, 1110 m.

Zoback, M.C., 1979, Geologic and geophysical investigation of the Beowawe geothermal area, north-central Nevada: Stanford University Publications, Geological Sciences, v. 16.

ABSTRACT — Results of a detailed geologic and geophysical investigation of a natural, hot-water geothermal system located near the town of Beowawe, north-central Nevada are reported. Geologic mapping revealed an alluvial deposit of gravels and tuffaceous sediments at the base of the Cenozoic section; this alluvial deposit is overlain by a series of mid-Miocene basaltic andesite flows which cap the modern range. The Cenozoic section was deposited unconformably on Paleozoic siliceous rocks of the upper plate of the Roberts Mountain thrust. Paleozoic carbonate rocks comprise the autochonous basement at depth.

The basaltic andesite varies in thickness from roughly 100 m on the northeast end of the range to more than 1 km in the vicinity of the hot springs and to the west. This variation in thickness is attributed to a NNW-trending graben developed in mid-Miocene time into which the flows accumulated and eventually overflowed. The main uplift and gentle, southeast tilting of the modern range was subsequently accomplished along a ENE-trending Basin and Range normal fault; however, movement has apparently continued on the NNW faults resulting in a nearly orthogonal, cross-faulting trend. This cross-faulting trend is associated with mild topographic expression; activity along it is most likely responsible for large landsliding (area roughly 3.5 km^2) along the Mal Pais ridge near a major intersection of the two trends.

Current geothermal activity is limited to the southwestern end of the range where a 65 m high siliceous sinter terrace has built up along the main bounding fault. By estimating the volume of silica deposited and assuming pre-exploitation silica concentrations and flow rate for the entire life of the system, the age of the modern system was calculated to be around 200,000 years with an uncertainty of about 50%. Using an estimate of the discharge of the natural system and assuming a base temperature of 215°C (from geochemical data and shallow drilling results) a convective heat flux of 91 HFU was calculated.

The localization of the modern geothermal system along the range-front fault attests to the important role that normal faulting plays in the movement of thermal waters to the surface. A shallow, near-surface magma body is unlikely as a heat source because of the nature and age of the most recent volcanism (basaltic rocks probably 6-10 m.y. in age); however, the heat source for this system and numerous others in the area is no doubt related to the Battle Mountain high, a broad region of extremely high heat-flow values in north-central Nevada. Deep circulation of meteoric water along normal faults would encounter hot rock at the observed reservoir temperatures (210°-215°) at depths of only 6-7 km in this high heat-flow region.

Geophysical investigations were undertaken to establish signatures for the known geothermal area and to examine other faulting for geothermal activity lacking surface manifestations. Surveys within the active hot springs and geyser area revealed a bipole-dipole resistivity low, a broad positive self-potential anomaly (+80 mv) with many superimposed short wavelength fluctuations, and a relatively high seismic noise level. Most susceptible to lateral variations in resistivity, the bipole-dipole survey outlined a low associated with the present active area; however, gave no information as to the depth extent of the anomaly. The self-potential anomaly emerges well above the noise level and is thought to reveal upwelling of water primarily along a subsidiary range front fault within the active hot springs area. The anomaly pattern is probably complicated by a complex pattern of flow—both lateral and vertical—near the surface. A seismic noise survey was plagued by the strong dependence of measured amplitudes on recorder site geology.

The valley in the vicinity of the main NNW-trending cross faulting was investigated for possible subsurface geothermal activity. A small, N-S resistivity low as well as a localized noise anomaly was detected in this region. The favored interpretation of the resistivity and seismic noise data, consistent with the self-potential data, is that the anomalies are related to a possible eastward extension of a sub-parallel, subsidiary, ENE-trending range front fault. The anomalies might then be correlated with fluid movement along this fault. Because both hot and cold springs are aligned along this subsidiary fault it is unknown whether the moving fluid is thermal or ordinary meteoric water.

The geothermal system at Beowawe is apparently characterized by permeable zones and storage at several different levels: a deep zone of circulation presumably located within the carbonate rocks of the lower plate of the Roberts Mountains thrust (based on geochemical data), a possible intermediate level fracture zone (approximately 1 km depth) created by complex fault intersections and tapped by both the main and the subsidiary range front fault, and a shallow (about 200 m depth) reservoir presumably within the basaltic andesite section in the uplifted, range block. Meteoric water is probably heated conductively by rocks at

roughly 7 km depth within a highly permeable (possibly cavernous) region in the autochonous carbonate sequence. Intersection of the main range front fault with this deep permeable zone provides a channel for rapid upward migration of the geothermal water. Structural controls have apparently resulted in significant northeastward lateral diversion (at least 2.5 km) of water rising along the main range front fault at some level above 2.9 km depth.

NEW MEXICO

Goff, F.E., C.O. Grigsby, P.E. Trujillo, Jr., Dale Counce, and Andrea Kron, 1981, Geology, water geochemistry and geothermal potential of the Jemez Springs area, Cañon de San Diego, New Mexico: Journal of Volcanology and Geothermal Research, v. 10, p. 227-244.

ABSTRACT — Studies of the geology, geochemistry of thermal waters, and of one exploratory geothermal well show that two related hot spring systems discharge in Canon de San Diego at Soda Dam (48°C) and Jemez Springs (72°C). The hot springs discharge from separate strands of the Jemez fault zone which trends northeastward towards the center of Valles Caldera. Exploration drilling to Precambrian basement beneath Jemez Springs encountered a hot aquifer (68°C) at the top of Paleozoic limestone of appropriate temperature and composition to be the local source of the fluids in the surface hot springs at Jemez Springs. Comparisons of the soluble elements Na, Li, Cl, and B, arguments based on isotopic evidence, and chemical geothermometry indicate that the hot spring fluids are derivatives of the deep geothermal fluid within Valles Caldera. No hot aquifer was discovered in or on top of Precambrian basement. It appears that low- to moderate-temperature geothermal reservoirs ($\leq$100°C) of small volume are localized along the Jemez fault zone between Jemez Springs and the margin of Valles Caldera.

Goldstein, N.E., M.W. Malloy, and W.R. Holman, 1982, Final report of the Department of Energy reservoir definition review team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory Report No. LBL-14132, 52 p.

NO ABSTRACT. This report contains papers on geology, geophysics, geochemistry, drilling, reservoir definition, prediction of reservoir performance, and fracture stimulation experiments.

Jiracek, G.R., C.A. Swanberg, Paul Morgan, and M.D. Parker, 1983, Evaluation of the geothermal resource in the area of Albuquerque, New Mexico: NTIS Report No. DE833016066, 179 p.

ABSTRACT. Factors indicating a potential geothermal resource near Albuquerque are: (1) nearby volcanoes active as recently as 120,000 years ago, (2) gravity interpretation indicating a potential reservoir averaging 1.5 km thickness, (3) high heat flow near the city, (4) warm waters (>30°C) in municipal wells, (5) recent seismicity indicating active faulting, thereby, allowing the possibility of deep hydrothermal circulation, (6) high shallow (<30 m) temperature gradients (>100°C/km) discovered in our drillholes, (7) deeper (<500 m) gradients from water wells exceeding 80°C/km, and (8) chemical analyses of 88 groundwater samples yielding estimated base reservoir temperatures as high as 190°C. An area of elevated shallow temperature gradients (140 °C/km) was discovered a few kilometers west of Albuquerque by our 69 hole drilling program. Resistivity, magnetic, and gravity measurements combined with computer modeling suggests that heated ground water is forced closer to the surface here by flow over a buried ridge. A well drilled nearby yielded the highest recorded temperature in the Albuquerque area at its maximum depth (32.8°C at 364 m). The deep gradient is 35°C/km. An oil test well close by reported large volumes of water at 1 km; therefore, the possibility of a low temperature (> 50°C) geothermal resources exists west of Albuquerque at less than 1 km depth.

Laughlin, A.W., 1981, The geothermal system of the Jemez Mountains, New Mexico and its exploration, in Rybach, L., and Muffler, L.J.P. (eds.), Geothermal Systems; Principles and Case Histories: John Wiley & Sons, p. 295-320.

NO ABSTRACT. The main sections in this paper are Introduction; Regional Geological and Geophysical Setting of the Jemez Mountains; Geology, Geophysics, and Hydrology of the Jemez Mountains; Geothermal Exploration in the Jemez Mountains; and The Geothermal System of the Jemez Mountains.

Sanford, R.M., R.L. Bowers, and Jim Combs, 1979, Rio Grande rift geothermal exploration case history: Elephant Butte prospect, south central New Mexico: Geothermal Resources Council, Transactions, v. 3, p. 609-612.

