SF 11718

GEOTHERMAL ENERGY ABSTRACT SETS

SPECIAL REPORT NO. 14

1984 — 1985



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SPECIAL REPORT NO. 14

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UNITED STATES DEPARTMENT OF ENERGY

Compiled and Edited By Claudia Stone

1984 - 1985

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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

Exploration Strategies	-21
RILLING (Printed Set 1984) In An Under Pressured Geothermal Reservoir25	-27
ESERVOIR ENGINEERING (<i>Printed Set 1984</i>) Geothermal Reservoir Engineering	-38
JECTION (Nov. 1984)	-50
EOTHERMAL WELL LOGGING (Dec. 1984)	-66
NVIRONMENTAL CONSIDERATIONS IN GEOTHERMAL DEVELOPMENT (Feb. 1985)	-76
EOTHERMAL WELL PRODUCTION (March 1985)	-84
EOTHERMAL MATERIALS (April 1985)	-93
LECTRIC POWER PRODUCTION (June 1985)	103
IRECT UTILIZATION OF GEOTHERMAL ENERGY (Sept. 1985) 104-	112
CONOMICS OF GEOTHERMAL ENERGY (Oct. 1985)	120
EGAL, REGULATORY and INSTITUTIONAL ASPECTS OF GEOTHERMAL ENERGY (Dec. 1985)	127

Case Histories

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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 mWm² (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 km². 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 km² 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 heatsource 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, SiO₂, 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/cm²). 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. I, 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 km², 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 wellby-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. Subsurface 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 km² 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 aguifer 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 fracturedominated 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 km² 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 km³ 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/cm³, 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 x 10⁷ 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 x 10⁷ 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 Lakesize 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 seismicrefraction 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 pressureboundary 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 m²) 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 km² 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 strikeslip 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 sand-

stones, 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 $20~\mu$ cal/cm² 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 shallowdepth 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 rangebounding 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 km² 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 soilmercury 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 selfpotential 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 km²) 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 selfpotential 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 aguifer (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 aguifer was discovered in or on top of Precambrian basement. It appears that low- to moderate-temperature geothermal reservoirs (≤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 Albuguerque 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 Techni-

cal 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/m²), 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 eastwest 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 hightemperature 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

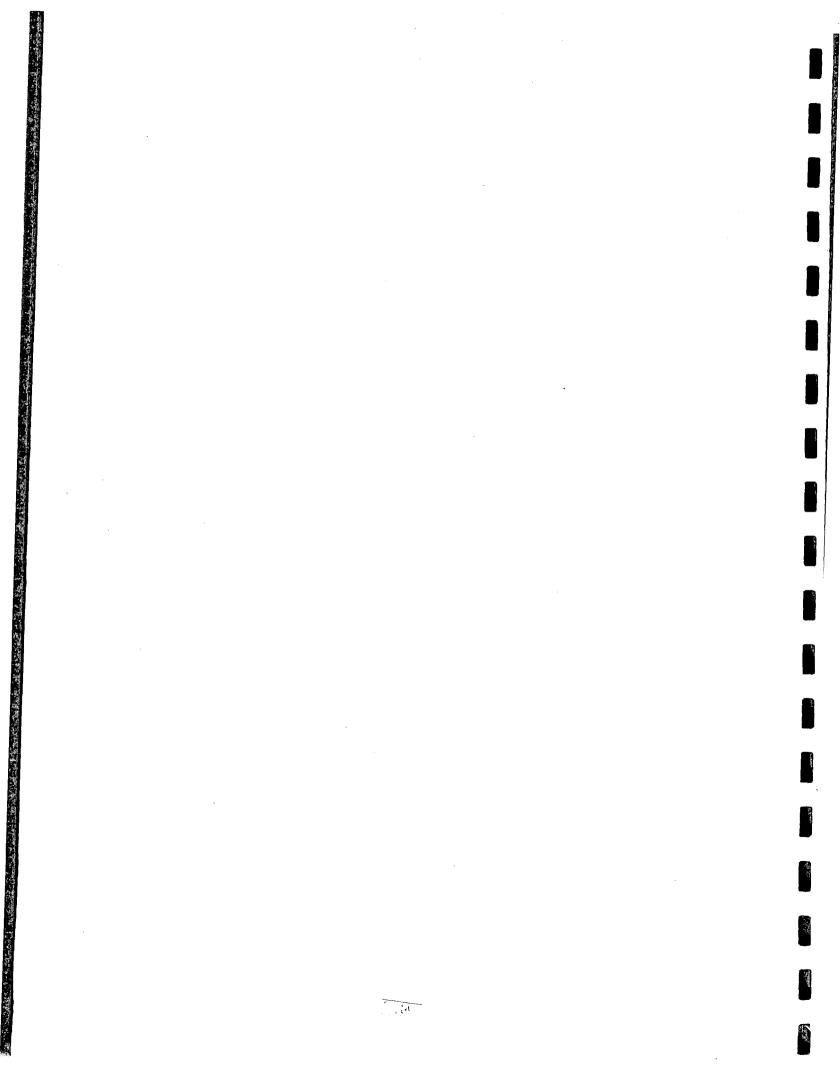
Journal of Geophysical Research, 1977, v. 82, no. 26. Yellowstone National Park, Wyoming — eight papers

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. 为,我们们也是一个人,我们们的人,他们是一个人,他们们的人,他们也是一个人,他们也是一个人,他们们是一个人的人,他们就是一个人的人,他们们的人,他们的人们的人, 第二章

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 environments. 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.

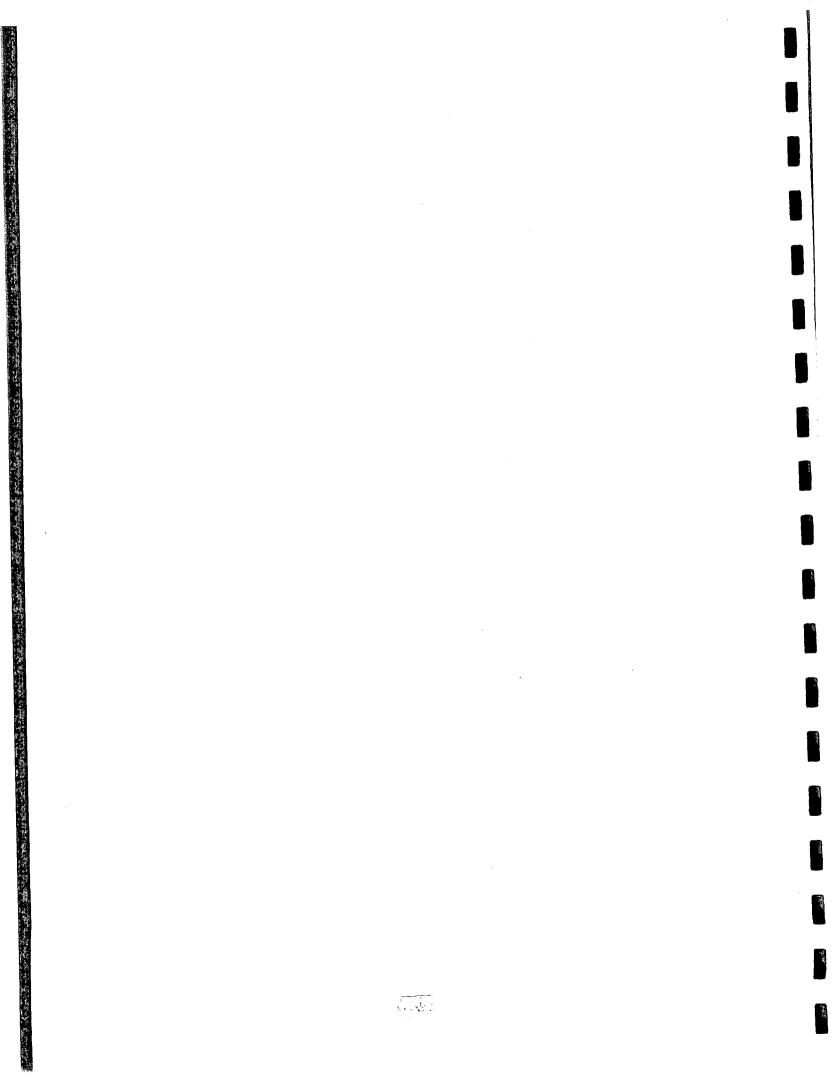
Stilwell, W.B., 1980, Drilling for geothermal energy: Proceedings, 33rd Annual Conference of the Australas Institute of Metals, University of Auckland, May 1980, p. 173-177.

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. Solu-

tions 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 Darcymeters (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/m², and heat recharge from below is about 2 W/m². 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 wellfield, 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 (MWe) evaluated. The results obtained indicate that the old wellfield can sustain steam production of 30 MWe for 30 years. The estimated power potential of the new wellfield is 20 MWe 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-bywell 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 well-bore. 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 westsouthwest 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 x 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 x 10 ¹⁰ lb. mass and 4.2 x 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 MWe. 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 MWe by 1979.

The reservoir rock consists of naturally fractured gray-wacke, 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.

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 MWe) of fluids may be produced for the near injection case, but only 3000 kg/s (equivalent to approximately 150 MWe) 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 x 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, wrenchstyle 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 MWe, 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 MWe 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 cemented 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-MWe 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-MWe power plant (reservoir longevity). The reservoir capacity is estimated to be 10¹² 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-MWe 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.

SPECIAL PUBLICATIONS

- Geothermal Resources Council, 1982, Fractures in geothermal reservoirs, Special Report 12, 174 p.
- Grant, M.A., I.G. Donaldson, and P.F. Bixley, 1982, Geothermal reservoir engineering: New York, Academic Press, 369 p.
- Rybach, L., and L.J.P. Muffler (eds.), 1981, Geothermal systems: Principles and case histories: New York, John Wiley & Sons, 359 p.
- DOE-ENEL Workshop on Cooperative Research in Geothermal Energy, Lawrence Berkeley Laboratory, 1st (1979) and 2nd (1980).
- Geothermal Resources Council, Transactions, v. 1 (1977) through v. 8 (1984).

- Geothermics, Special issue: Cerro Prieto Geothermal Field, Proceedings of Symposia, 1st (1980, v. 9, no. 1/2), 2nd (1981, v. 10, no. 3/4), 3rd and 4th (1984, v. 13, no. 1/2).
- Invitational Well-Testing Symposium, Lawrence Berkeley Laboratory, 1st (1977), 2nd (1978), and 3rd (1981).
- Proceedings of the New Zealand Geothermal Workshop, Auckland, 1st (1979) through 5th (1983).
- Workshop on Geothermal Reservoir Engineering, Stanford University, 1st (1975) through 9th (1983).

Special Report 14 Addendum

Injection

Abstracts reviewed by Gudmundur S. Bodvarsson, Roland N. Horne, and Walter E. Nellis

BRINE CHEMISTRY, CLARIFICATION, FILTRATION
AND SOLIDS REMOVAL

Dahlstrom, D.A., R.W. Moore, and R.C. Emmett, Jr., 1982, Clarifying geothermal fluids: Chemical Engineering Progress, v. 78, p. 50-55.

ABSTRACT — Reinjection of the brines from geothermal wells requires separation of fine, suspended solids after desupersaturation of silica. A solids-contact clarifier for promoting crystal growth was tied in with a filter. This paper describes a method which has been developed whereby a Reactor-Clarifier machine can be employed to reduce silica to the saturation point without addition of chemicals. Simultaneously, scaling has been prevented by using the internally recycled solids as seed for crystal growth. By recirculating thickened solids to the pressure flash vessels and crystallizers employed for steam generation, it also appears that scaling can be eliminated in these units. Pressure filtration can be used to produce dewatered solids which can be disposed of in any environmentally acceptable way. Spent brine clarified by granular dual-media filters can be reinjected into the formation at a reasonably constant volumetric rate per unit of pressure drop. Total costs per kWh of electrical production appear reasonable.

Featherstone, J.L., R.H. Van Note, and B.S. Pawlowski, 1979, Costeffective treatment system for the stabilization of spent geothermal brines: Geothermal Resources Council, Transactions, v. 3, p. 201-204.

ABSTRACT — A treatment system has been developed in which spent geothermal brines from a flash tank heat extraction plant are stabilized to permit reinjection of the treated brine while maintaining the integrity of the wells over an extended period. This treatment system is both cost-effective and environmentally sound. It incorporates the following unit process operations:

Reconstituting the minerals which were dissolved from the geothermal strata formations in a Reactor-Clarifier by solids contact precipitation reactions.

Polishing of the clarifier effluent in a gravity dual media filter.

Thickening and storage of sludge produced in the Reactor-Clarifier.

Dewatering of the sludge to an optimum cake moisture suitable for handling and land disposal.

Owen, L.B., E. Raber, C. Otto, R. Netherton, and R. Neurath, 1979, Assessment of the injectability of conditioned brine produced by a reaction clarifier-gravity filtration system in operation at the Salton Sea geothermal field, southern California: NTIS Report No. UCID-18488, 30 p.

ABSTRACT — A Demonstration Reaction Clarifier - Gravity Filtration System with a 1600 GPM throughput capability was in operation at the joint DOE-SDG and E-MAGMA test facility located in the Salton Sea Geothermal Field, southern California, during the summer of 1979. The system, which was designed to condition spent effluent from a 10 MWe size geothermal power plant, removes supersaturated dissolved species and residual suspended solids from brine prior to subsurface brine disposal via injection wells. The post-processing chemical stability of conditioned effluents was established by means of anaerobic incubation tests at 90°C. The effect of residual dissolved polymer, that might be used for the purpose of scale control in upstream power plant components on the efficiency of reaction clarification, was also evaluated. Membrane filtration and core tests were used to assess the injectibility of processed brine. It was found that the clarifier-filter operational procedures and system design permitted oxygenation of the brine by air intrusion. This resulted in partial stabilization of dissolved silica and precipitation of oxides of iron. As a consequence, conditioned brine injectability was poor. However, elimination of the air intrusion problem would result in a substantial improvement in brine quality. Residual amounts of dissolved polyaminoethylene (20 ppm, by weight), a powerful antisilica precipitant, in brine was shown by means of bench-scale tests carried out at approx. 90°C to improve the efficiency of the clarification process where the additive appears to function as a flocculant.

Quong, R., F. Schoepflin, N.D. Stout, and G.E. Tardiff, 1979, Processing of geothermal brine effluents for injection: Geothermal Resources Council, Transactions, v. 2, p. 551-554.

ABSTRACT — Brine effluents from the San Diego Gas & Electric/Department of Energy Geothermal Loop Experimental Facility were characterized for particulate concentration and chemical composition. Bench scale tests were conducted with inorganic and organic coagulants as a means of enhancing the sedimentation process for separation and removal of suspended solids, principally amorphous silica. The effects of temperature, retention time, and pH on the precipitation of supersaturated silica, subsequent floc settling properties, and supernatant clarity were determined. A pilot sized clarifier with mixed media sand or precoat pressure filtration have been successfully tested as a means of producing injectable brine effluents. Preliminary cost estimates range in the vicinity of 20¢/1000 gallons.

Raber, E., and R.E. Thompson, 1979, Processing of high salinity brines for subsurface injection: NTIS Report No. UCRL-83122 (Rev. 1), 10 p.

ABSTRACT — Different chemical pretreatments and filtration methods were evaluated a possible means of clarifying and improving the injectivity of hypersaline brines. Based upon the concentration of suspended solids and chemical composition of the brine, the main emphasis was placed on evaluating downflow granular media (combinations of coal, garnet and/or sand) filters. Six different media combinations were evaluated over the three sites, utilizing test data from 4 inch diameter pilot filters. In addition, tests were conducted with one hollow fiber ultrafilter unit and two types of disposable cartridge filters. The test procedures employed in this study involved: (1) a bench-scale evaluation of pretreatment chemical acids, (2) pilot tests with and without chemical coagulants on downflow granular media filters, ultrafilters, and cartridge filters, and (3) particular techniques developed by LLL for the assessment of injectability utilizing filter membrane plugging factor tests. Over fifty inorganic salts and polymers were evaluated as coagulants/flocculants by a combination of jar testing and bench-scale filtration techniques. In summary, the results showed that high-molecular weight anionic polymers and aluminum salts (or aluminum salts plus nonionic polymers) were the most effective. Average turbidities were lowered from 10 to .20 NTU after addition of these chemicals. Anionic polymers have also been found to be effective coagulants in hypersaline geothermal brine.

Vetter, O.J., 1981, Suspended solids removal prior to brine reinjection: Geothermal Resources Council, Transactions, v. 5, p. 377-380.

ABSTRACT — Reactor-clarification in combination with a multimedia sandbed filter has been successfully used to treat a heat-depleted geothermal brine prior to reinjection. The various components of a reactor-clarification system have been split into individual hardware com-

ponents. This split allows for the study of all critical parameters that determine the overall efficiency of a future brine treatment facility. Based upon experimental results, a reactor-clarification system can be easily designed for future field applications. It is felt that the removal of suspended particles will not offer unsurmountable problems in future geothermal operations.

Weres, O., and J.A. Apps, 1979, Prediction of chemical problems in the reinjection of geothermal brines, in Narasimhan, T.N. (ed.), Recent trends in hydrogeology: Geological Society of America Special Paper 189, p. 407-426.

ABSTRACT — Amorphous silica and silicates, and the carbonates and sulfates of calcium, strontium, and barium are the solids most commonly deposited by geothermal brines. The phenomenology and kinetics of their precipitation are reviewed in this paper. Practical methods of avoiding or reducing reinjection well damage are discussed, with emphasis on the important and well-researched problem of removing colloidal amorphous silica from spent geothermal brines before reinjection.

Need for further research is also discussed. It is concluded that the interaction of the reinjected brine with the reservoir rock and the brine's effect on rock properties are the areas that most need further research.

INJECTION MONITORING

Wilt, M.J., K. Pruess, G.S. Bodvarsson, N.E. Goldstein, 1983, Geothermal injection monitoring with DC resistivity methods: Geothermal Resources Council, Transactions, v. 7, p. 477-482.

ABSTRACT — Injection into an idealized geothermal reservoir is considered, assuming that the injected water differs in temperature and salinity from in-place fluids. Changes in formation resistivity resulting from temperature and salinity variations are evaluated, and numerical simulation methods are used to predict effects which would be observed by means of dc resistivity monitoring. The resistivity calculations were performed using a three-dimensional computer code to simulate results from two different resistivity arrays, a dipole-dipole array and a downhole-surface array. Calculations show that the dipole-dipole method is relatively insensitive to changes due to injection, but downhole-surface measurements are very sensitive. From the simulated downhole-surface measurements a bellshaped curve for resistivity change is obtained, from which the position of the chemical front may be approximately determined. Resisivity changes from temperature variations are rather small and probably cannot be detected in field measurements. Resistivity measurements are more than twice as sensitive when injected water is more saline than the in-situ reservoir fluid. This suggests that it may be easier to monitor the location of injected water if geothermal brine is reinjected rather than fresher water.

Younker, L., J. Hanson, E. Didwell, P. Kasameyer, and A. Smith, 1982, Geothermal injection monitoring project. Phase I Status Report, April 1981 - April 1982: NTIS Report No. UCID-19497, 154 p.

ABSTRACT — The feasibility of using remote geophysical techniques to monitor the movement of injected brine has been evaluated. It was established that no single approach is likely to be identified than can be used to accurately monitor the precise location of the injected fluid. Several approaches have been considered in parallel because they add new dimensions to the existing monitoring capabilities, and are likely to cover a range of applications at a variety of geothermal sites. These include: microseismicity - a seismic net is used to record small magnitude events associated with injection; streaming potential - self potential anomalies produced by a moving fluid identity fluid flow direction; cross borehole geotomography - two dimensional image of flow pathways is constructed using electromagnetic waves; and well pressure response to solid earth tide - changes in pore pressures are used to discriminate fracture/pore porosity and estimate fracture orientations.

INJECTION AND TRACER TESTING

Ahmed, U., K.W. Walgemuth, A.S. Abou-Sayed, J.F. Schatz, and A.H. Jones, 1980, Raft River geothermal site: A reinjection study: Geothermal Resources Council, Transactions, v. 4, p. 385-388.

ABSTRACT — Analysis of transient pressure tests combined with spinner surveys and a knowledge of the geology of the area have allowed us to define the injectivity potential of the Raft River geothermal site. The present two injection wells will allow approximately two to four months of injection at the required rate of 2500 gpm without fracturing the formation. A numerical simulator has been used to model the injection portion of the reservoir to investigate options such as hydraulic fracturing or the drilling of an additional well to provide sufficient subsurface disposal.

Allen, T.S., and J.R. Baza, 1980, Role of step-rate injectivity testing in liquid dominated, highly fractured geothermal reservoirs: Paper SPE 9275, 55th Annual Fall Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, Dallas.

ABSTRACT — A step-rate injectivity testing program was designed to obtain additional operating parameters and reservoir data of the Roosevelt Known Geothermal Resource Area (KGRA). Beaver County, Utah. The testing program consisted of injecting fresh water at rates varying between one half (0.5) BPM and sixty (60) BPM into four producers and one injector. The rates, wellhead pressures and subsurface pressure data collected was used to size injection equipment for future field development, verify the highly fractured reservoir and cross check previous permeability calculations by using the multiple rate transient technique.

Benson, S.M., and G.S. Bodvarsson, 1982, Nonisothermal effects during injection and falloff tests: Paper SPE 11137, 57th Annual Fall Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, New Orleans.

ABSTRACT — Injection tests are commonly performed in geothermal wells to obtain reservoir and well parameter data. Most of the tests are analyzed assuming that either the injected fluid is the same temperature as the reservoir fluid or that a stationary boundary separates the reservoir regions of different fluid properties. In general, neither of these assumptions are appropriate for the analysis of nonisothermal injection tests. Pressure transients in response to nonisothermal injection are controlled, to a great extent by the temperature-dependent fluid properties, viscosity and density. In this study, numerically simulated pressure transients during injection and falloff tests are analyzed to develop methods for obtaining the correct permeability-thickness of the reservoir and the skin factor for the well.

The results show that to correctly analyze pressure transients governed by a moving thermal front, the values used for the fluid properties must correspond to the temperature of the injected fluid. On the other hand, for pressure falloff tests and for injection tests conducted in a well cooled by previous injection or drilling, the physical properties of the in situ reservoir fluids must be used. It is also shown that the application of conventional isothermal methods for calculating skin values from injection and falloff data will give erroneous results. A new method is presented for calculating skin values from injection and falloff data that accurately corrects for nonisothermal effects. A number of detailed examples are given that illustrate the suggested method of analysis. The technique is applied to the analysis of injection test data from a well located in the East Mesa geothermal field in southern California.

Benson, S.M., and G.S. Bodvarsson, 1983, Pressure transient method for front tracking: NTIS Report No. LBL-16574, 22 p.

ABSTRACT — A pressure transient technique for tracking the advance of cold water fronts during water flooding and geothermal injection operations has been developed. The technique is based on the concept that the steady state pressure buildup in the reservoir region inside the front can be calculated by a fluid skin factor. By analyzing successive pressure falloff tests, the advance of the front in the reservoir can be monitored. The validity of the methods is demonstrated by application to three numerically simulated data sets, a nonisothermal step-rate injection test, a series of pressure falloffs in a multilayered reservoir, and a series of pressure falloff tests in a water flooded oil reservoir.

Dobbie, T.P., B.R. Maunder, and A.D. Sarit, 1982, Reinjection experience in the Philippines: Proceedings Pacific Geothermal Conference, incorporating the 4th New Zealand Workshop, Auckland, p. 223-228.

ABSTRACT — Reinjection trials have assisted with the environmentally acceptable disposal of geothermal brine during testing of the Tongonan and Palimpinon fields as well as determining the effects of fluid injection wells and reservoirs. Well parameters were measured to provide baseline data and well performance has been monitored at appropriate intervals. The performance of injection wells has generally been encouraging with an increase in injectivity as injection has proceeded. In the few trials where a decrease in injectivity has occurred, it has been associated with an interruption to reinjection. This phenomenon is under continuing investigation. Tracer tests have been used to tract subsurface fluid movement and the results have indicated rapid communication between injection and production wells although tracer returns have been small. Reinjection testing continues and the accumulation of experience will be expanded substantially by the imminent commissioning of the Leyte I and Palimpinon I power stations.

Downs, W.F., R.E. McAtee, R.M. Capuano, and W. Sill, 1983, Hydrothermal injection experiments at the Raft River KGRA, Idaho: NTIS Report No. EGG-M-27982, 4 p.

ABSTRACT — The optimal development and management of a geothermal resource requires a knowledge of the hydrological characteristics of the reservoir. Reservoir engineering analysis techniques for permeable acquifers have been undergoing development for several decades but little attention has been paid to fracture-dominated systems. A program to test the ability of Huff-Puff tests to help characterize a fracture-dominated reservoir is presented: Several series of these injection (Huff)-backflow (Puff) tests were conducted at the Raft River KGRA in southern Idaho. These test series are described and preliminary results and interpretations are discussed.

Gulati, M.S., S.C. Lipman, and C.J. Strobel, 1978, Tritium tracer survey at The Geysers: Geothermal Resources Council, Transactions, v. 2, p. 237-239.

ABSTRACT — The steam condensate reinjection at The Geysers was started in 1969. The primary purpose of reinjection was disposal of condensate. Soon after the start of reinjection, the nearby production wells were monitored closely for reduction in steam enthalpy and the production rate. There were five objectives in running a tracer survey: to determine if any of the injected water is being produced as steam at the nearby production wells; to determine the regional flow pattern of fluid in the reservoir; to determine if the efficiency of water vaporization is declining or staying constant with time; and to determine if the regional flow pattern will undergo a substantial change when new units go on stream. This test provided direct physical evidence that rock heat is being mined over real time and

not geologic time; the rate of heat transfer from rock to the fluid is a function of the fracture intensity. A tritium tracer survey is the only way to find the time involved in heat transfer in a fractured system.

Horne, R.N., 1981, Tracer analysis of fractured geothermal systems: Geothermal Resources Council, Transactions, v. 5, p. 291-294.

ABSTRACT — Recent field experiments in Japan have emphasized the importance of performing tracer tests in any geothermal utilization in which reinjection is in use or is planned. This is because rapid short-circuiting between reinjection and production wells may occur due to the fractured nature of the system. In cases where fracturing is such that preferred pathways exist in the reservoir, the result may be a rapid thermal drawdown of the field production. Tracer testing provides a method of evaluating the magnitude of such problems. Previous methods used to analyze the Onuma, Hatchobaru, and Otake tracer tests have used early and long time data, this paper discusses the use of the field concentration/time profile in fractured systems.

McCabe, W.J., B.J. Barry, and M.R. Manning, 1981, Radioactive tracers in geothermal underground water flow studies: NTIS Report No. INS-R-298, 52 p.

ABSTRACT — Radioactive tracers have been used to study the movement of water in several geothermal fields, including Wairakei and Broadlands, in New Zealand. This technique has been particularly useful in hot water reinjection investigations for detecting the invasion of reinjected water into the production zone. Iodine-131 has been used as the tracer and the methods and equipment used to inject, sample and measure it are described. The single well dilution method of estimating horizontal flow velocities was found to be useful as a preliminary step to multi-well testing. A number of tests in both fields are discussed, and some details of the results presented. Peak velocities as high as 17 m/hr were observed and tracer recoveries of over 10% obtained. Possible interpretation of some of the results in relation to available geological descriptions are made. The dominating influence of faulting on water movement, and the inadvisability of relying on distance alone to prevent cold water re-entering into a production field, is stressed.

Owen, L.B., P.W. Kasameyer, R. Netherton, and L. Thorson, 1978, Predicting the rate by which suspended solids plug geothermal injection wells: NTIS Report No. UCRL-80529, 10 p.

ABSTRACT — Standard membrane filtration tests were used to evaluate injection at the Salton Sea Geothermal Field, Southern California. Results indicate that direct injection into reservoir zones with primary porosity is not feasible unless 1 mu m or larger particulates formed during or after the energy conversion process are removed.

Petty, Susan, and Susan Spencer, 1981, Injection in Basin and Range type reservoirs - The Raft River experience: Geothermal Resources Council, Transactions, v. 5, p. 307-310.

ABSTRACT — Injection testing at the Raft River KGRA has yielded some interesting results which can be useful in planning injection systems in Basin and Range type reservoirs. Because of inhomogeneities and possible fracturing in basin fill sediment, rapid pressure response to injection has been observed in one shallow monitor well, but not others. In some monitor wells in the injection field, pressure drops are observed during injection suggesting plastic deformation of the sediments. Seismicity, however, has not accompanied these observed water level changes.

Vetter, O.J., 1978, Use of tracers in geothermal injection systems: Proceedings Second Invitational Well-Testing Symposium, NTIS Report No. LBL-8883, p. 81-89.

ABSTRACT — The use of tracers is critical in geothermal injection systems. The hydrodynamic break-through of reinjected brine can be monitored in a very precise way using tracers. No other method is known which allows produced brine monitoring with the same precision. Thus, precalculated and monitored break-through profiles can be compared and the expected temperature front can be estimated in a very precise way. This use of tracers can be considered a "pre-warning" system.

The choice of tracers for geothermal reservoirs is rather limited. Tritiated water, introduced into the reservoir in a controlled manner, is the best choice. However, this monitoring technique eliminates the use of naturally occurring tracers for reservoir studies. The pros and cons for the use of naturally occurring tritium and other tracers are described.

Man-made tracers, particularly tritiated water, can be utilized to obtain quantitative data on reservoir parameters not available by other means. Pressure transient testing and tracer injection are complementary methods from which one can obtain the maximum information about critical reservoir parameters.

Present tracer techniques are hampered by a lack of information on the dispersion coefficient of the tracer in the flowing brine and the precise adsorption characteristics of the tracer on the rock material. Better quantitive evaluations of various reservoir characteristics will be possible if further research is conducted on the most critical adsorption properties under reservoir conditions.

REINJECTION OF BRINE, WASTE EFFLUENT, AND MAKE-UP WATERS

Blair, C.K., and L.B. Owen, 1981, An evaluation of reinjection into geopressured reservoirs: Geothermal Resources Council, Transactions, v. 5, p. 271-274.

ABSTRACT — Data from five geopressured reservoirs were evaluated to determine energy requirements and total production enhancement resulting from reinjection of spent brine into the producing formations. Thermal and hydraulic energy availabilities of the produced brines were compared to injection energy requirements to assess the viability of deep reinjection. Production lifetimes possible using deep reinjection were then compared to those attainable from a primary pressure depletion mode of reservoir utilization to enable assessment of total methane recovery enhancement via deep reinjection. For the reservoir cases studied, thermal and hydraulic energy availability ranged from 70 to 100 percent of the energy required for deep injection. Total methane recovery via a production/deep reinjection scheme was three to ten times that possible via primary pressure depletion production.

Chasteen, A.J., 1976, Geothermal steam condensate reinjection: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 1335-1336.

ABSTRACT — The simplest and most economical way to dispose of steam condensate and other geothermal fluids after power extraction is by reinjection into the geothermal reservoir. This process also offers opportunities for extraction of additional energy from the reservoir. Injection wells can be retired production wells. However, communication between injection wells and currently producing wells must be avoided. Also, the injectivity of individual wells may decline with time unless preventive steps are taken. Brief case histories are given here of successful reinjection projects in three geothermal areas: The Geysers and Imperial Valley, California; and Valles Caldera, New Mexico.

Darnell, A.J., and R.L. Eichelberger, 1982, Bibliography: Injection technology applicable to geothermal utilization: NTIS Report No. ETEC-82-11, 119 p.

ABSTRACT — This bibliography cites 500 documents that may be helpful in planning, analysis, research, and development of the various aspects of injection technology in geothermal applications. These documents include results from government research; development, demonstration, and commercialization programs; selected references from the literature; symposia; references from various technical societies and installations; reference books; reviews; and other selected material. The cited references are from (1) subject searching, using indexing, storage, and retrieval information data base on the Department of Energy's Technical Information Center's on-line retrieval system. RECON; (2) searches of references from the RECON data

base, of work by authors known to be active in the field of geothermal energy research and development; (3) subject and author searches by the computerized data storage and retrieval system of Chemical Abstracts, American Chemical Society, Washington, D.C.; and (4) selected references from tests and reviews on this subject. Each citation includes title, author, author affiliation, date of publication, and source. The citations are listed in chronological order (most recent first) in each of the subject categories for which this search was made. The RECON accession number is also given.

Einarsson, S.S., A. Vides R., and G. Cuellar, 1976, Disposal of geothermal waste water by reinjection: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 1349-1363.

ABSTRACT — Highly mineralized waters represented a major problem for the exploitation of the Ahuachapan geothermal field. Large-scale reinjection experiments were successfully carried out in 1970 and 1971, during which time almost 2,000,000 cu m of water at 150 °C were reinjected at the rates of 91 and 164 liters/sec by using a combination of gravity and vapor pressure as the driving force. The water was injected into the high-temperature aquifer at depth, and the resulting cooling effect was observed. No technical difficulties from scaling or of any other nature were experienced.

It was concluded that reinjection should be carried out within the high-temperature system, which means recycling the water with the residual heat after flashing to the reservoir, thus practically eliminating any danger of insufficient water for heat extraction even with limited natural recharge, and possibly at the same time effecting significant conservation of energy.

The local cooling effect around the point of injection, which should be a minimum of 1.5 km away from the production area, was estimated and found to be of minor significance in relation to the expected benefits.

The cost of reinjection was estimated to be approximately 1 US mill/kWh, and the reinjection of the waste water is considered a technically and economically feasible disposal method.

Horne, R.N., 1984, Reservoir engineering aspects of reinjection: Prepared for Seminar on Utilization of Geothermal Energy for Electric Power Production and Space Heating, Florence, Italy, May 1984.

NO ABSTRACT — This paper discusses three problems of importance in reinjection: (1) obtaining reliable and consistent injectivity in the reinjection well; (2) determining where the reinjected water goes; and (3) declines of discharge enthalpy and steam flow rate caused by return of a certain amount of reinjected water to the production wells.

Jorda, R.M., 1978, Engineering study of water reinjection for geothermal systems. Section I. Water injection well fundamentals. Section II. The injection well model. Section III. Sources of water contaminants. Section IV. Simulating the down-hole behavior of injectors. Section V. The overall influence of damage near the well bore: NTIS Report No. SAND-78-7009, 107 p.

ABSTRACT — Information related to the effects of suspended solids and, to some extent, vapor bubbles on injection well performance is presented. The means of evaluating the tolerable amounts of solids in injected water are presented, and all necessary derivations, equations, test procedures and correlations are explicitly described. Methods of determining whether surface filtration of solids, deep bed filtration of solids, or solids pass-through occurs in the well, and two sets of correlation parameters are presented. An injection well typical of those expected in Gulf Coast geopressured energy recovery systems is described, and optimum injection tubing sizes are calculated. It is concluded that the predominant sources of suspended solids in a system not containing atmospheric, uncovered ponds will be corrosion products and scale particles. Trace oxygen causes a devastating type of pitting corrosion. A technique is used to simulate injection well performance and provides data which illustrate the danger of injecting waters which contain finely devided, flocced solids, and demonstrates that injection problems caused by rigid particulates in the low micron size range will be minimal if the process system is designed to produce and handle treated injection water containing specified limits of particulate content, size, and texture. The effects of well damage over a wide range of conditions is presented in a graph which demonstrates that continuous invasion of the reservoir by trappable particulates should be avoided.

Jorda, R.M., 1979, Predicting injector performance at the proposed Magma-SDG & E fifty megawatt geothermal power plant: NTIS Report No. SAND-78-7128, 25 p.

ABSTRACT — The spent geothermal brine will be treated in a sludge-bed clarifier, followed by filtration through rapid mixed-media filters for suspended solids removal. The injection water treating system and the reinjection well are scheduled to be ready for testing by late Spring, 1979. Some insight is provided to the question of the injection test duration necessary to provide an assessment of the well's long-term injection capability. An advanced method is included for assessing changes in injection well receptivity, the Injection Performance Map (IPM). Data are included which suggest that three to four months' continuous operation with properly treated injection water may be sufficient to forecast the well's long-term injection potential.

Jorda, R.M. 1980, Performance evaluation of Magma Power Company's reinjection well No. 46-7 at the East Mesa KGRA, California: NTIS Report No. SAND-79-7127, 35 p.

The performance of the Magma Power Company's well No. 46-7 at East Mesa has been examined. Water was cooled to 100°F (+ -) to stimulate total heat extraction and then tested using membrane filter flow procedures. The cooled water contains particles which are in the high colloid size range, and formation impairment by these particles is unlikely. There is evidence that acid soluble corrosion products and calcium compounds constitute about two thirds of the particulates, and that the acid insoluble residue contains precipitated silica, insoluble corrosion products, and possibly formation fines carried in the produced water. Under stabilized conditions, the suspended solids content of the water is less than 2 parts per million. However, during the frequent production well start ups, a higher concentration of suspended solids is conveivably augmenting fill in the injector. But most likely, fill occurs when the injection well surges during shut-downs, because of inadequate sand control in the well completion. At the time of the test, the injection well was found to be severely impaired. Back flowing the well restored the injectivity to a calculated maximum sub-frac injection capacity of about 60,000 b/d of water at T = 350°F, which corresponds to a calculated maximum hypofrac injection capacity of about 20,000 b/d of cold water (T = 100°F).

Jorda, R.M., 1980, Use of data obtained from core tests in the design and operation of spent brine injection wells in geopressured or geothermal systems: NTIS Report No. SAND-80-7047.

ABSTRACT — The effects of formation characteristics on injection well performance are reviewed. Use of data acquired from cores taken from injection horizons to predict injectivity is described. And methods for utilizing data from bench scale testing of brine and core samples to optimize injection well design are presented. Currently available methods and equipment provide data which enable the optimum design of injection wells through analysis of cores taken from injection zones. These methods also provide a means of identifying and correcting well injection problems. Methods described in this report are: bulk density measurement; porosity measurement; pore size distribution analysis; permeability measurement; formation grain size distribution analysis: core description (lithology) and composition; amount, type and distribution of clays and shales; connate water analysis; consolidatability of friable reservoir rocks; grain and pore characterization by scanning electron microscopy; grain and pore characterization by thin section analysis; permeability damage and enhancement tests; distribution of waterborne particles in porous media; and reservoir matrix acidizing effectiveness. The precise methods of obtaining this information are described, and their use in the engineering of injection wells is illustrated by examples, where applicable.

Kandarpa, V., and O.J. Vetter, 1981, Prediction of salt precipitations due to injecting foreign waters into geothermal reservoirs:

Geothermal Resources Council, Transactions, v. 5, p. 341-344

ABSTRACT — The present paper describes two specific applications of a semi-empirical model which can be used to generate information related to the chemical incompatibility of imported injection waters into a geothermal reservoir. The model is applied to predict the sulfate precipitations in two geothermal operations, namely the Mercer and Currier leases in the Imperial Valley, California. The foreign waters considered for injection are the Salton Sea, Colorado River and ditch water. The results of the study are described. Also, the ways of combatting the problems that may arise due to chemical incompatibility are discussed. These types of evaluations can serve as guidelines for other geothermal operations.

Raber, E., L.B. Owen, and J.E. Harrar, 1979, Using surface waters for supplementing injection at the Salton Sea geothermal field (SSGF), southern California: Geothermal Resources Council, Transactions, v. 3, p. 561-564.

ABSTRACT — The flash-steam conversion cycle is most suitable for electric power production at the SSGF. However, large-scale development of the SSGF may require use of makeup water supplements to injected brine for a viable reservoir pressure maintenance program. Since steam condensate will probably be required to satisfy power plant cooling needs, local surface waters have been evaluated for their potential use as sources of injection makeup. It was found that direct injection of untreated makeup water is not feasible because of high suspended solids loading and potential incompatability problems. However, mixtures of ambient temperature makeup water and higher temperature (80 to 90°C) brine effluent, in a 1:4 mass ratio, are potentially injectable following processing by reaction clarification and granular media filtration.

Studt, F.E., 1980, Geothermal fluid injection—Experience in New Zealand and the Philippines: Paper presented at NATO CCMS Geothermal Conference, Paris, France.

ABSTRACT — Geothermal development on the Wairakei model is unlikely to be repeated, not only on account of environmental problems with surface discharge of effluents but also because it is believed that reinjection would have improved the long term performance of the field. At Tongonan, in the Philippines, the arsenic and boron contents of the effluents are so high that surface discharge is restricted even for test purposes. Small scale reinjection has been in progress in both countries for some years.

Experience to date indicates little trouble with silica deposits in high temperature injection, compatible with single flash operation. Varied results were recorded in low temperature tests, depending on reservoir, injection, and injection environment temperatures, as well as travel time, pH, and salinity. Generally, low temperature injection has

been successful in low temperature reservoirs, but not in high temperature reservoirs.

The effect of reinjection on the energy resource is difficult to assess. Even in very fractured country the flow paths were shown to be complex. The return of injected water is extremely difficult to detect except by tracers and the chemical and thermal effects may not become apparent for many years.

Tsang, C.F., G.S. Bodvarsson, M.J. Lippmann, and J. Rivera R., 1980, Some aspects of the response of geothermal reservoirs to brine reinjection with application to the Cerro Prieto field: Geothermics, v. 9, p. 213-220.

ABSTRACT — It has become generally accepted that reinjection will be necessary for optimizing the exploitation of a geothermal field. Not only does this afford a way to solve the problem of disposing cooled geothermal brine, but it also serves the purpose of maintaining reservoir pressure, thus reducing possible subsidence effects and sustaining production flow rates. In addition, reinjection enhances thermal energy extraction from the reservoir rocks.

However, reinjection creates a zone of relatively cold water around each injection well that will grow with time and eventually reach the production wells. When the cold water appears ('breakthrough') in the producing wells, the efficiency of the operation may be drastically reduced. It is, therefore, important to design the system of injection wells to prevent cold-water breakthrough before a specified time. For a given production field, it is essential that both the locations and flow rates of the injection wells be optimized.

In this paper, preliminary results of two reinjection studies will be described:

- (1) Initial investigation of several possible reinjection patterns for the Cerro Prieto geothermal field have been made based on a method developed by Gringarten and Sauty (1975). The resulting data show what may be expected from different reinjection schemes and may provide useful guidelines for the eventual choice of an optimal well arrangement.
- (2) A numerical model was used to study the injection pressure expected when colder water is injected into a hot reservoir. Because of the large difference in the viscosities of cold and hot water, the usual Thesis (1935) solution using one value for viscosity has had to be modified. The numerical model includes not only the viscosity variation but also the effects of the transition region between hot and cold water. The calculation can be easily generalized to a multiple-injection and production well system such as the Cerro Prieto field.

Vetter, O.J., and V. Kandarpa, 1982, Scale formation at various locations in a geothermal operation due to injection of imported waters: NTIS Report No. DOE/ET/27146-T13, 96 p.

ABSTRACT — The injection of waters that are not native to a geothermal formation generates various physical and chemical problems. The major chemical problem resulting from such injections is the formation of sulfate scales (particularly CaS04, BaS04 and SrS04) at various locations starting from the injection well through the production well to the surface facilities of any geothermal operation. One of the ways to prevent this type of scale formation is by reducing the sulfate concentration of the injection waters. The effect of sulfate deionization on scale formation at various locations of the geothermal operations is studied. Some experimental results on the CaS04 scale formation in porous media upon heating an injection water with and without addition of scale inhibitors are also given.

Vetter, O.J., and V. Kandarpa, 1982, Chemical simulation of geothermal injection wells: NTIS Report No. DOE/ET/27146-T12, 34 p.

ABSTRACT — Various types of chemical stimulation methods have been considered. High pH fluids seem to be a logical choice for some wellbore and/or reservoir stimulations. However, forming of secondary deposits and creating of new reservoir damages due to chemical reactions between the rock material and these stimulation fluids make it advisable not to consider any of these high pH fluids in high temperature geothermal reservoirs. Fluids having a neutral pH can be successfully used in chemical stimulation methods only in a very few and rare instances. Low pH fluids, i.e. acids, have by far the best chance to be used for these chemical stimulation jobs. The major part of this report is concerned with acidizing techniques for geothermal injection wells. The acidizing techniques to be used for an experimental and the routine stimulation of injection wells are described. Some recent field experiences and the results of some laboratory work are described.

Vetter, O.J., and V. Kandarpa, 1982, Reinjection and injection of fluids in geothermal operations (State of the art) NTIS Report No. DOE/ET/27146-T17; VR-82-05-11, 101 p.

ABSTRACT — A summary of the problems (encountered as well as anticipated) associated with reinjection of heat-depleted brines and injection of other fluids such as imported brines and gases is presented. Covered are only injection and reinjection problems which are related to the exploitation of liquid-dominated resources by flash-cycle power plants. Suggestions (proven as well as probable) which may offer solutions to many of the identified problems are also covered. In addition, some ideas that should or could be implemented in planning of implementing and/or executing any new geothermal injection operation are described.

SITE STUDIES

Cuellar, G., M. Choussy, and D. Escobar, 1978, Extractionreinjection Ahuachapan geothermal field: Proceedings Second Invitational Well-Testing Symposium, NTIS Report No. LBL-8883, p. 15-25.

ABSTRACT — A review of the geology and thermodynamics of the Ahuachapan Geothermal Field is given. The intensive mass extraction of the steam-water mixture started after the first unit began operating. The total mass extraction until August 1978 reached 50,478 kilotons. A continuous program of measurements was made in order to obtain a complete history of pressures, temperatures, and chemistry changes of the reservoir fluids as a result of the controlled extraction-reinjection system.

Horne, R.N., and M.A. Grant, 1982, New Zealand: An update on reinjection experience: Proceedings 6th Annual Geothermal Conference and Workshop, Snowbird, Utah, Electric Power Research Insitute Report No. EPRI-AP-2760.

ABSTRACT — Extensive injection testing has been carried out in recent years in New Zealand in the process of designing a reinjection scheme for upcoming Ohaki (Broadlands) geothermal field development. In addition, there have been a number of long-term injections at Wairakei. Actually, all were unintentional arising from downflowing colder water within certain wells; however, much valuable information was obtained. The results summarized in this paper fall into three categories of interest: permeability changes due to injection (both increases and decreases have been observed); tracer returns from injection wells to other producers; and thermal influence of injection on the injection well itself and on its surrounding producers.

Skiba, P.A., 1982, Response of RRGI 6 and RRGI 7 to injection during the 5-MW plant operations, March 25 to June 15, 1982, at Raft River, Idaho: NTIS Report No. EGG-M-28082, 6 p.

ABSTRACT — Injection testing conducted between March 25 and June 15, 1982 at the Raft River Site generated a substantial quantity of non-isothermal and various temperature transient pressure data. Injection pressure build-up measured at the wellhead strongly responds to temperature changes of the injected fluid. An increase in the fluid temperature results in an injection pressure increase while a temperature decrease is followed by an injection pressure decline. Data analysis indicate that changes in fluid viscosity and density due to temperature changes do not explain pressure build-up responses. The pressure build-up behaviors are attributed to the reservoir transmissivity changes. The absolute wellhead pressure value are significantly lower than predicted for the cold fluid injection.

Spencer, S.G., and D.M. Callan, 1980, Analysis of the response of the Raft River monitor wells to the 1979 injection tests: NTIS Report No. EGG-2057, 33 p.

ABSTRACT — The geothermal resource for the Department of Energy's (DOE) Raft River Geothermal 5 MWe Power Project is located in closed ground-water basin in south central Idaho. Chemical analyses indicate the existence of natural communication along fractures between the geothermal reservoir and the shallower aquifers developed for irrigation. Much of the ground water that is presently used for irrigation is of poor quality. Injection of geothermal fluids at intermediate depths may increase communication between the reservoir and the aguifer, resulting in further degradation of shallow ground water quality over time. Seven monitor wells, ranging in depth from 150 m to 400 m, were drilled to evaluate the potential for this degradation. Monitoring of these wells during two 21-day injection tests at the Raft River Geothermal Injection Well-6 (RRGI-6) indicates two types of response in the shallow aguifer system. First, the water level in Monitor Well-4 (MW-4) increased an average of 0.4 m/week during injection, indicating direct fracture connection between the injection zone and the aquifer penetrated by MW-4. Second, water levels in MW-5, MW-6, and MW-7 showed a step function decrease which coincided with the period of the injection tests. Analyses indicate that this response may be caused by elastic deformation in the aquifer matrix.

THEORETICAL

Gringarten, A.C., and J.P. Sauty, 1975, A theoretical study of heat extraction from aquifers with uniform regional flow: Journal of Geophysical Research, v. 80, p. 4956-4970.

ABSTRACT — A mathematical model is presented for investigating the non-steady state temperature behavior of a pumped aquifer during reinjection of a fluid at a temperature different from that of the native water. Results are presented in terms of dimensionless parameters and should be helpful in the design of geothermal space-heating projects. Applications to practical cases are also included.

Sigurdsson, Omar, G.S. Bodvarsson, and Valgardur Stefansson, 1983, Non-isothermal injectivity index can infer well productivity and reservoir transmissivity: Proceedings 9th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-74, p. 211-212.

ABSTRACT — In geothermal wells injection tests are commonly used to obtain well and reservoir data. These tests are typically conducted in a series of step rates followed or preceded by a complete shutin. Usually the temperature of the injected fluid is different from that of the reservoir fluid.

Because of the strong temperature dependence of fluid viscosity and to a lesser extent, fluid density, nonisothermally related pressure responses must be considered. The nonisothermal injectivity index obtained from these tests depends on the mobility ratio of the cold region to the hot reservoir and the extent of the cold spot. This paper proposes a method of estimation of the apparent viscosity which accounts for these effects and relates the nonisothermal injectivity index to the isothermal injectivity index.

THERMAL INTERFERENCE

Bodvarsson, G.S., 1972, Thermal problems in the siting of reinjection wells: Geothermics, v. 1, p. 63-66.

ABSTRACT — This paper presents a theoretical discussion of the thermal problems involved in the disposal of flash water from geothermal power plants by reinjection. The basic equations for the subsurface temperature field in the injection zone are derived both for rocks with intergranular and fracture flow. The extent of the thermal contamination by the reinjected water is discussed. In the case of a continuous mass flow of flash water of 1000 kg/sec for a period of 25 years, the contamination may reach out to as much as 5 kilometers or more from the point of re-entry, depending on the type of rock involved.

Bodvarsson. G.S., and C.H. Lai, 1982, Studies of injection into naturally fractured reservoirs: Geothermal Resources Council, Transactions, v. 6, p. 245-248.

ABSTRACT — A semi-analytical model for studies of cold water injection into naturally fractured reservoirs has been developed. The model can be used to design the flow rates and location of injection wells in such systems. The results obtained using the model show that initially the cold water will move very rapidly through the fracture system away from the well. Later on, conductive heat transfer from the rock matrix blocks will retard the advancement of the cold water front, and eventually uniform energy sweep conditions will prevail. Where uniform energy sweep conditions are reached the cold water movement away from the injection well will be identical to that in a porous medium; consequently maximum energy recovery from the rock matrix will be attained. The time of uniform energy sweep and the radical distance from the injection well where it occurs are greatly dependent upon the fracture spacing, but independent of the fracture aperture.

Bodvarsson, G.S., K. Pruess, and M.J. O'Sullivan, 1983, Injection and energy recovery in fractured geothermal reservoirs: NTIS Report No. LBL-15344, 16 p.

ABSTRACT — Numerical studies of the effects of injection on the behavior of production wells completed in fractured two-phase geothermal reservoirs are presented. In these

studies the multiple-interacting-continua (MINC) method is employed for the modeling of idealized fractured reservoirs. Simulations are carried out for a five-spot well pattern with various well spacings, fracture spacings, and injection fractions. The production rates from the wells are calculated using a deliverability model. The results of the studies show that injection into two-phase fractured reservoirs increases flow rates and decreases enthalpies of producing wells. These two effects offset each other so that injection tends to have small effects on the usable energy output of production wells in the short term. However, if a sufficiently large fraction of the produced fluids is injected, the fracture system may become liquid-filled and an increased steam rate is obtained. Our studies show that injection greatly increases the long-term energy output from wells, as it helps extract heat from the reservoir rocks. If a high fraction of the produced fluids is injected, the ultimate energy recovery will increase many fold.

Bodvarsson, G.S., and C.F. Tsang, 1982, Injection and thermal breakthrough in fractured geothermal reservoirs: Journal of Geophysical Research, v. B87, p. 1031-1048.

ABSTRACT — In this study, the problem of cold water injection into a fractured geothermal reservoir is considered. During injection, the cold water will advance along the fractures, gradually extract heat from the adjacent rock matrix, and eventually arrive at the production wells. If the injected water has not fully heated (up) by then, detrimental effects on energy production from decreasing fluid enthalpies may result. This indicates the need to establish criteria for designing an injection/production scheme for fractured geothermal reservoirs. The model considered in this work consists of an injection well fully penetrating a fractured geothermal reservoir containing equally spaced horizontal fractures. A constant-temperature liquid water is injected into the fracures, and with the rock matrix assumed to be impermeable, the effect of heat conduction on the advancement of the 'cold' water along the fractures is observed. Key dimensionless parameters that describe the physical system are identified and type curves are generated. This work is pertinent to waste disposal of waste water.

Grant, M.A., 1981, Effect of cold water entry into a liquid-dominated two-phase geothermal reservoir: Water Resources Research, v. 17, p. 1033-1043.

ABSTRACT — The effect of fluid withdrawal and injection into a two-phase geothermal reservoir is considered. The geothermal reservoir matrix is modeled as a homogeneous porous medium, except that fracturing ensures that injected fluid mixes fully into two-phase fluid. Withdrawal of fluid causes a pressure drop. Injection of fluid causes a pressure change dependent on the fluid enthalpy and rate of injection, nearly always a pressure drop for cold fluid injection. To stabilize the two-phase fluid by minimizing the advance of such intrusions, a stability criterion is derived.

Hayashi, Masao, Toshimitsu Mimura, and Tatsuo Yamasaki, 1978, Geological setting of reinjection wells in the Otake and the Hatchobaru geothermal field, Japan: Geothermal Resources Council, Transactions, v. 2, p. 263-266.

ABSTRACT — The geology and alteration mineralogy of the fields were studied. At Otake, all reinjection wells met a fault plane at depths from 300 to 500 m, corresponding to the depth of the main production zone. The reinjection of 70°C water had the beneficial effect to increase the vapor output in some production wells, but a productive well nearby the fault was damaged. At Hatchobaru, both reinjection and production wells encountered at about 100 m depth the same conformity which was the main reservoir. The reinjection more or less affected the cooling of all production wells. These facts suggest that the communication between the two kinds of wells through those permeable zones should be avoided. In the case where both wells are drilled in the same formation, the minimum acceptable distance between reinjection and production wells will be 150 m, as an approximate standard. In conclusion, important factors concerning reinjection are summarized.

Horne, R.N., 1982, Geothermal reinjection experience in Japan: Journal of Petroleum Technology, v. 34, p. 495-503.

ABSTRACT — The five liquid-dominated geothermal fields under production in Japan (Otake, Onuma, Onikobe, Hatchobaru, and Kakkonda) represent more than half the liquid-dominated fields now in production worldwide. All five have total liquid reinjection programs, and thus collectively represent a major fraction of all full-scale water reinjection operations in the world. The implications of the Japanese reinjection experience are therefore of extreme importance to future liquid-dominated geothermal development. The major impact of the experience in these fields is that, with the exception of Otake, the reinjection wells show a rapid interference with the production wells. In most cases, the reinjected water travels to the production zone within a very short time, and there is consequently a discernible thermal drawdown.

Kasameyer, P.W., and R.C. Schroeder, 1977, Application of thermal depletion model to geothermal reservoirs with fracture and pore permeability: Energy Research and Development Administration, Oak Ridge, TN 37830, Report No. CONF-761221-1, 10 p.

ABSTRACT — If reinjection and production wells intersect connected fractures, it is expected that reinjected fluid would cool the production well much sooner than would be predicted from calculations of flow in a porous medium. A method for calculating how much sooner that cooling will occur was developed. Basic assumptions of the method are presented, and possible application to the Salton Sea Geothermal Field, the Raft River System, and to reinjection of supersaturated fluids is discussed.

Lippmann, M.J., C.F. Tsang, and P.A. Witherspoon, 1977, Analysis of the response of geothermal reservoirs under injection and production procedures: NTIS Report No. LBL-6328, 15 p.

ABSTRACT — The response of a liquid-dominated geothermal reservoir to injection and production from a single well is studied. Different injection-production schemes are analyzed to explore how to minimize temporary cooling around the injection well and to optimize thermal recovery. The pressure response is also calculated, and found to be affected significantly by temperature-dependent viscosity variations. This will have implications on well-test methods for geothermal reservoirs. Vertical consolidation of the geothermal system during fluid withdrawal is also discussed, showing the need to establish previous stress history before attempting to predict the reservoir deformation. The transport of heat and fluid through a porous reservoir is computed using a numerical model. The onedimensional consolidation theory of Terzaghi has been coupled to the heat and fluid flow to calculate reservoir compaction. No attempt is made of model chemical reactions or precipitation that might occur when waters of a different temperature and salinity are injected into the

O'Sullivan, M.J., and K. Pruess, 1980, Numerical studies of the energy sweep in five-spot geothermal production/injection systems: NTIS Report No. LBL-12166, 11 p.

ABSTRACT — The present work is aimed at helping to improve the qualitative and quantitative understanding of injection into a geothermal reservoir by considering a few idealized problems. First a vapor-dominated, single layer reservoir is considered, next a vapor-dominated, four layer reservoir, and finally a liquid-dominated, single layer reservoir. In each case varying injection rates are considered and in some cases the injection is changed at different times. The SHAFT9 simulator is used to calculate the reservoir behavior in each case. The calculations are made for a five-spot configuration of alternate, off-set rows of producers and injectors. A calculation mesh with 34 nodes is used, which is barely sufficient to give accurate results. In fact, some of the results exhibit small oscillations with time due to this relatively coarse discretization.

Pruess, K., and G.S. Bodvarsson, 1984, Thermal effects of reinjection in geothermal reservoirs with major vertical fractures: Journal of Petroleum Technology (in press).

ABSTRACT — In many geothermal fields there is evidence for rapid migration of injected fluids along "preferential flow paths," presumably along fractures. The potential for unacceptable fluid temperature decline at production wells as a consequence of large scale injection is of obvious concern to geothermal developers, and methods are needed for evaluating the thermal response of "fast-paths" to injection. One difficulty encountered in analyzing test data is that the geometry of the flow path(s) may be speculative and ambiguous, leading to unreliable predictions of thermal interference. Fast pathways may often be provided by major vertical or nearly vertical fractures and faults with

approximately linear flow geometry. This paper discusses possibilities for characterizing the thermal properties of fast paths by means of different types of tests (tracers, pressure transients, non-isothermal injection). Thermal breakthrough in vertical fractures is examined in some detail, using an idealized model for which an analytical solution is available. The model shows that rapid tracer returns are not necessarily indicative of rapid thermal interference. Thermal breakthrough predictions can be made from tracer data only, if both fluid residence time and tracer dispersion are taken into account. However, due to the geometric simplifications necessary in analyzing the tracer data. thermal interference estimates on this basis appear questionable. Pressure transient tests can provide additional parameters for thermal interference predictions, but they cannot resolve the problem of non-uniqueness. A more reliable determination of thermal characteristics of fast paths appears possible from non-isothermal injection tests, combined with numerical simulation. We employ a mixed numerical/semi-analytical approach to model the three-dimensional fluid and heat flow in injectionproduction systems in vertical fractures, with heat transfer to and from the adjacent rock matrix. Illustrative calculations of thermal recovery after different injection periods suggest that shutting-in an injection well can prevent unacceptable temperature declines at production wells.

Schroeder, R.C., M.J. O'Sullivan, K. Pruess, R. Celati, and C. Ruffilli, 1982, Reinjection studies of vapor-dominated systems: Geothermics, v. 11, p. 93-119.

ABSTRACT — This paper explores the effects of cold water injection into idealized model reservoirs using numerical simulation techniques. The rock matrix parameters and thermodynamic conditions employed are representative of the Larderello steam fields. Injection into a two-phase reservoir usually prolongs its economic production and increases the recovery factor, but may decrease the production rate in the short-term. In a field such as Larderello, which has been exploited over a very long period without reinjection, the conditions are now such as to permit a higher long-term recovery as well as increased short-term production.

Tsang, C.F., D.C. Mangold, C. Doughty, and M.J. Lippmann, 1982, Prediction of injection effects on the Cerro Prieto geothermal system: NTIS Report No. LBL-14895, 25 p.

ABSTRACT — The response of the Cerro Prieto geothermal field to different reinjection schemes is predicted using a two-dimensional vertical reservoir model with single- or two-phase flow. The advance of cold fronts and pressure changes in the system associated with the injection operations are computed, taking into consideration the geologic characteristics of the field. The effects of well location, depth, and rates of injection are analyzed. Results indicate that significant pressure maintenance effects may be realized in a carefully designed reinjection operation.

Tsang, Y.W., and C.F. Tsang, 1978, An analytic study of geothermal reservoir pressure response to cold-water injection: Proceedings 4th Workshop on Geothermal Reservoir Engineering, Stanford University, p. 322-331.

ABSTRACT — One consideration of practical relevance in reinjection into a geothermal reservoir is the calculation of the pressures required for reinjection. These pressures determine the pumping requirements, which are important input into the technical and economical feasibility of the project. The pressures may also be used as baseline data. For example, if the measured pressure becomes much greater with time than calculated values, some kind of plugging may be occurring, and remedial action should be taken.

Injection of cold water into a hot reservoir is considered a moving boundary problem. Inside a boundary enclosing the injection well, the parameters correspond to those of the injected cold water; outside, the parameters correspond to those of the reservoir hot water. Of course, due to heat conduction between the hot and cold water, the boundary is not sharp. The width of the boundary depends on the heat conductivity and capacity of the aquifer, increasing with time as the boundary (or cold temperature front) moves outward from the injection well.

The present work is an analytical calculation of such a problem when several approximations are applied. Solutions of transient pressure are obtained in terms of well-known functions or in terms of one integral. These calculations are checked against numerical model results.

Witherspoon, P.A., G.S. Bodvarsson, K. Pruess, and C.F. Tsang, 1982, Energy recovery by water injection: NTIS Report No. LBL-14820, 30 p.

ABSTRACT — Several analytical and numerical studies that address injection and thermal breakthrough in fractured geothermal reservoirs are described. The results show that excellent thermal sweeps can be achieved in fractured reservoirs, and that premature cold water breakthrough can be avoided if the injection wells are appropriately located.

Special Report 14 Addendum

Geothermal Well Logging

Abstract reviewed by Mark Mathews, S.K. Sanyal, and Donald Towse

CASE STUDIES

Applegate, J.K., and T.A. Moens, 1980, Geophysical logging case history of the Raft River geothermal system, Idaho: NTIS Report No. LA-8252-MS, 34 p.

ABSTRACT — Drilling to evaluate the geothermal resource in the Raft River Valley began in 1974 and resulted in the discovery of a geothermal reservoir at a depth of approximately 1523 m (500 ft.). Several organizations and companies have been involved in the geophysical logging program. There is no comprehensive report on the geophysical logging, nor has there been a complete interpretation. The objectives of this study are to make an integrated interpretation of the available data and compile a case history. Emphasis has been on developing a simple interpretation scheme from a minimum of data sets. The Raft River geothermal system occurs in the Raft River Valley, which is a portion of the Basin and Range geomorphic province located in south central Idaho, south of the Snake River Plain. The valley is a late Cenozoic structural downwarp bounded by faults on the west, south, and east. The downwarp is filled with Tertiary and Paleozoic sediments, metasediments, and volcanics that overlie Precambrian rocks. The variety of rock types, the presence of alteration products, and the variability of fracturing make reliable interpretations difficult. However, the cross plotting of various parameters has allowed a determination of rock types and an analysis of the degree of alteration and the density of fractures. Thus, one can determine the relevant data necessary to assess a geothermal reservoir in similar rock types and use cross plots to potentially define the producing zones.

Benoit, W.R., D.K. Sethi, K. Darshan, W.H. Fertl, and Mark Mathews, 1980, Geothermal well log analysis at Desert Peak, Nevada: Transactions SPWLA 21st Annual Well Logging Symposium, Lafayette.

ABSTRACT — A discussion is presented of the geologic framework, logging operations and formation evaluation concepts based on well logs and cuttings as encountered in this geothermal test well. Several log responses are related to various rock types. Support data includes frequency crossplots, histograms and cutting descriptions.

Davis, D.G., and S.K. Sanyal, 1979, Case history report on East Mesa and Cerro Prieto geothermal fields: Los Alamos National Laboratory Report No. LA-7889-MS.

ABSTRACT — The geothermal resource has become an increasingly important alternate energy source in recent years. This has led to increased emphasis on developing and refining the technology involved in the development and production of geothermal energy.

Well log analysis as applied to the geothermal industry is one of the areas of technology in great need of further development. One means of improving log analysis technology is to study case histories of the past uses of log analysis as applied to specific fields. The project described in this report involved case history studies on two well-known geothermal areas in North America: The East Mesa field in California and the Cerro Prieto field in Mexico. Since there was considerably more pertinent material available on East Mesa, a major part of the effort on this project was devoted to studying the East Mesa field.

One particular problem that first came to attention when studying the Cerro Prieto data was the difficulty in determining actual formation temperature at the time of logging. Since the temperature can have a significant effect on well log readings, an accurate temperature determination was considered to be important. This problem concerns all geothermal well logging so considerable effort was devoted to it in this study.

Glen, W.E., J.B. Hulen, and D.L. Nielson, 1981, A comprehensive study of LASL well C/T-2, Roosevelt Hot Springs KGRA, Utah, and applications to geothermal well logging: NTIS Report No. LA-8686-MS, 175 p.

ABSTRACT — Utah State Geothermal Well 9-1 in the Roosevelt Hot Springs KGRA, Beaver County, Utah, has been donated by Phillips Petroleum Company to the Los Alamos Scientific Laboratory (LASL) for calibration and testing of well-logging equipment in the hot, corrosive, geothermal environment. It is the second Calibration/Test Well (C/T-2) in the Geothermal Log Interpretation Program. The Earth Science Laboratory/University of Utah Research Institute, on behalf of LASL, has completed a study of cuttings and well logs from Well C/T-2. This synthesis and data presentation contains most of the subsurface geologic information needed to effect the total evaluation of geophysical logs acquired in this geothermal calibration/test well, C/T-2.

Glenn, W.E., and H.P. Ross, 1982, A study of well logs from Cove Fort-Sulphurdale KGRA, Millard and Beaver counties, Utah: UURI Report No. DOE/ID/12079-62, 61 p.

ABSTRACT — Union Company drilled four geothermal test wells in the Cove Fort-Sulphurdale KGRA between 1975 and 1979. A fairly complete suite of well logs were recorded for the three deeper holes, and these data are presented as composite well log plots in this report. The composite well log plots have facilitated the interpretation of limestone, dolomite, sandstone, quartz-monzonite, serpentine, and volcanic lithologies and the identification of numerous fractures. This has been especially helpful because of the extensive lost circulation zones and poor cuttings recovery. Intraformational flow was identified by a fluid migration-temperature tracer log at depth in CFSU 31-33.

Well log crossplots were computed to assist in lithologic identification and the determination of physical properties for specific depth intervals in a given hole. The presence of hydrous minerals sometimes results in neutron porosity somewhat higher than the true nonfracture porosity, which is generally less than 4%. Permeability is clearly controlled by fractures. A maximum well temperature of 178.9°C, low

flow rates and low probable percent flash indicate these wells are subeconomic for electric generation at present. The well log study has substantially improved our understanding of the reservoir as previously drilled.

Glenn, W.E., H.P. Ross, and J.W. Atwood, 1982, Review of well logging in the Basin and Range Known Geothermal Resource Areas: Journal of Petroleum Technology, v. 34, p. 1104-1118.

ABSTRACT — A discussion is presented of applications and interpretations of well logs to Basin and Range Province geothermal exploration and development. Problems experienced in use of conventional oilfield tools and techniques are reviewed, and methods to circumvent these problems are illustrated. Particular examples focus on log responses and matrix effects in complex lithologies.

Halfman, S.E., M.J. Lippmann, R. Zelwer, and J.H. Howard, 1982, Fluid flow model of the Cerro Prieto geothermal field based on well log interpretation: NTIS Report No. LBL-14898, 17 p.

ABSTRACT — The subsurface geology of the Cerro Prieto geothermal field was analyzed using geophysical and lithologic logs. The distribution of permeable and relatively impermeable units and the location of faults are shown in a geologic model of the system. By incorporating well completion data and downhole temperature profiles into the geologic model, it was possible to determine the direction of geothermal fluid flow and the role of subsurface geologic features that control this movement.

Keller, G.V., J.C. Murray, and G.H. Towle, 1974, Geophysical logs from the Kilauea geothermal researh drill hole: NTIS Report No. NSF/RA/N-74/324, 19 p.

ABSTRACT — A borehole was drilled to a depth of 4123 feet beneath the summit of Kilauea Volcano on the island of Hawaii. The purposes were: (1) to obtain engineering information related to the possible occurrence of geothermal energy in a basaltic volcano; and (2) to obtain scientific information about the internal nature and workings of Kilauea Volcano. The scientific program included a comprehensive suite of geophysical logs for determining the physical properties of the basalt rocks penetrated. The basalts occurred variously as thin to thick flow units and massive units that may be sills or frozen lava ponds. Porosities generally were high. The solid material in the basalt had nearly a uniform grain density over the entire depth of the borehole. Acoustic wavespeed logs indicated the wavespeed for rocks with zero porosity would be approximately 18,800 feet per second. Young's modulus, as determined from a full-wave-form acoustic log and a gamma-gamma density log, was in the range from 2 to 6 x 10¹³ kilograms per square meter.

Keys, W.S., and J.K. Sullivan, 1979, Role of borehole geophysics in defining the physical characteristics of the Raft River geothermal reservoir, Idaho: Geophysics, v. 44, p. 1116-1141.

ABSTRACT — Numerous geophysical logs have been made in three deep wells and in several intermediate depth core holes in the Raft River geothermal reservoir, Idaho. Laboratory analyses of cores from the intermediate depth holes were used to provide a qualitative and quantitative basis for a detailed interpretation of logs from the shallow part of the reservoir. A less detailed interpretation of logs from the deeper part of the reservoir is based on much less corroborative evidence. Extensive use was made of computer plotting techniques to arrive at some interpretations. Both the stratigraphic correlation utilizing a full suite of logs and the attitude of bedding calculated from acoustic televiewer logs indicate gentle dips throughout most of the reservoir with some local flexures. Televiewer logs permitted the location and orientation of numerous fractures and several features that may be faults. Temperature and flowmeter logs provide evidence that these fractures and faults are conduits that conduct hot water to the wells. One of the intermediate depth core holes penetrated a hydrothermally altered zone that includes several fractures producing hot water. This altered production zone could be distinguished by several logs. Borehole gamma spectrometry can be used to identify anomalous concentration of uranium, thorium, and potassium which are probably due to transportation by hydrothermal solutions.

McNitt, J.R., C.A. Petersen, and S.K. Sanyal, 1981, Drilling, logging and preliminary well testing of geothermal well Susan 1, Susanville, Lassen County, California: NTIS Report No. DOE/ET/27040-T1, 95 p.

ABSTRACT — Susan 1, a hot water production well, was drilled late in 1980 for the City of Susanville, California, as part of its geothermal space-heating project. A history of drilling, logging, completion and pump testing of this well is presented. Susan 1 was drilled to 930 feet using local river water with a 17-½-inch bit from 50 to 540 feet and a 12-½-inch bit from 540 to 927 feet. A 12-¾-inch solid casing was set from surface to 350 feet, a slotted casing from 350 to 538 feet, and a 8-5%-inch slotted casing from 520 to 925 feet. Interpretations of the following logs and test data from this well are presented: drilling logs (penetration rate, water loss and gain, return temperatures); formation logs (description of well cuttings, caliper, spontaneous potential, electrical resistivity, gamma ray, neutron); production logs (temperature, spinner); and pump test data.

Prian, R.C., 1979, Lithological correlations of the Cerro Prieto wells, based on well-log interpretation: Geothermics, v. 8, p. 183-189.

ABSTRACT — This paper presents the results of correlations of the geophysical well logs obtained from wells drilled at the Cerro Prieto geothermal field. From this correlation, a structural interpretation of the 'receptacle' holding the geothermal fluids has been obtained. Based on the temperature and electrical resistivity logs, the pressure of two main geothermal reservoirs has been established. It

was also found that most of the wells were completed such that production is obtained simultaneously from several sandy layers.

Rigby, F.A., and G.P. Zebal, 1981, Case history on geothermal-welllog interpretation: Surprise Valley, California: NTIS Report No. LA-8598-MS, 63 p.

ABSTRACT — Well logs from a 1972 geothermal well drilled in California's Surprise Valley are discussed. The well is in an igneous formation, primarily basalt in the logged interval, and had a bottom-hole temperature of about 170°C at a total depth exceeding 1400 m. It produced good flow rates from what is presumably a formation with predominately fracture-related permeability. The well has special interest because fractures could be located approximately by the appearance of well-defined secondary crystallization in the drill cuttings. The original use of the log data in evaluating the well when it was drilled is discussed. In addition, the log data are reviewed and valuable data are obtained on log response in basalts, the effects of secondary mineralization, fracture detection, and aspects of the resistivity logs. The Surprise Valley well gives a clear demonstration of the value of thorough logging in geothermal exploratory wells, especially in the identification and location of potential production zones.

Rudman, A.J., 1978, Analysis of geophysical logs from the Hawaii Geothermal Project well: NTIS Report No. HIG-78-9, 29 p.

ABSTRACT — A 6445-foot test well was completed on April 27, 1976 in the Puna Area of Hawaii as part of an extensive project to investigate a geothermal reservoir for energy production. Because bottom hole temperatures exceeded 300°C, it was possible to run geophysical logs in the upper 3500 feet only. Study of conventional and induction resistivity, self potential, neutron, gamma ray, caliper, temperature, temperature differential and drilling rate logs show that porosity, permeability and fluid flow are qualitatively identified on the logs. Lithologic logs of sample cuttings taken at five- to ten-foot intervals (together with cores taken at approximately 700-foot intervals) substantiate preliminary findings of the porous and permeable zones. Although the logs investigated are above many of the zones of production, new information was obtained about the in-situ nature of permeability in Hawaiian basalts.

Sanyal, S.K., and W.E. Glenn, 1981, Lithology determination from digitized well logs—Examples from Ore-Ida No. 1 geothermal well, Ontario, Oregon: Geothermal Resources Council, Transactions, v. 5, p. 311-314.

ABSTRACT — This paper presents some of the advantages and pitfalls of lithology determination from digitized well logs. Examples are provided from the Ore-Ida No. 1 geothermal well in Ontario, Oregon, drilled through a sequence of siltstone, clay, tuff and basalt/andesite. The use of histograms and crossplots to differentiate various lithological units and to identify alteration is illustrated.

FRACTURE IDENTIFICATION

Albright, J.N., C.F. Pearson, and M.C. Fehler, 1980, Transmission of acoustic signals through hydraulic fractures: Transactions SPWLA 21st Annual Well Logging Symposium, Lafayette.