ABSTRACT — The Elephant Butte Prospect, situated within the Rio Grande Rift of south central New Mexico, was selected as a geothermal prospect due to the hot springs and Quaternary volcanics in the vicinity. Subsurface temperatures calculated from silica and Na-K-Ca geothermometers appear to be less than 150°C. An extensive electrical resistivity survey primarily provided determinations of depths to electrical basement and the delineation and extension of known faults. Fourteen shallow heat flow boreholes indicate that the Prospect area is characterized by an average heat flow of 2.0 HFU, compared with the regional value of 2.5 HFU based on published data. The low heat flow values appear to be the result of ground-water circulation. Exploration costs of about $6.15/hectare failed to define any positive indication of economic high temperature geothermal resources situated within the Prospect. The geothermal leases evaluated by this exploration effort were therefore dropped.

Union Oil Company of California, 1982, Baca Project: Geothermal demonstration power plant. Final report: USDOE Technical Information Center, Oak Ridge, Report No. DOE/ET/27163-T2, 456 p.

NO ABSTRACT. Note from Report Overview: The final report describes the various activities that have been conducted by Union in the Redondo Creek area while attempting to develop the resource for a 50 MW power plant. The results of the geologic work, drilling activities and reservoir studies are summarized. In addition, the report contains sections discussing the historical costs for Union's involvement with the project, production engineering (for anticipated surface equipment), and environmental work.

OREGON

Bowen, R.G., 1981, Mount Hood exploration, Oregon — A case history: Geothermal Resources Council Special Report No. 10, p. 21-23.

ABSTRACT — An assessment program of Mount Hood is giving information useful for geothermal development in the area and is expected to characterize and aid in exploration of other Cascade volcanoes. These studies have shown the presence of thermal waters coming to the surface around the south flank of the mountain and subsurface flow in other areas. Geothermal gradient drilling show the average heat flow in the area to be about two times normal increasing toward the summit. Two commercial exploration programs resulting in drilling are underway; Northwest Natural Gas is exploring the west side for direct utilization in the Portland area, and Wy'East is exploring near Timberline Lodge on the south flank. On the west side adequate temperatures have been found but the wells have not found enough permeability to be useful. At Timberline Lodge a 4000' well appears to have sufficient temperature, but it has not yet been tested. Further exploration and testing will continue this summer.

SOUTH DAKOTA

Martinez, J.A., 1981, Geothermal development of the Madison Group aquifer — A case study: Geothermal Resources Council, Transactions, v. 5, p. 541-543.

ABSTRACT — A geothermal wells has been drilled at the St. Mary's Hospital in Pierre, South Dakota. The well is 2176 feet deep and artesian flows 375 gpm at 106°F. The well is producing fluids from the Mississippian Madison Group, a sequence of carbonate rocks deposited over several western states. The project was funded by the Department of Energy to demonstrate the geothermal potential of this widespread aquifer. This case study describes the development of the project through geology, drilling, stimulation, and testing.

TEXAS

Taylor, Bruce, R.F. Roy, and J.M. Hoffer, 1980, Hueco Tanks: An initial evaluation of a potential geothermal area near El Paso, Texas: Geothermal Resources Council, Transactions, v. 4, p. 253-256.

ABSTRACT — A potential geothermal resource about 40km northeast of El Paso, Texas is under investigation. The presence of old hot wells indicated the area of interest, and a geochemical survey outlined the possible geothermal anomaly. A shallow drilling programme has revealed gradients consistently over 100°C/km and as high as 300 °C/km on the Texas side of the state line, and a 300m hole yielded a heat flow of 8.3 H.F.U. in the limestone bedrock.

Electrical soundings have shown the presence of a shallow conductive layer (probably hot and/or mineralized water) and a recently completed gravity survey delineates the faulting pattern apparently responsible for the uprise of thermal waters. Indications are presently not of an electricity-grade resource, but of a hot water reservoir, with temperatures maybe reaching 120-140°C.

UTAH

Hulen, J.B., and S.M. Sandberg, 1981, Exploration case history of the Monroe KGRA, Sevier County, Utah: University of Utah Research Institute, Earth Science Laboratory Report No. ESL-49; DOE/ID/12079, 82 p.

ABSTRACT — The University of Utah Department of Geology and Geophysics (UU/GG) and TerraTek Inc., of Salt Lake City completed an integrated multi-dicipline geoscientific evaluation of the Monroe KGRA, in south-central Utah, between 1975 and 1978. This study was designed not only to characterize and develop the Monroe geothermal resource, but also to assess the value of various techniques in exploration for low- to moderate-temperature geothermal systems elsewhere. Methods applied at Monroe comprised: large scale (1:18,900) mapping of geology, springs and spring deposits, and alteration; statistical analysis of the alteration; spring geochemistry and geothermometry; gravity; ground magnetics; dipole-dipole resistivity surveying; shallow thermal gradient drilling; test well drilling; and finally, production well drilling.

The Monroe KGRA is centered on the village of Monroe, at the eastern boundary of Sevier Valley, a deeply alluviated Basin and Range graben in south-central Utah. The valley is separated from the Sevier Plateau, to the east, by the Sevier fault zone, a structure with up to 1800 m (5905.6 ft) normal displacement. The plateau, including that portion encompassed by the KGRA, is constructed of mostly intermediate-composition volcanics of Oligocene to Pliocene age. Several 'hot' (61-76.3°C/141.8-169.4°F) springs and associated travertine deposits are aligned along the Sevier fault zone within the KGRA. Alluvium around these deposits, as well as landslide debris and volcanic bedrock, are argillized and propylitically altered in scattered patches along faults and fractures.

Large-scale (1:18,900) mapping at Monroe primarily demonstrated control by the Sevier fault zone and allied structures of the springs, spring deposits and alteration. Most of the alteration was shows to be very young and probably related to present geothermal activity because of its development in faults disrupting surficial deposits.

Reservoir temperatures estimated by geothermometry of the sodium chloride-sulfate spring waters at Monroe varied from 60°C (140°F) (alpha cristobalite) to 179°C (354°F) (Na-K-1/3Ca). Actual maximum temperature encountered by the deepest drilling at Monroe (82.2°C/180°F) was closely approximated by the chalcedony geothermometer (81°C/ 178°F).

Detailed gravity and ground magnetic studies confirmed the presence of the Sevier fault zone and indicated it to consist of echelon segments rather than a single structure. Dipole-dipole resistivity surveying delineated an elongate resistivity low tightly controlled by the Sevier fault zone, centered on the 'hot' springs and associated travertine mounds, extending beneath these mounds to depths of at least 400 m (1312.4 ft). A zone of shallow thermal fluid leakage in permeable alluvium was also detected.

Shallow ($\leq$ 100 m/328 ft) thermal gradient/heat flow drilling at Monroe showed highest heat flow values, up to 81 HFU (3400 mW/m^2), approximately coinciding with the travertine mounds. An empirically derived relationship between heat flow and resistivity allowed extrapolation of heat flow contours beyond actual drill hole control.

Results of the geological and geophysical investigations strongly suggested direct-heating potential for the Monroe resource. Accordingly, two shallow (110.3 /362 ft and 251.6 m/825.5 ft) test wells were drilled to define better the subsurface thermal and structural regimes and guide placement of a production well. Both wells produced strong artesian flows at 74°C (165°F) from the Sevier fault zone, which separates alluvium from subjacent latite bedrock.

These encouraging results led to completion of a production well. The well intersected alluvium, a thick, unanticipated limestone sequence, then (as predicted) the Sevier fault zone, with artesian thermal fluid flow, between 320 and 350.5 m (1050 and 1150 ft). The well then entered latite bedrock, in which it remained to its total depth of 457.2 m (1500 ft).

After development, the production well produced an artesian flow of 280 gpm at a temperature of 73.3°C (164°F). Pump tests at 330 gpm for 70 hours and 600 gpm for 30 hours produced drawdowns internally and in test wells of up to 76 m (250 ft). All springs near the production well dried up during pump testing.

Analysis of the pump test results indicated that unacceptably large drawdowns would occur during projected peak winter heating periods for Monroe. This discouraging forecast, the rather low reservoir temperatures encountered in the production well, and the inflationary factors rendering geothermal energy at Monroe uncompetitive with coal as a heat source, led to cancellation of plans to further develop the resource. The UU/GG-TerraTek exploration program at Monroe nonetheless remains an impressive technical success.

Ross, H.P., J.N. Moore, and O.D. Christensen, 1982, The Cove Fort-Sulphurdale KGRA: A geologic and geophysical case study: University of Utah Research Institute, Earth Science Laboratory Report No. ESL-90, 47 p.