ABSTRACT — Acoustic signals transmitted between wells have been used to study the structure of the hot dry rock geothermal reservoir at Fenton Hill, New Mexico. The signals produced, using commercially available logging tools, traveled paths as long as 45.7 m (150 ft.) in fractured granitic basement rock. Both P- and S-waves were transmitted, the amplitude of the latter varying with the inclination between logging positions in each well. On pressurization of the reservoir, the signals showed changes in attenuation and waveform. The change in attenuation varied from a value of -2 dB above the fractured portion of the reservoir to -30 dB near the fracture well-bore intersections. The signals, having amplitude content in the frequency range from 6 to 16 kilohertz, were severely attenuated in the higher frequencies. Signal waveforms were limited to one of three distinctive types — the first having a pronounced S-wave arrival, the other two having either no S-wave arrival or apparent distributed P- and Swave arrivals. The general character of each waveform seems to depend on the absence or presence of fractures along the signal travel paths, on the multiplicity of fractures, and on their pressure states. The propogation velocity of the signals did not change perceptibly on reservoir pressurization. However, the velocity did change as much as 6% locally in the reservoir following a prolonged period of heat extraction and pressure cycling, resulting in extensive microfracturing of the bulk rock.

Fehler, M., and C.F. Pearson, 1981, Acoustic radiation patterns for borehole sources: NTIS Report No. LA-UR-81-1092, 20 p.

ABSTRACT — Amplitudes of S and P waves from commercial borehole acoustic logging tools depend on the angle between the borehole axis and the direction of propagation as well as the distance between source and receiver. Knowledge of the angular dependence or radiation pattern is necessary to properly measure the attenuation of waves traveling between two boreholes. Functional expressions are shown for the S and P-waves amplitudes. Experimental work in relatively homogeneous granite suggests that this relationship adequately describes the radiation pattern for both explosive sources and for acoustic transducers placed in fluid filled boreholes. Using these functional expressions for the S and P-wave amplitudes a technique was developed to estimate Q, the quality factor, and locate discrete fractures in crystalline rock that compose the Hot Dry Rock Geothermal Reservoir at Fenton Hill, New Mexico.

Hartenbaum, B.A., and G. Rawson, 1980, Topical report on subsurface fracture mapping from geothermal wellbores. Phase I. Pulsed radar techniques. Phase II. Conventional logging methods. Phase III. Magnetic borehole ranging: NTIS Report No. DOE/ET/27013-T1, 139 p.

ABSTRACT — To advance the state-of-the-art in Hot Dry Rock technology, an evaluation is made of (i) the use of radar to map far-field fractures, (ii) the use of more than twenty different conventional well logging tools to map borehole-fracture intercepts, and (iii) the use of magnetic dipole ranging to determine the relative positions of the injection well and the production well within the fractured zone. It is found that according to calculations, VHF backscatter radar has the potential for mapping fractures within a distance of 50 ± 20 meters from the wellbore. A new technique for improving fracture identification is presented. Analyses of extant data indicate that when used synergistically the (1) caliper, (2) resistivity dipmeter, (3) televiewer, (4) television, (5) impression packer, and (6) acoustic transmission are useful for mapping boreholefracture intercepts. Improvements in both data interpretation techniques and high temperature operation are required. The surveying of one borehole from another appears feasible at ranges of up to 200 to 500 meters by using a low frequency magnetic field generated by a moderately strong dipole source (a solenoid) located in one borehole, a sensitive B field detector that traverses part of the second borehole, narrow band filtering, and special data inversion techniques.

Keys, W.S., 1982, Location and character of fractures in geothermal wells: Geothermal Resources Council Special Report No. 12, p. 17-27.

ABSTRACT — Fractures are the major conduits for movement of hot water and steam in most geothermal reservoirs. It is important to understand these fractures in order to decrease costs and increase the effectiveness of geothermal exploration and development. Data on the location, orientation, apparent width, water movement, and relationship of fractures to lithology have been obtained from borehole geophysical logs of geothermal wells. Large open fractures produce anomalies on most kinds of logs, but the correct interpretation of these logs requires the synergistic analysis of all available data. Because log analysis is not well understood in the altered igneous and metamorphic rocks common in geothermal reservoirs, the interpretation of fractures in this matrix is even more difficult. Borehole-acoustic techniques with a wide frequency range are the most useful in providing unambiguous fracture information, but nuclear, electric, mechanical, and temperature logs also have added to our knowledge.

Kintzinger, P.R., F.G. West, and R.L. Aamodt, 1977, Downhole electrical detection of hydraulic fractures in GT-2 and EE-1: NTIS Report No. LA-6890-MS, 14 p.

ABSTRACT — Electrical geophysical methods including mise a la masse and self-potential (SP) for determination of hydraulic fracture characteristics were used at the hot dry rock geothermal project. Electrical and induction logs indicated that the resistivity contrast between the granite and 200°C water at the 2926-m (9600-ft) depth is a factor of 1000 or more. Thus the water in a hydraulic fracture, formed to connect two adjacent deep holes, is a good conductor

compared to the confining granite. Mise a la masse-type measurements were made to help determine the characteristics for hydraulic fractures formed in each of the two geothermal holes GT-2 and EE-1. Once a hydraulic fracture has been formed, mise a la masse effects are obtained both with the fracture pressurized above hydrostatic and when depressurized to hydrostatic. This indicates that once the fracture has been created, enough natural propping exists that a conductive zone persists even when the fracture is deflated. A fracture was formed in a 18-m (60-ft.) zone immediately below 1957 m (6420 ft.) in EE-1. Later a set of SP logs was run in this zone with no pressure, with pressure building, with pressure decreasing, and again with the fracture depressurized. Results show that during times of change of parameters in hydraulically fractured regions in the hole, natural SP logging helps to determine the position of the fracture. However, after a fracture has come to equilibrium with fluid parameters such as temperature, pressure, salinity, and pH, an effect of the fracture may not be evident. Self-potential logs provide an excellent method for locating the bottom of steel casing that has been set in the hole.

Mathews, M.A., James Scott, and C.M. LaDelfe, 1983, A preliminary report on fractured igneous rock environment test pits: Geothermal Resources Council, Transactions, v. 7, p. 519-524.

ABSTRACT — Geophysical well logs can now be calibrated for the measurement of physical properties of some igneous and metamorphic lithologies and for the determination of fracture porosity. These geologic conditions are routinely encountered in geothermal reservoirs and geothermal fields.

Three large calibration models or test pits were completed on May 1, 1981, at the United States Geological Survey (USGS) Denver Federal Center Calibration Facility. Each calibration model was constructed of large stone blocks that have a cored borehole and wire-sawn simulated fractures. Details of the test pit sizes, simulated fracture locations, rock type of each test pit, and location and access of these pits are discussed herein.

Geophysical well logs were obtained from these test pits and these data are shown and discussed.

Sanyal, S.K., L.E. Wells, and R.E. Bickham, 1979, Fracture detection from geothermal well logs: Proceedings 5th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-40, p. 343-348.

NO ABSTRACT — From the Introduction: "This paper will discuss the state-of-the-art of fracture detection from geothermal well logs and provide a case history." (The case history is the Ore-Ida well in Ontario, OR).

INSTRUMENTATION

Butz, J.R., 1979, Design and test of downhole probes to measure parameters of two-phase flow in geothermal wells: Geothermal Resources Council, Transactions, v. 3, p. 81-84.

ABSTRACT — As part of a DOE contract, the Denver Research Institute has designed and built instrumentation to make measurements of parameters in the two-phase flow zone of producing geothermal wells. The original probe is capable of measuring both pressure and temperature in real time, and a second probe, which was recently fabricated, incorporates a spinner-type flowmeter and a phase (gas/liquid) sensing device in addition to the original transducers.

DRI has run six well tests with this equipment, and several more tests are scheduled in the remainder of 1979. The tests have been successfully run in government owned and privately owned geothermal wells that cover the range of commercial interest in terms of flowrate, temperature and salinity (TDS). DRI has developed extensive expertise in the logging of flowing wells with tests at temperatures above 260°C (500°F) and flowrates over 230,000 kg/hr (500,000 lb/hr). A considerable effort has been put into development of suitable agreements with private owners regarding liability during testing and treatment of data obtained during tests.

Chang, H.T., 1982, High-temperature electronic components and circuit designs: NTIS Report No. SAND-81-2505C, 5 p.

ABSTRACT — Downhole logging instruments for geothermal application must have electronic circuits capable of operating from room temperature to 250°C. Previous research was centered on low voltage/low current hybrid microcircuits. However, a nondestructive evaluation (NDE) instrument for geothermal wells requires a circuit that can be operated at high voltage and high current in order to provide high-power output. In designing such a circuit, Sandia Laboratories is developing a high-power, high-speed, cold-cathode switching tube to be used as a substitute for SCRs or thyratrons. The possibility of using low-leakage JFETs beyond their rated temperature in a circuit design will be discussed. Commercial high-temperature components will be reviewed.

Coquat, J.A., 1979, Cablehead assembly for hostile environment well logging: Geothermal Resources Council, Transactions, v. 3, p. 133-135.

ABSTRACT — One of the most challenging problems in geothermal logging is to develop a cablehead that interconnects the wire line cable to the downhole instrument such that the system will successfully operate in a geothermal well. A high temperature (275°C), corrosion resistant logging cablehead for use with single conductor cables is described. The head has demonstrated the ability to solve electrical communications problems (leakage

resistance) generally associated with the cable-to-sonde interface while logging hostile environment geothermal wells.

Coquat, J.A., 1980, Semiconductors for high temperature active devices: Silicon, GaAs, and GaP: NTIS Report No. SAND-80-0379C, 10 p.

ABSTRACT — This paper reviews developments during the past three years in the area of high-temperature active semiconductor devices for use at 275°C in instrumentation needed to characterize geothermal resources. Surveys of silicon bipolar, MOS, and JFET devices operated at high temperature and development work on high temperature silicon CMOS logic and DI analog circuits are reviewed. The initial results of developmental work on GaAs and GaP diodes are discussed. These efforts have identified several promising devices for high temperature applications; however, further development is required to resolve such problems as excessive leakage currents, metallization degradation, device stability, and long term aging.

Garney, T.A., and R.E. Roesner, 1980, Development of a wireline service for use in producing geothermal wells: Geothermal Resources Council, Transactions, v. 4, p. 329-332.

ABSTRACT — A reliable surface/subsurface system for logging geothermal wells has been developed by Dresser Atlas. This system consists of a full suite of high temperature logging instruments, which operate in conjunction with a high temperature single conductor logging cable. The surface support equipment includes a Geothermal Wireline Blowout Preventer, special high temperature lubricator, and a Wireline cooler.

This program resulted in various elastomeric compounds, electrical connectors, and electromechanical components being upgraded for geothermal application both downhole and on the surface.

This new Geothermal Logging System has proven itself in commercial operation over the past two years.

Haney, J., C. Goranson, R. Solbau, and R. Schroeder, 1979, A review of LBL geothermal well testing equipment: Geothermal Resources Council, Transactions, v. 3, p. 287-290.

ABSTRACT — The high temperatures and hostile environments of geothermal reservoirs have prevented the use of high precision downhole well testing instrumentation. For the measurement of temperature, pressure, and flow at temperatures in excess of 150°C, reservoir engineers have had to rely on less accurate non-electrical instrumentation. Sandia's development of high temperature electronics and the introduction of high temperature cable has now increased the temperature range of certain instruments utilizing downhole active electronics to 275°C. However, this instrumentation is not yet commercially available.

Development of high temperature instrumentation with moderate accuracy utilizing passive electronics downhole has only been limited by the non-availability of high temperature multi-conductor cable. With the recent introduction of 275°C multi-conductor cable, the simultaneous measurement of moderate to high precision temperature, pressure, and flow is possible this year. The accurate measurement of two-phase flow at the surface will also soon be technically possible. The involvement of the LBL Geothermal Reservoir Engineering Group in the development and evaluation of geothermal well testing instrumentation is presented.

Heard, F.E., and T.J. Bauman, 1983, Development of a geothermal acoustic borehole televiewer: NTIS Report No. SAND-83-0681, 85 p.

ABSTRACT — Most geothermal wells are drilled in hard rock formations where fluid flow is through systems of open fractures. Productivity of these wells is usually determined by the extent of intersection of the wellbore with the fracture system. A need exists for fracture mapping methods and tools which can operate in a geothermal environment. In less hostile environments, the acoustic borehole televiewer has been shown to be a useful tool for determining location, orientation, and characterization of fractures as they intersect the borehole and for general wellbore and casing inspection. The development conducted at Sandia National Laboratories to adapt an acoustic borehole televiewer for operation in a geothermal environment is described. The modified instrument has been successfully tested at temperatures as high as 280°C and pressures up to 5000 psi, and used successfully to map fractures and casing damage in geothermal wells.

Itoh, Toshinobu, Makoto Miyairi, Kiyoshi Kimura, 1980, High temperature well logging system for geothermal well: Transactions SPWLA 21st Annual Well Logging Symposium, Lafayette.

ABSTRACT — A description is presented of various tools developed for geothermal well logging. The environmental conditions of these tools are: temperature as high as 275°C and pressure as high as 500 kg/cm². After the high temperature test of these tools, these tools were field tested during 1978 and 1979 at the borehole conditions of Depth: 1200 m, BTH: 202°C, BHP: 150 kg/cm². All the tools, except the optical borehole TV, were successfully operated during long period tests. According to the field test, the optical borehole TV, which consists of a camera tube, could be used only 4 hours at the borehole temperature of 150°C, and a high temperature TV, which consists of a semiconductor image sensor, is now under the development. The final temperature target of this TV camera is 4 hours at borehole temperatures as high as 250°C.

Kelly, R.D., 1977, Ceramic vacuum tubes for geothermal well logging: NTIS Report No. DOE/ET/28413-T5, 96 p. ABSTRACT — Useful design data acquired in the evaluation of ceramic vacuum tubes for the development of a 500°C instrumentation amplifier are presented. The general requirements for ceramic vacuum tubes are discussed for application to the development of high temperature well logs. Commercially available tubes are described and future contract activities that specifically relate to ceramic vacuum tubes are detailed. Supplemental data are presented in the appendix.

Kratz, H.R., E.A. Day, and W.G. Ginn, 1979, Improved geothermal well logging tools using no downhole electronics. Final Report: NTIS Report No. SAN-1315-1, 74 p.

ABSTRACT — A geothermal sonde for measuring temperature and pressure using no downhole electronics was designed and tested for operation at temperatures up to 275°C (527°F) and pressures of at least 10,000 psi. The measurement system uses variable resistance transducers which are powered in series by an uphole constant current supply. The output signals from the transducers are measured with a digital voltmeter having very high common mode and normal mode rejection ratios. The high rejection ratios of the digital voltmeter virtually eliminate any noise or pickup introduced into the measurement system. The system was tested in a hydroclave at temperatures up to 288°C (550°F) and at pressure up to 8,000 psi. The sonde was also tested in the Los Alamos geothermal well at temperatures up to 186°C (366°F) and pressures up to 4100 psi. The main problems encountered were associated with pressure transducers and the logging cable or the cable head and connector. The results of this project indicate that this is a feasible method of making geothermal measurements without the use of downhole electronics and that with further development the technique could be extended to higher temperatures and pressures.

Mathews, M., 1981, Wireline well logging — An underutilized technique in reservoir evaluation: Geothermal Resources Council, Transactions, v. 5, p. 295-298.

ABSTRACT — Wireline well logs have three general uses in geothermal exploration and reservoir evaluation: reservoir parameter analysis, lithologic column determination, and reservoir size resolution. Reservoir flow testing data are acquired to understand the flow rate, life, and production potential of the geothermal reservoir. These dara are a coarse subsurface measurement of the geothermal prospect. Wireline logs acquired from wells in a geothermal prospect are used to define in detail, or estimate the reservoir parameters of temperature, thickness, lateral size, amount of fracture and intergranular pore space, and the quantity and quality of fluid that might be produced. Laboratory measurements can be made on core samples and drill cuttings samples to define the intrinsic behavior of the materials and fluid that compose the geothermal reservoir. Wireline log measurements are needed to correlate and link the reservoir testing and core analysis, reduce the amount of time needed for flow testing, and predict the production life (amount of heat and fluid available) in a geothermal field.

McConnell, T.D., 1980, Pressure instrumentation for geothermal borehole logging: Geothermal Resources Council, Transactions, v. 4, p. 365-368.

ABSTRACT — Accurate geothermal logging requires pressure measurements with resolutions down to 0.01 psi in environments of up to 275°C and 15,000 psi. The characteristics of several basic types of pressure transducers are examined and compared to these requirements. Specific deficiencies are identified such as thermal stability and resolution limitations; R and D activities and results correcting these deficiencies are discussed.

Palmer, D.W., 1978, Hybrid microcircuitry of 300°C operation: Geothermal Energy, v. 6, no. 9, p. 24-29.

ABSTRACT — Microelectronic instrumentation for geothermal well logging must operate in ambient temperatures up to 300°C for several hundred hours. This study involved an extensive survey of 25 to 300°C operation of resistors, capacitors, conductors, interconnections, and active devices. Three major selection criteria were: 1) part lifetime of at least 1000 h at 300°C; 2) minimum change in electrical parameters from 25 to 300°C; 3) availability to the common circuit builder (no one of a kind). Certain thick film resistors, capacitors, and conductors were found compatible with such high-temperature operation. In addition, reconstituted mica and aluminum solid electrolytic capacitors were found useful up to 300°C.

Simple circuits for a geothermal temperature logging tool have been fabricated using these hybrid materials, components, and Si MOS and JFET devices. Oven tests show satisfactory stability from 25 to 300°C and at least 100-h circuit operation at 300°C.

Ross, E.W., N. Vagelatos, J.M. Dickerson, and V. Nguyen, 1982, Nuclear logging and geothermal log interpretation: Formation temperature sonde evaluation: NTIS Report No. LS-9159-MS, 61 p.

ABSTRACT — The theory and methodology of the neutron-based technique for the determination of the formation temperature in geothermal fields are discussed. The feasibility of the method was demonstrated before start of the present development phase. The present work is intended to evaluate the response of the temperature probe in a simulated fracture porosity granite matrix at temperatures likely to be encountered in known geothermal reservoirs. An above ground borehole model has been designed and constructed. The effect of high ambient temperatures on the response of the neutron detectors in the probe mockup used in the measurements was investigated and used to correct the detector counts. An improved

data analysis method has been developed to account properly for the effects of low porosity and high temperatures. Measurements, using the above ground borehole model, have shown that a linear correlation between the ratio of thermal counts from a Gd-filtered detector to counts from a bare detector and formation temperature is good at temperatures as high as 380°F. The present results are consistent with earlier data obtained in high-porosity laboratory models at lower temperatures (T < 167°F). Further measurements at high temperature at various porosities and formation neutron absorption cross sections would be necessary for a more extensive comparison.

Swanson, R.K., R.E. Anderson, J.I. Ash, R.E. Beissner, and V.D. Smith, 1978, Feasibility investigation and design study of optical well logging methods for high temperature geothermal wells: NTIS Report No. DOE/EV/05268-T1, 131 p.

ABSTRACT — The objective of this project was exploration of a novel approach to high temperature well logging, based on a system of optical transducers and an optical transmission line both theoretically capable of operation to at least 600°C. The scope of the work involved the accomplishment of ten specific tasks. These had as their objective the determination of feasibility, and identification of major problem areas, in the implementation of continuous temperature logging of geothermal wells using optical techniques. The following tasks are reported: literature review and data compilation, measurement of fiber properties production fiber procurement, investigation of methods of fiber termination, cable design and fabrication, and sensor and system studies.

Vegelatos, N., D.K. Steinman, and J. John, 1978, Neutron formation temperature gauge and neutron activation analysis brine flow meter. Final Report: NTIS Report No. IRT-7021-019, 138 p.

ABSTRACT — Feasibility studies of nuclear techniques applicable to the determination of geothermal formation temperature and two-phase brine flow downhole have been performed. The formation temperature gauging technique involves injection of fast neutrons into the formation and analysis of the moderated slow neutron energy distribution by appropriately filtered neutron detectors. The scientific feasibility of the method has been demonstrated by analytical computational and experimental evaluation of the system response. A data analysis method has been developed to determine unambiguously the temperature, neutron absorption cross section and neutron moderating power of an arbitrary medium. The initial phase of a program to demonstrate the engineering feasibility of the technique has been performed. A sonde mockup was fabricated and measurements have been performed in a test stand designed to simulate a geothermal well. The results indicate that the formation temperature determined by this method is independent of differences between the temperature in the borehole fluid and the formation, borehole fluid density, and borehole fluid salinity. Estimates of performance specifications for a formation temperature sonde have been made on the basis of information obtained in this study and a conceptual design of a logging system has been developed. The technique for the determination of fluid flow in a well is based on neutron activation analysis of elements present in the brine. An analytical evaluation of the method has been performed. The results warrant further, experimental evaluation.

Veneruso, A.F., and T.D. McConnell, 1980, Pressure measurements in low permeability formations: NTIS Report No. SAND-80-0705C, 19 p.

ABSTRACT — This paper examines the performance requirements and identifies candidate hardware implementations for pressure instrumentation that is needed to provide well test data in low permeability formations. Low permeability values are typically defined to be less than 1 microdarcy and are usually encountered in hard rock formations, such as granite, that are of interest in hot dry rock geothermal, deep exploration drilling, and fluid waste disposal. Groundwater flow in these tight formations has been shown to be dominated by flow-through fractures rather than through the formation's intrinsic permeability. In these cases, we cannot use Darcy's law or the usual dimensionless coefficients to estimate the expected scale factors and dynamic responses necessary to properly select and setup the wellbore pressure instrument. This paper shows that the expected instrument responses can be estimated using some recent work by Wang, Narasimhan, and Witherspoon. This paper further describes the minimum electronic capability that the downhole pressure instrument must have in order to provide the required measurement resolution, dynamic range, and transient response. Three specific hardware implementations are presented based on the following transducers: a quartz resonator, a capacitance gauge, and a resistance strain gauge.

Veneruso, A.F., 1981, Sourcebook on high-temperature electronics and instrumentation: NTIS Report No. SAND-81-2112, 229 p.

ABSTRACT — This sourcebook summarizes the hightemperature characteristics of a number of commercially available electronic components and materials required in geothermal well-logging instruments that must operate to 275°C. The sourcebook is written to provide a starting place for instrument designers, who need to know the hightemperature electronic products that are available and the design and performance limitations of these products. The electronic component information given includes the standard repertoire of passive devices such as resistors, capacitors, and magnetics; the active devices and integrated circuits sections emphasize silicon semiconductor JFETs and CMOS circuits; and, to complete the electronics, interconnections and packaging of hybric microelectronics are described. Thermal insulation and refrigeration alternatives are also presented in the sourcebook. Finally, instrument housing materials and high-temperature cables and cablehead connectors are listed. This information was compiled as part of the Geothermal Logging Instrumentation Development Program that Sandia National Laboratories conducted for the US Department of Energy's Division of Geothermal Energy from 1976 to 1981.

THEORETICAL

Conway, J.G., 1977, Deconvolution of temperature gradient logs: Geophysics, v. 42, p. 823-827.

ABSTRACT — A complete system for continuous logging of borehole temperature gradients has been developed and subjected to field tests with prototype equipment. To meet the requirements of this system, a time-domain operator was derived consisting of a smoothing term, a deconvolution term (to compensate for lag due to the thermistor time constant and probe velocity), and a gradient term. When convolved with raw field data, this combined operator will yield directly a high-precision, high-resolution temperature gradient profile.

*The system was field tested in two partially cased, water-filled boreholes. There was good correlation between gradient logs and thermal resistivity profiles from laboratory measurements on core material, indicating that even in cased wells the gradient log is a good approximation of the thermal resistivity profile. For a lowering rate of 18 m/minute, the gradient profile exhibits a repeatability better than ±0.5°C/km. Comparison of the gradient profile with a fine-scale geologic log indicates a stratigraphic resolution threshold on the order of 2 m for a 10-20 percent thermal resisitivity contrast. For isolated resistivity contrasts of 50-100 percent, the resolution is better than 0.5 m.

Sanyal, S.K., 1981, Estimation of steam saturation and rock alteration from geothermal well logs—A theoretical inquiry: Geothermal Resources Council, Transactions, v. 5, p. 373-376.

ABSTRACT — This paper considers the possibility of using well logs to estimate steam saturation (or steam quality) in a geothermal reservoir. The expected responses of density and neutron logs are calculated as a function of steam quality in the reservoir assuming a granitic matrix with 7 percent porosity. It is shown that only for small steam quality values, density and neutron log responses can be used to estimate steam saturation. Hydrothermal alteration in the rock should be identifiable from log responses, particularly gamma ray.

Sanyal, S.K., M. Che, R.E. Dunlap, and M.K. Twichell, 1982, Theoretical nuclear log responses of the components of The Geysers geothermal reservoir, California: Geothermal Resources Council, Transactions, v. 6, p. 165-168. ABSTRACT — This paper presents theoretically calculated matrix response parameters for nuclear logs for the common minerals encountered at The Geysers geothermal field, California. From fundamental equations, matrix responses were derived from 15 minerals for neutron, density and thermal neutron capture cross-section logs. Most of these matrix parameters are not available in the literature and cannot be readily obtained by other means. There parameters are invaluable in analysis of geothermal well logs from The Geysers.

Ucok, H., 1981, A laboratory study of the effect of temperature gradient on the development of spontaneous-potential in geothermal wellbore: Transactions SPWLA 22nd Annual Well Logging Symposium, Mexico City.

ABSTRACT — The geothermal borehole SP surveys are usually taken under non-isothermal conditions. Non-isothermal electrolitic systems are known to transform thermal energy into electrical energy. The effect of thermoelectricity generated under non-isothermal conditions on borehole SP surveys is investigated in the laboratory under simulated conditions. Laboratory experiments indicate that an appreciable amount of electromotive force is generated as a result of the temperature gradient in the system. However, it is found that thermoelectricity has no net effect on borehole SP measurement in sedimentary type geothermal reservoirs. This is because the decrease in liquid-junction potential and the increase in membrane potential, due to thermoelectricity, is equal in magnitude.

WELL LOGGING TECHNOLOGY

Fertl, W.H., 1980, Geophysical well logs applied to geothermal resource evaluation: Revue de l'Institut Français du Petrole, v. 35, no. 3, p. 461-468.

ABSTRACT — Geothermal reservoirs are frequently in fractured igneous and metamorphic rocks, which contain hot water or steam at temperature exceeding 150°C. The discussion focuses on present day logging technology, geologic and reservoir engineering objectives, and qualitative and quantitative formation interpretation techniques for geothermal resource evaluation. Specific field case studies illustrate the interpretive state-of-the-art, including examples from The Geysers dry steam field in the Imperial Valley of California, hot water fields in California, Nevada, and Idaho, and the LASL Hot Dry Rock test project in the Valles Caldera of New Mexico.

Reiter, M., A.J. Mansure, and B.K. Peterson, 1980, Precision continuous temperature logging and comparison with other types of logs: Geophysics, v. 45, p. 1857-1868.

ABSTRACT — For a variety of well environments, continuous temperature logs at different speeds, taken with appropriate equipment and fast time-response probes, can

yield temperature data often reproducible to several hundredths of a degree centigrade. Larger differences in reproducibility (several tenths of a degree centigrade) probably result from changes in the well bore. Below the liquid level, data need not be filtered through timeresponse characteristics of the probe to give accurate geothermal gradients (typically ± a few percent) that correlate with lithology. Resulting temperature-gradient logs are qualitatively correlated to other logs, such as inductionconductivity, gamma-ray seismic, bulk-density, and lithologic logs. Qualitative correlation with the inductionconductivity log appears best. Temperature gradients generally increase when other logs indicate the formation is becoming shaly or clayey (less sandy, silty, or limy), and/or less competent. The practical worth of the temperaturegradient log may be its ability to sense deformation properties inside casing and tubing. This characteristic of the temperature-gradient log may allow lithologic identification in shut-in wells and permit useful logging after casing has been set.

Ryley, D.J., 1980, Well logging, in Kestin, J.R. DiPippo, H.E. Khalifa, and D.J. Ryley (eds.), Sourcebook on the production of electricity from geothermal energy: U.S. Department of Energy Report No. DOE/RA/4051-1, p. 155-172.

NO ABSTRACT — This chapter discusses conventional well-logging equipment and the types of information obtained.

Sass, J.H., J.P. Kennelly, Jr., W.E. Wendt, T.H. Moses, Jr., and J.P. Ziagos, 1981, In-situ determination of heat flow in unconsolidated sediments: Geophysics, v. 46, p. 76-83.

ABSTRACT — Subsurface thermal measurements are the most effective, least ambiguous tools for locating geothermal resources. Measurements of thermal gradient in the upper few tens of meters can delineate the major anomalies, but it is also desirable to combine these gradients with reliable estimates of thermal conductivity, to provide data on the energy flux and to constrain models of the heat sources responsible for the anomalies. Problems associated with such heat flow measurements include the economies of casing or grouting holes, the long waits and repeated visits necessary to obtain equilibrium temperature values, the possible legal liability arising from disturbance of aquifers, the hazards presented by pipes protruding from the ground, and the security problems associated with leaving cased holes open for periods of weeks to months.

We have developed a technique that provides reliable realtime determinations of temperature, thermal conductivity, and hence, of heat flow in unconsolidated sediments during the drilling operation. Temperature, gradient, and thermal conductivity can be measured in one operation in 1 hour using a long (1.5 to 2 m) thin (6-mm diameter) probe containing three thermistors 0.5 or 0.15 m apart in its lower most 1.2 m. The probe is driven hydraulically through the bit up to 1.65 m into the formation, and a 20- to 25-minute temperature record is obtained for each thermistor, allowing calculation of the equilibrium temperature gradient. A line source heater is then switched on and a 10-to 15-minute temperature is obtained, allowing calculation of thermal conductivity. Two or three such experiments over the depth range of 50 to 150 m provide a high-quality heat flow determination at costs comparable to those associated with a standard cased gradient hole to comparable depths. The hole can be backfilled and abandoned after drilling, thereby eliminating the need for casing, grouting, or repeated site visits.

Traeger, R.K., and A.F. Veneruso, 1981, Logging technology for geothermal production logging: Geothermal Resources Council Bulletin, v. 10, no. 7, p. 8-11.

NO ABSTRACT — This paper summarizes results of the DOE program to develop instrumentation for logging geothermal wells. The program was managed and completed by Sandia National Laboratories.

WELL LOG INTERPRETATION AND ANALYSIS

Beck, A.E., 1976, The use of thermal resistivity logs in stratigraphic correlation: Geophysics, v. 42, p. 300-309.

ABSTRACT — Since it has been found that the heat flow along a borehole rarely deviates more than 20 percent from the mean equilibrium value and that formation thermal resistivities may vary by as much as an order of magnitude, the profile of temperature gradient versus depth is equivalent to a log of thermal resistivity (T-log). In this work high precision temperature measurements in cased boreholes were used which yielded temperature gradients as high as 140°C/km.

Using the equivalence between thermal resistivity and temperature gradients, it has been found that the T-logs are characteristic of the formations in which they were measured with a general negative correlation between thermal resistivity and electrical resistivity, except in coal (and perhaps gas) bearing formations.

In one instance, the character of the resistivity log was used to conclude that a horizon deduced from the electrical resistivity log had been mispicked by nearly 100 m.

Brown, S.L., B.D. Gobran, and S.K. Sanyal, 1980, Determining of TDS in geothermal systems by well-log analysis: Proceedings 6th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-50, p. 279-287.

ABSTRACT — An estimate of the chemistry of the fluid within a geothermal reservoir is required to establish the geological source and the possible environmental impact of the fluid as well as scaling and corrosion problems which might develop during production. While a detailed analysis

of the chemical composition of a geothermal fluid can only be obtained from a water sample, an estimate of the total dissolved solids (TDS) in equivalent sodium chloride (NaCl) concentration can be obtained from well logs. TDS can also be useful in geological correlation between wells. TDS can be determined directly from a pulsed neutron log and a porosity log, (if the type of formation is known), or from the water resistivity, Rw, and the temperature, T. Three approaches are used to find Rw and thus TDS. The first method uses a dual induction focused log and information from the log heading. Next, Rw is found by employing an electrical log and a porosity log. The last approach utilizes the spontaneous potential log and header data. Examples are provided to illustrate the techniques described which utilize calculated values of Rw to determine TDS.

Castaneda, M., and R.N. Horne, 1981, Location of production zones with pressure gradient logging: Geothermal Resources Council, Transactions, v. 5, p. 275-278.

ABSTRACT — The fact that geothermal wells produce from only a limited number of discrete fractures or "feed zones" often gives rise to confusing temperature and pressure logs. This is because the wells frequently are flowing from one zone to another while the measurements are made—even though the well is shut in. Interpretation of the temperature and pressure logs is then difficult unless the location of the feed zones can be determined and the internal flows recognized. Although this may often be determined by an experienced reservoir engineer there remains considerable room for ambiguity. This paper presents a method for locating the feed zones and simultaneously registering upward or downward flows by comparing the measured pressure gradient with the hydrostatic gradient calculated from a simultaneously run temperature log. Demonstration of the technique in Cerro Prieto is shown.

Ershaghi, Iraj, and Doddy Abdassah, 1984, Well log interpretation of certain geothermal fields in the Imperial Valley, California: Los Alamos National Laboratory Report No. LA-10067-MS, 32 p.

ABSTRACT — This study reviews the wireline log responses of some geothermal fields in the Imperial Valley, California. The fields under study include the Heber, the East Mesa, the Brawley, and the Westmoreland. The well logs used in the study did not include all the wireline surveys obtained by the operators. The selected well logs obtained under special arrangements with the operators were chosen to maintain the anonymity of specific well locations but are only representative of each area.

Analysis of the well logs indicates that on an individual field basis, the well logs are excellent for correlation purposes. The presence of extremely saline fluids in some fields precludes the monitoring of Q_{ν} (cation exchange capacity per unit volume) profile for detection of hydrothermally altered zones. The producing sections in all the fields are characterized by low porosity and high resistivity.

Ershaghi, I., E.L. Dougherty, and L.L. Handy, 1981, Formation evaluation in liquid-dominated geothermal reservoirs: NTIS Report No. DOE/ET/28384-T1, 106 p.

ABSTRACT — Studies relative to some formation evaluation aspects of geothermal reservoirs are reported. The particular reservoirs considered were the liquid-dominated type with a lithology of the sedimentary nature. Specific problems of interest included the resistivity behavior of brines and rocks at elevated tempertures and studies on the feasibility of using the well log resistivity data to obtain estimates of reservoir permeability. Several papers summarizing the results of these studies were presented at various technical meetings for rapid dissemination of the results to potential users. These papers together with a summary of data most recently generated are included. A brief review of the research findings precedes the technical papers. Separate abstracts were prepared for four papers. Five papers were abstracted previously for EDB.

Ershaghi, I., E.L. Dougherty, D.E. Herzberg, and H. Ucok, 1978, Permeability determination in liquid-dominated geothermal reservoirs using the dual induction laterlog: Transactions SPWLA 19th Annual Well Logging Symposium, El Paso, p. DD.1-DD.20.

ABSTRACT — A method has been developed to estimate the permeability profile in a geothermal well from a Dual Induction-Laterlog, a porosity log, and drilling data. The procedure is based on modeling the invasion of the drilling mud filtrate into the formation and using a history matching technique to arrive at the permeability profile. Input data to the computer model includes basic drilling mud properties, drilling hydraulics, and dimensions of the tubular goods. A permeability profile is assumed for the well and the computer program is run. The objective is to compare the invasion radius computed from the program to that derived from the logging data. The process is then repeated until a satisfactory match is obtained.

Ershaghi, I., S. Ghaemian, and D. Abdassah, 1981, Lithology and hydrothermal alteration determination from well logs for the Cerro Prieto wells, Mexico: NTIS Report No. LA-9075-MS, 33 p.

ABSTRACT — The purpose of this study is to examine the characteristics of geophysical well logs against the sandshale series of the sedimentary column of the Cerro Prieto Geothermal Field, Mexico. The study shows that the changes in mineralogy of the rocks because of hydrothermal alteration are not easily detectable on the existing logs. However, if the behavior of clay minerals alone is monitored, the onset of the hydrothermally altered zones may be estimated from the well logs. The effective concentration of clay-exchange cations, Qv, is computed using the data available from conventional well logs. Zones indicating the disappearance of low-temperature clays are considered hydrothermally altered formations with moderate to high-permeability and temperature, and suitable for completion purposes.

Howard, Jr., A.Q., 1981, Induction logging for vertical structures in the presence of a borehole fluid: Geophysics, v. 46, p. 68-75.

ABSTRACT — Mapping hydraulic fractures with borehole instrumentation presents many problems. The resulting fracture eddy currents can be expected to be smaller than the corresponding borehole fluid currents. The transmitting and receiver coils are vertical and are in close proximity to each other. This orientation is necessary to couple strongly to vertical structures and is much more difficult to analyze than the case of horizontal coils. The coils must be physically but not electrically isolated from probable hostile temperature and pressure environment. Analytic expressions are presented which predict the effect of the cavity, misalignment of the coils in the cavity, and an upper bound on the effect of the borehole fluid.

The analysis uses the mode matching method. The discrete cavity modes are matched to the continuous host rock modes through the boundary conditions. A nonstandard cavity expansion is developed which converges very rapidly in the usual situation where the cavity axial dimension between coils is much greater than the radial coil separation.

A simple approximate expression for the received magnetic intensity components Hp and Hp is derived. The numerical results of the model predict that, in the limit when the borehole fluid is assumed to be perfectly conducting, the ratio of axial total electric field to axial primary field can be as large as 10⁵. The configuration is an efficient magnetic to electric field converter.

An ideal vertical fracture model is also developed. For the case when the crack and the borehole are coincident, explicit modification formulas for the transmitter coil dipole angular patterns are given.

Keys, W.S., 1982, Borehole geophysics in igneous and metamorphic rocks: in Geothermal Log Interpretation Handbook, published by Society of Professional Well Log Analysts, Tulsa.

ABSTRACT — Activities in geothermal energy, radioactive and industial waste disposal, mineral exploration, engineering geology, and lunar and deep crustal exploration have increased the need for borehole geophysics in igneous and metamorphic rocks. Because there is a lack of knowledge and experience in the application of borehole geophysics to these rocks, the U.S. Geological Survey is conducting research in this area.

Igneous and metamorphic rocks usually present different petrophysical properties, such as porosity, density, resistivity, and mineralogy, than do sedimentary rocks. For this reason all conventional geophysical logging techniques may not be useful and petrophysics must be used to develop appropriate methods of log analysis. Core analyses plotted against log response and crossplotting of various logs in the computer are particularly useful for identifying the various rock types in an igneous complex. Hydro-

thermal alteration and fluid movement through fractures are very important parameters that are needed from logs. Hydrothermal alteration may be recognized on well logs through the use of crossplots and borehole gamma spectrometry. The acoustic televiewer supported by other logs has been highly successful for identifying fractures that are transmitting either hot or cold water.

Mathews, M.A., 1980, Log interpretation techniques to identify production zones in geothermal wells: Proceedings 6th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-50, p. 303-309.

ABSTRACT - Identification of production zones in a fractured or faulted geothermal well is quantitatively difficult. Temperature and spinner surveys along with flow tests are the techniques generally used to identify and describe these fractured zones during production testing. These techniques generally do not describe the production zones in any detail and they miss or bypass potential zones of production when fractures have been closed or plugged during the drilling process. These latter zones could possibly be stimulated (hydraulic fracturing, acidizing, explosive fracturing) and brought into production if all the fracture zones could be identified and described. Interpretation techniques using wireline logs show promise in identifying and describing fractured (open and closed) zones in geothermal wells. The strategy described in this paper on two different geothermal wells (the hot dry rock well and the Surprise Valley well) used a trial and error basis to outline and define the interpretation techniques that work best in each case. Fracture zones are identified that are both open and closed and this type of information gives a better estimation of reservoir size, flow control and reservoir life (production potential) from geothermal wells.

Mathews, M., B. Arney, and S. Sayer, 1979, Log comparison from geothermal calibration/test well C/T-1: Transactions SPWLA 20th Annual Well Logging Symposium, Houston.

ABSTRACT — The Geothermal Log Interpretation program (GLIP) has made the C/T-1 (Mesa 31-1) well in the East Mesa Geothermal Field available for use in quality control, testing, and calibrating wireline logging tools. The East Mesa Geothermal Field is located in the Imperial Valley of California approximately 30 km east of El Centro, California and 60 km north of the Cerro Prieto Geothermal Field, in Mexico. C/T-1 wells is 1880 m (6175 ft.) deep, is fully cased (75% inches O.D.), has a bottom hole temperature of approximately 165°C (330°F), and penetrates Plio-Pleistocene deltaic sandstones, siltstones, clays, and shales. Several suites of logs have been run in this well by different logging companies. These logs include: temperature, pressure, caliper, density, neutron, gamma-ray, and cement bond logs. A qualitative comparison will be made between these logs, the detailed lithologic log, and the open hole log run in this well. These data provide a background upon which future logging systems can be tested, quality controlled, and calibrated.

Mathews, M., and C. LaDelfe, 1981, Log data comparison and quantification: NTIS Report No. LA-UR-81-2718, 18 p.

ABSTRACT — Two geothermal wells were logged with similar wireline logs by several logging companies in a period of five years (1974 to 1979). The results of these equivalent logs are quantitatively different and in some cases qualitatively different. This difference also occurs between the same type of logs recorded at different time intervals by the same logging company. These various log data are related and qualified when logging equipment has not been properly calibrated. All depths referred to for either well are from their respective kelly bushing (KB). The first well (Mesa 31-1) is in the Imperial Valley of California and penetrates a sand, shale, and clay sedimentary lithology with a maximum temperature of 165°C (330°F) and a total depth of 1882 m (6175 ft.). The second well (Phillips 9-1) is in the Roosevelt Hot Springs known geothermal resource areas (KGRA) of southwestern Utah and penetrates hydrothermally altered (low-grade metamorphic) and igneous lithology with a maximum temperature of 225°C (440°F) and a total depth of 2098.5 m (6885 ft.). During that period (1974 to 1979) calibration of logging equipment in metamorphic and igneous lithologies could not be done. The logging data from this well is not qualitatively comparable in all cases and indicates the need for calibration. The openhole log data acquired from Mesa 31-1 and Phillips 9-1 wells were compared to core data from these wells and comparison factors were calculated to better quantify the openhole log data. Then open-hole log data were compared to the cased-hole log data from various companies and additional comparison factors were calculated for the cased-hole log data. These comparison factors allow for some quantification of these uncalibrated log data.

Muramoto, F.S., and W.A. Elders, 1984, Correlation of wireline log characteristics with hydrothermal alteration and other reservoir properties of the Salton Sea and Westmorland geothermal fields, Imperial Valley, California, USA: Los Alamos National Laboratory Report No. LA-10128-MS, 100 p.

ABSTRACT — The Salton Sea and Westmorland geothermal systems are developed in the Plio-Pleistocene sediments of the Colorado River delta. In the Salton Sea, field temperatures as high as 360°C are encountered at depths less than 7100 ft. (2134 m), and brines contain up to 260,000 parts per million (ppm) of total dissolved solids. In the Westmorland field four miles (6.4 km) to the south, considerably lower temperatures (252°C at 7500 ft. [2286 m]) and less saline brine concentrations (maximum salinity approximating 72,000 ppm) are found.

A detailed study of wireline logs from 11 wells in the Salton Sea and Westmorland geothermal systems was undertaken in order to determine the effects of hydrothermal alteration on the response of electrical and gamma-gamma density well logs. For the Salton Sea geothermal field, definite correspondence between log responses and hydrothermal mineralogy is evident, which in turn is related to the physical properties of the rocks. Three hydrothermal and one unaltered zone can be identified from log data on

shales. These are: (1) the unaltered "montmorillonite zone" (<100°-190°C); (2) the "illite zone" (100°-190°C to 230°-250°C); (3) the "chlorite zone" (230°-250°C to 290°-300°C); and (4) the "feldspar zone" (>290°-300°C). The characteristic responses on well logs by which these zones are identified result primarily from changes in clay mineralogy of the shales and increases in density with progressive hydrothermal metamorphism.

In the Westmorland geothermal field, differentiating mineral zones from log responses was only partially successful. However, analyses of both well log and petrologic data for wells Landers 1 and Kalin Farms 1 suggest that the former is heating up and the latter is cooling.

Other methods that were found to be effective in delineating mineral zones from log data on shales are the resistivity-density and N-resistivity (where N = neutron porosity/density) crossplots. The latter crossplot distinguishes mineral zones better than the former since another variable, neutron porosity, is used. Both crossplots are, however, unsuccessful in differentiating mineral zones in sandstones.

In addition to the 11 wells, 7 more wells in the Salton Sea geothermal field were studied in order to test the empirical methods developed in this study. It was found that the lack of porosity data inhibited the effectiveness of distinguishing the zones.

Three conditions must be considered in order to interpret log data accurately by the empirical methods in this study. These are a knowledge of the downhole salinity profile, concentrations of resistive minerals in a section of a well, and the presence of thick shale horizons.

Gamma-gamma density logs, petrophysical and petrographic data indicate that net induration of the sandstone and shales has occurred in all altered zones. The gamma-gamma density log was shown to be fairly accurate in recording the true formation density in a hydrothermal environment. Use of Archie's equation to obtain porosity from electric logs was also studied. This method proved unsuccessful in this case, but under different conditions this method may be of value.

Three different methods were used to calculate salinity from wireline logs. The log-derived salinity values are in poor agreement with the actual formation water salinity. Nevertheless, the trend of the log-derived salinity profile may reflect the trend of the true salinity profile.

A comparison of electric log data for the Salton Sea and Cerro Prieto reservoirs indicates that the high salinity in the Salton Sea field (250,000 mg/l) has lowered the overall resistivity responses in all zones in relation to Cerro Prieto (18,000 mg/l).

Rigby, F.A., 1980, Benefit analysis for geothermal log interpretation: Proceedings 6th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-50, p. 310-315.

ABSTRACT — Formation evaluation is of great importance in geothermal development because of the high capital

costs and the fact that successful exploration will only pay off through a subsequent decision to construct a power plant or other utilization facility. Since much formation data is available from well logging, development of new techniques of log interpretation for application to geothermal wells is called for. An analysis of potential near-term benefits from this program and the types of formation data called for is discussed. Much useful information can be developed by adaptation of techniques used in oil and gas reservoirs, but the different demands of geothermal development from hydrocarbon production also open up new data requirements.

Rigby, F.A., 1981, Applications of geothermal well log data for evaluation of reservoir potential: NTIS Report No. LA-8778-MS, 71 p.

ABSTRACT — A great many geothermal reservoirs are naturally fractured systems with porosity supplied by both the macroscopic fracture system and by dispersed intergranular or vuggy porosity. Flow properties, the use of log data for well test interpretation in such systems, and the log derivable parameters that may be of most value for evaluation are discussed here. Parameters for describing behavior of two-phase geothermal systems are also mentioned. Determination of reservoir dimensions is another important problem aggravated in geothermal resource evaluation by our limited knowledge of the geophysics of geothermal systems. The use of resistivity log data to deduce constraints on the inversion of surface resistivity data is examined. Potentially valuable applications of resistivity log data in deducing reservoir dimensions and reaching decisions on exploratory drilling are indicated.

Rigby, F.A., and R.B. McEuen, 1980, Example of resistivity log extrapolation with MT data for a geothermal site: Paper SPE 9497, 55th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Dallas.

ABSTRACT — Well logging tools measure many of the same formation properties as are detected by surface geophysical measurements. When measurements from a borehole are available, the possibility of using such data to provide known points to aid in the inversion of surface measurements offers considerable benefits. While such opportunities are being pursued with seismic data in cases of exploration for hydrocarbons, combinations of surface and borehole data in geothermal exploration may be of value when applied to resistivity data. An example is given of results obtained using magnetotelluric data from the East Mesa field. The possibility for achieving improved information about reservoir dimensions and for extrapolating reservoir extent below the bottom of the borehole are considered.

Roux, Brian, S.K. Sanyal, and S.L. Brown, 1980, An improved approach to estimating true reservoir temperature from transient temperature data: Paper SPE 8888, 1980 California

Regional Meeting of the Society of Petroleum Engineers of AIME, Los Angeles.

ABSTRACT — In order to develop good estimates on the heat content of a geothermal reservoir and its formation resistivities, and for various drilling and completion decisions, one needs an accurate estimate of the formation temperature. Previous methods to determine static temperature required long shut in periods. The static temperature obtained using the conventional Horner plots were lower than the true reservoir temperature. A quick and easy method has been developed to calculate static temperature from early shut in data in geothermal wells. This method determines static temperature values which are closer to the true reservoir temperature than those obtained from the conventional Horner plot. Recommendations for recording pertinent data to be used in the analysis of temperature buildup and determining initial reservoir temperatures are provided. Several examples are also given.

Sanyal, S.K., M. Che, R.E. Dunlap, and M.K. Twichell, 1982, Qualitative response patterns on geophysical well logs from The Geysers, California: Geothermal Resources Council, Transactions, v. 6, p. 313-316.

ABSTRACT — This paper presents a set of qualitative response patterns on the geophysical well logs from The Geysers geothermal field, California. The response patterns were diagnosed from the analog prints of gamma ray, density, neutron and caliper logs. These patterns were verified from core data, production test results and a detailed computer analysis performed later. The paper shows that much information can be gained by simply scanning the analog prints of well logs from The Geysers.

Sanyal, S.K., M. Gardner, J.B. Koenig, and J. McIntyre, 1980, Wellsite evaluation of logs from a geothermal well: Geothermal Resources Council, Transactions, v. 4, p. 471-473.

ABSTRACT — This paper presents the case history of a well-site analysis of a suite of logs from a moderate temperature (350°F) geothermal well. From logs and drill cuttings data, a set of diagnostic criteria for each of the lithologic types in the well was developed. From these criteria a lithologic zonation of the reservoir was derived. Using a set of fracture detection criteria based on all available well logs, the probability of occurrence of fractures at various depths was qualitatively evaluated. Although the mud log showed significant methane concentration, the detection and estimation of reservoir gas content from well logs was not successful because of data limitation. The equilibrium formation temperature was estimated from logs but is not discussed in this paper in detail.

Sanyal, S.K., S. Juprasert, and M. Jusbasche, 1982, An evaluation of a rhyolite-basalt-volcanic ash sequence from well logs: in Geothermal Log Interpretation Handbook, published by Society of Professional Well Log Analysts, Tulsa.

ABSTRACT — This paper reports an empirical and innovative approach toward evaluation of logs from a well of "unusual" lithology: rhyolites, basalt and volcanic ash. The study was based on Borehole Compensated Sonic, Compensated Neutron-Formation Density, Temperature and drill cuttings logs. About 5000 ft. of the gamma ray log, and of the porosity logs were digitized and analyzed with the help of a computer.

No standard matrix parameters were available for the lithologic components encountered in this well. However by a careful and synergistic analysis, the well was evaluated as regards its lithology, zonation and the location of fracture zones. Gamma ray and neutron responses were most useful for lithology discrimination in this well.

The well section could be divided into 36 distinct zones based on lithologic and pore geometrical characteristics. Lithologies of each zone, particularly the ash content could be estimated. Several permeable zones were identified from the porosity, caliper and temperature log information and a rough estimate of the total thickness of permeable zones was possible. Most apparent permeable zones were found to occur below 9,000 feet and were associated with basaltic layers.

Sanyal, S.K., and J.M. Jusbasche, 1979, Calculation of geothermal water salinity from well logs—A statistical approach: Geothermal Resources Council, Transactions, v. 3, p. 613-616.

ABSTRACT — This paper presents a simple, statistical technique of estimating average geothermal water salinity from any section of a well. The method is based on crossplotting resistivity data from shallow and induction well logs, the slope of the crossplot being proportional to the formation water salinity. Examples are given from several sections of the well RRGE #1 at the Raft River geothermal field. The salinities estimated for these zones agree well with the salinity measured from the produced water.

Sanyal, S.K., and R. Weiss, 1978, Borehole geophysical logging as complement to well effluent sampling: Proceedings of the Second Workshop on Sampling Geothermal Effluents: NTIS Report No. EPA-600/7-78-121, p. 211-216.

ABSTRACT — Sampling and analysis of well effluents is an important means of detecting ground water pollution. There are, however, some drawbacks in this technique. If water is sampled from an uncased (open hole) well, the water represents a mixture of water from various permeable layers, rather than from an individual layer. This is an undesirable situation if water quality varies significantly from layer to layer. If the water is sampled from a cased well, the sample represents only the layers at the depths of well completion. One way of obtaining a continuous vertical profile of water quality with depth is to apply geophysical borehole logging to complement well effluent sampling and analysis, in both open and cased holes. Both real and hypothetical examples are given to illustrate the potential role of borehole geophysical logging in pollution monitoring.

Sanyal, S.K., L.E. Wells, and R.E. Bickham, 1980, Geothermal well log interpretation; state of the art; final report: NTIS Report No. LA-8211-MS, 321 p.

ABSTRACT — An in-depth study of the state of the art in Geothermal Well Log Interpretation has been made encompassing case histories, technical papers, computerized literature searches, and actual processing of geothermal wells from New Mexico, Idaho and California. A classification scheme of geothermal reservoir types was defined which distinguishes fluid phase and temperature, lithology, geologic province, pore geometry, and salinity and fluid chemistry.

Major deficiencies of Geothermal Well Log Interpretation are defined and discussed with recommendations of possible solutions or research needed for solutions.

The Geothermal Well Log Interpretation study and report has concentrated primarily on Western U.S. reservoirs. Geopressured geothermal reservoirs are not considered.

Sanyal, S.K., L.E. Wells, Charles Cleneay, and Mark Mathews, 1980, Computer analysis of a limited well log suite in a geothermal well—A case history: Geothermal Resources Council, Transactions, v. 4, p. 475-478.

This paper presents the case history of analysis of a "limited" logging suite (density, sonic, gamma ray, caliper and temperature) from a geothermal well with a complex mixture of sedimentary and igneous lithologies. The drill cuttings description listed at least nineteen lithologic types. Starting with the drill cutting description and digitized log data, a detailed lithologic zonation of the well was achieved by systematic analysis of the clustering of data points on crossplots. Because of the large number of lithologic types and a limited logging suite, quantitative estimates of the various lithologic components and porosity could not be obtained. However by comparing all log responses and lost circulation data, the porous zones could be identified. An estimate of mechanical strength of various zones from density and sonic logs correlated well with caliper log and physical characteristics expected of various lithologies.

Sanyal, S.K., L.E. Wells, and Mark Mathews, 1979, Classification of geothermal reservoirs from the viewpoint of log analysis: Transactions SPWLA 20th Annual Well Logging Symposium, Tulsa.

ABSTRACT — Several possible classification schemes are proposed for geothermal reservoirs from the viewpoint of well log analysis; the hope being that the vast number of known geothermal reservoirs can be grouped into a small number of reservoir classes, each with its distinct set of log responses and typical log analysis problems. Each of the following reservoir and fluid properties was chosen as the basis of a classification scheme: lithology, fluid phase, fluid chemistry, reservoir temperature, pore geometry and certain overall geologic factors. Each scheme is examined in detail as to its relevance to log analysis and the reservoir classes under each scheme are described. Examples are

given from the United States. Logging problems for each class are discussed. Frequency of occurrence of each class is considered.

Seamount, Jr., D.T., and W.A. Elders, 1981, Use of wireline logs at Cerro Prieto in identification of the distribution of hydrothermally altered zones and dike locations, and their correlation with reservoir temperatures: NTIS Report No. CONF-810399-5, 6 p.

ABSTRACT — Downhole electrical and gamma-gamma density logs from nine wells were studied and these wireline log parameters with petrologic, temperature, and petrophysical data were correlated. Here, wells M-43, T-366, and M-107 are discussed in detail as typical cases. Log data for shales show good correlation with four zones of hydrothermal alteration previously recognized on the basis of characteristic mineral assemblages and temperatures. These zones are the unaltered montmorillonite zone (<150°C), the illite zone (150°C to 230°C to 245°C), the chlorite zone (235°C to 300°C, equivalent to the calcsilicate I zone in sands), and the feldspar zone (>300°C, equivalent to the calcsilicate II zone in sands).

Sheff, J.R., and J.W. Upton, Jr., 1979, Comments on utility of geothermal well logs and an evaluation of the logs from Coso-BHD-1: Transactions SPWLA 20th Annual Well Logging Symposium, Tulsa.

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ABSTRACT — The log evaluations reported are for a geothermal test well, COSO-BDH-1. The hole was drilled to a depth of 1346 ft. (410 m) as part of the geothermal exploration of the COSO area for geothermal energy development. Data is reported on temperature in the hole, the hole diameter, the rock lithology, the formation density, the natural gamma ray emissions, the neutron log (generally used as a porosity indicator), and an acoustic log. The log analysis generally showed inadequate data was taken for a complete analysis, but that definite signs could be found pointing to the utility of logging as an aid to geothermal resource evaluation. The interpretation of logs was hampered by inadequate models of expected log behavior in geothermal fields.

Silva, P. and Z. Bassiouni, 1981, Accurate determination of geopressured aquifer salinity from the SP log: Geothermal Resources Council, Transactions, v. 5, p. 737-740.

ABSTRACT — The amount of gas dissolved in geopressured brine is water salinity dependent. When water samples are available, water salinity is determined by direct analysis. In the absence of water samples, which is often, water salinity is estimated using conventional well logging interpretation techniques. The water resistivity, Rw, is first calculated from the SP log. The salinity is then obtained using available

correlations. It is not unusual to obtain poor correlations between the values obtained from water samples and those estimated from the SP especially in deep geopressured south Louisiana formations.

The basic SP equation SP = -K log ($_{aw/amf}$) was examined. The parameter K was found to vary with the shale resistivity Rsh. A new interpretation chart relating SP to Rsh, Rmf and Rw was obtained.

The use of the new equation resulted in a significant improvement in the correlation between water salinity values obtained from water samples and those estimated from the SP log.

Society of Professional Well Log Analysts, 1982, Geothermal log interpretation handbook: Tulsa, Society of Professional Well Log Analysts.

NO ABSTRACT — Individual papers are presented under the following chapter headings: Objectives, Geothermal Reservoirs, Parameters and Desired Information, Drill Cuttings and Core Analysis, Temperature Measurements, Calibration, Case Histories, Nomenclature, and Bibliography.

Wells, L.E., S.K. Sanyal, and M.A. Mathews, 1979, Matrix and response characteristics for sonic, density and neutron: Transactions SPWLA 20th Annual Well Logging Symposium, Tulsa.

ABSTRACT — The search for energy and minerals in the last few years has led the log analyst to new geographical settings with lithologies unfamiliar to him. The data on Matrix response characteristics for the sonic, density and neutron tools in these lithologies are sparse at best and scattered in various published and unpublished sources.

A search of the petroleum, geophysical and related literature has been made and a computerized listing system developed to establish a matrix data information source for the Log Analyst without a large reference library.

The listing is designed to readily accept additions, updating and verifications. Contributors of new data will receive updated listings.

West, F.G., and A.W. Laughlin, 1976, Spectral gamma logging in crystalline basement rocks: Geology, v. 4, p. 617-618.

ABSTRACT — Spectral gamma logging in the crystalline basement rocks of two deep holes of the Los Alamos Scientific Laboratory's Hot Dry Rock Geothermal Project indicates that this type of log is useful for determining rock types, detecting fracture zones, and examining mobility of the heat-producing elemens, U. Th, and K.

Special Report 14 Addendum

Environmental Considerations in Geothermal Development

Abstracts reviewed by: Robert P. Breckenridge, Dwight L. Carey, Gerald Katz, and David W. Layton

CASE HISTORIES

Axtmann, R.C., 1975, Environmental impact of a geothermal power plant: Science, v. 187, p. 795-803.

NO ABSTRACT — The major focus of the study is on the effluents of New Zealand's Wairakei plant and their chemical, physical, and biological consequences.

Brown, K.W., and G.B. Wiersma, 1981, Geothermal environmental assessment baseline study: Vegetation and soils of the Roosevelt Hot Springs geothermal resource area: NTIS Report No. EPA-600/4-81-060, 109 p.

ABSTRACT — Identification and elemental concentrations of indigenous soil and plant systems found on the Roosevelt Hot Springs KGRA are described. Twenty-three different soils and five separate plant communities are geographically mapped and identified. One hundred forty-seven plant species were identified. Forbs, shrubs, and grasses are represented by 58, 53, and 36 species respectively. Three sites, each measuring 25 hectares, were selected for long-term vegetative assessment. At these locations a permanent enclosure measuring 24.4 meters x 24.4 meters was constructed to assess long-term effects of livestock grazing. Biomass, plant species, percentage composition, ground cover and livestock carrying capacities were determined at each site. Surface soils and Artemisia tridentata leaf tissue were collected for elemental analysis.

Ermak, D.L., and P.L. Phelps, 1978, An environmental overview of geothermal development: The Geysers-Calistoga KGRA, Volume 1. Issues and recommendations: NTIS Report No. UCRL-52496, v. 1, 17 p.

ABSTRACT — Geothermal resource development at The Geysers-Calistoga Known Geothermal Resource Area (KGRA) has been impeded by concerns over the impacts of development on local communities and environment. Issues have arisen on air quality, water quality, geologic effects, ecosystem effects, noise effects, socioeconomic impacts, and health effects. This report identifies and establishes priorities among these issues and recommends needed research and assessment studies to resolve each issue. The major requirement is for more effective control over emissions of hydrogen sulfide, a constituent of the geothermal steam. Other high priority needs are related to controlling noise from geothermal development, land-use conflicts between geothermal and other potential uses, impacts from landslide and soil erosion induced by geothermal development, and protection of rare and endangered species in the region.

Hill, J.H. (ed.), 1978, Workshop on environmental control technology for The Geysers-Calistoga KGRA (Known Geothermal Resource Area), 1978: NTIS Report No. UCRL-52887, 50 p.

ABSTRACT — This report is the proceedings of six work groups that discussed techniques to prevent and abate

noise, hydrogen sulfide emissions, and accidental spills of chemicals and geothermal wastes at The Geysers-Calistoga KGRA (Known Geothermal Resource Area). Problems associated with well completion and production, and with systems, components, and materials, and their effects on emissions were also discussed. The comments and recommendations of the work groups are included in the proceedings.

Layton, D.W., W. Morris, and J. Hill (eds.), 1980, Assessment of geothermal development in the Imperial Valley of California, Volume 1. Environment, Health, and Socioeconomics: NTIS Report No. DOE/EV-0092, v. 1, 242 p.

ABSTRACT — Utilization of the Imperial Valley's geothermal resources to support energy production could be hindered if environmental impacts prove to be unacceptable or if geothermal operations are incompatible with agriculture. To address these concerns, an integrated environmental and socioeconomic assessment of energy production in the valley was prepared. The most important impacts examined in the assessment involved air quality changes resulting from emissions of hydrogen sulfide, and increases in the salinity of the Salton Sea resulting from the use of agricultural waste waters for power plant cooling. The socioeconomic consequences of future geothermal development will generally be beneficial.

Leitner, P., R. Osterling, D. Price, and J. Westermeier, 1981, Baca geothermal demonstration project baseline ecosystem studies of cooling tower emission effects: NTIS Report No. DOE/ET/27163-6, 30 p.

ABSTRACT — Results of baseline studies for boron, arsenic, mercury, and fluorine in vegetation and soil near the Baca Geothermal Demonstration Power Plant are provided for the 1980 sampling season. Preliminary results of visual vegetation assessments and population density studies of soil invertebrate fauna are also provided. Foilage samples were collected for chemical analysis on a total of 17 plots on 5 transects. Two to five plant species were sampled at each plot. Samples were collected in June-July and September. Soil samples were collected at each plot during September. Visual vegetation inspections were conducted along each transect. Eighty-eight soil samples were collected for soil invertebrate studies. Boron, arsenic, mercury, and fluorine levels in vegetation were within normal range for natural vegetation and crops. Concentrations of soil arsenic and mercury were comparable to foliage concentrations. Boron concentrations were lower in soil than foliage, whereas soil fluorine concentrations were considerably higher than foliage concentrations. With the exception of heavy insect infestations in June-July, no vegetation abnormalities were noted. Preliminary soil invertebrate analysis indicated an overall arthropod density of approximately 1,000,000/m which appears within the normal range encountered in forest and meadow soil.

O'Banion, Kerry, and Charles Hall, 1980, Geothermal energy and the land resource: conflicts and constraints in The Geysers-Calistoga KGRA: NTIS Report No. UCRL-52970, 34 p.

ABSTRACT — This study of potential land-related impacts of geothermal power development in The Geysers region, one component of the Lawrence Livermore National Laboratory (LLNL)/Lawrence Berkeley National Laboratory (LBNL) socioeconomic program, focuses on Lake County because it has most of the undeveloped resource and the least regulatory capability. We first characterize the land resource in terms of its ecological, hydrological, agricultural, and recreational value; intrinsic natural hazards; and the adequacy of roads and utility systems. Based on those factors, we identify the potential land-use conflicts and constraints that geothermal development may encounter in the region and determine the availability and relative suitability of land for such development. We conclude with a brief review of laws and powers germane to geothermal land-use regulation.

The material in this study will be dovetailed with economic and demographic forecasts, now in preparation, in a combined final report in late 1980. The final report will include a more detailed analysis of potential socioeconomic impacts and land-use outcomes, as well as an evaluation of policy options to mitigate adverse impacts.

Pasqualetti, M.J., J.B. Pick, and E.W. Butler, 1979, Geothermal energy in Imperial County, California: Environmental, socio-economic, demographic, and public opinion research conclusions and policy recommendations: Energy, v. 4, p. 67-80.

ABSTRACT — It is estimated that thousands of megawatts of electricity could be generated from the geothermal fluids which underlie agricultural fields in Imperial County, California. Many potential environmental problems appear generally controllable. The possible inter-relationships between geothermal development and subsidence, seismicity, and water availability are, however, difficult to predict, and evaluation must await long-termed, commercial-sized operations. County population will interact with energy development through employment, geographical distribution, and interaction with the larger Mexican labor pool. Exportation of the bulk of the generated electricity, however, will limit the local socioeconomic impact. County residents favor geothermal development at a ratio of almost 9:1. Thirteen policy recommendations applicable to other known geothermal resources areas in the western U.S. include: the desirability of positive public opinion, the encouragement of on-line electrical power at an early stage in the development process, the importance of determining economic-technological exploitation feasibility, and the influences of local, state, and federal regulations.

Spencer, S.G., B.F. Russell, and J.F. Sullivan (eds.), 1979, Potential use of geothermal resources in the Snake River basin: an environmental overview: NTIS Report No. EGG-2001, variously paginated.

ABSTRACT — Environmental baseline data for the Snake River Plain known geothermal resource areas (KGRAs) are evaluated for geothermal development. These KGRAs are: Vulcan Hot Springs, Crane Creek, Castle Creek, Bruneau,

Mountain Home, Raft River, Island Park, and Yellowstone. Air quality, meteorology, hydrology, water quality, soils, land use, geology, subsidence, seismicity, terrestrial and aquatic ecology, demography, socioeconomics, and heritage resources are analyzed. This program includes a summary of environmental concerns related to geothermal development in each of the KGRAs, an annotated bibliography of reference materials (Volume II), detailed reports on the various program elements for each of the KGRAs, a program plan identifying future research needs, and a comprehensive data file.

Thurow, T.L., and L.S. Cahn, 1982, Final environmental report: INEL Geothermal Environmental Program: NTIS Report No. EGG-2215, 86 p.

SUMMARY — This report provides an overview of environmental monitoring programs and research during development of a moderate temperature geothermal resource in the Raft River Valley. One of the major objectives was to develop programs for environmental assessment and protection that could serve as an example for similar types of development. The monitoring studies were designed to establish baseline conditions (pre-development) of the physical, biological, and human environment. Potential changes were assessed and adverse environmental impacts minimized. No major environmental impacts resulted from development of the Raft River Geothermal Research Facility. The results of the physical, biological, and human environment monitoring programs are summarized in Volume 1.

The Physical Environmental Monitoring Program collected baseline data on geology, subsidence, seismicity, meteorology, and air quality. No increase in seismic activity was detected as a result of geothermal development, and it appears that the Research Facility is located in an area that is closely related to the inactive Snake River Plain. Although 0.9 m of subsidence was recorded in the northern Raft River Valley in the last 40 years because of excessive irrigation ground-water pumping, no changes in elevation were documented as a result of geothermal production or injection.

Air quality was identified as a major environmental concern. However, emissions generated from the Raft River geothermal development were measured as being well below National Ambient Air Quality Standards. Air quality in the area was found to be mainly affected by dust from agricultural and natural causes.

The Biological Environmental Monitoring Program collected baseline data on the flora and fauna of the fragile cold-desert ecosystem of the area, and surveyed the aquatic communities of the Raft River. Raptor disturbance research established a 0.6-km buffer zone that must be maintained around ferruginous hawk nest sites to protect this sensitive species. The nesting success of the ferruginous hawk in the Raft River Valley was not impaired by geothermal development and associated human activity as long as buffer zones were maintained. Declines in the nesting success of the ferruginous hawk population were associated with the

natural cyclic trend in the black-tailed jackrabbit population. A survey of passerine birds suggested that sage thrashers and sage sparrows may be sensitive indicators of environmental change in sagebrush, greasewood, and shadscale communities because they are habitat specific. No spills of geothermal water into the Raft River occurred during the development and operation of the geothermal facility.

The Human Environment Monitoring Program surveyed historic and archaeological sites, the socioeconomic environment, and documented incidences of fluorosis in the Raft River Valley. The development of the Raft River Research Facility had no impact on known historic or archaeological sites, and no undiscovered sites were located during construction activities. The closest archaeological site discovered is 0.8 km from the development and the rest are at least 3 km away. Proper planning during all phases of the geothermal project ensured that adverse socioeconomic impacts were minimized and potential benefits to local residents realized. A survey of the dental health of Raft River Valley school children was conducted by a dentist in 1978. The dental health of these children was usually poor, and 19% of the children displayed symptoms of fluorosis. Further studies failed to determine the source of fluoride.

In addition to the environmental monitoring programs, research on biological direct-applications was conducted at the Raft River Geothermal Facility. Survivability and productivity of various agricultural, aquacultural, rangeland, and silvicultural species were tested. Studies were also conducted to assess the potential of biological systems such as wetlands for water purification through bioaccumulation of elements from the water. Results of these efforts are presented at the end of Volume 1.

The effects of geothermal development of the water quality and hydrology were a major environmental concern. Volume II discusses the Monitor Well Program. Changes in ground-water quality observed were negligible. Short transient pressure responses were noted as a result of geothermal production and injection. Potentiometric head values returned to original levels when production/injection ceased. Thus, the effects of development at the Raft River Research Facility on groundwater were negligible. Because of the short duration of the hydrologic test, however, no long-term predictions can be made.

As of June 15, 1982, the engineering test phase of the 5-MW(e) facility was completed. The total accumulated amount of power generated by the facility since the plant was started was 2410.8 MWh. Engineering data gathered is presently being prepared in a final report.

On April 1, 1982, a Solicitation for Cooperative Agreement Proposals was issued by DOE to select a user for the facility. Since no proposals were received, the plant is currently in the process of being placed in cold standby prior to turnover to the General Services Administration for sale or disposition. All INEL project involvement in the power plant will be complete by October 1982.

ECOSYSTEMS

Brown, K.W., 1981, Geothermal environmental assessment: Behavior of selected geothermal brine contaminants in plants and soils: Science of the Total Environment, v. 22, p. 61-77.

ABSTRACT — Plants and soils were studied for the presence of elements found in geothermal fluids. Soil columns and selected plant species determined the kinetics of such potential contaminants. Lithium proved to be the best indicator of geothermal contamination and was detected in a variety of soils.

Cushman, R.M., S.G. Hildebrand, and R.W. Brocksen, 1977, Potential impacts on aquatic ecosystems from the release of trace elements in geothermal fluids: NTIS Report No. ORNL/TM-6057, 26 p.

ABSTRACT — Analyses of 14 trace elements found in hydrothermal fluids from various geothermal reservoirs in the western United States are presented. The concentrations of these elements, which include As, B, Ba, Br, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Rb, Ti and Zn, vary over orders of magnitude between reservoirs. Potential impacts are conservatively assessed on the basis of toxicity to freshwater biota, and bioaccumulation in food fish to the point where consumption might be hazardous to human health. Trace element concentrations generally range from benign levels to levels which might prove toxic to freshwater biota and contaminate food fisheries. The need for site-specific analyses and careful handling of geothermal fluids in order to minimize potential impacts is stressed.

Leitner, P., 1978, An environmental overview of geothermal development: The Geysers-Calistoga KGRA, Volume 5. Ecosystem quality: NTIS Report No. UCRL-52496, v. 5, 52 p.

是一个人,我们也是一个人,我们也是一个人,我们就是一个人,我们就是一个人,我们们也是一个人,我们就是一个人,我们也是一个人,我们也是一个人,我们们们的人,我们们

ABSTRACT — Increased utilization of geothermal steam for generation of electricity in The Geysers-Calistoga Known Geothermal Resource Area (KGRA) has raised concerns about possible adverse impacts on the natural and agricultural ecosystems of the region. Objectives of the Geothermal Overview Project for this KGRA were identification of ecosystem issues, evaluation of the existing data base, and recommendation of additional research needed to resolve key issues. The issue of highest priority is the lack of complete and accurate data on the status and distribution of rare or endangered plants and animals within the KGRA. Several studies are recommended to provide adequate information:

- A KGRA-wide effort to identify rare plants and their habitats.
- A site-specific determination of peregrine falcon foraging habitat.
- A compilation of available data on other wildlife species of special concern.

Medium-priority issues include the possible impacts of hydrogen sulfide emissions on vineyard and orchard crops and the ecological effects of boron and heavy metals released from geothermal power plants in cooling tower

drift. The potential for adverse effects is uncertain and research should be initiated promptly to determine whether these effluents pose serious problems. A third medium-priority issue concerns the potential for long-term cumulative impacts of geothermal development on natural ecosystems. To detect and evaluate such effects, it will be necessary to carry out additional baseline studies of terrestrial and aquatic ecosystems and to follow this with carefully designed monitoring programs. Several issues were given low priority in planning for additional research needs. For example, further studies of the biological effects of accidential spills of steam condensate and other potentially hazardous wastes are not recommended at this time: emphasis should be placed on spill prevention. Geothermal noise effects on wildlife have been studied within the KGRA: because of methodological problems, additional work would probably not be productive. Water vapor and aerosol emissions from cooling towers may affect agricultural operations by increasing the frequency of fogging and icing conditions. Studies elsewhere, however, should yield sufficient data to resolve this issue.

Shinn, J.H., R.R. Ireland, J.R. Kercher, J.J. Koranda, and G.A. Tompkins, 1979, Investigation of ecosystems impacts from geothermal development in Imperial Valley, California: NTIS Report No. UCRL-82996, 5 p.

ABSTRACT — Three years of field ecological investigation conducted in Imperial Valley, Calif., yield data concerning the potential impacts of geothermal energy development to aquatic and terrestrial ecosystems. Aquatic studies examined the effects of briny discharges on freshwater communities. Brine movement in soil and release of trace metals in plants were studied in agricultural analyses.

U.S. Fish & Wildlife Service, 1978, Impact prediction manual for geothermal development: U.S. Fish & Wildlife Service Report No. FWS/OBS-78/77, 158 p.

ABSTRACT — Described are techniques for predicting the probable effects of geothermal energy development on fish and wildlife resources. The techniques are designed to predict effects of a broad range of potential commercial-scale geothermal projects in the western U.S., and are intended to assist planners and decision-makers in evaluating and modifying development proposals. The techniques are based on an approach that recognizes that impacts on fish and wildlife from geothermal development tend to occur as a result of chains of cause-and-effect. Such chains typically lead from the physical action of some development activity through one or more intermediate effects in the environment, each of which constitutes a link in the chain of causeand-effect. Users are instructed to qualitatively and quantitatively analyze certain links to determine the importance of the chains in the projects being assessed.