ABSTRACT — Geological, geochemical and geophysical data are presented for one of the major geothermal systems in the western United States. Regional data indicate major tectonic structures which are still active and provide conduits for the geothermal system. Detailed geologic mapping has defined major glide blocks of Tertiary volcanics which moved down from the Tushar Mountains and locally act as a leaky cap to portions of the presently known geothermal system. Mapping and geochemical studies indicate three periods of mineralization have affected the area, two of which are unrelated to the present geothermal activity. The geologic relationships demonstrate that the major structures have been opened repeatedly since the Tertiary.

Gravity and magnetic data are useful in defining major structures beneath alluvium and basalt cover, and indicate the importance of the Cove Fort-Beaver graben and Cove Creek fault in localizing the geothermal reservoir. These structures and a high level of microearthquake activity also suggest other target areas within the larger thermal anomaly. Electrical resistivity surveys and thermal gradient holes both contribute to the delineation of the known reservoir.

Deep exploration wells which test the reservoir recorded maximum temperatures of 178°C and almost isothermal behavior beginning at 700 to 1000 m and continuing to a depth of 1800 m. Costly drilling, high corrosion rates and low reservoir pressure coupled with the relatively low reservoir temperatures have led to the conclusion that the reservoir is not economic for electric power production at present. Plans are underway to utilize the moderate-temperature fluids for agribusiness, and exploration continues for a deep high-temperature reservoir.

Ross, H.P., D.L. Nielson, and J.N. Moore, 1982, Roosevelt Hot Springs geothermal system, Utah—Case study: The American Association of Petroleum Geologists Bulletin, v. 66, p. 879-902.

ABSTRACT — The Roosevelt Hot Springs geothermal system has been undergoing intensive exploration since 1974 and has been used as a natural laboratory for the development and testing of geothermal exploration methods by research organizations. This paper summarizes the geological, geophysical, and geochemical data which have been collected since 1974, and presents a retrospective strategy describing the most effective means of exploration for the Roosevelt Hot Springs hydrothermal resource.

The bedrock geology of the area is dominated by metamorphic rocks of Precambrian age and felsic plutonic phases of the Tertiary Mineral Mountains intrusive complex. Rhyolite flows, domes, and pyroclastic rocks reflect igneous activity between 0.8 and 0.5 m.y. ago. The structural setting includes older low-angle normal faulting and east-west faulting produced by deep-seated regional zones of weakness. North to north-northeast-trending faults are the youngest structures in the area, and they control present fumarolic activity. The geothermal reservoir is controlled by intersections of the principal zones of faulting.

The geothermal fluids that discharge from the deep wells are dilute sodium chloride brines containing approximately 7,000 ppm total dissolved solids and anomalous concentrations of F, As, Li, B, and Hg. Geothermometers calculated from the predicted cation contents of the deep reservoir brine range from 520 to 531°F (271 to 277°C). Hydrothermal alteration by these fluids has produced assemblages of clays, alunite, muscovite, chlorite, pyrite, calcite, quartz, and hematite. Geochemical analyses of rocks and soils of the Roosevelt Hot Springs thermal area demonstrate that Hg, As, Mn, Cu, Sb, W, Li, Pb, Zn, Ba, and Be have been transported and redeposited by the thermal fluids.

The geothermal system is well expressed in electrical resistivity and thermal-gradient data and these methods, coupled with geologic mapping, are adequate to delineate the fluids and alteration associated with the geothermal reservoir. The dipole-dipole array seems best suited to acquire and interpret the resistivity data, although controlled source AMT (CSAMT) may be competitive for near-surface mapping. Representations of the thermal data as temperature gradients, heat flow, and temperature are all useful in exploration of the geothermal system, because the thermal fluids themselves rise close to the surface. Self-potential, gravity, magnetic, seismic, and magnetotelluric survey data all contribute to our understanding of the system, but are not considered essential to its exploration.

GENERAL

The following abstracts and publications either contain information on a number of geothermal areas or they are special issues devoted in whole or in part to a major geothermal area.

Benoit, W.R., and R.W. Butler, 1983, A review of high-temperature geothermal developments in the northern Basin and Range province: Geothermal Resources Council Special Report No. 13, p. 57-80.

ABSTRACT — Intensive geothermal exploration in the northern Basin and Range province has resulted in the discovery of nine high-temperature (>200°C) geothermal reservoirs:

1) Roosevelt Hot Springs, Utah
2) Beowawe, Nevada
3) Humboldt House, Nevada
4) Brady's Hot Springs, Nevada
5) Desert Peak, Nevada
6) Northern Dixie Valley, Nevada
7) Soda Lake, Nevada
8) Steamboat Springs, Nevada
9) Coso, California

In addition, there is geological, geophysical, and geochemical evidence to indicate an undiscovered reservoir in the Long Valley caldera, California. Delays in Federal leasing are the main reason this reservoir has not yet been located.

Four of these areas occur along the east or west margins of the province and are spatially associated with Quaternary or Recent siliceous volcanic centers. Five are in or near the Carson Basin in northwestern Nevada and lack evidence for magmatic heating. The Beowawe reservoir has a unique occurrence near the east-west center of the province. Most reservoirs are closely associated with known or suspected Basin and Range normal faults.

With the exceptions of the localized shallow steam production at Coso and bicarbonate-rich water at Beowawe, the known reservoir waters have a dilute sodium chloride composition. Reservoir temperatures typically range from 200 to 220°C. The maximum reported temperature in the northern Basin and Range province is 271°C at Roosevelt Hot Springs.

The most thoroughly evaluated reservoirs are Roosevelt Hot Springs and northern Dixie Valley with 13 and 10 deep wells respectively. The most limited data are from the Soda Lake, Steamboat Springs, Humboldt House, and Long Valley prospects where only two or three deep wells per prospect have been drilled. Depths of the producing intervals vary from about 300 to 3000 m, but production is often from less than 1200 m.

Only one high-temperature, geothermal power plant at Roosevelt Hot Springs is under construction in the province. Extensive negotiations between developers and utilities have taken place regarding the Beowawe, Dixie Valley, and Desert Peak reservoirs.

EG and G Idaho, Inc., 1981, Case studies of low-to-moderate temperature hydrothermal energy development: NTIS Report No. IDO-10098, 126 p.

ABSTRACT — Six development projects are examined that use low- (less than 90°C (194°F)) to moderate- (90 to 150°C (194 to 302°F)) temperature geothermal resources. These projects were selected from 22 government cost-shared projects to illustrate the many facets of hydrothermal development. The case studies describe the history of this development, its exploratory methods, and its resource definition, as well as address legal, environmental, and institutional constraints. A critique of procedures used in the development is also provided and recommendations for similar future hydrothermal projects are suggested.

(The projects are Susanville, CA; Pagosa Springs, CO; White Sulphur Springs, MT; Pierre, SD; Monroe, UT; and Sandy, UT.)

McLaughlin, R.J., and J.M. Donnelly-Nolan (eds.), 1981, Research in The Geysers-Clear Lake geothermal area, northern California: U.S. Geological Survey Professional Paper 1141, 259 p.

This volume presents 23 papers that resulted mainly from a geothermal research program by the Geologic Division of the U.S.G.S. from 1972 to 1980. Geology, geochronology, geochemistry, and geophysics are discussed, along with a few papers that are not directly related to geothermal research. Individual papers have abstracts.

Stringfellow, J. (ed.), 1982, The industry coupled case study; Final report: University of Utah Research Institute, Earth Science Laboratory Report No. ESL-102; DOE/ID/12079-81, 106 p.

This report presents an overview of the Industry Coupled Case Study Program and documents the technical results and open-file data base (through a compilation of abstracts) resulting from the program.

Ward, S.H., H.P. Ross, and D.L. Nielson, 1981, Exploration strategy for high-temperature hydrothermal systems in the Basin and Range province: American Association of Petroleum Geologists Bulletin, v. 65-1, p. 86-102.

ABSTRACT — A 15-phase strategy of exploration for high-temperature convective hydrothermal resources in the Basin and Range province features a balanced mix of geologic, geochemical, geophysical, hydrologic, and drilling activities. The strategy, based on a study of data submitted under the Department of Energy's Industry Coupled Case Study Program, provides justification for inclusion of exclusion of all pertinent exploration methods. With continuing research on methods of exploration for, and modeling of, convective hydrothermal systems, this strategy is expected to change and become more cost-effective with time. The basic strategy may vary with the geology or hydrology. Personal preferences, budgetary constraints, time and land position constraints, and varied experience may cause industrial geothermal exploration managers to differ with our strategy. For those just entering geothermal exploration, the strategy should be particularly useful; many of its elements apply in other geologic settings.

Geothermal Resources Council, 1983, Transactions, v. 7.
Unalaska Island, Alaska — six papers
Cascade Range — nine papers

Geothermics, 1980, v. 9, no. 1/2. Special issue: Cerro Prieto Geothermal Field, Proceedings of the First Symposium held 20-22 September 1978, San Diego, Calfornia.