Williams, J.M., 1982, Study of the potential health and environmental impacts from the development of liquid-dominated geothermal resources: NTIS Report No. LA-9407-P, 57 p.

ABSTRACT — This document describes seven programs to provide scientific input, understanding, and forecasting capability for hydrothermal energy areas needing resolution. The three major areas addressed are (1) the impacts on living components of the aqueous and terrestrial ecosystems, (2) the impacts on the quality of the abiotic environment itself, and (3) the techniques needed to measure releases from hydrothermal activities.

ENVIRONMENTAL GEOLOGY (Seismicity, Subsidence, Landslides)

Atherton, R.W., E.J. Finnemore, and M.L. Gilliam, 1976, The analysis of subsidence associated with geothermal development. Volume 1. Handbook: NTIS Report No. 5139-1; NSF/RA-760414, 287 p.

ABSTRACT — This study evaluates the state of knowledge of subsidence associated with geothermal development, and provides preliminary methods to assess the potential of land subsidence for any specific geothermal site. The results of this study are presented in three volumes. Volume 1 is designed to serve as a concise reference, a handbook, for the evaluation of the potential for land subsidence from the development of geothermal resources.

Atherton, R.W., E.J. Finnemore, and M.L. Gilliam, 1976, The analysis of subsidence associated with geothermal development. Volume 2. Research Report: NTIS Report No. 5139-2; NSF/RA-760415, 668 p.

ABSTRACT — Volume 2 provides a compendium of research results on subsidence and geothermal energy. It provides backup information to the subsidence Handbook. Topics treated included the fundamentals of geothermics, the geology and physical processes of subsidence, a survey of subsidence and reservoir models, and methods for evaluating subsidence potential via analogy or analysis methods.

Gilliam, M.L., B.E. Kenks, and R.W. Atherton, 1976, The analysis of subsidence associated with geothermal development. Volume 3. Information Bank: NTIS Report No. 5139-3; NSF/RA-760416, 185 p.

ABSTRACT — Volume 3 consists of four major parts: (1) A glossary of specialized terms as they are used in geothermal subsidence and directly related topic areas, (2) A listing of institutions and organizations possessing specialized collections of documents related to geothermal subsidence, (3) A keyword index of the documents obtained, and (4) An alphabetical listing of more than 1000 documents collected and catalogued during the study.

Bacon, F.C., P.Y. Amimoto, R.W. Sherburne, and J.E. Slosson, 1976, Engineering geology of The Geysers geothermal resource area, Lake, Mendocino, and Sonoma Counties, California: California Division of Mines and Geology Special Report 122, 35 p. NO ABSTRACT — This report provides guidelines for the engineering geology assessment of The Geysers Geothermal Resource Area (GRA).

Crow, N.B., 1978, An environmental overview of geothermal development: The Geysers-Calistoga KGRA, Volume 4. Environmental geology: NTIS Report No. UCRL-52496, v. 4, 72 p.

ABSTRACT — This report is one of a series of volumes reporting the results of an overview study of environmental issues in The Geysers-Calistoga Known Geothermal Resource Area region in the Northern California Coast Ranges. Part I presents the recommended projects together with supporting discussions of the environmental issues and related geologic information, thus serving as an executive summary. These recommendations are intended as a guide to detailed planning, and are not project work statements. Part II is a review of the published and open-file earth sciences literature about the region. It describes the regional framework of the geology, geophysics, and hydrology and provides information about the geothermal resources and the several kinds of geologic hazards accelerated erosion including landslides, potential interrelationships between geothermal fluids and both potable and thermal ground water, subsidence, and induced seismicity - that may affect the environment as consequences of geothermal development.

Studies should be concentrated in relatively small areas where geothermal development is likely. Some of the projects recommended are:

- Planning assessments (normally at map scales of 1:24,000) of the potential for accelerated erosion, landslides, and related hazards for small key localities likely to be developed for geothermal production.
- Characterizing potable and thermal ground-water resources likely to be affected by geothermal development. This includes a reconnaissance geohydrologic study and periodic collection of water chemistry and flow data from important ground-water sources for a period of 1-3 years.
- Continuing existing land surface movement and seismograph networks around The Geysers field, and extending them to the region to the northeast of present production.

The Appendix to this report is a comprehensive bibliography of scientific information about the Clear Lake—The Geysers region, compiled by David P. Adam of the U.S. Geological Survey, Menlo Park, California.

Dwyer, M.J., 1975, Regional mitigation of landslide induced impacts in The Geysers-Calistoga KGRA: Geothermal environmental seminar, Clear Lake, California, November 1975, Report No. CONF-7511133, p. 135-143.

ABSTRACT — The purposes of this paper are: (1) to briefly describe landslide conditions in The Geysers-Calistoga KGRA, (2) to summarize the impacts landsliding can have on the environment and on geothermal development, and

(3) to discuss how these impacts can be significantly reduced through the predevelopment preparation of regional landslide and landslide susceptibility maps. Although the contents of this paper are directed primarily to geothermal development in The Geysers-Calistoga KGRA, the methods described would be applicable to other resource areas in mountainous, unstable terrain.

Eberhart-Phillips, Donna, and D.H. Oppenheimer, 1984, Induced seismicity in The Geysers geothermal area, California: Journal of Geophysical Research, v. 89, p. 1191-1207.

ABSTRACT — A simultaneous inversion for hypocenters, velocities, and station delays was performed from the P arrival times of 55 microearthquakes and four explosions distributed throughout a 90- by 100-km region centered at The Geysers geothermal area in northern California. The resulting one-dimensional layered model shows velocity increasing with depth from 4, 4 km/s at the surface to 5, 9 km/s at 8 km and deeper. Using a new velocity model, 7215 earthquakes which occurred between May 1975 and February 1982 were relocated. The relocations show significant clustering within the steam field about steam production zones that was not apparent in earlier studies as well as the appearance of new seismicity in previously aseismic regions after production commenced. An examination, both qualitatively and quantitatively, is then made of the relation of steam well location and production history to earthquake activity. It is shown that the seismicity is apparently not influenced by either steam withdrawal or fluid injection rates but appears to be increasing with time in contrast to stable or declining production rates.

O'Rourke, J.E., and B.B. Ranson, 1979, Instruments for subsurface monitoring of geothermal subsidence: NTIS Report No. LBL-8616, 135 p.

ABSTRACT — The requirements for a subsurface geothermal subsidence instrument were reviewed. Available instruments for monitoring subsurface displacements, both vertical and horizontal, were studied and the most capable instruments identified. Techniques and materials for improving existing or developing new instruments were evaluated. Elements of sensor and signal technology with potential for high temperature monitoring of subsidence were identified. Drawing from these studies, methods to adapt production wells for monitoring were proposed and several new instrumentation systems were conceptually designed. Finally, four instrumentation systems were selected for future development. These systems are: triple sensor induction sensor probe (with casing collar markers); triple sensor gamma ray detector probe (with radioactive markers); triple sensor reed switch probe (with magnet markers); and triple sensor oscillator-type magnet detector probe (with magnet markers). All are designed for use in well casing incorporating slip couplings or bellows sections, although the gamma ray detector probe may also be used in unlined holes. These systems all measure vertical movement. Instruments to measure horizontal displacement due to geothermal subsidence were studied and the required instrument performance was judged to be beyond

the state-of-the-art. Thus, no conceptual designs for instruments to monitor horizontal movement are included.

Ryall, A.S., and U.R. Vetter, 1982, Seismicity related to geothermal development in Dixie Valley, Nevada: NTIS Report No. DOE/NV/10054-3, 106 p.

ABSTRACT — A ten-station seismic network was operated in and around the Dixie Valley area from January 1980 to November 1981; three of these stations are still in operation. Data from the Dixie Valley network were analyzed through 30 June 1981, and results of analysis were compared with analysis of somewhat larger events for the period 1970-1979. The seismic cycle in the Western Great Basin, the geologic structural setting, and the instrumentation are also described.

Stilwell, W.B., W.K. Hall, and John Tawhai, 1975, Ground movement in New Zealand geothermal fields: Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, v. 2, p. 1427-1434.

ABSTRACT — Ground subsidence and horizontal movement in water-dominated geothermal fields has been clearly demonstrated following almost 20 years of exploitation of the Wairakei field and some 10 years of leveling and control surveys. Recent check surveys have indicated movement of local control points toward the area of greatest subsidence and have highlighted the difficulties in selecting basic control points.

Establishing a comprehensive and reliable level network and survey control at the earliest possible opportunity is one of the major requirements of a geothermal exploration program, particularly in its application to the siting of and design of engineering structures.

The new Broadlands field afforded an excellent opportunity to proceed on from the Wairakei experiences in establishing an adequate survey network. During a period of 5 years of exploitation, a distinct pattern of subsidence occurred although this may now be influenced to some extent by the discovery of a new feed zone.

A further example is reported at Kawerau where a new exploration program is about to commence to assess the field potential. A large pulp and paper mill which draws on steam from a small part of the field may well influence the extent of development of the whole field, and hence careful monitoring takes on a very real significance.

GENERAL

Layton, D.W., and K.D. Pimentel, 1980, Geothermal power production: Impact assessments and environmental monitoring: NTIS Report No. UCRL-83681, 7 p.

ABSTRACT — The role that baseline and postoperational environmental monitoring plays in assessing impacts of geothermal power production is emhasized. Based on experience in the Imperial Valley, where substantial geothermal resources exist, the important characteristics of monitoring programs involving subsidence, seismicity, and air and water quality are examined. The importance of environmental monitoring for situations where predictive models either do not exist (e.g., seismicity), or are still being developed (e.g., land subsidence) are discussed. In these cases the need for acquiring and analyzing data that can provide timely information on changes caused by geothermal operations are emphasized. Monitoring is also useful in verifying predictions of air quality changes - in particular, violations of ambient standards after control technologies are implemented. Water quality can be monitored with existing sampling programs where the potential for geothermal impacts is thought to be rather small. The significant issues in these environmental areas, the status of baseline data and predictive capability that currently exists, and the need for future monitoring and modeling programs to assess the impacts of geothermal development are summarized.

Pasqualetti, M.J., 1980, Geothermal energy and the environment: The global experience: Energy, v. 5, p. 111-165.

ABSTRACT — The significant environmental impacts include conflicts in land use, air pollution, induced seismicity, blowouts, and noise, and every country has encountered some difficulty with one or more of these problems. Development plans have been slowed by environmental concerns in some countries. In the U.S.A., this problem has been the emission of hydrogen sulfide; in Japan, land use in national parks plus waste-water disposal: in El Salvador, waste-water disposal. Other environmental impacts which have not had an appreciable effect on development plans include: waste-water disposal and subsidence in New Zealand, land use and air pollution in Mexico. Italy has encountered no particular environmental barriers yet, but this may be a function of minimal monitoring. Collectively, the environmental difficuties at the operating power stations around the world have been minor compared to the actual disasters that have befallen other processes of generating electricity. Even the potential environmental hazard of geothermal energy development is much less. Geothermal development faces an array of rules and regulations which, in view of world-wide environmental experience, need not be so strict. Regulation is particularly tight in the United States.

HEALTH AND SAFETY

Holdren, J.P., K.B. Anderson, P.M. Deibler, P.H. Gleick, I.M. Mintzer, and G.P. Morris, 1983, Health and safety impacts of renewable, geothermal, and fusion energy: Health Risks of Energy Technologies Report, University of California, Berkeley, p. 141-209.

ABSTRACT — The health and safety impacts of solar, wind, biomass, geothermal, and fusion energies are estimated. Occupational impacts from these energy systems are more easily quantified than public impacts, and injuries are more easily identified than illnesses. Using conventional economic measures, damages from the above systems are shown to be modest compared with the numbers of fatalities society tolerates in connection with the use of the energy involved.

Layton, D.W., and L.R. Anspaugh, 1982, Health impacts of geothermal energy: Proceedings International Symposium on Health Impacts of Different Sources of Energy, Nashville, June 1981, Report No. CONF-810652, p. 581-594.

ABSTRACT — Geothermal resources are used to produce electrical energy and to supply heat for non-electric applications like residential heating and crop drying. The utilization of geothermal energy consists of the extraction of hot water or steam from an underground reservoir followed by different methods of surface processing along with the disposal of liquid, gaseous, and even solid wastes. The focus of this paper is on electric power production using geothermal resources greater than 150°C because this form of geothermal energy utilization has the most serious health-related consequences. Based on measurements and experience at existing geothermal power plants, atmospheric emissions of non-condensing gases such as hydrogen sulphide and benzene pose the greatest hazards to public health. Surface and ground waters contaminated by discharges of spent geothermal fluids constitute another health hazard. In this paper it is shown that hydrogen sulphide emissions from most geothermal power plants are apt to cause odour annoyances among members of the exposed public — some of whom can detect this gas at concentrations as low as 0.002 ppmv. A risk-assessment model is used to estimate the lifetime risk of incurring leukemia from atmospheric benzene caused by 2000 MW (e) of geothermal development in California's Imperial Valley. Also assessed is the risk of skin cancer due to the ingestion of river water in New Zealand that is contaminated by waste geothermal fluids containing arsenic. Finally, data on the occurrence of occupational disease in the geothermal industry is briefly summarized.

Layton, D.W., L.R. Anspaugh, and K.D. O'Banion, 1981, Health and environmental effects document on geothermal energy— 1981: NTIS Report No. UCRL-53232, 61 p.

ABSTRACT — We assess several of the important health and environmental risks associated with a reference geothermal industry that produces 21,000 MWe for 30 y (equivalent to 20 x 10¹⁸ J). The analyses of health effects focus on the risks associated with exposure to hydrogen sulfide, particulate sulfate, benzene, mercury, and radon in air and arsenic in water. Results indicate that emissions of hydrogen sulfide are likely to cause odor-related problems in 29 of 51 geothermal resources areas, assuming that no pollution controls are employed. For individuals living within an 80 km radius of the geothermal resources, chronic exposure to particulate sulfate (an oxidation by-product of hydrogen

sulfide in the atmosphere) could result in between 0 to 95 premature deaths per 1018 J of electricity generated. The mean population risk of leukemia from the inhalation of benzene was calculated to be 3 x 10 cases per 1018 J; at the 95th cumulative percentile of risk, 8.5 x 10⁻² cases per 10¹⁸ J were predicted. Exposure to elemental mercury in the atmosphere could produce between 0 and 8.2 cases of tremors per 10¹⁸ J of electricity. Inhalation of radon and its short-lived daughters poses a mean population risk of 4.2 x 10-1 lung cancer per 10¹⁸ J and 1.3 cases per 10¹⁸ J at the 95th cumulative percentile of risk. Our analysis of skin cancer risk from the ingestion of surface water contaminated with geothermally derived arsenic suggests that an existing linear, dose-response model is probably incorrect. It is inconsistent with data showing that arsenic is an essential element and that excessive body burdens do not appear even when arsenic reaches 100 µg/liter in drinking water. We based our estimates of occupational health effects on rates of accidental deaths and occupational diseases in surrogate industries. According to our calculations, there would be 14 accidental deaths per 10¹⁸ J of electricity and 340 cases of occupational diseases per 10¹⁸ J. The analysis of the effects of noncondensing gases in vegetation showed that ambient concentrations of hydrogen sulfide and carbon dioxide are more likely to enhance rather than inhibit the growth of plants. Finally, we studied the possible consequences of accidental releases of geothermal fluids and concluded that probably less than 5 ha of land would be affected by such releases during the production of 20 x 1018 J of electricity.

NOISE

Leitner, P., 1978, An environmental overview of geothermal development: The Geysers-Calistoga KGRA, Volume 3. Noise: NTIS Report No. UCRL-52496, v. 3, 8 p.

ABSTRACT — Noise from geothermal resource development at The Geysers-Calistoga Known Geothermal Resource Area will be an annoyance to nearby communities unless low noise level standards are set and obeyed. Steam vents are the loudest noise source, and can reach 100-125 DBA at 20-100 ft. Other noise results from construction activities; most of these sources are less than 100 DBA. Data exist that would be useful for decision-making purposes, but they must be compiled. Communities in the area must decide on noise level criteria; residential areas will require more stringent controls than will be required by open spaces. Existing technology will reduce noise levels somewhat, but more effective silencing devices are needed.

Norris, T.R., 1982, Environmental noise need not hinder geothermal power development: Geothermal Resources Council, Transactions, v. 6, p. 509-512.

ABSTRACT — Acceptable noise levels for residential communities and noise levels of standard geothermal operations were compared to determine the feasibility of drilling

at a distance of 1000 ft. from rural communities. The CNR noise criteria method, based upon octave band noise spectra rather than a-weighted sound levels, was used to determine acceptable noise levels. Noise sources from exploratory and developmental drilling, both with air and steam, well testing, production, and power plant operations were determined. It was found that with full use of demonstrated noise control technology, noise from operations can be reduced to levels acceptable to rural communities at a distance of about 100 ft.

AIR QUALITY

Freeman, D.E., W.G.N. Slinn, and J.A. Cooper (eds.), 1980, Air quality impacts related to the development of geothermal energy sources in the state of Oregon: NTIS Report No. UCRL-15302, 166 p.

ABSTRACT — Information is needed to make decisions pertaining to future atmospheric/environmental effects of geothermal energy development in Oregon. Generic air quality issues encountered in previous developments are examined and the kinds of data necessary to identify and quantify potential air quality impacts are summarized. Specific areas of Oregon identified as having high geothermal development potential are studied. Topics include: climate; topography; available source, meteorological and air quality data; and factors which may enhance air quality impacts locally. Those issues and impacts, real and perceived, that appear to be most significant for geothermal energy development in Oregon are summarized. Conclusions are drawn and needs for additional data and research are outlined.

Gudiksen, P.H., D.L. Ermak, K.C. Lamson, M.C. Axelrod, and R.A. Nyholm, 1979, Potential air quality impact of geothermal power production in the Imperial Valley: NTIS Report No. UCRL-52797, 42 p.

ABSTRACT — A regional assessment of the potential impact on air quality of developing the Imperial Valle's geothermal resources for power production is presented. A network of six stations was installed to characterize the air quality and atmospheric transport properties of the valley before development. These measured the ambient air concentrations of H2S, SO2, O3, NO, NOx, CO2, Hg, Rn, and particulates. Wind velocity and the directional variability of the winds were also measured to determine atmospheric stability. The geothermal fluids were analyzed chemically to estimate potential emission rates of H₂S, NH₃, CO₂, CH₄, Hg, and Rn from future power plants. Using these data and advanced air quality modeling led to the prediction of the potential valley-wide impact of a 3000 MW development scenario. The impact analysis reveals that H₂S is the principal gaseous pollutant of concern due to its noxious odor and the potential release rate. The ambient H₂S concentrations that would result from generating 3000 MW without emission controls exceed the California air quality standard (30 ppb) at least 1% of the time for an area in the northern part of the valley that is roughly 1500 km in size. This compares with current ambient air concentrations that exceed the standard much less than 0.1% of the time. The population center most impacted is Calipatria, where the standard could be exceeded almost 10% of the time. In addition, the odor of H $_2$ S will be noticeable at least 1% of the time for most of the valley if the 3000 MW are placed on-line without abatement systems.

Robertson, D.E., E.A. Crecelius, J.S. Fruchter, and J.D. Ludwick, 1977, Mercury emissions from geothermal power plants: Science, v. 196, p. 1095-1098.

ABSTRACT — Geothermal steam used for power production contains significant quantities of volatile mercury. Much of the mercury escapes to the atmosphere as elemental mercury vapor in cooling tower exhausts. Mercury emissions from geothermal power plants, on a per megawatt basis, are comparable to releases from coal-fired power plants.

Rosen, L.C., and C.R. Molenkamp, 1978, An environmental overview of geothermal development: The Geysers-Calistoga KGRA, Volume 2. Air quality: NTIS Report No. UCRL-52496, v.2, 55 p.

ABSTRACT — This report identifies key issues, evaluates available information, and recommends areas of research related to changes in air quality resulting from development of geothermal resources at The Geysers-Calistoga Known Geothermal Resource Area. Of the emitted pollutants, hydrogen sulfide and boron are identified as producing detrimental effects on the environment. We recommend additional research directed towards (1) reducing emissions of these identified pollutants, (2) developing a numerical transport and diffusion model for complex terrain, and (3) validating this model with additional airquality and meteorological data collected at The Geysers.

Serpa, D.P., L.R. Anspaugh, P.L. Phelps, and A.J. Soinski, 1977, Geysers geothermal power plant: Environmental impact of the release of ²²²Rn: University of California, Livermore, Report No. 420-77.22, 10 p.

ABSTRACT — The emission rate of ²²²Rn at The Geysers averages 3.2 mCi/(MWe-day). Ambient air concentrations of short-lived radon daughters are not increased above those reported for other locations, except in a few rare areas of possible occupational exposure. External exposure rate measurements indicated no significant accumulation of gamma-emitting radon daughters in either the power plant components or environs.

Tesche, T.W., 1982, Air quality modeling of geothermal power plants in complex terrain: Geothermal Resources Council, Transactions, v. 6, p. 517-519.

ABSTRACT — To determine the impact that development of The Geysers Geothermal Field in Northern California

would have on air quality, an integrated program of ambient aerometric monitoring, tracer diffusion experiments, cooling tower plume rise studies and numerical air quality simulation modeling was conducted. The aim was to provide estimates of potential short-term—approximately 1 hour—impacts on air quality. A series of diffusion experiments were conducted to evaluate model performance. Agreement within a factor of two was reached over 60% of the time.

Urban, P., 1981, Geothermal hydrogen sulfide removal: NTIS Report No. DOE/ET/27203-1, 56 p.

ABSTRACT — UOP Sulfox® technology successfully removed 500 ppm hydrogen sulfide from simulated mixed phase geothermal waters. The Sulfox process involves air oxidation of hydrogen sulfide using a fixed catalyst bed. The catalyst activity remained stable throughout the life of the program. The product stream composition was selected by controlling pH; low pH favored elemental sulfur, while high pH favored water soluble sulfate and thiosulfate. Operation with liquid water present assured full catalytic activity. Dissolved salts reduced catalyst activity somewhat.

Application of Sulfox technology to geothermal waters resulted in a straightforward process. There were no requirements for auxiliary processes such as a chemical plant. Application of the process to various types of geothermal waters is discussed and plans for a field test pilot plant and a schedule for commercialization are outlined.

Wilson, S.C., 1982, Evaluation of control needs for hazardous air emissions (non-H2S) from geothermal processes: Geothermal Resources Council, Transactions, v. 6, p. 529-532.

ABSTRACT — The results of a study of emissions of ammonia, arsenic, benzene, boron, fluoride, hydrocarbons other than benzene, mercury, radon, and sulfur oxide from geothermal development sites are presented. Over 40 geothermal development sites worldwide were examined. The health and environmental effects of the contaminants at various exposure levels were determined, and the potential non-H\$\Delta\$ contaminants were quantified based upon representative geothermal sites. It was found that most of the contaminants were either not environmentally significant or easily controllable with currently available technology.

WATER QUALITY

Layton, D.W., and W.F. Morris, 1981, Geothermal power: Accidental fluid...releases and waste disposal: Chemical Engineering Progress, April, 1981, p. 62-67.

ABSTRACT — The most important environmental concerns related to the use of water from towers in the Salton Sea area are blowdown disposal, which can be toxic to fish, and drift emissions, which are potentially harmful to crops.

Nakahara, H., M. Yanokura, and Y. Murakami, 1978, Environmental effects of geothermal waste water on the near-by river system: Journal of Radioanalytical Chemistry, v. 45, p. 25-35.

ABSTRACT — Geothermal power facilities in southern Japan have been discharging geothermal wastewater into a nearby river system. Ordinary chemical analysis and neutron activation analysis of the river's chemical characteristics indicate that serious effects (salinity and trace metal presence) of past high discharge rates can still be detected, particularly in river sediments. Chemical pollution has been greatly alleviated since reinjection procedures were begun; the current discharge rate of 90 ton/hr of geothermal hot water does not seem to cause serious problems. Arsenic and cesium are the best chemical specifics to trace the long-term effects of geothermal wastewater discharge using neutron activation analysis.

Pimentel, K.D., 1978, Environmental overview of geothermal development: The Geysers-Calistoga KGRA, Volume 6. Water quality: NTIS Report No. UCRL-52496 v. 6, 54 p.

ABSTRACT — This report identifies key issues, assesses available information, and recommends research related to water quality degradation resulting from geothermal development in The Geysers-Calistoga Known Geothermal Resource Area. Data necessary for making decisions to minimize damage while allowing development is lacking in three areas: For the whole KGRA, there is insufficient information on the relation of industry-related construction to erosion, with its resulting increase in sediment and silt in area streams. The effects of cooling tower drift on soils and vegetation near power plants should be studied as precursors of potential effects on water quality. For the hotwater resource area in the eastern portion of the KGRA, a long-range program of water quality monitoring is needed to establish a baseline.

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Slotta, L.S., and J.A. Cooper (eds.), 1980, Water resources and water quality impacts related to the development of geothermal energy sources in the state of Oregon: NTIS Report No. UCRL-15302, 104 p.

ABSTRACT — A survey of Oregon's Known Geothermal Resource Areas (KGRAs) is provided particularly in regard to regional water resource characteristics and 1979 geothermal development activities. Water use requirements were estimated from a projected 25 year development scenario for nine major geothermal resource areas in Oregon. Potential significant water use requirements include: the Alvord and Vale KGRA's, which reportedly have geothermal resources particularly suited for electrical power generation, and the Cascades' hot water resources, which have potential use in direct heating. A review of the chronological account of geothermal activities and impacts was projected for each of Oregon's KGRA's. Water quality issues and concerns regarding prospective geothermal activities within the resource areas were identified and ranked. The major concerns were: potential surface water pollution and degradation, changes in the ground-water regime, both chemical, thermal and hydraulic, erosion and sedimentation, subsidence and land mass movements. Water quality baseline information was collected about Oregon's geothermal resources. The chemical attributes of Oregon's hot springs and wells were compared and considered as models for heated waters to be drawn for electrical power generation or direct use heating. On the basis of water quality standards, most of the thermal spring waters would be undesirable to discharge directly to surface waters following thermal recovery.

Weiss, R.B., T.D. Coffey, and T.L. Williams, 1979 Geothermal environmental impact assessment: Ground water monitoring guidelines for geothermal development: NTIS Report No. EPA-600/7-79-218, 232 p.

ABSTRACT — This report discusses potential ground water pollution from geothermal resource development, conversion, and waste disposal, and proposes guidelines for developing a ground water monitoring plan for any such development. Geothermal processes, borehole logging, and injection well technology as they relate to geothermal development and ground water monitoring are also outlined.

Special Report 14 Addendum

Geothermal Well Production

Abstracts reviewed by Andy Drenick, R.J. Hanold, and Walter E. Nellis

DRILLING TECHNIQUES AND WELL COMPLETION

Denver Research Institute, 1982, Geothermal-well design hand-book: NTIS Report No. DOE/ET/27141-4, 103 p.

ABSTRACT — A simplified process is presented for estimating the performance of geothermal wells which are produced by natural, flashing flows. The well diameter and depth, and reservoir conditions must be known; then it is possible to determine the total pressure drop in a flowing well, and therefore to find the fluid pressure, temperature, and steam quality at the wellhead. By applying the handbook process to several input data sets, the user can compile sufficient information to determine the interdependence of input and output parameters.

Koczan, S.P., W.W. Patterson, and R.H. Rochester, 1982, Drill-pipe severing tool with high-temperature explosive: NTIS Report No. LA-9483-MS, 12 p.

ABSTRACT — A special-purpose borehole explosive tool designed to meet a need of the Los Alamos National Laboratory Hot Dry Rock (HDR) Geothermal Energy Development Program is described. This tool's particular purpose is to sever stuck drill pipe in deep (>4500 m), hot (>320°C), water-filled wellbores. No commercial severing tools are known to us that can be operated at temperatures above 260°C.

Nelson, E.B., 1979, Development of geothermal-well completion systems. Final report: NTIS Report No. DOE/ET/28324-9, 189 p.

ABSTRACTS — Results of a three year study concerning the completion of geothermal wells, specifically cementing, are reported. The research involved some specific tasks: (1) determination of properties an adequate geothermal well cement must possess; (2) thorough evaluation of current high temperature oilwell cementing technology in a geo-

thermal context; (3) basic research concerning the chemical and physical behavior of cements in a geothermal environment; (4) recommendation of specific cement systems suitable for use in a geothermal well.

Rudisill, J.M., 1978, Case history: The completion of a shallow, over-pressured geothermal well: Geothermal Resources Council, Transactions, v. 2, p. 587-590.

ABSTRACT — This paper presents a case history of the drilling and completion of a shallow over-pressured geothermal well situated in the Roosevelt Geothermal Field, Beaver County, Utah. The problems encountered and the techniques used in completing this well are reported to assist other operators in safely drilling and completing in such shallow, over-pressured resources. The tasks of greatest difficulty were (1) the running of the 9-5% in. production casing and (2) remedying cementing of the 13-3% in. surface casing. Patience, cooling of the well, and carefully performed and evaluated cement jobs were the techniques employed which contributed to the successful completion of these tasks.

Sandia National Laboratories, 1981, GEOTEMP predicts geothermal well temperatures: Computer program is especially useful for planning drilling and completion phases: NTIS Report Nos. SAND-79-7118 and SAND-79-7119.

ABSTRACT — A new computer program, GEOTEMP, has been developed to predict downhole temperatures in and surrounding geothermal wells. The program computes the temperature as a function of time in a flowing stream, in the wellbore, and in the soil. These temperatures are to be used as design data for the selection of cement, casing, drilling and packer fluids, drill bits, downhole valves, and other equipment. Although GEOTEMP is designed for applications to geothermal wells, it is a valuable tool for all wells. The program is described in two reports. The first discusses

the theoretical background used in developing the thermal simulator for computing downhole temperatures. The second report describes how to input data to the code and what results are printed out, provides six examples of both input and output, and supplies a listing of the code.

FLOW TESTING AND ANALYSIS

Bilicki, Z., J. Kestin, and E.E. Michaelides, 1981, Flow in geothermal wells: Part III. Calculation model for self-flowing well: NTIS Report No. DOE/ET/27225-8, 84 p.

ABSTRACT — The theoretical model described predicts the temperature, pressure, dynamic dryness fraction, and void fraction along the vertical channel of two-phase flow. The existing data from operating wells indicate good agreement with the model.

Butz, J., and M. Plooster, 1979, Subsurface investigations at the Roosevelt KGRA, Utah. Final report: NTIS Report No. DOE/ET/28389-1, 81 p.

ABSTRACT — An investigation of the geothermal reservoir in the Roosevelt Hot Springs Known Geothermal Resource Area in Utah was carried out. The objective of this effort was to develop predictions for well production capacities, based on data taken during field tests and through use of a computer model. In turn, the production information could then be used in design optimization and economic analyses for development of the resource under study. Flow tests of a geothermal well, Utah State 14-2, were conducted. Data consisting of pressure and temperature logs as a function of depth were obtained. Maximum recorded temperature was 503°F (262°C) and maximum pressure, 954 psia (6.58MPa) as measured under flow conditions. Tests were run at rates of up to 580,000 lb/hr (73.3 kg/sec) total flow. The information gathered during the testing was reduced and compared to results of a predictive computer model. Reservoir conditions in the Roosevelt Hot Springs KGRA are such that two-phase flow exists in the wellbore and, in some cases, also in the reservoir itself. The computer model employed in the analysis reflects current efforts to improve the state-of-the-art in the prediction of two-phase pressure drops in vertical systems. Predictions at flow rates of up to 300,000 lb/hr (38 kg/sec) matched quite well with test data, while modeling at higher flow rates (to maximum tested) showed progressively greater deviation from test data. Cause of the observed degradation is postulated to be the movement of the flash horizon into the reservoir, due to drawdown at high flow rates.

Gould, T.L., 1974, Vertical two-phase steam-water flow in geothermal wells: Journal of Petroleum Technology, v. 26, p. 833-842.

ABSTRACT — The efficient design and operation of a geo-

thermal wellbore requires an understanding of the complex interactions of heat transfer, fluid flow, phase change, flow regime change, and steam-water slip. The equations and concepts presented here account for those interactions and are used in simulating two-phase steamwater flow in a wellbore.

Miller, C.W., S.M. Benson, M.J. O'Sullivan, and Karsten Pruess, 1982, Wellbore effects in the analysis of two-phase geothermal well tests: Society of Petroleum Engineering Journal, v. 22, p. 309-320.

ABSTRACT — A method of designing and analyzing pressure transient well tests of two-phase (steam/water) reservoirs is given. Wellbore storage is taken into account, and the duration of it is estimated. It is shown that the wellbore flow can dominate the downhole pressure signal completely such that large h changes in the downhole pressure that might be expected because of changes in kinematic mobility are not seen. Changes in the flowing enthalpy from the reservoir can interact with the wellbore flow so that a temporary plateau in the downhole transient curve is measured. Application of graphical and nongraphical methods to determine reservoir parameters from drawdown tests is demonstrated.

Nathenson, M., 1974, Flashing flow in hot-water geothermal wells: Journal of Research of the U.S. Geological Survey, v. 2, no. 6, p. 743-751.

ABSTRACT — The production characteristics of hot-water geothermal wells which flash to steam-water mixtures in the cased part of the hole were analyzed. The flashing flow is assumed to be isenthalpic and, for purposes of calculating pressure drop, a finely dispersed mixture of equal average velocity. Water flow in the aquifer is treated using steady, radial Darcy flow. Calculations for a typical geothermal well show the effects on production of varying the system parameters of aquifer permeability, depth to water table, and base temperature. Field data from Wairakei, New Zealand, demonstrate the reductions in flow caused by mineral deposits in the bore. Data from Imperial Valley, Calif., agree well with calculated results.

Riney, T.D., and S.K. Garg, 1982, Analysis of production test data from selected Baca wells: Geothermal Resources Council, Transactions, v. 6, p. 309-312.

ABSTRACT — Results are presented of analyses of the downhole pressure buildup data for wells located in the Redondo Creek area of the Baca Geothermal Field. The downhole drilling information and pressure/temperature surveys are first interpreted to locate zones at which fluid enters the wellbore from the fractured formation and to estimate the initial reservoir temperature and pressure in these zones. Interpretation of the buildup data for each well considers wellbore effects, the CO2content of the fluid and differentiates between the single-phase and two-phase portions of the data. Estimates for the effective formation kh

are made for selected wells.

Ryley, D.J., 1980, Mass discharge of a geofluid from a geothermal reservoir—well system with flashing flow in the bore: Geothermics, v. 9, p. 221-235.

ABSTRACT — In this analysis the reservoir and wellbore are treated as a single open system. By appealing to the conservation equations for mass, energy and momentum and identifying the components of pressure drop through the system the mass discharge is calculated in terms of the terminal conditions, parametric quantities and well constants. A numerical example is used to illustrate the respective effects upon the mass discharge of single and two-phase friction factor, wellhead pressure, phase slip and reservoir drawdown.

Upadhyay, R.N., J.D. Hartz, B.N. Tomkoria, and M.S. Gulati, 1977, Comparison of calculated and observed pressure drops in geothermal wells producing steam-water mixtures: Paper SPE 6766, 52nd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Denver.

ABSTRACT — This paper contains comparisons of calculated and observed flowing pressure profiles from geothermal wells located in the United States and Philippines. Comparisons are included for tubular flow as well as flow through the casing-tubing annulus. Our comparison shows that for tubular flow, the Orkiszewski correlation makes the best prediction, whereas for annular flow, no clear-cut choice of a correlation can be made.

SCALE CONTROL AND BRINE CHEMISTRY

Auerbach, M.H., R.A. Reimer, R.G. Olander, and P.M. Rapier, 1983, Calcium carbonate scale inhibitor for direct-contact binary geothermal service: Journal of Petroleum Technology, v. 35, p. 1546-1552.

ABSTRACT — A 500-kw direct-contact binary-cycle pilot geothermal power plant was constructed and successfully operated free of scale at the U.S. DOE East Mesa geothermal test facility. The pilot plant used an Elgin tower direct-contact heat exchanger (DCHX) with isobutane as the working fluid. Initial tests with the untreated 340°F (170°C) geothermal brine gave heavy calcium carbonate fouling of the brine boost pump, flow monitors, and flow-control valves within 20 to 50 hours of startup.

Awerbuch, Leon, V.C. Van der Mast, and A.N. Rogers, 1982, Geothermal scale control by crystallization: Proceedings Sixth Annual Geothermal Conference and Workshop: Electric Power Research Institute Report No. EPRI AP-2760, p. 5.31-5.44.

ABSTRACT — Bechtel has developed a simple, straight-forward process and equipment for the control of all types of geothermal scale. The process is based on the well known slurry seeding technique, which has been in successful commercial use in food and chemical industries for many years. The seeding and slurry settling steps are conducted in two flasher-crystallizer-separators of novel design, described in this paper which effect the prompt contacting of brine with a large number of seed crystals at the instant of flashing. The two-scale design segregates the high-temperature scale rich in heavy metals from the chemically different, low-temperature scale. The overflow brine, still somewhat supersaturated, is completely stabilized by reheat and dilution by means of a small fraction of the flashed steam and of the turbine condenser condensate.

Crane, C.H., and D.C. Kenkeremath, 1981, Review and evaluation of literature on testing of chemical additives for scale control in geothermal fluids. Final report: NTIS Report No. DOE/ID/12183-T1, 182 p.

ABSTRACT — A selected group of reported tests of chemical additives in actual geothermal fluids are reviewed and evaluated to summarize the status of chemical scale-control testing and identify information and testing needs. The task distinguishes between scale control in the cooling system of a flash plant and elsewhere in the utilization system due to the essentially different operating environments involved. Additives for non-cooling geothermal fluids are discussed by scale type: silica, carbonate, and sulfide.

Gudmundsson, J.S., J. Ortiz-Ramirez, and E. Granados, 1984, Twophase flow and calcite deposition in geothermal wells: SPE Paper 12741, California Regional Meeting of Society of Petroleum Engineers of AIME, Long Beach.

ABSTRACT — The literature on two-phase flow in geothermal wells shows that the Orkiszewski method has found wide application in state-of-the-art wellbore simulators. Such a simulator was developed and then used for the problem of wellbore deposition of calcite in the Miravalles geothermal field in Costa Rica. The output of wells suffering calcite deposition decreases slowly at early time but rapidly at late time. The simulator was also used to estimate the deliverability curve for a large diameter well in the Svartsengi geothermal field in Iceland. The view is presented that more accurate wellbore simulators will make new reservoir engineering studies possible in geothermal fields.

Harrar, J.E., C.H. Otto, Jr., S.B. Deutscher, R.W. Ryon, and G.E. Tardiff, 1979, Studies of brine chemistry, precipitation of solids, and scale formation at the Salton Sea Geothermal Field: NTIS Report No. UCRL-52640, 20 p.

ABSTRACT — Factors affecting the precipitation of solids and deposition of scale from the hypersaline brines of the Salton Sea geothermal field - two potential problems in the proposed utilization of these brines for electric power

generation - were investigated. The average physical and chemical composition of the fulid from Magmamax No. 1 well was noted and the effects of changes in well flow rate on the chemistry of the brine and the formation of solids were determined. The effects of pH on the process stream chemistry and on the composition and rates of formation of solids and scale that precipitated from this brine were studied. Reduction of the pH from 6 to 4-5 decreased the scaling rates and increased the proportions of barium sulfate and calcium fluoride in the scales and precipitated solids. These studies were conducted using a small-scale four-stage brine flash system constructed at the site.

Harrar, J.E., F.E. Locke, C.H. Otto, Jr., L.E. Lorenson, S.B. Monaco, and W.P. Frey, 1982, Field tests of organic additives for scale control at the Salton Sea Geothermal Field: Society of Petroleum Engineering Journal, v. 22, p. 17-27.

ABSTRACT — A pilot-size brine handling system was operated from Magmamax Well 1 in southern California to study the characteristics of siliceous scale deposition and to evaluate the possibility of treating the brine with chemical additives to control scaling. The rates of formation, chemical constitution, and morphology of the scales were examined as functions of temperature, brine salinity, substrate material, and antiscalant additive activity. The most active classes of compounds were those containing polymeric chains of oxyethylene and polymeric nitrogen compounds that are cationic in character. The best single compound was Corcat P-18.

Henley, R.W., 1983, pH and silica scaling control in geothermal field development: Geothermics, v. 12, p. 307-321.

ABSTRACT — Due to the increase of amorphous silica solubility as significant silicate ion forms in the pH range 7 to 8.5, the potential for the deposition of silica scale during reticulation (pipeline transmission) of waste geothermal waters to disposal sites is dependent on steam separation temperature, silica concentration and pH of the residual fluid. The Wairakei and Broadlands (Ohaaki) fields are used as examples of these design considerations in relation to the reservoir chemistry of the field and possible changes during extensive exploitation.

Howard, S.C., and W.H. Bohli, 1980, Development of a cavitating descaling technique for on-line geothermal pipe and component cleaning and scale removal. Final report: NTIS Report No. DOE/ET/28452-1, 78 p.

ABSTRACT — The use of cavitation for cleaning and removing geothermal scale from pipes and system components is discussed. A study of the technical feasibility of using cavitation to remove scale is described including the preliminary fold test, the GLEF in-plant field demonstration, a production line cleaning trial, and recommendations.

Kochelek, J.T., and D.F. Zienty, 1981, Use of organic flocculants in

spent brine clarification: Geothermal Resources Council, Transactions, v. 5, p. 353-355.

ABSTRACT — Republic Geothermal Incorporated and Tretolite Division of Petrolite Corporation recently performed clarification studies using organic flocculants to aid in the removal of suspended solids from spent geothermal fluids. The investigation took place at a recent well test in the Salton Sea area of the Imperial Valley. Organic flocculants were added to an atmospheric brine stream which fed a pilot-scale clarification vessel. Influent and effluent suspended solids levels were monitored while flocculant dosage and brine flow rate were independently varied. This paper also investigates the implications of cost-effective flocculant treatment.

Tomson, M.B., K.M. Sloan, L. Vignona, C.C. West, and J.V. Matson, 1983, Scale inhibitor evaluation and brine chemistry: NTIS Report No. GRI-83/0048, 128 p.

ABSTRACT — A theory of how chemical inhibitors prevent precipitation and scale formation in brine systems was developed and applied to production from Geopressured-Geothermal gas wells. The brine from these wells is typically saturated with calcium and carbonate such that serious scaling problems in the pipes and processing equipment results when the pressure and temperature are changed by production. A method to determine the degree of supersaturation, called the saturation index (SI), based on simple chemical tests, was developed. Charts and a nomograph were prepared based on the governing saturation index equations to quickly determine the seriousness of the scaling problem and whether inhibitors can control the problem. The effectiveness of several commercial inhibitors was evaluated and reported by their generic name. Proprietary formulations sold by trade name were not evaluated. Tests were performed both in laboratory equipment designed especially for this and on actual wells operated by the DOE. Low concentration 'threshold' inhibitors were found to be an efficient and low cost way to prevent scale in these gas wells.

Vetter, O.J., and D.A. Campbell, 1979, Scale inhibition in geothermal operations: Experiments with Dequest 2060 phosphonates in Republic's East Mesa field: NTIS Report No. LBL-9089, 61 p.

ABSTRACT — Two calcium carbonate (CaCO3) scale inhibition tests have been performed at East Mesa wells number 16-29 and number 56-30. The first test at well number 16-29 could not be finished due to downhole pump problems. However, two inhibitor concentration runs were completed and a third run started before the pump failed. A follow-up test at well number 56-30 was completed according to the original plan. Typical power plant conditions (i.e., pressure and temperature drops, flow conditions) were simulated by using test loops (pipe diameters of eight inches at well number 16-29 and twelve inches at well number 56-30) and field separators. Untreated East Mesa brine exhibits a calcium carbonate scale tendency as soon as the pressure is dropped below 75 psig. The uninhibited

brine from well number 16-29 formed a maximum scale thickness of 0.5 inch in an eight inch ID pipe after a 92.75 hour test run at an average production rate of 375,000 lb/hr. The brine from well number 56-30 formed a maximum scale thickness of 1.25 inches in a twelve inch ID pipe after a 104 hour test run at an average production rate of 722,000 lb/hr. The principal conclusions of this test work are listed.

SURFACE AND DOWNHOLE PRODUCTION FACILITIES

Austin, J.C., 1980, Transportation and distribution of geothermal fluids: Geothermal Resources Council Special Report No. 9, p. 1-4.

ABSTRACT — Transportation of geothermal fluids through pipelines from wellheads to the energy user is common in most geothermal applications. Several factors including pipe material, size and installation, insulation, and pumping should be considered when designing the transmission pipeline or comparing system economics. This paper addresses some of the technical aspects which should be considered prior to final system selection.

Cliff, W.C., W.J. Apley, and J.M. Creer, 1979, Evaluation of potential geothermal well-head flow sampling and calorimeter methods: NTIS Report No. LBL-9248, 27 p.

ABSTRACT — The results of the evaluation of potential geothermal well-head calorimeter systems and flow sampling techniques are presented. The candidate calorimeter systems and flow sampling configurations are presented and discussed. The systems and configurations are compared and ranked relative to their potential usefulness for obtaining enthalpy measurements and representative sample flows at geothermal well heads. A preliminary test plan is presented to briefly indicate the type of field tests that are recommended for further development of selected candidate calorimeter methods and sample flow withdrawal apparatus.

Hanold, R.J., 1983, Geothermal pumping systems: NTIS Report No. LA-UR-83-3071, 17 p.

ABSTRACT — Improvements in electric submersible pumping systems have resulted in a demonstrated downhole running life of one year for low horsepower units operating in 180°C brine. The implementation of a prototype pressurized lubrication system to prevent brine intrusion and loss of lubricating oil from the motor and protector sections has been successfully tested. Second generation pressurized lubrication systems have been designed and fabricated and will be utilized in downhole production pumping tests during FY 84. Pumping system lifetime is currently limited by available power cable designs that are degraded by high-temperature brine. A prototype metalsheathed power cable has been designed and fabricated

and is currently undergoing destructive and nondestructive laboratory testing. This cable design has the potential for eliminating brine intrusion into the power delivery system through the use of a hermetically sealed cable from the surface to the downhole motor.

Harrison, R.F., and R.B. Dean, 1978, Availability ratio for performance of pipeline components in two-phase flow: Journal of Fluids Engineering, v. 100, 0. 350-352.

ABSTRACT — The majority of natural geothermal fields consist of a pressurized hot water aquifer which, when tapped, produce a flashing steam-water mixture at the wellhead. This can be efficiently utilized if the whole two-phase mixture is piped to the power-station, which may be up to 2 km away from the borefield. Reliable and complete information on the performance of steam-water flows through the many different pipework components encountered in a transmission system is essential before an efficient and safe network can be designed. A new method is presented which uses the steady flow availability function to analyze the efficiency with which energy can be transmitted in a pipeline. It is suggested that the availability approach can be used to compare the performance of all types of pipeline components such as bends, diffusers, etc., and their effect on the power available at the power turbine.

Hasbrouck, R.T., L.B. Owen, and R. Netherton, 1979, Automated system for membrane filtration and core tests: Geothermal Resources Council, Transactions, v. 3, p. 301-304.

ABSTRACT — An existing manually operated LLL system for obtaining data on injectability of geothermal effluents has been automated. Membrane filters and core samples are exposed to geothermal brine at representative injection pressure and formation confining pressure to study the potential effects of scaling and suspended solids deposition on the performance of injection wells. An electronic controller provides for operation under conditions of either constant differential pressure or constant flow. A data logger is used to obtain continuous records of all major system parameters. The new system is being used to assess the injectability of effluents produced by Magma Power Company's reaction clarifier-filter preinjection treatment facility operated in conjunction with the Geothermal Loop Experimental Facility at the Salton Sea Geothermal Field, southern California.

James, Russell, 1980, Suppression of steam condensate corrosion at Wairakei geothermal project: Geothermal Energy, v. 8, p. 11-21.

ABSTRACT — Corrosion of steam transmission pipelines at Wairakei is due to the small quantities of almost pure water condensing en route and containing dissolved carbon dioxide gas. Ironically, this results from highly effective scrubbing of chemicals by water extraction pots installed at intervals along the lines. Fewer extraction pots are now esti-

mated as adequate for this duty, so an easy reduction in corrosion should follow the closure of the up-stream pots.

King, G.G., 1980, Geothermal design of buried pipelines: ASME Paper No. 80-Pet-15, 8 p.

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ABSTRACT — Methods for predicting buried pipe temperatures and heat flow to ground are presented. Heat flow theory is based on source-sink flow models with pseudosteady extensions to handle transient effects of latent heat for predicting thaw and frost bulb growth rates. Predictions are tested against data from operating pipelines and field tests. Typical situations are discussed and systems with insulation, heat tracing and refrigeration are designed to prevent deleterious thermal efects. Techniques are extended to cover insulation requirements of buried multiple pipes.

Kumataka, M.K., and W.B. Bayard, 1982, Remote control of a geothermal steam pipeline: Journal of Petroleum Technology, v. 34, p. 989-994.

ABSTRACT — This study discusses design, operation, and future objectives of this control system. The design covers selection of the control system, data acquisition and control requirements for individual wells, pipeline overpressure-relief system control, and condensate reinjection system. The operation of the steam pipeline since power plant start-up has been very favorable. Steam delivery-pressure fluctuations are controlled to less than ± 0.5 psi (± 4 kPa) under normal conditions. Shift operators are capable of responding to power plant upsets (turbine trips and load reductions) in minutes, minimizing steam venting to the atmosphere.

Nichols, K.E., D. Prigmore, H. Matthews, and J. Halat, 1977, Design and field test of a steam powered downhole geothermal pump: Proceedings 12th Intersociety Energy Conversion Engineering Conference, Paper No. 779134, v. 1, p. 877-883.

ABSTRACT — A totally new concept for pumping geothermal wells has been designed and tested in a well. The pump work required is extracted from the thermal energy of the brine by a downhole boiler. The resulting steam drives a turbopump delivering pressurized brine to the surface. The exhaust steam is ducted to the surface where it is condensed and returned to the downhole boiler. The TPU (turbine pump unit) utilizes a single stage mixed flow impeller that achieves pumping efficiencies over 80%, driven by a two-stage steam turbine. The shaft is supported by water-lubricated bearings that have been tested at temperatures over 400°F. Pumping tests were successful and it was demonstrated that the steam powered concept is feasible.

WELL STIMULATION

Johnson, Wayne, 1978, Improved method of flashing and shocking

geothermal wells: Geothermal Resources Council, Transactions, v. 2, p. 337-339.

ABSTRACT — A quick and effective method to flash initially and/or shock a geothermal well utilizing a coiled tubing unit and nitrogen gas is described. Most of the geothermal wells in the Imperial Valley need a catalyst for initial flashing. The completion mud may be displaced with fresh water and with time the water will gain enough heat to flash. Solid carbon dioxide, or dry ice, is sometimes placed into the well where it gains heat and converts to a gas. The carbon dioxide gas provides enough additional energy to initiate flow. A quicker and more positive approach to initiate flow is accomplished by displacing the wellbore fluids utilizing nitrogen gas circulated through coiled tubing.

Katagiri, Kunio, and W.K. Ott, 1983, Frac treatment boosts geothermal well production: World Oil, v. 197, p. 64-65.

ABSTRACT — Production history of two geothermal wells in Hokkaido, Japan, has established the commercial value of hydraulic fracturing. Before treatment, combined steam production from both wells was 40 tons per hour. After two treatments, steam output increased threefold and has remained at high levels. On the basis of this experience, the authors suggest that geothermal well frac treatment should employ up to 500,000 bbl of hydroxypropy 1 guar polymer fluid, pumped at a rate of 80 to 100 bpm through an openhole packer. Ordinary silica frac sand, at a maximum concentration of 6 to 8 ppg, is a suitable propping agent.

Mumma, D.M., F. McCullough, Jr., E.W. Schmidt, D.S. Pye, and W.C. Allen, 1982, GEOFRAC: An explosives stimulation technique for a geothermal well: NTIS Report No. LA-UR-82-2020, 5 p.

ABSTRACT — The first known use of explosives for stimulating a geothermal well was successfully conducted in December 1981 with a process called GEOFRAC. The 260°C well was located at the Union Oil Company's Geysers Field in northern California. For the initial test, 364 kg of a new explosive called HITEX II was placed at a depth of 2256 meters and detonated to verify techniques. The explosive was contained in an aluminum canister to separate it from the well fluids. In the second test, 5000 kg of explosive was used representing a column length of approximately 191 meters. The explosive was detonated at a depth of 1697 meters in the same well. The results of these tests show that HITEX II can be safely emplaced and successfully detonated in a hot geothermal well without causing damage to the well bore or casing.

Republic Geothermal, Inc., 1981, Hydraulic fractures stimulation treatment of well Baca 23. Geothermal Reservoir Well-Stimulation Program: NTIS Report No. DOE/AL/10563-T15, 82 p.

ABSTRACT — Well Stimulation Experiment No. 5 of the Geothermal Reservoir Well Stimulation Program (GRWSP)

was performed on March 22, 1981 in Baca 23, located in Union's Redondo Creek Project Area in Sandoval County, New Mexico. The treatment selected was a large hydraulic fracture job designed specifically for, and utilizing frac materials chosen for, the high temperature geothermal environment. The well selection, fracture treatment, experiment evaluation, and summary of the job costs are presented herein.

Republic Geothermal, Inc., 1981, Chemical stimulation treatment, The Geysers: Ottoboni State 22, Geothermal Reservoir Well Stimulation Program: NTIS Report No. DOE/AL/ 10563-T11, 39 p.

ABSTRACT — Experiment No. 6 of the Geothermal Reservoir Well Stimulation Program (GRWSP) was performed at The Geysers Field in Sonoma County, California. This well had low productivity (46,000 lb/hr), probably because it did not intersect the primary natural fracture system of the reservoir. Surrounding production wells are considered to be good wells with an average flow rate of about 100,000 lb/hr. The stimulation technique selected was an acid etching treatment (Halliburton Services' MY-T-ACID). A small water prepad was used to provide tubular cooling and fluid loss control. Following the water prepad were 500 to 750 bbl of high viscosity crosslinked gel fluid and 400 to 500 bbl of a hydrofluoric-hydrochloric (HF - HCl) acid solution. The frac fluids were expected to enter only a single or limited fracture zone within the open interval. Frac rates of 20 to 40 BPM and surface pressures of 3000 psig were estimated for this treatment. During the job, however, no significant surface pressure was recorded, and all fluids flowed easily into the interval. Subsequent evaluation of the well performance showed that no noticeable stimulation had been achieved even though the frac fluids were properly injected. Temperature and gamma ray surveys along with tracer studies indicated that the frac fluids entered natural fracture channels over a 650-foot zone of the open interval, which probably prevented the staged acid etching treatment from functioning as designed.

Republic Geothermal, Inc., 1981, Hydraulic-fracture stimulation treatments at East Mesa, Well 58-30. Geothermal Reservoir Well-Stimulation Program: NTIS Report No. DOE/AL/10563-T13, 95 p.

ABSTRACT — East Mesa Well 58-30 was selected for two stimulation treatments: a conventional hydraulic fracture in a deep, low permeability interval, and a dendritic fracture in a shallow, high permeability interval of completion. The well selection, pre-stimulation evaluation, fracture treatment design, and post-stimulation evaluation are presented.

Republic Geothermal, Inc., 1982, Review of surface-equipment requirements for geothermal well stimulation. Geothermal Reservoir Well-Stimulation Program: NTIS Report No. DOE/AL/10563-T12, 26 p.

ABSTRACT — A summary of stimulation equipment avail-

able to geothermal industry is presented and some modifications from which it could benefit are discussed. Equipment requirements for hydraulic fracturing, acid fracturing, acidizing, and other chemical treatments are included. Designs for the following are reviewed: equipment for premixing and storing treatment fluids, proppant handling equipment, pump trucks, special equipment for foam fracturing, intensifier pumps, manifolding, and monitoring and control devices.

Republic Geothermal, Inc., 1982, Fracturing-fluid evaluation (laboratory work). Geothermal Reservoir Well-Stimulation Program: NTIS Report No. DOE/AL/10563-T14, 66 p.

ABSTRACT — Work done to characterize by chemical methods the temperature/time degradation behavior of polymer based fluids that may be used in stimulating geothermal wells by fracturing is described. The polymers tested were hydroxypropylguar (HP guar), hydroxyethylcellulose (HEC), carboxymethylcellulose (CMC), and XC Polymer. Also, two commercially available cross-linked HP guar systems were tested. The development of analytical techniques for characterizing the polymers and the results of static and dynamic high temperature aging of the polymers in various salt water environments are covered. The fluids were tested at 150, 200 and 250°C. The implications of these results based on the time/temperature degradation of the polymers and the relative ease of removing the degraded polymer from a sandpack are covered.

Republic Geothermal, Inc., 1982, Geothermal-Reservoir Well-Stimulation Program. Program Status Report: NTIS Report No. DOE/AL/10563-T9, 36 p.

ABSTRACT — Seven experimental fracture stimulation treatments completed to date and the laboratory work performed to develop the stimulation technology are described. A discussion of the pre-stimulation and poststimulation data and their evaluation is provided for each experiment. Six of the seven stimulation experiments were at least technically successful in stimulating the wells. The two fracture treatments in East Mesa 58-30 more than doubled the producing rate of the previously marginal producer. The two fracture treatments in Raft River and the two in Baca were all successful in obtaining significant production from previously nonproductive intervals. However, these treatments failed to establish commercial production due to deficiencies in either fluid temperature or flow rate. The acid etching treatment in the well at The Geysers did not have any material effect on producing rate.

Republic Geothermal, Inc., 1982, Requirements for downhole equipment used for geothermal well stimulation. Geothermal Reservoir Well-Stimulation Program: NTIS Report No. DOE/AL/10563-T10, 21 p.

ABSTRACT — The needs for new and improved downhole stimulation equipment for geothermal wells are identified. The following kinds of equipment are discussed:

mechanical downhole recording instruments, electric line logging tools, and downhole tools used for zone isolation.

Sinclair, A.R., F.J. Pittard, and R.J. Hanold, 1980, Geothermal well stimulation: Geothermal Resources Council, Transactions, v. 4, p. 423-426.

ABSTRACT — All available data on proppants and fluids were examined to determine areas in technology that need development for 300 to 500°F (150° to 265°C) hydrothermal wells. While fluid properties have been examined well into the 450°F range, proppants have not been previously tested at elevated temperatures except in a few instances. The latest test data at geothermal temperatures is presented and some possible proppants and fluid systems that can be used are shown. Also discussed are alternative stimulation techniques for geothermal wells.

Vetter Research, 1982, Acidification of geothermal wells: Laboratory experiments. Geothermal Reservoir Well-Stimulation Program: NTIS Report No. DOE/AL/10563-T16, 49 p.

ABSTRACT — The laboratory testing of the reactions of

acetic, formic, hydrochloric, and hydrofluoric acids with calcium carbonate, kaolin, sepiolite, and two formation materials at geothermal temperatures is described. A workable test procedure was developed which provided information regarding the relative reactivities of selected minerals or formation materials with three of the four acids investigated. Tests with hydrochloric acid were complicated by reactions of the acid with the test vessel materials and therefore, only very limited work could be done with this acid at the desired temperatures. In spite of these difficulties, information regarding the amount of soluble material in the various acids was obtained. From this information an approximate value for the percent dissolution of the minerals under the different reaction conditions could be calculated. Additional information regarding the formation of solid secondary reaction products upon cooling of the reacted acid was also obtained. The implication of the mineral reactivities with the different acids and the formation of secondary solids on geothermal acidizing operations are discussed. Some selected scale inhibitors (for calcium carbonate) were tested for their hydrothermal stability. Their efficiency in inhibiting the formation of calcium carbonate scale before and after aging at 500°F was measured. The implications of the loss of efficiency of these materials and recommendations for their use in the field are discussed.

Special Report 14 Addendum

Geothermal Materials

Abstracts reviewed by: William Boyle, Alan R. Hirasuna, and L.E. Kukacka

Barsoumian, J.L., 1982, Improved energy sealing capability: Conference Proceedings, Applying Current Geothermal Corrosion/Materials Technology to Today's Projects, Sponsored by U.S. Department of Energy, San Diego, October 1982, p. 73-78.

ABSTRACT — In response to the need for tapping national energy resources, an improved high temperature sealing material has been developed through the sponsorship of the Department of Energy. Parker Seal was selected as one of the technology transferees from L'Garde Inc. and has optimized this transferred technology for further improved performance capabilities and acceptable plant processing. This paper summarizes Parker Seal's testing and evaluation efforts on L'Garde's Y267 transferred technology for a new geothermal and steam service material. This new product, Parker's E962-85 is described in this paper.

Caskey, B.C., 1981, Use of an inert drilling fluid to control geothermal drill pipe corrosion: NTIS Report No. SAND-80-1726C, 30 p.

ABSTRACT — The results of a geothermal drill pipe corrosion field test are presented. When a low-density drilling fluid was required for drilling a geothermal well because of an underpressured, fractured formation, two drilling fluids were alternatively used to compare drill pipe corrosion rates. The first fluid was an air-water mist with corrosion control chemicals. The other fluid was a nitrogen-water mist without added chemicals. The test was conducted during November 1980 at the Baca Location in northern New Mexico, USA. Data from corrosion rings, corrosion probes, fluid samples, and flow line instrumentation are plotted for the ten day test period. It is shown that the inert drilling fluid (nitrogen) reduced corrosion rates by more than an order of magnitude. Test setup and procedures are also discussed. Development of an on-site inert gas generator could reduce the cost of drilling geothermal wells by extending drill pipe life and reducing corrosion control chemical costs.

Conrad, R.K., J.P. Carter, and S.D. Cramer, 1983, Corrosion of selected metals and a high-temperature thermoplastic in hypersaline geothermal brine: U.S. Bureau of Mines Report No. 8792, 20 p.

ABSTRACT — Weight loss, pitting and crevice corrosion, Ubend stress corrosion, and electrochemical polarization measurements were made in brine and steam process environments produced from high-enthalpy hypersaline brine from geothermal well Magmamax No. 1 at the Salton Sea Known Geothermal Resources Area, Imperial Valley, Calif. Cadmium (and by extension cadmium coatings) and a 6061-T6 aluminum alloy were unsatisfactory because of high general corrosion rates and, in the case of aluminum, severe pitting. Molybdenum and niobium were resistant to general corrosion, pitting, and crevice corrosion. Copper alloys corroded at rates that may preclude their use in wellhead brine. Titanium alloys were resistant to general corrosion and stress corrosion cracking; they exhibited crevice corrosion in some environments and Ti6A14V pitted in brine environments. A 40-pct-graphite-fiber-reinforced Ryton composite deteriorated in wellhead brine and failed in all of the brine and steam process environments; Ryton coatings on 316L stainless steel were adherent and performed well.

Daedalean Associates, Inc., 1978, Results of the initial feasibility program on cavitation descaling techniques for pipes and tubes used in geothermal energy plants: NTIS Report No. HCP/T2289-01, 61 p.

ABSTRACT — The purpose of the program is to develop input parameters and to establish design specifications for a cavitating hydrojet descaling system for pipe cleaning applications. Various design input parameters have been identified in order to establish associated cleaning rates for the type of scale and thickness that has been obtained from field operating environments. Specifically, the following are addressed: (1) the relationship between the jet speed and the cleaning rate; (2) the size and geometry of the noz-

zle as related to the surface area cleaned; (3) the minimum intensity of erosion for cavitation cleaning; (4) the optimum cavitation parameter as a function of cleaning rate; and (5) the specific horsepower requirements for the most efficient cleaning rates as defined by the cavitation descaling system. These specific areas of technical evaluation establish the design guidelines for the cavitating hydrojet descaling technique in order to effectively and efficiently remove geothermal scale. The phenomenon of cavitation and the cavitation inception parameter applicable to the descaling and cleaning technique are discussed. The experimental facility, test procedures, results, discussion of data and conclusions and recommendations for the initial feasibility program are identified.

Dennis, B.R., J. Johnson, and B. Todd, 1981, Armored instrumentation cable for geothermal well logging: NTIS Report No. LA-UR-81-3345, 7 p.

ABSTRACT — Multiconductor armored well-logging cable is used extensively by the oil and natural gas industry to lower various instruments used to measure the geological and geophysical parameters into deep wellbores. Advanced technology in oil-well drilling makes it possible to achieve borehole depths of 9 km (30,000 ft.). The higher temperatures in these deeper boreholes demand advancements in the design and manufacturing of wireline cable and in the electrical insulating and armoring materials used as integral components. If geothermal energy is proved an abundant economic resource, drilling temperatures approaching and exceeding 300°C will become commonplace. The adaptation of teflons as electrical insulating material permitted use of armored cable in geothermal wellbores where temperatures are slightly in excess of 200°C, and where the concentrations of corrosive minerals and gases are high. Teflon materials presently used in wireline cables, however, are not capable of continuous operation at the anticipated higher temperatures.

Dumitru, E.T., R.J. Lagow, and L.E. Kukacka, 1982, New fluorocarbon elastomers for seals for geothermal and other aggressive environments: Conference Proceedings, Applying Current Geothermal Corrosion/Materials Technology to Today's Projects, Sponsored by U.S. Department of Energy, San Diego, October 1982, p. 79-84.

ABSTRACT — Geothermal brines at 600°F which contain metallic salts, H 2S, and hydrocarbons quickly degrade conventional hydrocarbon elastomers, and hydrolyse crosslinks. Carbon-carbon and carbon-fluorine, bonds are expected to be superior, but no such elastomer is now commercially available.

We have prepared crosslinked, perfluorocarbon elastomers by radiation crosslinking VDFHFP and TFEP (alternating) copolymers in film and sheet form, and then converting C-H bonds to C-F bonds with elemental fluorine gas. EPDM elastomers became brittle on fluorination.

The best products exceeded 100 days survival at 300°C in simulated geothermal brine.

Tensile, elongation, solvent swelling, and TGA methods were used to study the products.

Ellis, II, P.F., C.C. Smith, R.C. Keeney, D.K. Kirk, and M.F. Conover, 1983, Corrosion reference for geothermal downhole materials selection: NTIS Report No. DOE/SF/11503-1, 332 p.

ABSTRACT — Geothermal downhole conditions that may affect the performance and reliability of selected materials and components used in the drilling, completion, logging, and production of geothermal wells are reviewed. The results of specific research and development efforts aimed at improvement of materials and components for downhole contact with the hostile physiochemical conditions of the geothermal reservoir are discussed. Materials and components covered are tubular goods, stainless steels and non-ferrous metals for high-temperature downhole service, cements for high-temperature geothermal wells, high-temperature elastomers, drilling and completion tools, logging tools, and downhole pumps.

Ellis, II, P.F., and M.F. Conover, 1981, Materials selection guidelines for geothermal energy utilization systems: NTIS Report No. DOE/RA/27026-1, 489 p.

ABSTRACT — This manual includes geothermal fluid chemistry, corrosion test data, and materials operating experience. Systems using geothermal energy in El Salvador, Iceland, Italy, Japan, Mexico, New Zealand, and the United States are described. The manual provides materials selection guidelines for surface equipment of future geothermal energy systems. The key chemical species that are significant in determining corrosiveness of geothermal fluids are identified. The utilization modes of geothermal energy are defined as well as the various physical fluid parameters that affect corrosiveness. Both detailed and summarized results of materials performance tests and applicable operating experiences from forty sites throughout the world are presented. The application of various non-metal materials in geothermal environments are discussed. Included in appendices are: corrosion behavior of specific alloy classes in geothermal fluids, corrosion in seawater desalination plants, worldwide geothermal power production, DOE-sponsored utilization projects, plant availability, relative costs of alloys, and composition of alloys.

Fontana, J.J., and A. Zeldin, 1979, Concrete polymer materials as alternate materials of construction for geothermal applications—Field test evaluations: NTIS Report No. BNL-25957, 22 p.

ABSTRACT — A serious problem in the development of geothermal energy is the availability of durable and economical materials of construction for handling hot brine and steam. Hot brine and other aerated geothermal fluids are highly corrosive and they attack most conventional materials of construction. Brookhaven National Laboratory has been investigating the use of concrete polymer

materials as alternate materials of construction for geothermal processes. To date, successful field tests have been demonstrated at The Geysers, US Bureau of Mines Corrosion Facility, and at the East Mesa Geothermal Facility. This is a survey of field and laboratory evaluations of concrete polymer materials which have been shown to be durable and economical as alternate materials of construction.

Friese, G.J., 1982, Pitfalls of elastomer compatibility testing: Conference Proceedings, Applying Current Geothermal Corrosion/Materials Technology to Today's Projects, Sponsored by U.S. Department of Energy, San Diego, October 1982, p. 85-89.

ABSTRACT — An extensive compatibility test program was conducted starting with 34 compounds and six 190°C fluids. Both immersion tests and simulation tests were conducted for time periods ranging from 46 hours to over six months. Deficiencies in both types of tests were determined. Immersion tests, while useful for reducing the number of candidate compounds, can easily lead to incorrect conclusions. It is essential that simulation tests be conducted before a final elastomer is selected for use in a critical design.

Friese, G.J., 1983, Development of modifications for coflexip flexiible drilling pipe for high-temperature and -pressure geothermal service: NTIS Report No. SAND-82-7203, 55 p.

ABSTRACT — Coflexip (France) flexible drilling pipe can provide economies in drilling geothermal wells. However, the current liner materials cannot take the high temperatures (approx. 250°C) and pressures (approx. 69 MPa). Development was undertaken to replace the liner with higher temperature materials and, thus increase the temperature capability of the flexible pipe. DuPont Teflon PFA 350, L'Garde EPDM Y267 and L'Garde AFLAS 291 were considered but they all require backing by a closely woven stainless steel fabric to prevent extrusion. A graphite-reinforced EPDM elastomer was developed which has the potential of meeting the pressure-temperature requirements without the metal fabric reinforcement.

Gillette, Howard, 1982, A fabrication report on L'Garde Y267 geothermal compound: Conference Proceedings, Applying Current Geothermal Corrosion/Materials Technology to Today's Projects, Sponsored by U.S. Department of Energy, San Diego, October 1982, p. 63-67.

ABSTRACT — A technology transfer was made from L'Garde to Precision Rubber Products for the fabrication of L'Garde geothermal seal compound Y267. Precision Rubber reports their experience as fabricators and gives field reports from three of their customers. Most of the experience has been very successful.

Hehemann, R.F., A.R. Troiano, B. Abu-Khater, and S. Ferrigno, 1976, Hydrogen sulfide stress corrosion cracking in materials for geothermal power: NTIS Report No. COO-2576-3, 34 p.

ABSTRACT — Studies to evaluate the performance of alloys used in geothermal power systems are reported. Alloys which are commercially available and those which have modified metallurgical structures and/or composition modifications were tested to determine the corrosive effects of the H 2S and thermal environments in geothermal fluids. Hydrogen embrittlement and sulfide stress corrosion cracking were tested. Test results showing the effects of alloy composition, tempering temperatures, fluid temperature and salt content, and ageing on sulfide stress cracking are tabulated.

Hendrickson, R.R., R.W. Winzenried, and A.H. Jones, 1981, Hightemperature seals and lubricants for geothermal rock bits. Final Report: NTIS Report No. SAND-81-7076, 60 p.

ABSTRACT — High temperature seals (elastomeric and mechanical) and lubricants were developed specifically for journal-type rock bits to be used in geothermal well drilling. Results at simulated downhole conditions indicate that five selected elastomeric seals (L'Garde No. 267, Utex Nos. 227, 231 and HTCR, and Sandia Glow Discharge Coated Viton) are capable of 288°C (500°F) service. Two prototype mechanical seals did not achieve the life determined for the elastomeric seals. Six lubricants (Pacer PLX-024 oil, PLX-043 oil, PLX-045 oil, Geobond Oil, and Geobond Grease) demonstrated 316°C (600°F) capability. Recommendation is made for full-scale simulated geothermal drilling tests utilizing the improved elastomeric seals and lubricants.

Hirasuna, A.R., G.D. Bilyeu, D.L. Davis, R.A. Sedwick, C.A. Stephens, and G.R. Veal, 1979, Geothermal elastomeric materials (GEM) program. Final Report: NTIS Report No. SAN-1308-2.

ABSTRACT — This Final Report is a comprehensive description of the work performed by L'Garde, Inc., on the Geothermal Elastomeric Materials (GEM) Program.

The primary program objective, to develop a geothermal packer elastomer to withstand 260°C (500°F) geothermal brine with 300 ppm H 2S, 1,000 ppm CO 2, 25,000 ppm NaCl in aqueous solution for 24 hours, was successfully accomplished. In fact the requirement for one elastomer was exceeded, compounds from four elastomeric polymer systems were successfully developed to meet the GEM requirements providing good flexibility for various situations.

Several secondary spin-offs also resulted. The compounds were developed for casing packer seal application and it was demonstrated that these compounds are directly applicable to the static O-ring and other elastomer applications in similarly unusually severe envionments. There is also indication based on drill bit seal tests that the basic compounds will be adaptable to high-temperature dynamic seal applications.

Another secondary spin-off is a different conceptual

approach to the thermal casing packer problem. This approach concentrates on minimizing the stresses subjected on the sealing element. Since it is fundamentally different, it has a good chance of advancing thermal packer capability in a revolutionary manner as opposed to an evolutionary manner.

And finally, art was invented which addresses the same thermal packer capability problem that is fundamentally different from the other work. A patent application submitted by DOE is in progress for the "Cure-In-Place" process. The process results in reduced seal element stresses in the packed-off configuration.

Hirasuna, A.R., D.L. Davis, G.J. Friese, and J.W. Trailer, 1983, Geothermal elastomeric materials, Technology Application (GEM-TA) Program: NTIS Report No. SAN-11537-1.

ABSTRACT — In 1979, L'Garde, Inc. completed the development of several geothermal elastomer compounds for the U.S. Department of Energy (DOE) Division of Geothermal Energy under Contract DE-AC03-77ET28309. Major advances in the state-of-the-art were achieved with successes at extreme conditions such as temperatures up to and exceeding 320°C (608°F), pressures up to and exceeding 138 MPa (20,000 psi), and fluids ranging from brines to hydrocarbons.

Because various geothermal projects had many elastomers problems and their solutions were critical to the project success, the DOE sponsored this effort to help provide the advantages of the earlier developed technology described above. This Final Report is a comprehensive description of the work performed by L'Garde, Inc. on the Geothermal Elastomeric Materials Technology Application (GEM-TA) Program under DOE/San Francisco Operation, Fossil Geothermal and Solar Division Contract DE-AC03-81SF11537. The technology applications supported are as follows: pump lineshaft bearings; seals for Freon® 114, synthetic hydrocarbon, and brine service; electrically insulative seals for logging tools; seals for nitrate salt explosive and steam service; and cementing wiper plugs. In addition there were minor efforts to further disseminate information associated with the elastomer development and case history experiences.

Hirasuna, A.R., G.F. Friese, and C.A. Stephens, 1983, A proven elastomer compound for extremely hostile geothermal and oilfield environments: IADC/SPE 1983 Drilling Conference, New Orleans, Paper No. IADC/SPE 11407.

ABSTRACT — Since 1979 the Y267 EPDM elastomer has been independently tested by other organizations in a variety of field and laboratory applications. The following are some examples. The same Y267 EPDM O-rings worked with no leaks as logging tool seals for multiple trips to 4600M (15k ft.) at 320°C (608°F) BHST. A packer element performed flawlessly for five months in a 204°C (400°F) continuous steam injection well and was retrieved at the end of the test in as as-new condition. A high-pressure Y267 EPDM packer test was performed with complete success at

232°C (450°F) for a 7.5 day test in sour crude with differential pressures to 138 MPa (20 ksi) and the seal condition was only very slightly changed by the test. Comprehensive compatibility testing of 34 compounds from 15 companies in geothermal brine, isobutane, and oil at 191°C-266°C (375-510°F) showed that the Y267 EPDM was best of the 34 in all three fluids.