Geothermics, 1981, v. 10, no. 3/4. Special issue: Cerro Prieto Geothermal Field, Proceedings of the Second Symposium held 17-19 October 1979, Mexicali, Mexico.

Geothermics, 1984, v. 13, no. 1/2. Special issue: Cerro Prieto Geothermal Field, Proceedings of the Third and Fourth Symposia. Held in San Francisco, California, March 1981 and in Guadalajara, Jalisco, August, 1982.

Journal of Geophysical Research, 1976, v. 81, no. 5.
Long Valley, California — 12 papers

Journal of Geophysical Research, 1977, v. 82, no. 26.
Yellowstone National Park, Wyoming — eight papers

Journal of Geophysical Research, 1980, v. 85, no. B5.
Coso, California — 12 papers

Journal of Geophysical Research, 1982, v. 87, no. B4.
Mount Hood, Oregon — five papers

Journal of Volcanology and Geothermal Research, 1983, v. 15, no. 1-3. Special issue: Geothermal Energy of Hot Dry Rock.

Drilling

Drilling in an under-pressured geothermal reservoir

Abstracts reviewed by James R. Kelsey, Gene Polk, and John C. Rowley

Bannerman, J.K., Neal Davis, and R.M. Wolke, 1978, Geothermal drilling fluids systems: Geothermal Resources Council, Transactions, v. 2, p. 27-29.

ABSTRACT — Drilling aspects are reviewed; these include air drilling, common problems, casing, drilling fluid characteristics, corrosion control and sepiolite muds. It is concluded that problems associated with geothermal drilling can be minimized by the proper choice and control of the drilling fluid. Lost circulation can be reduced by using sepiolite muds or air drilling. High bottomhole temperature gellation of conventional muds can be avoided by employing the sepiolite mud systems. Corrosion rates can be minimized in both conventional drilling fluids and in air drilling with new corrosion-control products. Stuck pipe problems are lessened with close control over solids, minimizing wall cake build-up.

Carney, L.L., and R.L. Meyer, 1976, A new approach to high temperature drilling fields: Paper SPE 6025, 51st Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, New Orleans, unpaginated.

ABSTRACT — The clay mineral sepiolite has been under investigation since 1972 by our laboratories for possible use in drilling fluids. This paper reviews the work done on this clay mineral in an effort to obtain a drilling fluid capable of withstanding temperatures in the ultra high range. This includes a study on the rheology of sepiolite slurries that have been subjected to temperatures up to 800°F. X-ray diffraction techniques and scanning electron microscope studies were used to examine the crystalline structure of the sepiolite before and after exposure to these high temperatures. There appears to be some changes in the sepiolite after being subjected to temperatures up to 800°F. However, the basic structure seems to be stable. Data is given showing that slurries prepared from sepiolite and other additives have favorable rheological and fluid loss properties over wide temperature ranges.

Carney, L.L., Necip Guven, and G.T. McGrew, 1982, Investigation of high-temperature fluid loss control agents in geothermal drilling fluids: Paper SPE 10736, 1982 California Regional Meeting of the Society of Petroleum Engineers of AIME, San Francisco, p. 191-193.

ABSTRACT — This paper is a report on research work recently accomplished on examination of various polymers for the purpose of controlling the fluid loss in drilling fluids when subjected to temperatures of up to 371°C (700°F). Investigations have shown that attapulgite and sepiolite will transform to smectite under downhole conditions of temperature and pressure.

While this improves the rheology and fluid loss, to some degree, of a system containing attapulgite or sepiolite when subjected to high temperature, there is a need to further lower the fluid loss.

A series of polymers, copolymers and terpolymers have been evaluated for further control of both rheology and fluid loss.

These systems prove to be superior to conventional water base systems used in oil and gas drilling.

The clay constituents of the fluids have been examined with both x-ray diffraction and electron microscopy. The newly formed smectite has been dehydrated and rehydrated to make up a system for high temperature drilling.

Improvements are noted in the process of dehydrating and rehydrating the newly formed smectite for obtaining viscosity for temperature stable fluids.

The newly formed smectites coupled with high temperature stable polymers have resulted in the formation of a temperature stable drilling fluid for use in geothermal drilling.

Dareing, D.W., 1981, Balanced pressure techniques applied to geothermal drilling: NTIS Report No. SAND-81-7130, 98 p.

ABSTRACT — The objective of the study is to evaluate balanced pressure drilling techniques for use in combating lost circulation in geothermal drilling. Drilling techniques evaluated are: aerated drilling mud, parasite tubing, concentric drill pipe, jet sub, and low density fluids. Based on the present state of the art of balanced pressure drilling techniques, drilling with aerated water has the best overall balance of performance, risk, availability, and cost. Aerated water with a 19:1 free air/water ratio reduce maximum pressure unbalance between wellbore and formation pressures from 1000 psi to 50 psi. This pressure unbalance is within acceptable operating limits; however, air pockets could form and cause pressure surges in the mud system due to high percent of air. Low density fluids used with parasite tubing has the greatest potential for combating lost circulation in geothermal drilling, when performance only is considered. The top portion of the hole would be aerated through the parasite tube at a 10:1 free air/mud ratio and the low density mud could be designed so that its pressure gradient exactly matches the formation pore pressure gradient. The main problem with this system at present is the high cost of ceramic beads needed to produce low density muds.

Hilscher, L.W., and W.R. Clements, 1982, High-temperature drilling fluid for geothermal and deep sensitive formations: Paper SPE 10737, 1982 California Regional Meeting of the Society of Petroleum Engineers of AIME, San Francisco, p. 201-203.

ABSTRACT — A new high temperature drilling fluid system has been developed. The system which uses a thermally stable deflocculant and fluid loss additive has been tested in the laboratory at temperatures up to 450°F (232°C). It provides stable rheological properties and good filtration control even in the presence of severe cement contamination. Lime may be used with the system to inhibit shale swelling and dispersion.

Hinkebein, T.E., V.L. Behr, and S.L. Wilde, 1983, Static slot testing of conventional lost circulation materials: NTIS Report No. SAND-82-1080, 40 p.

ABSTRACT — A study of the utility of conventional lost circulation materials and testing methods was performed using a modified API slot tester. Five lost circulation materials were elevated in 266 tests at both room temperature and temperature-aged conditions simulating expected geothermal enviromnents. A large variation in the maximum pressure (or sealing pressure) the plug could withstand was attributed to nonrepeatability in plug strengths. Plugs were composed to multiple or single particle bridges, with the latter providing stronger, better sealing plugs. Seals occurred on the upstream surface of the slots in all cases. Sealing pressures generally decreased with increasing slot widths and decreasing solids concentration. When the slot width was less than the size of the largest rigid particle in the lost circulation slurry, sealing pressure was maximized. When the slot width was greater than three times the maximum rigid particle size, no significant sealing ability was observed with the conventional materials tested. Additionally, cellulosic lost circulation materials are severely degrated by temperature aging. Mud gellation provided no significant improvement in lost circulation material sealing ability.

Karvelas, C.T., 1976, Technique and problems in drilling geothermal wells, in Augustithis, S.S. (ed.), Proceedings of the International Congress on Thermal Waters, Geothermal Energy and Vulcanism of the Mediterranean area: Geothermal Energy, v. 1, p. 324-336.

ABSTRACT — Geothermal drilling methods are practically similar to those applied in oil field drilling. However, an adaptation of the technique and equipment is required to meet the specific conditions in geothermal wells. Drilling rigs are of medium depth but must withstand higher loads than those used in oil fields since for harnessing endogenous fluid larger castings should be used. Considering the stability of the ground around the well, consolidation grouting might be required for reducing the risk of blow-outs by steam or gas from a shallow depth.

Drilling mud, comparatively stable in high temperatures, should be formulated by special additives and a cooling tower should be provided for cooling down. Casing operation is very important in well completion and should be carried out with special care, since difficulties in setting and cementation may be faced. The basic aim of cementation is to fill up the space between each casing pipe or between the casing and the hole wall, in order to protect the well from caving of the rock around or erosion of the casing, from the penetration of water from low temperature acquifiers. The main difficulties in cementation are caused by the high temperatures which range from values higher than 100°C with maximum at 250°C. Therefore a selected cement quality having special composition and after passing laboratory tests should be used for this operation. Poor and unsuccessful cementation can cause troubles mainly due to the thermal stresses in the casings which are so severe as to result even in breakages.

Kelsey, J.R., 1981, Geothermal drilling and completion technology development program. Quarterly Progress Report, January 1981 - March 1981: NTIS Report No. SAND-81-1020, 250 p.

NO ABSTRACT — Chapter 7 of this report discusses lost circulation control methods. Subheadings are Lost Circulation/Cementing Test Facility; Lost Circulation Material Screening Apparatus; Evaluation of Techniques and Hardware for Drilling Through Lost Circulation Zones.

Nuckols, E.B., D. Miles, R. Laney, G. Polk, H. Friddle, and G. Simpson, 1981, Drilling fluids and lost circulation in hot dry rock geothermal wells at Fenton Hill: Geothermal Resources Council, Transactions, v. 5, p. 257-266.

ABSTRACT — Geothermal hot dry rock drilling at Fenton Hill in Northern New Mexico encountered problems of catastrophic lost circulation in cavernous areas of the Sandia Limestones, severe corrosion due to temperatures of up to 320°C, and torque problems caused by 35° hole angle and the abrasiveness of Precambrian rock.

The use of polymeric flocculated bentonite fluid, clear water, fibrous material, dry drilling, oxygen scavengers, a biodegradable lubricant mixture of modified triglicerides and alcohol, and maintenance of a high pH, were some of the approaches taken toward solving these problems.

Shyrock, S.H., and D.K. Smith, 1982 Methods of combating lost circulation during drilling and casing cementing: Geothermal Resources Council Special Report No. 12, p. 67-80.

ABSTRACT — The success or failure of drilling and completing geothermal wells depends greatly on available cementing processes. (Figure 1) The cementing services which might be used require not only the selection of temperature stable competent materials but also a complete understanding of hole preparation, casing running procedures, mud displacement, lost circulation and the mixing-placing of the cement slurry. (Figures 2-5).

Many steam fields are located where the formation contains poorly consolidated sedimentary deposits, rubblized shales and fractured volcanic rock (Figure 6). These formations are fragile in that some upheaval may have occurred disrupting the structural stability, and, with low reservoir pressures, make them prime candidates for lost circulation problems. Many of the geothermal wells have to be drilled through and/or into these fractured formations. Loss of drilling mud or any other fluid put into the hole usually occurs, creating problems which are expensive to eliminate. This paper offers methods which have been demonstrated successful in combating lost circulation during drilling and casing cementing.

Stilwell, W.B., 1980, Drilling for geothermal energy: Proceedings, 33rd Annual Conference of the Australas Institute of Metals, University of Auckland, May 1980, p. 173-177.

ABSTRACT — The design of geothermal wells includes the selection of casing diameters and depths, materials, siting and surface requirements. Hazards likely to be encountered include blowouts, casing and valve failures. Deviated drilling, or controlled directional drilling is a technique having a number of applications, including bringing wild wells under control, and drilling to areas otherwise inaccessible from the surface. Nonconventional drilling techniques being investigated include turbo drilling, melt drilling and the creation of artificial reservoirs in areas of hot dry rock.

Sutton, D.L., D.L. Roll, and R. DeLeon, 1983, New cement handles both high temperature, lost circulation (Successful in hot, lost circulation-prone, geothermal, and steam injection wells): World Oil, v. 196, no. 5, p. 101-104.

ABSTRACT — This article discusses a HSMS (high strength microsphere) low density thermal cement formulation that shows good temperature stability and improved strength. The additive, consisting of hollow inorganic microspheres, has exceptional low particle density, low water absorbency, can withstand pressures up to 8,000 psi and is stable at temperatures exceeding 1,000°F. For use, primarily, in geothermal wells, the system has been field-tested, and results of case histories are given.

Note: Case histories are a well nearly Brawley, California, USA, and Cerro Prieto, Mexicali, Mexico.)

Reservoir Engineering

Geothermal Reservoir Engineering

Abstracts reviewed by J.S. Gudmundsson, Marcelo J. Lippmann, and C.W. Morris

GENERAL

Brigham, W.E., and W.B. Morrow, 1977, p/Z behavior for geothermal steam reservoirs: Society of Petroleum Engineers Journal, v. 17, p. 407-412.

ABSTRACT — Certain of the natural geothermal-energy reservoirs are of the type called "vapor dominated." These reservoirs contain steam in the top of the reservoir and may contain boiling water below. Some simplifying assumptions were made to predict the pressure and temperature vs production history of such reservoirs. These predictions are compared with normal hydrocarbon gas reservoirs using the standard p/Z plots.

The results show that the presence of a boiling water phase will have a considerable effect on the pressure behavior of such systems. Further, the porosity of the system will have a marked effect. Extrapolations of early data will be optimistic if the porosity is low and pessimistic if the porosity is high. In all cases, the steam zone will remain at the original temperature, though the temperature of the boiling water drops as the pressure declines.

Economides, M.J., D.O. Ogbe, F.G. Miller, and H.J. Ramey, Jr., 1982, Geothermal steam well testing: State of the art: Journal of Petroleum Technology, v. 34, p. 976-988.

NO ABSTRACT — From the Summary: This paper presents a comprehensive state of the art discussion in pressure transient analysis of geothermal steam wells. The techniques encompass drawdown and conventional buildup as well as the newer fractured parallelepiped models. The latter have been used successfully in the analysis of field data from Larderello, Italy, and The Geysers, California. Field examples follow the presentation of each technique.

Garg, S.K., 1980, Pressure transient analysis for two-phase (water/steam) geothermal reservoirs: Society of Petroleum Engineers Journal, v. 20, p. 206-214.

ABSTRACT — A new diffusivity equation for two-phase (water/steam) flow in geothermal reservoirs is derived. The geothermal reservoir may be initially two-phase or may evolve into a two-phase system during production. Solutions of the diffusivity equation for a continuous line source are presented. Comparison of the theory with a limited number of computer-simulated drawdown histories shows excellent agreement.

Grant, M.A., 1983, Geothermal reservoir modeling: Geothermics, v. 12, no. 4, p. 251-263.

ABSTRACT — A quantitative model of a geothermal reservoir represents the culmination of the work of many people in different professions. It should be comprehensible to most of them, and be a coherent summary of concepts of the reservoir, at a consistent level of detail. It should match known history of the reservoir and be used to give predictions of future performance.

Grant, M.A., P.F. Bixley, and I.G. Donaldson, 1983, Internal flows in geothermal wells: Their identification and effect on the wellbore temperature and pressure profiles: Society of Petroleum Engineers Journal, v. 23, p. 168-176.

ABSTRACT — Geothermal wells exhibit a variety of internal flow effects caused by the flow of water, steam, or both between distinct permeable zones tapped by the well. These internal flow effects are described and it is shown how they may be recognized from downhole pressure and temperature profiles.

Pressure transients measured at depths other than that of the well's primary permeable zone can be corrupted by such flows. The effects of such flows on injection and discharge transients are discussed.

Grant, M.A., and M.L. Sorey, 1979, The compressibility and hydraulic diffusivity of a water/steam flow: Water Resources Research, v. 15, p. 684-686.

ABSTRACT — Physical parameters are defined for a flow of water and steam in a porous medium: dynamic and kinematic viscosity, density, and compressibility. These permit single-phase pressure transient theory to be applied to two-phase flow provided that the pressure changes are not too large.

Idaho National Engineering Laboratory, 1982, Low-to-moderate temperature hydrothermal reservoir engineering handbook: NTIS Report No. IDO-10099, 84 p.

NO ABSTRACT — From the Forward: This document, which provides guidelines to developers and consultants in evaluating reservoir characteristics, contains sections on reservoir classification, conceptual modeling, testing during drilling, current theory of testing, test planning and methodology, instrumentation, and a sample computer program.

Martin, J.C. 1975, Analysis of internal steam drive in geothermal reservoirs: Journal of Petroleum Technology, v. 27, p. 1493-1499.

ABSTRACT — Petroleum reservoir analysis methods are applied to simple closed geothermal reservoirs that produce by internal steam drive. The fundamental assumption is that fluid flow in a geothermal reservoir can be treated as flow through a porous medium, and Darcy's law and relative permeabilities are applicable. Calculated performances are given for various types of reservoirs. Results indicate that hot-water reservoirs can have complicated behaviors.

Narasimhan, T.N., and P.A. Witherspoon, 1979, Geothermal well testing: Journal of Hydrology, v. 43, p. 537-553.

ABSTRACT — Just as in the case of hydrogeology and petroleum engineering, well testing is an invaluable tool in assessing the resource deliverability of geothermal reservoirs. While the techniques of production testing and interference testing already developed in hydrogeology and petroleum engineering provide a strong foundation for geothermal well testing, the latter is challenged by some special problems. These special problems stem primarily from the difficulties associated with the measurement of mass flow rate, pressure and temperature under the hostile environment prevalent within geothermal wells. This paper briefly looks into the state-of-the-art of geothermal well testing and provides a few illustrative field examples.