Over 15 laboratory and over 20 field case histories of Y267 EPDM such as the above examples are reported. All strongly establish that Y267 EPDM is the cutting edge of technology.

Hirasuna, A.R., G.J. Friese, and C.A. Stephens, 1984, Y267 EPDM elastomer in hydrocarbons, important and unexpected very high temperature case histories; Corrosion 84, Paper No. 137, 39 p.

ABSTRACT — Y267 EPDM was recently developed for aqueous geothermal seal applications. The compound has proven eminently successful operating at temperatures in excess of 316°C (600°F), differential pressures over 69 MPa (10,000 psi), and for multiple exposures before changing the seals. The technology was transferred to three American firms and parts are currently commercially available from them.

There have been opportunities to test the Y267 EPDM technology in numerous fluids beyond geothermal brine, for which it was originally intended. The combination of the opportunity to do some well controlled comprehensive testing, along with special evaluation equipment which tests actual seals under operational conditions enabled radical revelations to be made.

The data are indicating that the cardinal rule against using EPDMs in hydrocarbon applications may be invalid. Significant data are presented illustrating Y267 EPDM technology to be a viable candidate for hostile hydrocarbon service. The data show viable candidacy to the extreme worst case end of the spectrum, i.e., highly aromatic hydrocarbons.

Several case histrories are provided which include careful well controlled and comprehensive laboratory tests; independent tests by major tool manufacturers, national laboratories, and major oil companies; and actual field case histories.

The paper also discusses how immersion tests can be highly misleading and that swell can really be a friend rather than a foe.

Jacobson, W.O., P.M. Henry, A.N. Rogers, and F. Schoepflin, 1979, Scale and corrosion parameters at a geothermal loop experimental facility: 40th International Water Conference, Annual Meeting, Pittsburgh, October 30 - November 1, 1979, p. 115-126.

ABSTRACT — San Diego Gas & Electric Company (SDG&E) operates a Geothermal Loop Experimental Facility (GLEF). The facility is located in southern California in the Salton Sea Known Geothermal Resource Area. This paper discusses studies conducted to aid in the inhibition or

handling of the brine scaling in the flash vessels and associated piping to avoid excessive plant outages, and in the selection of suitable materials of construction to minimize corrosion failures. It was found that certain non-metallic materials, Teflon PFA, ceramics, and vinyl esters, were extremely resistant to the Salton Sea brines. Other organic materials failed, some due to loss of the bonding adhesive holding the coating to the carbon steel substrate. Nickel base alloys exhibited the lowest corrosion rates in both the well head fluid and separated steam and brine from the first stage.

Kaeding, A.O., 1981, Design and fabrication of polymer-concretelined pipe for testing in geothermal-energy processes. Final Report: NTIS Report No. BNL-33019, 115 p.

ABSTRACT — A specific polymer-concrete formulation was applied as a steel pipe liner in response to a need for durable, economical materials for use in contact with high temperature geothermal brine. Processes are described for centrifugally applying the liner to straight pipe, for casting the liner in pipe fittings, and for closure of field joints. Physical properties of the liner materials were measured. Compressive strengths of up to 165.8 MPa (24,045 psi) and splitting tensile strengths of 23.5 MPa (3408 psi) were measured at ambient temperature. Compressive strengths of 24 MPa (3490 psi) and splitting tensile strengths of 2.5 MPa (366 psi) were measured at about 150°C (302°F). A full-scale production plant is described which would be capable of producing about 950 m (3120 ft.) of lined 305-mm-diam (12 in.) pipe per day. Capital cost of the plant is estimated to be about \$8.6 million with a calculated return on investment of 15.4%. Cost of piping a geothermal plant with PC and PClined steel pipe is calculated to be \$1.21 million, which compares favorably with a similar plant piped with alloy steel piping at a cost of \$1.33 million. Life-cycle cost analysis indicates that the cost of PC-lined steel pipe would be 82% of that of carbon steel pipe over a 20-year plant operating life.

Lagow, R.J., 1982, New fluorocarbon elastomers for seals for geothermal and other aggressive environments. Final Report: NTIS Report No. BNL-33129, 77 p.

ABSTRACT — Saturated ethyllenic elastomers having a range of methyl group substitution, and a range of partial fluorine substitution were screened. Elastomers based on vinylidene fluoride hexafluoropropylene (VDFHFP) and those based on tetrafluoroethylenepropylene (TFEP) (alternating) were successfully cross-linked by electron-beam radiation and fluorinated to yield elastomeric products, but those based on ethylene-propylene-diene (EPDM) elastomer became brittle after fluorination. The best products were evaluated using tensile strength, elongation at break, solvent swelling, thermogravimetric analysis and infrared. A wide range of carbon-black filled compositions using the TFEP elastomer were cross-linked. The compositions were then fluorinated at or near room temperature for extended periods of time. After fluorination the samples were subjected to geothermal brine at 300°C. The best carbon-black filled composition again lasted at least 100 days in the geothermal brine. This filler-elastomer composition was chosen for use in the production of O-rings. The O-rings were produced by compression molding using a 30 ton hydraulic press. Various sizes O-rings were produced ranging from 0.8 to 2.0 inches in diameter and from 1/16 to 3/16 inches in width. The final O-rings were cross-linked at 40 Mrad and fluorinated under the optimized conditions developed for the samples.

L'Garde, Inc., 1982, Short and long-term tests of elastomers with hot hostile fluids. Environmental compatibility test program final report: Brookhaven National Laboratory Report No. LTR-82-GF-110.

ABSTRACT — The objective of this program was to determine the best elastomers for use in medium temperature wells — with emphasis on binary plants in which isobutane is the working fluid.

Fifteen companies submitted thirty-four high-temperature elastomer compounds for test. Tensile specimens were immersed in 190°C brine, isobutane and four types of oil for 120 hours. Eight compounds were selected based upon the least change in weight, volume, ultimate tensile, hardness and elasticity.

These eight were tested as static O-ring seals in brine, isobutane and ASTM No. 1 oil. Test temperatures were 190°C, 230°C, and 265°C. The tests lasted 46 hours with a 21 MPa pressure differential across the seal. The eight compounds were also immersion tested for two and six months at 190°C.

Finally, the best four compounds were tested as 0-ring seals in 204°C brine, isobutane and ASTM No. 1 oil for about six months at a 21 MPa differential pressure.

Conclusions and recommendations are given for both elastomer compatibility and compatibility testing. A surprise result was that the EPDM O-rings (L'Garde Y267 and Parker E692-75) were among the best in ASTM No. 1 oil — a conclusion that would not be reached using immersion test results.

L'Garde, Inc., 1984, Elastomers accelerated ageing study. Final Report: Brookhaven National Laboratory Report No. LTR-84-GF-104.

ABSTRACT — Government and industry extensively use accelerated ageing in order to select the best material in a reasonable time period. Unfortunately, the best or even an acceptable material is often missed because of improper test conditions. The failures are costly and time consuming; so are the original tests especially if the results are incorrect.

This experimental program was conducted as an initial effort to determine the validity and limits of accelerated ageing for selecting elastomers for use in geothermal drilling and energy extraction processes. The test program was limited to a) 12 elastomers — each a different polymer; b) nitrogen as the immersion fluid; c) 5 accelerated ageing temperatures with a 265°C maximum, and d) 1 year maximum time at the 190°C service temperature. It was concluded that the results from an accelerated immersion test

in nitrogen do approximate the results obtained from normal ageing (within the above limitations and with a potential exception involving the Viton AHV and B compounds).

Use of nitrogen limited the potential reactions of the elastomers to those caused by temperature alone. The results encourage completion of the experimental program to include fluids of interest to the geothermal community. Hostile fluids (such as brine, oil, et cetera) increase the reactions that will occur within an elastomer, and therefore expose the material to the effects of temperature PLUS specific chemistries. The initial program also showed that specimens should be tested at more temperatures and times to reduce data scatter.

Lorensen, L.E., and C.M. Walkup, 1978, Polymeric and composite materials for use in systems utilizing hot, flowing geothermal brine. II: NTIS Report No. UCRL-81019, 27 p.

ABSTRACT — Further progress is reported on a continuing experimental program designed to select high-performance polymeric materials for use in geothermal power plants. In field tests 12 nozzles, 27 wear plates, and 2 types of polymer lined pipe were tested. Nozzles made of Teflons TFE and PFA, Tefzel, Ryton PPS and H-Resin/carbon cloth were little changed except for some scaling. The fluorocarbons scaled least rapidly. All blade type wear plates eroded, those based on Tefzel, PPQ, and PPS the least. Fluorocarbon lined pipes were little affected by exposure. In laboratory tests samples were heated at 250 and 300°C in brine. Several materials including fluorocarbon and unhydrolyzable aromatic or cross-linked aliphatic, thermally stable polymers survived for periods up to 1300 h. In erosion tests, coatings based on epoxy resins and a fluorocarbon were most resistant; good adhesion was required.

MacDonald, D.D., B.C. Syrett, and S.S. Wing, 1979, Use of potentialpH diagrams for the interpretation of corrosion phenomena in high salinity geothermal brines: Corrosion, v. 35, no. 1, p. 1-11.

ABSTRACT — Corrosion potentials and cyclic voltammograms are reported for A1S1 1010 carbon steel, E-Brite 26-1 stainless steel, A1S1 316L stainless steel, Haynes alloy 20 Mod, Carpenter 20 Cb-3, Inconel Alloy 625, Hastelloy Alloy G, Hastelloy Alloy C-276, Titanium 50A, and TiCode 12 in high salinity geothermal brine at 250°C. Potential-pH diagrams for the component metals (Fe, Ni, Cr, Ti) in the brine at 25 and 250°C are also derived, and are used to interpret the corrosion behavior and cyclic voltammetric responses of the alloys in the elevated temperature brine environment. A major factor in the economic exploitation of geothermal resources will be the cost-effective selection of materials that have sufficient resistance to corrosion to maintain component integrity.

National Technical Information Service, 1982, Corrosion resistant properties of Hastelloy C-276. 1966 - May, 1982 (Citations

from the Metals Abstracts Data Base): NTIS Report No. PB82-866344, 105 p.

ABSTRACT — This bibliography contains citations concerning the corrosion resistant properties of Hastelloy C-276 nickel base alloy. Topics include hydrogen embrittlement, stress corrosion cracking, and pitting corrosion. Primary applications include the chemical processing industry, oil and gas deep well recovery, geothermal brine, and nuclear fuel reprocessing. (This updated bibliography contains 102 citations).

National Technical Information Service, 1982, Geothermal power: Corrosion and material development. 1976 - July, 1982 (Citations from the Energy Data Base): NTIS Report No. PB82-870858, 301 p.

ABSTRACT — This bibliography contains citations concerning the corrosive environment in geothermal energy extraction, and the development of materials for geothermal systems. The studies cover materials for the drilling and the geothermal power phases. Materials include alloys, polymers, concretes, and inert drilling fluids. The citations also cover the degree of corrosion and scale, and how this build-up affects the geothermal operations. (Contains 297 citations fully indexed and including a title list).

National Technical Information Service, 1983, Corrosion Resistant Nickel Alloys for high sulfur and chloride environments. 1974 - July, 1983 (Citations from the Metals Abstracts Data Base): NTIS Report No. PB83-868521, 81 p.

ABSTRACT — This bibliography contains citations concerning the use of nickel alloys in highly corrosive chloride and sulfur environments. Applications include geothermal brines, sulfur oxide scrubbing, production of mineral acids, and flue gas desulfurization. (This updated bibliography contains 75 citations.)

National Technical Information Service, 1983, Geothermal energy: Corrosion and equipment. 1976 - June, 1983 (Citations from the NTIS Data Base): NTIS Report No. PB83-807818, 266 p.

ABSTRACT — Citations of Government-sponsored research reports on corrosion and equipment studies related to geothermal energy are presented. Studies on pumps, turbines, drilling equipment, pipes, nozzles, and well casings are covered, along with studies on materials including concretes, steels. and nonferrous alloys. Silica precipitation and scale formation on equipment are also cited. Performance of equipment in working fluids and brines and the chemical process affecting performance are included. (This updated bibliography contains 258 citations).

National Technical Information Service, 1983, Protective coatings for pipelines. 1976 - August, 1983, (Citations from the Energy Data Base): NTIS Report No. PB83-870758, 201 p.

ABSTRACT — This bibliography contains citations concern-

ing protective coatings for pipelines in terms of both internal and external corrosion and erosion. Topics include gas, water, and oil lines. Coating materials include plastics, alloy overlays, urethanes, and composites. Special problems associated with the pipeline transport of fluidized coal and geothermal brines are also discussed. (This updated bibliography contains 182 citations).

National Water Well Association, 1979, Economic impact of using nonmetallic materials in low to intermediate temperature geothermal well construction. Volume 1: NTIS Report No. BLN-51224 (V. 1) 63 p.

ABSTRACT — The results are presented of an exhaustive literature search and evaluation concerning the properties and economics of commercially available nonmetallic well casing and screens. These materials were studied in terms of their use in low to intermediate temperature geothermal well construction.

Rechard, R.P., and K.W. Schuler, 1983, Euler buckling of geothermal well casing: NTIS Report No. SAND-82-0863, 65 p.

ABSTRACT — Geothermal well operators have expressed concern over the vulnerability of unsupported casing to buckling from thermal elongation. Preliminary numerical and theoretical calculations are presented, which indicate the buckling phenomenon should not be serious in N-80 casing if the string is tension preloaded. Buckling would be detrimental for K-55 casing. The effect of wall contact was found to be beneficial for closely confined pipe strings and of no detriment when hole gaps are large. The weakness of API screw joints in bending appears to be the structural limitation. The analysis assumed stresses above yield constituted failure, that thermal expansion was strain controlled, and that the casing was continuous. Excessive internal pressure instability was ignored. The temperature variation considered was between cementing conditions of 100 to 200°F, (40 to 95°C) and shut-in conditions of 425 to 450°F (220 to 230°C).

Rogers, A.N., M.C. Weekes, and Fred Schoepflin, 1981, Corrosion studies: Geopressured aquifer gas production: NTIS Report No. GRI-80/0047, 95 p.

ABSTRACT — Corrosion test results on a number of metals, exposed to geothermal brines, were incorporated into matrix format to permit a ready comparison of corrosion resistance. The most promising materials were selected for further testing in flowing geopressured brine. The selection was directed toward the use of the materials in a geopressured gas separation system supplied with a brine having a postulated composition based on analyses of four existing geopressured wells and several thousand formation waters. A test plan was developed to determine the corrosion resistance of candidate materials in flowing geopressured brine. A rapid screening by the linear polarization technique is to be followed by a more extended exposure in a test loop. The use of clad or coated carbon steel for the

major gas plant components were analyzed. As an alternative, the injection of a small dosage of corrosion inhibitors into the brine was investigated.

Sakai, Jun-ichi-Nippon Kokan, Jpn Kawasaki, and Iwao Matsushima, 1976, Corrosion behavior of steels in geothermal steam power plant: Transactions, Iron Steel Institute of Japan, v. 16, no. 12, p. 688-694.

ABSTRACT — The steels investigated in the power plant were a plain 0. 14% C steel, weathering steel with 0. 09% C, 0. 74% Cr, and very small amounts of Mo and V, and steels with up to 13% Cr. Tests were conducted in the atmosphere, cooling water, hot water, and in a test loop simulating the steam well. Atmospheric corrosion could be reduced 50% by using the weathering steel. Resistance to condensed water was not improved by small amounts of alloying elements, as in the weathering steel. Corrosion by hot water decreased sharply with additions of Cr. Attack was almost negligible above 13% Cr. High Cr contents were also beneficial under steam/water two-phase flow which may cause severe erosion-corrosion to carbon steel. The failure of casing tubes experienced in practice is caused by erosioncorrosion initiated at areas where the flow is disturbed by unfavorable design such as slots in the pipe or gas at couplings. Surface irregularity caused by corrosion is also detrimental.

Salzbrenner, R., 1981, Drill stem steels for use in geothermal environments: Journal of Energy Resource Technoloy, v. 103, p. 159-165.

ABSTRACT — Steels which are used in drill stem for conventional drilling have been selected primarily to satisfy certain static strength requirements and cost considerations. As the environments in which drilling is performed become more severe (e.g., in geothermal fluids) additional considerations must be given to the design of alloys which are resistant to general corrosion, stress corrosion, and corrosion fatigue. General design considerations for steel alloys which should provide an enhanced resistance to geothermal drilling operations are presented.

Schroeder, J.E., 1981, Design and fabrication of polymer-concrete pipe for testing in geothermal-energy processes. Final Report: NTIS Report No. BNL-33130, 68 p.

ABSTRACT — Polymer concrete is a composite material which has strength and durability characteristics greatly superior to those of portland cement concrete and better durability in hot brine than steel. Polymer concrete has been successfully tested in brine, flashing brine, and steam at temperatures up to 260°C (500°F). Exposures were as long as 960 days. Glass-filament-wound polymer concrete pipe was developed with excellent strength, low weight, and a cost comparable to or less than Schedule 40 steel. Connections can be made with slip joints for low-pressure applications and flanged joints for high-pressure applications.

Suciu, D.F., and P.M. Wikoff, 1982, An evaluation of materials of systems using cooled, treated geothermal or high-saline brines: NTIS Report No. EGG-2213, 50 p.

ABSTRACT — Lack of adequate quantities of clean surface water for use in wet (evaporative) cooling systems indicates the use of high-salinity waste waters, or cooled geothermal brines, for makeup purposes. High-chloride, aerated water represents an extremely corrosive environment. In order to determine metals suitable for use in such an environment, metal coupons were exposed to aerated, treated geothermal brine salted to a chloride concentration of 10,000 and 50,000 ppm (mg/L) for periods of up to 30 days. The exposed coupons were evaluated to determine the general, pitting, and crevice corrosion characteristics of the metals. The metals exhibiting corrosion resistance at 50,000 ppm chloride were then evaluated at 100,000 and 200,000 ppm chloride. Since these were screening tests to select materials for components to be used in a cooling system, with primary emphasis on condenser tubing, several materials were exposed for 4 to 10 months in pilot cooling tower test units with heat transfer for further corrosion evaluation.

The results of the screening tests indicate that ferritic stainless steels (29-4-2 and SEA-CURE) exhibit excellent corrosion resistance at all levels of chloride concentration. Copper-nickel alloys (70/30 and Monel 400) exhibited excellent corrosion resistance in the high-saline water. The 70/30 copper-nickel alloy, which showed excellent resistance to general corrosion, exhibited mild pitting in the 30-day tests. This pitting was not apparent, however, after 6 months of exposure in the pilot cooling tower tests. The nickel-base alloys exhibited excellent corrosion resistance, but their high cost prevents their use unless no other material is found feasible. Other materials tested, although unsuitable for condenser tubing material, would be suitable as tube sheet material.

Troiana, A.R., and R.F. Hehemann, 1982, Localized corrosion in materials for geothermal power. Final Report: NTIS Report No. DOE/ET/28317-T2, 145 p.

ABSTRACT — The influence of 16 different geothermally related environments on a number of potentially useful steels was examined for both general and localized corrosion and at ambient and 150°C. Variation in chloride concentration of 1 to 20% generally demonstrated only minor aggressiveness in acidified solutions. In general, the presence of H 2 S raised the corrosion rate. However, very low concentrations (10 ppm) indicated higher rates than in saturated brines. This is rationalized on the basis of the inability to develop a semi-protective film at the low H 2 S concentration. The corrosion rate for the Cr-Mo steel was unexpectedly high at ambient, but improved substantially at 150°C. The Ni-Cu-Nb steel consistently demonstrated excellent resistance in all environments, except the 10 ppm H 2 S at ambient. At 150°C there were no exceptions to its superior performance. Maximum pit depth studies, analyzed statistically, indicated that the Ni-Cu-Nb alloy was the most resistant to localized attack. A clean (low inclusions) Mn-C and a clean vacuum melted steel ranked well. A comparison of two almost identical Mn-C steels one clean and one dirty clearly indicated the deleterious influence of inclusions on the tendency for localized corrosion. The profiling of a protected section of a creviced or pitted sample helped to delineate the nebulous line of demarcation between general and localized corrosion in these low alloy steels.

Troiana, A.R., R.F. Hehemann, and J.A. Peterson, 1979, Hydrogen sulphide stress corrosion cracking in materials for geothermal power. Final Report, Phase I: NTIS Report No. COO-2602-7, 91 p.

ABSTRACT — Two point bent beam, NACE tensile, C-Ring and DCB stress intensity type specimens were employed to examine a series of steels' SSC resistance in the standard NACE solution and in several modifications pertinent to geothermal environments. Where direct comparisons were possible, the different types of tests qualitatively ranked the alloys in the same order. Of the commercially available steels examined suitable for downhole service, a finegrained version of 4130 with additional Mo and some Cb appeared to have the highest yield strength break-point. High purity versions of this and similar type alloys did exhibit somewhat slightly better resistance to SSC. In this case of constructional type steels, those with higher carbon (.02 - .30C) and those requiring a higher tempering temperature to achieve a given yield strength appear to be more SSC resistant. These steels all exhibit a 15 to 20 percent higher yield strength break-point at service temperatures near 300 to 450°F and/or at pH values approaching 7. Several versions of well head equipment type steels with adequate hardenability have demonstrated satisfactory SSC threshold stress values at adequate yield strengths. The austenitic stainless steels displayed the usual sensitivity to chlorides and cold work. Overaging of several of the age hardenable variety improved the resistance to SSC with only a moderate reduction in strength. Two ferritic stainless steels have shown a higher threshold stress than their commonly employed counterpart. Examination of C-ring specimens cut from commercially treated casing and tubing clearly indicated the advantages of a tempered martensitic structure and the very real potential for temper embrittlement.

Veneruso, A.F., R.S. Simpson, and Arnold, Charles (eds.), 1979, High Temperature Electronics and Instrumentation Seminar Proceedings: NTIS Report No. SAND-80-0834C.

ABSTRACT — This report presents the results of a two day seminar that reviewed the state-of-the-art and the recent substantial progress in High Temperature Electronics and Instrumentation. Over 350 people participated in this meeting that was held in Houston, Texas, on December 3 and 4. This seminar was tailored to address the needs of the borehole logging industry and to stimulate the development and application of this technology, for logging geothermal, hot oil and gas, and steam injection wells. The technical sessions covered the following topics: hybrid circuits, electronic devices, transducers, cables and connectors, materials, mechanical tools and thermal protection. The

frontiers of this technology were shown to be rapidly moving beyond the 125°C, and new development is underway for 300°C hybrid and integrated circuits. Sandia National Laboratories organized and conducted this seminar with funding provided by the U.S. Department of Energy's Division of Geothermal Energy and Division of Fossil Fuel Extraction.

Wilson, J.G., G.A. Tibbitts, and A.D. Black, 1979, Improvements in rotary seals for downhole motors in geothermal applications: Geothermal Resources Council, Transactions, v. 3 p. 785-788.

ABSTRACT — The major limitation of downhole mud motors for geothermal well drilling as well as straighthole and oil well drilling is the bearing section. Reduced bearing life has been a direct result of the inability to seal lubricant in the bearing section. A reliable rotary seal is needed to extend bearing life and to allow high pressure drops across the drill bit for improved bottomhole clean-

ing and increased drilling rate. The endurance of high temperature rotary seal candidates is being measured in a full-scale laboratory seal tester capable of simulating the pressures and temperatures of geothermal well drilling. A description of the currently most successful high temperature seals and seal test results and findings are presented.

Zeldin, A.N., and L.E. Kukacka, 1980, Polymer-cement geothermalwell completion materials. Final Report: NTIS Report No. BNL-51287, 88 p.

ABSTRACT — A program to develop high-temperature polymer cements was performed. Several formulations based on organic and semi-inorganic binders were evaluated on the basis of mechanical and thermal stability, and thickening time. Two optimized systems exhibited properties exceeding those required for use in geothermal wells. Both systems were selected for continued evaluation at the National Bureau of Standards and contingent upon the results, for field testing in geothermal wells.

SPECIAL REPORT NO. 14

Abstract Sets Printed To Date:

CASE HISTORIES Exploration Strategies	1-21
DRILLING In An Under Pressured Geothermal Reservoir	25-27
RESERVOIR ENGINEERING Geothermal Reservoir Engineering	31-38
INJECTION	39-50
GEOTHERMAL WELL LOGGING	51-66
ENVIRONMENTAL CONSIDERATIONS IN GEOTHERMAL DEVELOPMENT	67-76
GEOTHERMAL WELL LOGGING	77-84
GEOTHERMAL MATERIALS	85-93

Special Report 14 Addendum

Electric Power Production

Abstracts reviewed by: Vasel Roberts, Douglas Powell, Ben Holt

BINARY POWER PLANTS

Bliem, C.J., 1983, Preliminary performance estimates and value analyses for binary geothermal power plants using ammonia-water mixtures as working fluid: NTIS Report No. EGG-GTH-6477, 28 p.

ABSTRACT — The use of ammonia-water mixtures as working fluids in binary geothermal power generation systems is investigated. The available thermodynamic data is discussed and the methods of extrapolating this data to give the quantities needed to perform analyses of the system is given. Results indicated that for a system without a recuperator and with a working fluid which is 50 percent by mass of each constituent, the geofluid effectiveness (watthr/lbm geofluid) is 84 percent of that for the 50 MW Heber Plant. The cost of generating electric power for this system was estimated to be 9 percent greater than for the Heber Plant. However, if a recuperator is incorporated in the system (using the turbine exhaust to preheat and partially boil the working fluid) the geofluid effectiveness becomes 102 percent of that for the Heber Plant, and the cost of electricity is 5-1/4 percent lower (relative to the Heber Plant) because of less expensive equipment resulting from lower pressure, better heat transfer, and less working fluid to handle for the ammonia-water plant. These results do not necessarily represent the optimum system. Because of uncertainty in thermodynamic properties, it was felt that detailed optimization was not practical at this point. It was concluded that use of nonzaeotropic mixtures of fluorocarbons as working fluids should be studied before expending further effort in the investigation of the ammonia-water mixtures.

Cassel, T.A.V., C.B. Amundsen, and P.D. Blair, 1983, Geothermal power plant R and D: An analysis of cost-performance tradeoffs and the Heber Binary-Cycle Demonstration Project: NTIS Report No. DOE/CS/30674-2, 174 p.

ABSTRACT — A study of advancements in power plant designs for use at geothermal resources in the low to moderate (300 to 400° F) temperature range is reported. In 3 case studies, the benefits of R and D to achieve these advancements are evaluated in terms of expected increases in installed geothermal generating capacity over the next 2 decades. A parametric sensitivity study is discussed which analyzes differential power development for combinations of power plant efficiency and capital cost. Affordable tradeoffs between plant performance and capital costs are illustrated. The independent review and analysis of the expected costs of construction, operation and maintenance of the Heber Binary Cycle Geothermal Power Demonstration Plant are described. Included in this assessment is an analysis of each of the major cost components of the project, including (1) construction cost, (2) well field development costs, (3) fluid purchase costs, and (4) well field and power plant operation and maintenance costs. The total cost of power generated from the Heber Plant (in terms of mills per kWh) is then compared to the cost of power from alternative fossil-fueled base load units. Also evaluated are the provisions of both: (a) the Cooperative Agreement between the federal government and San Diego Gas and Electric (SDG&E); and (b) the Geothermal Heat Sales Contract with Union Oil Company.

Heinrichs, T.C., 1984, Magmamax power plant — success at East Mesa: Proceedings Eighth Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. AP-3686, p. 6-21 to 6-30.

NO ABSTRACT — From Conclusions: "Magma's experience with the MAGMAMAX POWER PROCESS at the East Mesa facility has indicated it to be a technical success and with the available rates from Southern California Edison Company for qualifying facilities, economic projects can be developed using this process.

Lacy, R.G., and T.T. Nelson, 1982, Heber Binary Project: Binary-cycle geothermal demonstration power plant: NTIS Report No. EPRI-AP-2760, p. 5.1-5.7.

ABSTRACT — The following aspects of the 65 MW (gross) power plant are described: power cycle, design process, turbine-generator, heat exchanger and condenser optimization, materials selection, and cost estimate.

Michaelides, E.E., and Farid Fakhre-Shafaie, 1982, New binaryflashing plant for production of electricity: Geothermal Resources Council, Transactions, v. 6, p. 369-372.

ABSTRACT — The next expansion of geothermal power installations will cover the resources with temperatures less than 150°C. Binary plants are the only suitable for the utilization of these resources. A Modification to the conventional binary plant design is proposed here aiming at the production of more power. The new plant uses a flashing system and partial evaporation of the secondary fluid in the heat exchanger. The thermodynamic analysis shows that the proposed installation would provide approximately 25% more power than the conventional installation, a feature that makes it attractive for further technical and economic analyses.

经通行公司 一种复数分类,我们的自己不是一种,我们是一种,我们是一种,我们就是一种,我们就是一个人的,我们就是一个人的,我们们是一个人,我们是一个人的,我们是一个人的,我们

Pope, W.L., P.A. Doyle, R.L. Fulton, and L.F. Silvester, 1980, Importance of the specific heat anomaly in the design of binary rankine cycle power plants: Geothermal Resources Council, Transactions, v. 4, p. 523-526.

ABSTRACT — The transposed critical temperature (TPCT)* is shown to be an extremely important thermodynamic property in the selection of working fluids and turbine states for geothermal power plants operating on a closed organic (binary Rankine cycle).

When the optimum working fluid composition and process states are determined for specified source and sink conditions, turbine inlet states consistently lie adjacent to the working fluids' TPCT line for all resource temperatures, constraints, and cost and efficiency factors investigated.

Thorleifson, W.C., and A.P. Ibe, 1982, Equipment considerations for a binary cycle geothermal power plant: IEEE Transactions, Geosci. Remote Sensing, v. 6, p. 409-411.

ABSTRACT — The binary cycle geothermal power plant incorporates existing hydrocarbon handling technology proven in use by the petrochemical industry. Equipment sizing and hydrocarbon cycle control on the commercial plant scale, however, introduce some unknowns. This report discusses the various technical factors considered in the design, selection, and sizing of the major equipment for

use in the Heber Binary Cycle Geothermal Demonstration Power Plant.

CONDENSING AND COOLING SYSTEMS

Costantino, F., and A. Palama, 1982, Design of an atmospheric condenser for direct use of geothermal steam condensates: International Conference on Geothermal Energy, Florence, Italy, 11 May 1982, p. 55-61.

ABSTRACT — The difficulties involved in designing and constructing a direct geothermal condenser with an exchange capacity of 80 Gcal/h are described. The condenser is part of a system for recovering and transporting the heat discharged from the Piancastagnaio (Italy) geothermo-electric power plant. The latter discharges to the atmosphere because of high content of uncondensable gases in the geothermal fluid. A detailed study is made of the problems connected with reducing pressure losses in the condenser and achieving a high outlet temperature for the water uncondensable gases. The choice of materials is also discussed, the corrosive nature of the geothermal fluid being a source of trouble in this sector.

Demuth, O.J., 1983, Effects of vaporizer and evaporative-condenser size on geofluid effectiveness and cost of electricity for geothermal binary power plants: NTIS Report No. EGG-GTH-6376, 44 p.

ABSTRACT — A special study was conducted to investigate the influences of minimum approach temperature differences occurring in supercritical-heater/vaporizer and evaporative-condenser heat rejection systems on geothermal-electric binary power plant performance and cost of electricity. For the systems investigated optimum pinch points for minimizing cost of electricity were estimated to range from 5 to 7°F for the heater vaporizer. The minimum approach of condensing temperature to wetbulb temperature for evaporative condensers was estimated to be about 30°F in order to achieve the lowest cost of electricity.

Murphy, R.W., 1983, Field tests of a vertical-fluted-tube condenser in the prototype power plant at the Raft River Geothermal Test Site: NTIS Report No. ORNL-5940, 130 p.

ABSTRACT — A vertical-fluted-tube condenser was designed; fabricated, and tested with isobutane as the shell-side working fluid in a binary prototype power plant at the Raft River Geothermal Test Site. After shakedown and contamination removal operations were completed, the four-pass water-cooled unit (with 102 outside-fluted Admiralty tubes) achieved performance predictions while operating with the plant surface evaporator on-line. A sample comparison shows that use of this enhanced condenser concept offers the potential for a reduction of about 65%

from the size suggested by corresponding designs using conventional horizontal-smooth-tube concepts. Subsequent substitution of a direct-contact evaporator for the surface evaporator brought drastic reductions in system performance, the apparent consequence of high concentrations of noncondensible gases introduced by the brine/working-fluid interaction.

Murphy, R.W., and N. Domingo, 1982, Field tests of 2- and 40-tube condensers at the East Mesa Geothermal Test Site: NTIS Report No. ORNL-5852, 204 p.

ABSTRACT — Two water-cooled isobutane condensers. one with 2 tubes and one with 40 tubes, were subjected to field tests at the East Mesa Geothermal Test Site to assess relative heat transfer performance in both surface evaporator and direct-contact evaporator modes. The five groups of tests established that field performance was below earlier laboratory-determined levels and that directcontact evaporator mode performance was poorer than that for the surface evaporator mode. In all test situations, fluted condenser tubes performed better than smooth condenser tubes. Cooling water quality had no significant effect on performance, but brine preflash in the directcontact mode did promote some relative performance improvement. Important implications of these results for binary geothermal power plants are that (1) working-fluidside impurities can significantly degrade heat transfer performance of the power plant condensers and (2) provisions for minimizing such impurities may be required.

Shaffer, C.J., 1977, Floating power optimization studies for the cooling system of a geothermal power plant: NTIS Report No. TREE-1164, 94 p.

ABSTRACT — The floating power concept was studied for a geothermal power plant as a method of increasing the plant efficiency and decreasing the cost of geothermal power. The stored cooling concept was studied as a method of reducing the power fluctuations of the floating power concept. The studies include parametric and optimization studies for a variety of different types of cooling systems including wet and dry cooling towers, direct and indirect cooling systems, forced and natural draft cooling towers, and cooling ponds. The studies use an indirect forced draft wet cooling tower cooling system as a base case design for comparison purposes.

CORROSION CONTROL

Conover, M.F., 1983, Designing geothermal power plants to avoid reinventing the corrosion wheel: Geothermal Resources Council Bulletin, v. 12, p. 3-11.

ABSTRACT — This paper addresses how designers can take into account the necessary chemical and materials precautions that other geothermal power plant operators and engineers have learned. Current worldwide geothermal

power plant capacity is presented as well as a comparison of steam composition from seven different geothermal resources throughout the world. The similarities of corrosion impacts to areas of the power plants are discussed and include the turbines; gas extraction system; heat and rejection system; electrical/electronic systems; and structures. Materials problems and solutions in these corrosion impact areas are identified and discussed. A geothermal power plant design team organization is identified and the efficacy of a new corrosion/materials engineering position is proposed.

Van der Mast, V.C., Leon Awerbuch, and D.P. McGrath, 1983, Geothermal scale control using a flash-crystallizerseparator: Proceedings Seventh Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. EPRI AP-3271, p. 5-24 to 5-40.

NO ABSTRACT — Paper discusses scale-control methods, flash-crystallizer-separator design parameters, pilot plant design, proposed crystallizer design, test parameters, and test plan.

H2S CONTROL

Castrantas, H.M., 1980, Hydrogen sulfide abatement with hydrogen peroxide in geothermal operations: Geothermal Resources Council, Transactions, v. 4, p. 637-640.

ABSTRACT — Hydrogen peroxide is being used in hydrogen sulfide abatement processes in geothermal well drilling and power plant operations. This paper reviews the processes presently in use and suggests possible future uses in stacking, well venting and treatment of other geothermal fluids. The differences in the operating conditions and equipment for treating sulfide in steam condensate and steam are emphasized for these two treatments. In treating both steam and steam condensate, high sulfide abatement levels of 90% or greater are being readily attained.

Fleming, N., 1981, Hydrogen sulfide measurement to reduce costs when desulfurizing: Geothermal Resources Council, Transactions, v. 5, p. 333-336.

ABSTRACT — Analyzers and sample systems used to measure hydrogen sulfide (H₂S) in geothermal steam, in steam condensate and other liquid samples and for atmospheric monitoring are described.

Houston, R.M., and G. Domahidy, 1981, Steam stripping: A new process for control of H₂S emissions from geothermal power plants: Geothermal Resources Council, Transactions, v. 5, p. 471-474.

ABSTRACT — An experimental program has been conducted to determine the feasibility of a new process, known as Steam Stripping, for controlling hydrogen sulfide emissions from geothermal power plants. The tests were performed on a pilot plant scale apparatus, using simulated geothermal steam and condensate prepared by injecting hydrogen sulfide, ammonia, and carbon dioxide into boiler steam and tap water. Stripping tests were run under vacuum at pressures as low as 1.8 psia and at an atmospheric pressure of 12.2 psia. Stripper performance was not a function of pressure; concentrations of H₂S in the treated water of less than 5 ppmw were attained under both vacuum and atmospheric pressures.

Morris, W.F., and F.B. Stephens, 1981, Strategies for steam handling and H₂S abatement at geothermal power plants in The Geysers area of northern California: NTIS Report No. UCRL-53137, 66 p.

ABSTRACT — Strict limitations on the emission of H₂S from new geothermal power plants in The Geysers area of northern California have been imposed by Lake and Northern Sonoma County Air Pollution Control Districts. Lake County, under new source review rules, has stipulated that specific technologies shall be utilized to limit H₂S emissions to 5 lb/h as a condition for determination of compliance. The status of these technologies as well as other ongoing technology development efforts to conserve steam and abate H₂S are evaluated. Although projections indicate that it may be posible to meet the 5 lb/h limit, there is no firm assurance of achievement at this time because of the unproven, full-scale performance status of some key technologies specified by the air pollution control districts.

Sims, A.V., 1983, Direct chlorination process for geothermal power plant off-gas hydrogen sulfide abatement: NTIS Report No. DOE/SF/11664-T3, 59 p.