Ramey, Jr., H.H., 1976, Pressure transient analysis for geothermal wells: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 3, p. 1749-1757.

ABSTRACT — Throughout the geothermal literature, concern has been expressed many times about the potential effect of precipitation of solids at the wellbore face, throughout the drainage region of a geothermal well, and about the periphery of a geothermal reservoir as cold recharge fluid contacts the warmer geothermal fluids. Many field observations indicate such concern. For example, it is well known that steam wells in Larderello, Italy, decline in rate during production, and have an active life of about 12 years. Similar declines in production rate are often observed in the production histories of gas and oil wells. For this reason, the specialty of pressure transient analysis has been developed to aid determination of the reason for such rate decline. In addition to precipitation or plugging of the porous media near the well face, other reasons for decline in producing rates include a decrease in the formation pressure and low initial formation permeability. A review of the history of pressure transient analysis and applications to geothermal wells are presented in this paper.

Sudol, G.A., R.F. Harrison, and H.J. Ramey, Jr., 1979, Annotated research bibliography for geothermal reservoir engineering: NTIS Report No. LBL-8664, 150 p.

NO ABSTRACT — Provides reservoir-engineering citations to 1979 in the following categories: formation evaluation, modeling, exploitation strategies, and interpretation of production trends.

Witherspoon, P.A., T.N. Narasimhan, and D.G. McEdwards, 1978, Results of interference tests from two geothermal reservoirs: Journal of Petroleum Technology, v. 30, p. 10-16.

ABSTRACT — Results are presented from interference tests on two liquid-dominated geothermal reservoirs in the United States. The collected pressure data show that interference effects can be masked by earth tides and other effects. Well-known techniques of petroleum engineering and hydrogeology are used to estimate hydraulic characteristics and to infer the presence of barrier and leaky boundaries.

(Note: The two reservoirs are Raft River and East Mesa.)

ICELAND

Bodvarsson, G.S., S.M. Benson, Omar Sigurdsson, Valgardur Stefansson, and E.T. Eliasson, 1984, The Krafla geothermal field, Iceland; 1. Analysis of well test data: Water Resources Research (in press).

ABSTRACT — Extensive modeling studies of the Krafla geothermal field in Iceland are presented in a series of four papers. This first paper describes the geological settings of the field and the analysis of well test data.

The geothermal system at Krafla is very complex, with a single-phase liquid reservoir overlying a two-phase reservoir. The reservoir rocks are volcanic with sequences of basalt flows, hyloclastics, and intrusions. The fluid flow in the reservoir is fracture-dominated.

Considerable pressure transient data from injection tests have been gathered from the Krafla wells. These data are analyzed to yield the transmissivity distribution in the reservoir system. As the data are complicated by the various factors (wellbore effects, nonisothermal effects, two-phase flow, and fractured rocks) the applicability of conventional well test analysis methods is questionable. We have developed a methodology to analyze injection tests for such systems. The results obtained show that the transmissivity of the Krafla reservoir is low, averaging 2 Darcy-meters (Dm). The average transmissivity of most commercially successful geothermal fields is an order of magnitude higher.

Bodvarsson, G.S., K. Pruess, V. Stefansson, and E.T. Eliasson, 1984, The Krafla geothermal field, Iceland; 2. The natural state of the system: Water Resources Research (in press).

ABSTRACT — A model of the natural state of the Krafla reservoir system in Iceland has been developed. The model consists of a vertical cross section which includes reservoirs in both old and new well fields. The physical processes considered include mass transport, conductive and convective heat transfer and boiling, and condensation. Natural heat losses to surface manifestations (springs) are also included. The model matches very well all relevant data from the Krafla field. The natural flow of hot fluids through the reservoirs is estimated as approximately 20 kg/s. Steam escaping to surface springs constitutes the bulk of the heat losses in the area modeled. Conductive heat losses through the caprock are approximately 1 W/m^2, and heat recharge from below is about 2 W/m^2. The excellent match with observed data gives confidence in the transmissivity values inferred from the injection test data.

Bodvarsson, G.S., K. Pruess, V. Stefansson, and E.T. Eliasson, 1984, The Krafla geothermal field, Iceland: 3. The generating capacity of the field: Water Resources Research (in press).

ABSTRACT — This paper presents analytical and numerical studies of the generating capacity of the Krafla field. A general lumped-parameter model is developed, which can be used to obtain rough estimates of the generating capacity of a geothermal field based on the size of the well-field, the average formation porosity, and the amount of recharge to the system. The model is applied to the old wellfield at Krafla. More sophisticated calculations of the generating capacity of the Krafla field are also performed using distributed-parameter models. Two-dimensional areal models of the various reservoir regions at Krafla are developed and their generating capacities (MW_e) evaluated. The results obtained indicate that the old well-field can sustain steam production of 30 MW_e for 30 years. The estimated power potential of the new wellfield is 20 MW_e for 30 years. To obtain the required steam production several additional wells may be drilled in the old and new wellfields.

Pruess, K., G.S. Bodvarsson, V. Stefansson, and E.T. Eliasson, 1984, The Krafla geothermal field, Iceland: 4. History match and prediction of individual well performance: Water Resources Research (submitted).

ABSTRACT — A detailed distributed-parameter model, in which all wells are represented individually, is reported for the Krafla geothermal system. The model is based on a synthesis of geological, geophysical, geochemical, and reservoir engineering data from the field. Numerical simulations achieve an approximate match for production rates and flowing enthalpies for ten wells during the period 1976-1982. Predictions of future field performance on a well-by-well basis are presented for alternative field development plans, including additional production wells, and reinjection of waste fluids.

ITALY

Brigham, W.E., and Guiseppi Neri, 1981, A depletion model for the Gabbro Zone (northern part of Larderello field): Proceedings, Second DOE-ENEL Workshop for Cooperative Research in Geothermal Energy, Berkeley, California, October 1980, Lawrence Berkeley Laboratory Report No. LBL-11555, p. 434-463.

NO ABSTRACT — From the Introduction: The authors studied the pressure and production data available from the Gabbro Zone - a small producing interval north of the main producing area of the Larderello field. A new type of lumped parameter model was developed to match the data. This report summarizes the results of the modeling effort, and includes projections into the future.

Atkinson, P., A. Barelli, W. Brigham, R. Celati, G. Manetti, F.G. Miller, G. Neri, and H.J. Ramey, Jr., 1978, Well-testing in Travale-Radicondoli field: Geothermics, v. 7, p. 145-184.

ABSTRACT — The theory and applications of pressure transient (well test) analysis have been studied intensively for more than 40 years by petroleum reservoir engineers and groundwater hydrologists. Only in the past decade, however, have geothermal-fluid wells been tested for the purpose of making pressure transient studies. Results of these studies disclose various well conditions, for example, restrictions to fluid flow into the wellbore. They also disclose reservoir heterogeneities, boundaries and permeability-thickness products of reservoir rocks. Probably most important, they can be used in estimations of energy reserves. This powerful analytical tool is discussed with special reference to the Travale reservoir.

This reservoir is complicated geologically and hydrologically. It lies on the margin of a graben near a widespread outcrop of the reservoir rocks, which also form an absorption area for the meteoric waters. The area explored can be divided into three zones: in one of these (the nearest to the absorption area) some noncommercial wells produce two-phase water-steam mixtures; in the second zone the wells produce superheated steam, while a well drilled in the graben itself produces a fluid with an uncondensable gas content of about 80%. The reservoir is described in relation to defining areas for further exploration. The nature of the reservoir has affected the design of programs for collecting pressure-production data and other well performance data. The performance history prior to the advent of pressure transient studies pertains mainly to what is known as the 'old' Travale reservoir to the southwest of the 'new' Travale-Radicondoli reservoir in which the more recent wells are drilled and in which modern well test analysis methods have been applied. Data on the 'old' reservoir are discussed first.

Because of its initial performance and relationship to nearby wells the most important well in the 'new' reservoir is Travale well 22. It has been subjected to extensive well testing. Nearly all the wells in the 'new' reservoir have been involved, however, through well-interference tests. In these tests the wells surrounding Travale well 22 are shut in and their pressure responses to different Travale well 22 production rates are measured. Well interference tests indicate the characteristics of fluid flow in the reservoir between test wells and in a qualitative way the heterogeneous nature of the reservoir itself.

Pressure transient theory is developed from ideal system behavior: one vertical, fully-penetrating well producing at a constant rate from a horizontal reservoir of uniform thickness and of infinite extent in any direction from the wellbore. A great deal of research has been done to aid well-test analysts in their interpretation of pressure drawdown curves constructed from data taken on wells in actual reservoirs. This research generally is accomplished with model studies. Some of the models developed in the present research fit reasonably well with the build-up of Travale well 22.

The research done on the Travale reservoir is summarized here with the objective of showing what has been learned, how it can be applied, and what should be done next. Confidence in applications of pressure transient analyses in the Travale reservoir has been gained. New concepts of the reservoir system have emerged as a result of the research. Additional testing and more precise measurements in the field should lead to good engineering of energy reserves.

MEXICO

Lippmann, M.J., and G.S. Bodvarsson, 1983, Numerical studies of the heat and mass transport in the Cerro Prieto geothermal field, Mexico: Water Resources Research, v. 19, p. 753-767.

ABSTRACT — Numerical simulation techniques are employed in studies of the natural flow of heat and mass through the Cerro Prieto reservoir, Mexico and of the effects of exploitation on the field's behavior. The reservoir model is a two-dimensional vertical east to west-southwest cross section, which is based on a recent hydrogeologic model of this geothermal system. The numerical code MULKOM is used in the simulation studies. The steady state pressure and temperature distributions are computed and compared against observed preproduction pressures and temperatures; a reasonable match is obtained. A natural hot water recharge rate of about 1×10^{-2} kg/s per meter of field length (measured in a north-south direction) is obtained. The model is then used to simulate the behavior of the field during the 1973-1978 production period. The response of the model to fluid extraction agrees to what has been observed in the field or postulated by other authors. There is a decrease in temperatures and pressures in the produced region. No extensive two-phase zone develops in the reservoir because of the strong fluid recharge. Most of the fluid recharging the system comes from colder regions located above and west of the produced reservoir.

NEW ZEALAND, BROADLANDS

Grant, M.A., 1977, Broadlands — A gas-dominated geothermal field: Geothermics, v. 6, p. 9-29.

ABSTRACT — Broadlands geothermal field is a hot-water system containing a few percent of non-condensable gas (carbon dioxide). This small fraction of gas makes the field response markedly different from a conventional hot-water system like Wairakei. The gas pressures cause boiling at depths of about 2 km, so that bores exploit only the two-phase zone. The initial pressure response to exploitation is dominated by changes in gas pressures, so that conventional resource assessments are misleading. The fact that bores exploit the two-phase region means that they exploit only a confined area near a bore, and so are very sensitive to local variations in permeability. This contrasts with Wairakei experience. Most presently drilled good bores are in a confined sector of the field. This paper presents a model of the response of this subfield to exploitation, and its recovery.

Hitchcock, G.W., and P.F. Bixley, 1976, Observations of the effect of a three-year shutdown at Broadlands geothermal field, New Zealand: Proceedings of the Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 3, p. 1657-1661.

ABSTRACT — Drilling and testing 25 exploration wells over a period of 5 years resulted in a total discharge of 7.4×10^{10} lb. mass and 4.2×10^{13} Btu heat. Investigations ceased in August 1971 and, apart from minor brief discharges, all the bores remained shut until December 1974. This shut-in period, during which many downhole pressure and temperature measurements were made, has provided a unique opportunity to examine the recharge characteristics of the reservoir.

NEW ZEALAND, WAIRAKEI

Fradkin, L.J., M.L. Sorey, and Alex McNabb, 1981, On identification and validation of some geothermal models: Water Resources Research, v. 17, p. 929-936.

ABSTRACT — Various distributed and lumped parameter models of the Wairakei geothermal reservoir, New Zealand, are discussed within a unifying mathematical framework. The need for proper system identification is emphasized. The best lumped parameter model obtained by system identification techniques is presented and interpreted as a slow drainage model. Validation of different models is conducted by studying their forecasting powers with identified values for compatibility with additional data.

Grant, M.A., and R.N. Horne, 1980, The initial state and response to exploitation of Wairakei geothermal field: Geothermal Resources Council, Transactions, v. 4, p. 333-336.

ABSTRACT — All Wairakei well measurements have been reviewed and re-interpreted. In its natural state the field contained a liquid-dominated two-phase zone over a deeper liquid reservoir. The initial pressure distribution was about 10 percent above hydrostatic, the excess gradient driving the natural discharge. With exploitation and falling pressures, the two-phase zone expanded downwards, and within it a vapor-dominated zone developed. The changes with exploitation can be characterised by two pressures: a deep liquid pressure, reflecting mainly the reservoir mass balance, and a pressure in the steam zone, reflecting the reservoir heat balance. The heat balance indicates that most, but not all, of the recharge is hot water.

Production from wells is currently declining due to falling temperatures and pressures in both zones of the field. The liquid-dominated zone pressure can be raised by reinjection. Deep peripheral injection is estimated to have a payback time of about two years.

Mercer, J.W., and C.R. Faust, 1979, Geothermal reservoir simulation: 3. Application of liquid- and vapor-dominated hydrothermal modeling techniques to Wairakei, New Zealand: Water Resources Research, v. 15, p. 653-671.

ABSTRACT — A quasi three-dimensional, areal model based on finite-difference approximations is applied to the hydrothermal field at Wairakei, New Zealand. The model simulates heat transport associated with the flow of steam and water through porous media. An analysis is made of the production aquifier under steady-state and transient flow conditions, allowing vertical flow of heat and fluid through confining beds. Computed steady-state results correlate well with observed data and indicate that portions of the aquifier had a steam cap prior to exploitation. Computed transient results also match observed data and support the hypothesis that the production aquifier is recharged through underlying confining beds. The limiting factor on production is the amount of mass available, both from storage and leakage. Although simulation results indicate that the field can maintain production rates to the year 2000, such long range predictions are unreliable due to the lack of information on the leakage properties of the confining beds.

Whiting, R.L., and H.J. Ramey, Jr., 1969, Application of material and energy balances to geothermal steam production: Journal of Petroleum Technology, v. 21, p. 893-900.

ABSTRACT — The material-energy balance developed in this study has been used successfully to match performance and to forecast production for the Wairakei geothermal field of New Zealand. The equations should be applicable to other geothermal field reservoirs, provided the assumptions used are realistic.

PHILIPPINES

Whittome, A.J., 1979, Well testing in a liquid dominated two phase reservoir: Geothermal Resources Council, Transactions, v. 3, p. 781-784.

ABSTRACT — The Tongonan Geothermal Field, Leyte, Philippines is a good example of a liquid dominated geothermal system with extensive two phase conditions. This paper outlines the history of one well and a variety of test procedures including transient pressure testing methods, successfully used to identify characteristics of the reservoir and geothermal fluid adjacent to the well when flashing occurs within the rock as well as the wellbore. The effects of an experimental injection treatment are discussed.

UNITED STATES, CALIFORNIA

Lipman, S.C., C.J. Strobel, and M.S. Gulati, 1978, Reservoir performance of The Geysers field: Geothermics, v. 7 p. 209-219.

ABSTRACT — The Geysers Field, located in Northern California, has an installed generating capacity of 502 MW_e. Total withdrawal rate is approximately 8.5 million lb/h of steam from 95 wells. Four new generating plants are currently under construction, which will bring the installed capacity to 908 MW_e by 1979.

The reservoir rock consists of naturally fractured graywacke, a very competent rock with low interstitial porosity and permeability. The reservoir contains dry steam with an initial pressure of approximately 514 psia at sea level datum. Static pressure gradient is that of saturated steam to the total depths of wells drilled to date.

The initial development at The Geysers Field occurred in an area which has two shallow dry steam anomalies. Recent studies have shown that the steam in these anomalies is being fed through fractures connecting them with the deeper regional fracture system.

Development of the regional system has created two distinct pressure sinks. The larger of the two pressure sinks is in the oldest and most developed portion of the field. This sink has grown larger with the addition of new production capacity. There is no pressure interference between the two sinks, but pressure interference between wells in a given pressure sink is very rapid. Pressure behavior at observation wells in these sinks resembles an ideal single-phase system with constant pressure boundaries.

The expansion of the field has been the result of continued exploratory drilling and testing of new step-out wells. Based on the successful exploratory wells drilled to date, it is estimated that the generating capacity of The Geysers could reach 1800 MW by the mid-1980s.

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ppmann, M.J., and G.S. Bodvarsson, 1984, The Heber geothermal field, California: Natural state and exploitation modeling studies: Journal of Geophysical Research (submitted).

ABSTRACT — Using numerical simulation techniques and a simplified model of the Heber geothermal field the natural (pre-exploitation) state of the system and its response to fluid production are analyzed. The results of the study indicate that the Heber geothermal anomaly is sustained by the upflow of hot water through a central zone of relatively high permeability. The model shows that in its natural state the system is recharged at depth by a 15 MW (thermal) convective heat source. The existence of a radially symmetric convection pattern, whose axis coincides with the center of the Heber anomaly is suggested. At the lower part of the ascending hot water plume, the deep recharge water mixes with colder water moving laterally towards the axis of the system. In the upper part, the rising plume spreads radially outward after reaching the bottom of the caprock, at about 550 m depth. The model results suggest that the caprock is quite permeable, with convection controlling its temperature distribution. The results also show low permeability of the upper zones in the outer region of the system that may be due to mineral precipitation. In modeling the exploitation of the field, the generation rate is allowed to build up over a period of 10 years; after that, 30 years of constant power production is modeled. Full (100%) injection of the spent brines is considered; the fluids being injected 2250 m ("near injection") or 4250 m ("far injection") from the center of the system. The study shows that a maximum of 6000 kg/s (equivalent to approximately 300 MW_e) of fluids may be produced for the near injection case, but only 3000 kg/s (equivalent to approximately 150 MW_e) for the far injection case. The results indicate that the possible extraction rates (generating capacity) are generally limited by the pressure drop in the reservoir. The average temperature of the produced fluids will decline 10-18°C over the 40-year period.

Morris, C.W., and D.A. Campbell, 1981, Geothermal reservoir energy recovery — A three-dimensional simulation study of the East Mesa field: Journal of Petroleum Technology, v. 33, p. 735-742.

ABSTRACT — This paper describes the reservoir simulation model developed for Republic's East Mesa KGRA properties and summarizes the reservoir engineering evaluation of the reserves. Geothermal reservoirs should be evaluated in terms of efficient "energy mining" rather than fluid recovery. This fact presents the reservoir engineer with an exploitation concept fundamentally different from that encountered in oil and gas resource development. The energy mining approach, lack of analogues and lack of a long-term production history require that reserve estimates and development plans be based on reservoir simulation results from the beginning.

The simulation study reported here was performed using a three-dimensional, two-phase geothermal reservoir simulator to predict the behavior of the field under various scenarios of development designed to operate a proposed 64 MW electric power plant for 30 years. Basic reservoir information was derived from well production data, well interference data, well pressure drawdown/buildup data, petrophysical data, geochemical data and geological data. The recovery efficiency is shown to be related directly to the production/injection pattern chosen and the individual reservoir characteristics. Results indicate that the northern portion of Republic's leases in the East Mesa field will provide the required support for the power plant.

Morse, J.G., and R. Stone, 1979, Evaluation of reservoir properties in a portion of the Salton Sea geothermal field: NTIS Report No. UCRL-52756, 56 p.

ABSTRACT — A series of pressure-transient tests was performed using several geothermal wells in the southwestern portion of the Salton Sea Geothermal Field in the Imperial Valley, California. The objective of the tests was to evaluate the permeability and storage capacity of the geothermal reservoir. Measurement of pressure transients in the corrosive, high-temperature environment of geothermal wells was made possible by modifying commercially available instrumentation and fabrication of pressure-sensing devices from very corrosion-resistant material. Analysis of pressure-transient data associated with production from and injection into the geothermal reservoir provides estimates of reservoir permeability that vary from 70 to 1000 md, with most of the values in the range from 70 to 220 md. A reservoir porosity-compressibility product of 2.8×10^{-6} psi^{-1} was derived. The pressure responses to the tests appear to be characteristic of a confined, nonleaky reservoir. The vertical permeability of a 40-ft-thick shale layer within the reservoir was estimated to be between 0.1 and 1 md. No lateral positive or negative hydraulic boundaries were detected. The pressure response of the primary spent-brine injection well was indicative of combined fracture and matrix flow in the reservoir. This well's lifetime with no brine treatment prior to injection would be about 150 days at an injection flow rate of 600 gpm: simply cycling the brine through settling tanks prior to injection would increase the well's useful life to about two years at the same injection rate.

Schroeder, R.C., 1976, Reservoir engineering report for the Magma-SDG and E geothermal experimental site near the Salton Sea, California: NTIS Report No. UCRL-52094, 64 p.

ABSTRACT — A description of the Salton Sea geothermal reservoir is given and includes approximate fault locations, geology (lithology), temperatures, and estimates of the extent of the reservoir. The reservoir's temperatures and chemical composition are also reviewed. The flow characteristics are discussed after analyses of drillstem tests and extended well tests. The field production, reserves and depletion are estimated, and the effects of fractures on flow and depletion are discussed. The reservoir is believed to be separated into an "upper" and "lower" portion by a relatively thick and continuous shale layer. The upper reservoir is highly porous, with high permeability and productivity. The lower reservoir is at least twice as large as the upper but has much lower storativity and permeability in

the rock matrix. The lower reservoir may be highly fractured, and its temperatures and dissolved solids are greater than those of the upper reservoir. The proven reserves of heat in the upper reservoir are about 1/4 GW.yr (in the fluid) and 1/3 GW.yr (in the rock). In the lower reservoir in the proven reserves of heat are 5-3/4 GW. yr (in fluid) and 17 GW.yr (in the rock). Unproven reserves greatly exceed these numbers. Injection tests following well completion imply that hydraulic fracturing has taken place in two of the SDG and E wells and at least one other well nearby.

Stockton, A.D., R.P. Thomas, R.H. Chapman, and Herman Dykstra, 1981, A reservoir assessment of The Geysers geothermal field: California Department of Conservation, Division of Oil and Gas Publication No. TR27, 60 p.

ABSTRACT — Big Sulphur Creek fault zone, in The Geysers Geothermal field, may be part of a deep-seated, wrench-style fault system. Hydrothermal fluid in the field reservoir may rise through conduits beneath the five main anomalies associated with the Big Sulphur Creek wrench trend. Upon cresting, the fluid may descend through an extensive, moderately dipping, fracture network. Condensed steam at the steep reservoir flanks drains back to the hot water table. These flanks are defined roughly by marginally-producing geothermal wells. Field extensions are expected to be on the southeast and northwest.

Some geophysical anomalies (electrical resistivity and audio-magnetotelluric) evidently are caused by the hot water geothermal field or zones of altered rocks; others (gravity, P-wave delays, and possibly electrical resistivity) probably represent the underlying heat source, a possible magma chamber; and others (microearthquake activity) may be related to the steam reservoir.

A large negative gravity anomaly and a few low-resistivity anomalies suggest areas generally favorable for the presence of steam zones, but these anomalies apparently do not directly indicate the known steam reservoir.

Monitoring gravity and geodetic changes with time and mapping microearthquake activity are methods that show promise for determining reservoir size, possible recharge, production lifetime, and other characteristics of the known steam field. Seismic reflection data may contribute to the efficient exploitation of the field by identifying fracture zones that serve as conduits for the steam.

At the current generating capacity of 930 MW_e, the estimated life of The Geysers Geothermal field reservoir is 129 years. The estimated reservoir life is 60 years for the anticipated maximum generating capacity of 2,000 MW_e as of 1990.

Wells at The Geysers are drilled with conventional drilling fluid (mud) until the top of the steam reservoir is reached; then, they are drilled with air. Usually, mud, temperature, caliper, dual induction, and cement bond logs are run on the wells. Casing in the well is cememted at the top of the steam reservoir. Sometimes, a small amount of steam is allowed to escape from a well before it is connected to a power plant. This prevents steam from condensing in the well bore and quenching the well.

UNITED STATES, NEW MEXICO

Bodvarsson, G.S., S. Vonder Haar, M. Wilt, and C.F. Tsang, 1982, Preliminary studies of the reservoir capacity and the generating potential of the Baca geothermal field, New Mexico: Water Resources Research, v. 18, p. 1713-1723.

ABSTRACT — A 50-MW_e geothermal power plant is being considered for the Baca site in the Valles Caldera, New Mexico, as a joint venture of the Department of Energy (DOE) and Union Oil Company of California. To date, over 20 wells have been drilled on the prospect, and the data from these wells indicate the presence of a high-temperature, liquid-dominated reservoir. In this paper, data from the open literature on the physical characteristics of the field are used to estimate the amount of hot water in place (reservoir capacity) and the length of time the reservoir can supply steam for a 50-MW_e power plant (reservoir longevity). The reservoir capacity is estimated to be 10^{12} kg of hot fluid by volumetric calculations using existing geological, geophysical, and well data. The criteria used are described and the sensitivity of the results discussed. The longevity of the field is studied using a two-phase numerical simulator (SHAFT79). A number of cases are simulated based upon different boundary conditions and upon injection and production criteria. The results obtained from the simulation studies indicate that it is questionable that the Baca field can supply enough steam for a 50-MW_e power plant for 30 years. Although the estimated reservoir reserves greatly exceed those needed for a 50-MW_e power plant, the low transmissivity of the reservoir would cause localized boiling and rapid pressure decline during exploitation. It is therefore apparent that the conventional zero-dimensional (lumped parameter models) cannot be used to evaluate the generating capacities of low-permeability fields such as the Baca field.

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