ABSTRACT — The Direct Chlorination Process removes hydrogen sulfide from geothermal off-gases by reacting hydrogen sulfide with chlorine in the gas phase. Hydrogen chloride and elemental sulfur are formed by this reaction. The Direct Chlorination Process has been successfully demonstrated by an on-site operation of a pilot plant at the 3 MWe HPG-A geothermal power plant in the Puna District on the island of Hawaii. Over 99.5 percent hydrogen sulfide removal was achieved in a single reaction state. Chlorine gas did not escape the pilot plant, even when 90 percent excess chlorine gas was used. A preliminary economic evaluation of the Direct Chlorination Process indicates that it is very competitive with the Stretford Process. Compared to the Stretford Process, the Direct Chlorination Process requires about one-third the initial capital investment and about one-fourth the net daily expenditure.

Tajima, S., and M. Nomura, 1982, Optimization of non-condensable gas removal system in geothermal power plant: IEEE Transactions, Geosci. Remote Sensing, v. 6, p. 397-400.

ABSTRACT — Optimization of non-condensable gas (hereinafter called N.C.G.) removal system in geothermal power station, in a special case that the geothermal steam contains large amount of noncondensable gas, is discussed. Four different alternative N.C.G. removal systems are studied, which are steam jet gas ejectors, centrifugal gas compressors, combined systems of steam ejectors and centrifugal compressors and back pressure turbine-without N.C.G. removal system. This report summarizes the results and gives recommendations as to the most suitable gas removal system and also as to optimum condenser pressure, in cases of large quantity N.C.G. content in geothermal steam.

Van der Mast, V.C., M.C. Weekes, and D.P. McGrath, 1983, Field test of geothermal upstream reboiler: Proceedings Seventh Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. EPRI AP-3271, p. 5-41 to 5-53.

NO ABSTRACT — Paper discusses chemical and thermal behavior of the upstream reboiler, Cerro Prieto test site, and test plan and unit.

Weres, Oleh, 1981, Partitioning of hydrogen sulfide in the condenser of Geysers Unit 15: Proceedings Fifth Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. EPRI-AP-2098, p. 3.17-3.28.

NO ABSTRACT — Paper discusses modifying Unit 15's condenser from contact to surface type for more efficient removal of hydrogen sulfide.

HYBRID GEOTHERMAL SYSTEMS

Khalifa, H.E., 1981, Hybrid power plants for geopressured resources: Proceedings Fifth Annual Geothermal Conference and Workshop: Electric Power Research Institute Report No. EPRI AP-2098, p. 5A-11 to 5A-23.

NO ABSTRACT — Paper discusses the technical feasibility of hybrid power plants which simultaneously utilize the methane, thermal and hydraulic energy produced by a single geopressured well.

Khalifa, H.E., 1983, Combined cycles for hybrid fossil/geothermal power generation: Joint Power Generation Conference, Indian-apolis, Indiana, 25 September 1983.

ABSTRACT — The paper presents a preliminary technical and economic assessment of a combined cycle in which the bottoming cycle is fed both by the exhaust energy from a combustion engine topping loop and by moderate-temperature energy from a geothermal resource. It is shown that this arrangement offers significant performance

and economic advantages over the separate utilization of the two energy inputs. A gas-turbine-topped dual pressure toluene bottoming system matched to a 300°F (about 150°C) hydrothermal resource can produce 10 to 20% more power than would be obtained from two separate plants: a conventional flash or binary power plant for the geothermal fluid, and a 35%-efficient combustion power plant for the oil or natural gas burned in the topping loop. The superior performance of the hybrid plant results in a commensurate reduction in the cost of electricity.

MISCELLANEOUS PAPERS

Eliasson, E.T., G. Bjornsson, M. Matthiasson, R. Maack, S. Sigfusson, and V.K. Jonsson, 1982, Collection and transmission of two-phase geofluid at the Krafla geothermal power plant, Iceland: International Conference on Geothermal Energy, Florence, Italy, 11 May 1982, p. 201-215.

ABSTRACT — A short description is given of the general plant layout and operating characteristics of the Krafla Geothermal Electric Power Plant. Emphasis is placed on describing design criteria, constructional features and operating characteristics of the steam supply system. The methods of calculation adopted for the hydrodynamic design of the geofluid collection pipelines and the steam mains are outlined in the paper, which also compares calculated and actually measured pressure drops in the two phase collection pipelines. The comparison is made for flows at the high mass dryness fraction. It is found that the measured values agree with calculated values. The safety and transmission control of the steam supply system is described in outline detailing the performance of the close coupled high/low pressure cyclone separator system used in the Krafla flash separator station. Finally the operating experience obtained from this system is detailed and new developments dictated by the operating experience gained are outlined.

Ellis II, P.F., and T.F. Green, 1983, State-of-the-art assessment of geothermal downwell pump reliability: Proceedings Seventh Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. EPRI AP-3271, p. 5-58 to 5-67.

NO ABSTRACT — Paper discusses description of downwell pumps, downwell pumping environment, high-temperature downwell pump experience, causes of failure of lineshaft pumps, causes of failure to electric submersible pumps, operational factors, near-term pump life, individual pump availability, impact on brine supply, and novel pumping technologies.

Kochelek, J.T., and D.F. Zienty, 1981, Use of organic flocculants in spent brine clarification: Geothermal Resources Council, Transactions, v. 5, p. 353-356.

ABSTRACT — Republic Geothermal Incorporated and Tretolite Division of Petrolite Corporation recently performed clarification studies using organic flocculants to aid in the removal of suspended solids from spent geothermal fluids. The investigation took place at a recent well test in the Salton Sea area of the Imperial Valley. Organic flocculants were added to an atmospheric brine stream which fed a pilot-scale clarification vessel. Influent and effluent suspended solids levels were monitored while flocculant dosage and brine flow rate were independently varied. The implications of cost-effective flocculant treatment were also investigated.

Robertson, R.C., 1983, Waste heat disposal from U.S. geothermal power plants—an update: Geothermics, v. 12, p. 17-28.

ABSTRACT — Dissipation of the heat rejected from geothermal power plants is a major concern because the inherently low efficiencies result in heat rejection rates that are three to four times greater per kW of installed capacity than is typical of fossil- or nuclear-fueled stations. The most cost-effective methods of waste heat dissipation involve the evaporation of water, yet most of the important hydrothermal resources of the U.S. are located in areas where cooling tower makeup water for power plants is in short supply. Flashed-steam power cycles can use condensate derived from the geofluid for tower makeup unless reinjection is necessary, as is already required at some sites. Condensate is not available from binary cycles because the geofluid is reinjected. Geothermal station makeup water requirements have been estimated at 50 - 100 m³/yr per kW of electrical capacity. Some of the methods currently being studied in the U.S. for reducing waste heat dissipation system costs and water consumption are: allowing plant power output to vary with ambient conditions; use of ammonia to transport waste heat from the turbine condenser to air-cooled coils; development of plasticmembrane type wet/dry tower; marketing of steam turbines that can tolerate a wider range of back pressures; use of circulating water storage to delay heat dissipation until more favourable ambient conditions exist; development of tubes with enhanced heat transfer surfaces to reduce condenser capital costs; and use of evaporative condensers to reduce costs in binary cycles. Many of these projects involve large-scale tests that are now installed and producing some preliminary data. Definitive results from some of the tests may not be available until mid-1982 or later.

Tahara, M., 1981, New geothermal power plants in Azores and Kenya: Geothermal Resources Council, Transactions, v. 5, p. 41-42.

ABSTRACT — Two geothermal power plants were recently completed. One is 3 MW unit in Azores and another is 15 MW unit in Kenya. Both plants have very simple construction. For Azores, a packaged portable turbine generator is adopted to save the cost and installation term. 15 MW Olkaria plant which is adopted single flash cycle has produced first electricity by the geothermal energy in Africa.

This turbine generator has been installed on a steel foundation. Special site conditions have been taken into consideration and both plants are successfully running with certification of the suitable design concept.

Tesche, T.W., 1982, Air quality modeling of geothermal power plants in complex terrain: Geothermal Resources Council, Transactions, v. 6, p. 517-519.

ABSTRACT — Commercial energy development at The Geysers KGRA, California—the world's largest producing geothermal field—is confronted with increasingly more stringent air quality impact assessment requirements for not only regulated pollutants (e.g., hydrogen sulfide and primary particulates) but also unregulated species including benzene, ammonia. arsenic, Radon 222, boron, and mercury. An integrated program of ambient aerometric monitoring, tracer diffusion experiments, cooling tower plume rise studies, and numerical air quality simulation modeling was conducted for this mountainous region to provide estimates of potential short term (i.e., ~ 1 hour) impacts attributable to development of The Geysers steam resource. A series of atmospheric tracer diffusion experiments, focusing on aerodynamic downwash, nocturnal drainage, fumigation, and limited vertical mixing were conducted to provide a basis for air quality model performance evaluation. Upper air meteorological measurements and cooling tower plume rise studies were performed to develop data useful in evaluating windfield and plume rise submodels.

Whitbeck, J.F., R.H. Dart, J.D. Miller, and D.R. Brewer, 1983, Measurement and control techniques in geothermal power plants: NTIS Report No. TREE-1312, 83 p.

ABSTRACT — This information provided the background and source material used in preparing the chapter of the Geothermal Source Book on instrumentation, measurement, and control techniques. Here more complete and detailed information is presented than could be included in the source book chapter and is being published for reference. Included are detailed examples of instrumentation and control techniques currently being used in geothermal power plants. In addition, the basic guidelines and unique characteristics of instrumentation and control in geothermal systems, are presented. The instrumentation and control philosophy and the hardware involved in geothermal electric plants and their supply and injection systems are addressed. The intent is to address the unique characteristics of geothermal electric instrumentation and control (I and C) systems. Standard I and C practice is available in the general literature. Sources of information for standard I and C practice are listed in the Appendix. The information presents the philosophy of I and C system design; the development of the system, from power grid considerations through subsystem operation to specific system details; and component selection and operating considerations.

MODULAR EQUIPMENT

Nichols, K.E., 1982, Geothermal power system modules available for power on line in 1984: Proceedings Sixth Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. EPRI-AP-2760, p. 7.1-7.6.

ABSTRACT — The feasibility of geothermal power modules that can be factory built and field assembled to form well-head power plants is explored. The direct contact binary plant and the Matthews gravity-head plant are described.

Rogers Engineering Co., Inc., 1976, Modular 5 MW geothermal power plant design considerations and guidelines: NTIS Report No. UCRL-13684, 139 p.

ABSTRACT — The design considerations and guideline documents given define the principal design requirements for a nominal 5 MW geothermal power plant of a type to permit over-the-road transport of its several modules. The power plant system defined is supplied with steam from a single flash steam separator stage, located at the plant area, and supplied with steam from two wells at nominal pressure of 3.8 Kg/cm² Abs (54 psia). In some cases where the content of noxious noncondensable gases is high, a shell and tube condenser would be substituted for the direct contact type condenser specified and an additional module containing an H2S removal system would be added. Guidelines are given for the following: site preparation, collection system, plant installation, assembly, and test; turbine generator module; condenser and noncondensable gas removal module; plant control and switchgear module; cooling water circulation pump module; steamwater separator module; maintenance, office, and lavatory module; reinjection pump module; cooling tower modules; spray pond installation and piping; and auxiliary generator module.

POWER CONVERSION TECHNOLOGY

Campbell, R.G., 1981, Comparisons of advanced power conversion concepts: Geothermal Resources Council, Transactions, v. 5, p. 393-396.

ABSTRACT — A number of concepts have been proposed for converting geothermal energy to electricity. The subject study was made to analyze these concepts, and compare them with conventional systems and with each other. A comparison was made among all of the concepts studied, including the conventional binary and flashed steam cycles. None of the little-known concepts showed large potential improvement over the conventional systems. Several total-flow devices, particularly in hybrid applications, are concluded to be competitive with conventional schemes. The system which showed the best potential cost and efficiency is the Sperry gravity-head system.

Cedillo, R., and R.N. Yamasaki, 1981, Brawley 10 MWe power plant, Unit 1: Geothermal Resources Council, Transactions, v. 5, p. 397-400.

ABSTRACT - Southern California Edison Company's Brawley Geothermal Electric Project is the first flash-steam project in the United States to successfully demonstrate the feasibility of utilizing steam from highly saline geothermal fluids for electric power generation. The objective of Edison's Power Plant Unit 1 program at Brawley, California is to assess the technical feasibility of generating electricity from steam produced from highly saline geothermal fluids. The Edison plant is designed specifically for utilization of geothermal steam, and it employs principles found in conventional fossil-fueled electric generating plants. The design is simple and reliable. Where possible, the plant has been designed for low capital cost. The plant serves as a model of a full scale commercial plant, using systems and components which likely will be utilized in large scale follow-on units.

DiPippo, R., and R.A. Meyers, 1983, Geothermal power technology in Handbook of energy technology and economics: New York, John Wiley and Sons, p. 787-825.

ABSTRACT — This article begins with a brief history of the use of geothermal energy for electric power generation. Several geothermal systems that are candidates for exploitation for the generation of electricity are then described. It goes on to discuss geothermal energy conversion technology and gives a worldwide overview of geothermal power generation. Operating units are described and projections made about plants in construction and advanced planning stages. Finally, environmental consequences of geothermal power technology are discussed.

DiPippo, R., 1982, The effect of expansion-ratio limitations on positive-displacement, total-flow geothermal power systems: Geothermal Resources Council, Transactions, v. 6, p. 343-346.

ABSTRACT — Combined steam-turbine/positive-displacement engine (PDE) geothermal power systems are analyzed thermodynamically and compared with optimized reference flash-steam plants. Three different configurations of combined systems are considered. Treated separately are the cases of self-flowing and pumped wells. Two strategies are investigated that help overcome the inherent expansion-ratio limitation of PDE's: pre-flashing and pre-mixing. Parametrically-obtained results show the required minimum PDE efficiency for the combined system to match the reference plant for various sets of design conditions.

Jonsson, V.K., J.G. Einarsson, and K.J. Cornwell, 1982, Bubble lift cycle for generation of power from low grade heat: International Conference on Geothermal Energy, Florence, Italy, 11 May 1982, p. 275-281.

ABSTRACT — The bubble lift cycle is a thermodynamic cycle converting heat energy to work energy by using a two-phase flow loop, in which the flow is maintained by density differences. The cycle is designed to operate on a low temperature difference and to have a low capital cost per unit power. A small demonstration rig using refrigerant 113 as the working fluid is described and the design features of a 1 MW unit using waste or geothermal hot water as the heat source are examined.

Matthews, H.B., and W.D. McBee, 1982, Gravity-head geothermal energy conversion system: Geothermal Resources Council, Transactions, v. 6, p. 363-367.

ABSTRACT — A novel electric power generating system for low-temperature hot water geothermal resources is described. This so-called "gravity-head" system is a binary plant with the primary heat exchanger in the production well to a depth of 2200 feet. This configuration results in a novel heat-engine cycle which eliminates the "pinch effect" in the primary heat exchanger and the working fluid feed pump and provides a major decrease in brine pumping power. The net effect is a significant increase in net electric output power over a "conventional" binary plant under equivalent conditions and costs.

Thorleifson, W.C., and A.P. Ibe, 1982, Use of available geothermal moderate temperature resources for power generation Re: the Heber Binary Cycle Demonstration Plant: IEEE Transactions, Geosci. Remote Sensing, v. 6, p. 413-417.

ABSTRACT — The Heber Binary Cycle Demonstration Plant is undertaken to provide, on a commercially viable scale, an energy conversion technology utilizing liquid dominated, moderate temperature geothermal resources. Use of these abundant resources, available in many areas of the U.S.A., would be denied the nation without an effective and economical means to convert the energy of the hot geothermal brine into economical and available electric power. This paper discusses the technical considerations supporting the plant design criteria and power cycle definition for this first commercially sized binary cycle geothermal power plant.

SEPARATORS

Awerbuch, Leon, V.C. Van der Mast, and D.P. McGrath, 1983, Geothermal steam separator performance evaluation: Proceedings Seventh Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. EPRI-AP-3271, p. 5-1 to 5-23.

NO ABSTRACT — Paper discusses test results of three separators: bottom-outlet cyclone, impingement-type vane separator in conjunction with the bottom-outlet

cyclone, and mesh-type separator in conjunction with the bottom-outlet cyclone.

Michels, Donald E., 1980, Compact inline separator for sampling liquid and vapor from a 2-phase flowline: Geothermal Resources Council, Transactions, v. 4, p. 173-175.

ABSTRACT — A representative sample of vapor can be obtained in a 2-phase flow line by providing a space in which droplets of liquid are scarce. The material in that space can be sampled through a traveling probe and condenser setup, collecting condensate, non-condensable gases or both.

A counterpart space can be made also in which the liquid can accumulate essentially free of vapor. A sample can be taken through the same traveling probe apparatus as used for the vapor sample.

The method is an alternative to setting up a full-flow separator for early testing of a well when data on compositions of the separate phases are desired.

SMALL-SCALE POWER PLANTS

Bliem, Jr. C.H., 1983, Raft River 5 MW (e) Binary Geothermal-Electric Power Plant: Operation and Performance: Report No. EGG-M-14483; CONF-831041-18, 1983, 7 p.

ABSTRACT — A 5 MW (e) Pilot Geothermal Power Plant was built at Raft River, Idaho, as an integral part of the Department of Energy's plan for commercial development of geothermal energy. The purpose of the plant was to investigate the technical feasibility of utilizing a moderate temperature hydrothermal resource (275 to 300°F) to generate electrical power in an environmentally acceptable manner. The plant used a dual-boiling binary cycle with isobutane as the working fluid, and drew thermal energy from a 280°F liquid-dominated resource. This paper presents the results of that testing, comparing the system performance to the performance predicted prior to operation along with a summary of operational experience.

Callai, A., and R. DiFalco, 1982, Small capacity power plants in geothermal energy exploitation in Italy: Proceedings Sixth Annual Geothermal Conference and Workshop: Electric Power Research Institute Report No. EPRI-AP-2760, p. 6.39-6.52.

ABSTRACT — Two types of geothermal power plants are discussed: the direct back-pressure cycle and the direct condensate cycle. Factors governing the choice of cycle are discussed. The Molinetto and Lagoni Roissi 3 power plants are described.

Gudmundsson, J.S., 1982, Small-scale geothermal electric power units in Iceland: Proceedings Sixth Annual Geothermal Conference and Workshop: Electric Power Research Institute Report No. EPRI-AP-2760, p. 6.61-6.68.

ABSTRACT — There are five small-scale geothermal electric power units in Iceland: one 3 MWe, two 1 MWe, one 6 MWe and one 338 kWe. The first was installed in 1969 in Namafjall to gain experience in operating a geothermal electric power plant. The two 1 MWe and 6 MWe units are all in the (mainly) thermal power plant in Svartsengi, installed in 1978, 1979, and 1980. The smallest unit was installed in 1980 in Nesjavellir. There are several plans to install small-scale units to be operated in conjunction with thermal or direct uses of geothermal steam.

TURBINES

Aspnes, J.D., and J.P. Zarling, 1982, Electric power generation from a geothermal source utilizing a low-temperature organic Rankine cycle turbine: IEEE Transactions, Power Appar. Systems, v. 101, p. 4587-4592.

ABSTRACT — A demonstration project to generate electricity with a geothermal source and low-temperature organic Rankine cycle turbine in a rural Alaskan location is described. Operating data and a set of conclusions are presented detailing problems and recommendations for others contemplating this approach to electric power generation.

Cerini, D.J., and Jeff Record, 1983, Rotary separator turbine performance and endurance test results: Proceedings Seventh Annual Geothermal Conference and Workshop, Electric Power Research Institute Report No. EPRI-AP-3271, p. 5-75 to 5-86.

NO ABSTRACT — Paper discusses the five main components of the rotary separator turbine, field test installation, and field test results.

Dakin, Robin, 1981, Radial inflow turbine update: Proceedings Fifth Annual Geothermal Conference and Workshop: Electric Power Research Institute Report No. EPRI-AP-2098, p. 5B.23-5B.30.

NO ABSTRACT — Paper presents an update on the progress in the radial inflow turbine field, a study which was started in association with EPRI in 1977.

Demurth, O.J., 1984, Preliminary assessment of the Velocity Pump Reaction Turbine as a geothermal total-flow expander: NTIS Report No. EGG-GTH-6658, 44 p.

ABSTRACT — A preliminary evaluation was made of the Velocity Pump Reaction Turbine (VPRT) as a total flow

expander in a geothermal-electric conversion cycle. Values of geofluid effectiveness of VPRT systems were estimated for conditions consisting of: a 360° geothermal resource, 60°F wet-bulb ambient temperature, zero and 0.003 mass concentrations of dissolved noncondensible gas in the geofluid, 100 and 120°F condensing temperatures, and engine efficiencies ranging from 0.4 to 1.0. Achievable engine efficiencies were estimated to range from 0.47 to 0.77, with plant geofluid effectiveness values ranging as high as 9.5 Watt hr/lbm geofluid for the 360°F resource temperature. This value is competitive with magnitudes of geofluid effectiveness projected for advanced binary plants, and is on the order of 40% higher than estimates for dual-flash steam and other total flow systems reviewed. Because of its potentially high performance and relative simplicity, the VPRT system appears to warrant further investigation toward its use in a well-head geothermal plant.

Hughes, E.E., 1983, Geothermal rotary separator turbine: Wellhead power system tests at Milford, Utah: Proceedings Intersociety Energy Conversion Engineering Conference, Orlando, Florida, 21 August 1983, p. 280-285.

ABSTRACT — Through development of a separator/expander engine EPRI is improving the efficiency of single flash geothermal power systems. Under cost-shared contracts with Biphase Energy Systems and Utah Power and Light Company (UPand L), a wellhead power generating system has been built and tested. The wellhead unit has been operated for 4000 hours at Roosevelt Hot Springs near Milford, Utah. Phillips Petroleum Company operates the geothermal field at this site. The rotary separator turbine (RST) is a separating expander that increases the resource utilization efficiency by extracting power upstream of a steam turbine in either a 1-stage or 2-stage flash power system. The first power output was achieved October 28, 1981, six weeks after arrival of the RST at the site. The RST system produced 3270 MWh(e) gross and 2770 MWh(e) net to the UP and L grid. Total equivalent power produced by the wellhead RST (actual power output of the RST plus the power obtainable from the steam flow out of the RST) is 15 to 20 percent above the power that would be produced by an optimum 1-stage direct flash plant operated on the same geothermal well.

James, R., 1981, Optimising net turbine power for gas content of geothermal steam: Proceedings New Zealand Geothermal Workshop, Auckland, New Zealand, 9 November 1981, p. 173-176.

ABSTRACT — The gas content of geothermal steam varies over a wide range and consists mostly of carbon dioxide. For equal weights, this gas is half as effective as steam when expanded through a turbine for power. Hence, its elimination from the entry steam - by chemical or other means - can reduce the electric energy generated by turbines which discharge to the atmosphere. But for the more efficient condensing turbine (vacuum exhaust), the reverse is true; this is because of the large amount of power required to

pump the gases from the condenser. If the gas cannot be economically removed to increase net power, then optimising leads to a specific condenser pressure required for any particular gas concentration in the steam. Graphed results present the relationship and permit ease of selection of the condenser vacuum pressure.

Marochek, V.I., N.N. Popov, A.Ye Rudakova, and S.P. Solov'yev, 1981, The possibilities of using standard steam turbines in geothermal exploration and developmental operations: Informenergo, Moscow, USSR: New York, Plenum Publishing Corp., 7 p.

ABSTRACT -Expenditures for exploratory and developmental operations can be sharply reduced if the steam which is produced from the first geothermal well is used in a steam turbine which runs an electric generator to insure power for further operations. The turbine should be of simple design with a minimum amount of auxiliary equipment, compact and low in weight. This will make it possible to exhaust the steam turbines into the atmosphere. Such easily transportable units can be made on the basis of standard low-power turbine units with minimal redesign. Their performance characteristics are given. A method of evaluating them and monitoring data on expected characteristics of turbines are given. The amount of the annual dollar savings brought about by a sharp reduction of consumption of liquid fuel in exploratory and developmental operations for a 1,000 kilowatt unit is approximately 200,000 rubles.

Printup, W.O., and S. Sigurdson, 1982, Performance testing of geothermal steam turbines: Geothermal Resources Council, Transactions, v. 6, p. 381-384.

ABSTRACT — At the present time the ASME Performance Test Codes do not address the testing of geothermal turbines that contain non-condensable gases in the inlet steam. This paper presents a method for conducting performance tests for this class of turbine. The determination of the separate quantities of steam and non-condensable gases as well as their respective enthalpies is necessary to the calculation for determination of compliance with the guarantees.

Toney, S., O. Tuncel, and M. Cohen, 1982, Geothermal turbines — materials evaluation and design aspects: Geothermal Resources Council, Transactions, v. 6, p. 419-422.

ABSTRACT — A considerable number of on-site material test programs have been conducted at different geothermal sites to provide a data base which permits characterization of materials used, or considered potentially useful, for geothermal turbine applications. These programs have included the exposure of test specimens of different materials to geothermal steam from a steam resource, as at The Geysers, or in flashed steam from a hydrothermal source, such as at Baca, New Mexico (1) and Cerro Prieto,

Mexico (2). The results of an on-site test program, performed at The Geysers for more than three years, are presented. Some aspects of geothermal turbine design which take into account materials behavior in geothermal steam are also discussed.

Toril, A., and M. Nomura, 1981, Design and constructions features of geothermal steam turbine: Geothermal Resources Council, Transactions, v. 5, p. 451-454.

ABSTRACT — Because of the properties of geothermal steam - low pressure, low enthalpy, low density and

contains noncondensable gases, moisture, dust and dissolved solids which cause material erosion/corrosion and steam path clogging - special considerations are paid when designing steam turbine for geothermal application. The main areas which differ from turbines for conventional power plant are in turbine arrangement, steam path design, casing construction, material and valve type and arrangement. Many of these design features are derived from ample experience on steam turbine operating for power generation in geothermal field, and will ensure the reliability of geothermal power plants.

Special Report 14 Addendum

Direct Utilization of Geothermal Energy

Abstracts reviewed by Jon S. Gudmundsson, Paul J. Lienau and Ben Lunis

CASE HISTORIES

Longyear, A.B., H.S. Stephens and C.A. Stapleton (eds.), 1982, Case histories of four agricultural and municipal direct use projects in the western US: International Conference on Geothermal Energy, Florence, Italy, p. 131-142.

ABSTRACT — Engineering and economic studies have been conducted on four agricultural and municipal direct energy projects. Two of the projects located in Northern California are being constructed in 1981 and will be operating in 1981-82. Two others in Northern California and Southern Idaho have not progressed beyond the paper studies. The Susanville, Mountain Home, Kelley Hot Spring and Litchfield projects are summarized in terms of engineering and economic, institutional, permitting issues and financing and conclusions are drawn from the evolution and maturing of geothermal direct use projects in the US in the 1975-81 time period. The institutional, financial and management factors delaying two of the projects are addressed. The characteristics of successful geothermal direct use projects in the US are discussed. Three of the projects have been funded by the US Department of Energy. One of the projects is a private-local government-state funded effort that will displace over 2000 m³ of oil per year.

Sun Kaiyao and Su Jialin, 1985, The latest development in geothermal utilization in Tianjin, China: Geothermal Resources Council, International Symposium Volume, p. 373-377.

ABSTRACT — This report presents the latest development of geothermal utilization in Tianjin, the largest user of low temperature geothermal energy in China.

This report first gives information about the test carried out in a building heated by low temperature geothermal water of slightly more than 50°C. As a result of the test, data and information have been gathered in terms of heat consumption of a building heated by low temperature geothermal water, corrosion and scaling caused by

geothermal water in the equipment, and variations in the level and temperature of the geothermal water at the wellhead during a constant heating period. The information shows that the low temperature geothermal water is well suited for space heating and as a result extensive utilization is proposed for Tianjin. The report then gives a brief introduction to the extensive utilization of geothermal energy for space heating in the Dagang District, and for agricultural greenhouses.

Since geothermal energy has been put into use on a large scale in Tianjin, the authors believe that further utilization of geothermal energy in Tianjin will be possible on the basis of scientific tests, high-level techniques and advanced equipment.

COMPUTER SIMULATION

Barmettler, E.R., 1978, Controlled environment livestock production system computer simulation and analysis (dairy): NTIS Report No. CONF-780133, p. 37-48.

ABSTRACT — Digital computer simulation was used to investigate the peak, steady energy utilization of a geothermal energy-supported dairy. A digital computer program was also written to assess the lifetime economics of the dairy operation. A dynamic simulation program was written to design water storage tanks under diurnal transient loading.

DIRECT HEAT SYSTEMS INCLUDING HEAT PUMPS AND HEAT EXCHANGERS

Amstutz, D., 1981, Development of a geothermal heat pump. Final Report: NTIS Report No. DOE/R7/01100-TI, 19 p.

ABSTRACT — In the development of a geothermal heat pump a water source heat pump was connected to a 1½ inch water line, 2200 feet long, buried in an endless loop 10 feet deep. The system is closed, circulating the same water continuously through the heat pump back to the field again. This water line 10 feet deep is the geothermal heat source. No matter how cold the air temperature gets on a winter day the water temperature to the heat pump will always be above 45° F. This system has efficiently heated our house the past year using no supplemental heat.

Balzhiser, James K., 1980, Geothermal heat exchangers: Geothermal Resources Council Special Report No. 9, p. 5-9.

ABSTRACT — This paper is based on the practical aspects and experience gained from projects in direct heating using geothermal heat in the 100 to 200°F. This paper illustrates the temperature ranges for heat exchangers that are common to the direct heat application. All systems shown (heat pump, radiant panels or downhole pipe coil) are all heat exchangers.

Breindel, B., R.L. Harris and G.K. Olson, 1978, Geothermal absorption refrigeration for food processing industries: NTIS Report No. CONF-780133, p. 85-90.

Geothermally driven absorption refrigeration systems can be effectively applied for food freezing and storage. Based upon typical electric power rates, geothermal absorption refrigeration systems with moderate well costs will compete favorably with conventional vapor compression units. An economic analysis of the potato processing, freeze drying and large scale beef packing industries indicates that acceptable rates of return are achievable with cascaded use of the geothermal resource.

Culver, G.G., and G.M. Reistad, 1978, Evaluation and design of downhole heat exchangers for direct application: Klamath Falls, Geo-Heat Center, Oregon Institute of Technology.

ABSTRACT — Over 400 wells with downhole heat exchangers are in use in Klamath Falls, Oregon. Some have been in use for nearly 30 years. Despite the large number and the long experience, the exact nature of the mechanism of heat exchange and, therefore, the maximum output was not known, except that it had been theorized that convection cells were established in the well. Oregon Institute of Technolgy and Oregon State University are jointly involved in a project to study the heat exchange process and economics of the downhole heat exchanger system.

The existence of significant convection cell circulation has been established and measured using a "spinner," hot film anemometer, and by energy balance calculations. Based on these measurements, analytical models have been developed which predict heat extraction rates within 15% of actual measured values. The existence of significant mixing of "new" and circulating well fluid has been established and can

be calculated, although at this time not accurately predicted before testing a well.

Based on the analytical models, multi-tube heat exchangers have been designed and very recently tested with outputs within 15% of predicted values.

Economic analyses shows that for small to moderate extraction rates, about 300 kW thermal, and shallow wells, DHE's may be more economical than pumped systems when surface discharge is not acceptable.

Drew, Stephen R., 1985, Improved energy utilisation from the Rotorua geothermal field: Geothermal Resources Council, International Symposium Volume, p. 311-318.

ABSTRACT — The Rotorua geothermal field in New Zealand is unique with its spectacular geysers and other thermal activity. Over the last few years there has been increasing conflict between the preservation and the exploitation interests associated with the field's development. A Geothermal Task Force team was established in 1983 to find the most cost effective way of improving the energy utilisation and so reducing withdrawal from the field. The team can now confirm the level of fluid withdrawal from the 350 shallow bores and the extent of the current wastage of geothermal energy. Most of the existing heating systems utilise only 10 percent of the available heat in the withdrawn fluid and by applying standard energy conservation techniques, significant energy savings can be made. This improved energy utilisation can only be achieved by a management plan that encourages further bore sharing because most of the existing production bores cannot produce at low flow rates and require far more users. Group heating systems within city blocks could make the best use of the existing bores for production as well as injection. Management proposals for the field are scheduled for release in November 1985.

Hopkirk, R.J. and D.J. Gilby, 1985, Vertical tube earth heat exchangers—the Swiss experience: Geothermal Resources Council, International Symposium Volume, p. 443-446.

ABSTRACT — Recently in Switzerland, vertical tube earth heat exchangers in combination with heat pumps have become increasingly popular as an economically attractive domestic energy source. Knowledge of the typical performance characteristics of these systems needed for licensing decisions is being acquired by a combination of theoretical and field studies. Based on results of this work to date, the long-term performance characteristics and the perturbations of the naturel temperature field are discussed. It is concluded that such systems offer an interesting alternative energy source especially when coupled with a simple solar recharge unit.

Keller, J.G., 1977, Heat pumps. Primer for use with low temperature geothermal resources: NTIS Report No. IDO-1570-T17, 24 p. ABSTRACT — Attention is focused on using heat pumps to obtain heat energy from low temperature geothermal resources. The principles of heat pumps are examined to explore applications in residential and commercial heat requirements. Availability and costs are discussed. This is intended to serve as a primer and user document requiring no background in heat pump technology.

Ryan, G.P., 1981, Equipment used in direct heat projects: Geothermal Resources Council, Transactions, v. 5, p. 483-486.

ABSTRACT — Geothermal well pumps are normally either the submersible type or the turbine type. If a turbine pump can be used, a variable speed driver should be considered. These drivers permit no load starting, reduce shock and vibration, and minimize horsepower requirements. The power savings is about 40% when compared to regulating flow by throttling. Plate heat exchangers are less expensive and more effective than tube heat exchangers in the usual geothermal applications. They can be used as the key component in a two loop system to minimize the effect of corrosion and deposits. Limiting consideration for nonmetallic pipe is the geothermal water temperature. Burying a pipeline achieves an insulating effect. The minimum acceptable delivered water temperature must be considered. Space heating can be accomplished using geothermal water as low as 85°F. Methods used are dependent on the temperature of the water available. Finned tubes in forced air ducting are a very effective method of heating.

Wehlage, E.F., 1981, Case for dollars versus geothermal heat pumps: Ground Water Heat Pump Journal, v. 2, no. 3, p. 12-14.

ABSTRACT — Heat pumps using geothermal energy are currently attracting interest at a critical time period in their development as auxiliaries to extend the range of cooler geothermal fluids while acting as electrical levers which boost the heating value inherent in every kilowatt of input. Energy awareness is certianly a characteristic of the business community and just about everywhere the people who are building, owning, occupying and operating residential, commercial, institutional or industrial buildings, are acquiring some specific concerns about costs, power shortages, pollution, the conservation of energy, and replacements. However, money situations may govern. The author presents a case history of a 99-bed nursing facility with an 85°F well available on site. The client asked for replacement of heating and cooling equipment. Results of well-testing and explanation of a Water-Loop Heat Pump utilizing the geothermal source are presented. Despite a projected 25% reduction in electricity used by the suggested system, the client chose a conventional system at a lower initial capital cost.

DISTRICT HEATING

Austin, J.C., L.M. Fettkether, and B.J. Chase, 1984, Idaho capitolizes

on its geothermal resources: Geothermal Resources Council Bulletin, v. 13, no. 8, p. 21-23.

ABSTRACT — The state of Idaho is utilizing one of its material resources, geothermal energy, to heat the entire Capitol Mall Complex in Boise, Idaho. The 160°F geothermal water provides the space heating needs for 800,000 square feet of office space, idling four high-pressure steam boilers and virtually shutting the natural gas valve. System efficiencies and design techniques culminating in energy cost savings have become a benchmark for other direct use geothermal systems.

Coudert, J.-M., J.-M. Lejeune, J. Rojas and J. Varet, 1985, Normal-gradient geothermal energy: Technical and economic characteristics: Geothermal Resources Council, International Symposium Volume, p. 71-84.

ABSTRACT — A particularity of French geothermal engineering is the development of industrial projects in normal-gradient, nonconvective areas. The economic feasibility of exploiting highly productive wells (above 150 and up to 350 m³/h for temperatures of 60 to 100°C and depth of 1,500 to 2,000 m) in sedimentary basins with normal gradient for direct heat production is now proven by 40 operations heating over 500,000 people and constructed during the last few years. This experience opens new ways for geothermal energy development the world over, and in particular in areas displaying dense heat demand (over 2,500 Toe/year in a few square km).

Reasonable reservoir engineering as well as environmental considerations show that reinjection is a necessity. Until now, mathematical tools used for well siting — such as the "METERNIQ" program — were based on homogeneous reservoir models.

The recent and fast development of geothermal projects in France, in particular in the Paris basin provides better knowledge of the characteristics of the Jurassic "Dogger" layer, which is tapped by most doublets. Lithological and diagraphic correlations — flow-meter and in-situ chemical sampling in particular — provide precise knowledge of lateral variations within this limestone reservoir. The geological model arising from the data necessitated the development of new mathematical tools for reservoir engineering, taking into account the various heterogeneities encountered.

Data collected systematically bring up new information on several other reservoirs ranging in temperature from 30 to 100°C, which will be liable to new developments in the future.

Einarsson, S.S., 1973, Geothermal district heating, in Armstead, H.C.H. (ed.), Geothermal Energy: A review of research and development: Paris, UNESCO, Earth sciences, v. 12, p. 123-134.

NO ABSTRACT — From Introduction: "The present paper will report on developments that have taken place in utilizing geothermal energy for house heating in various parts of the

world, describe the technology employed and discuss some pertinent economic aspects."

Gudmundsson, J.S., 1982, Low-temperature geothermal energy use in Iceland: Geothermics, v. 11, no. 1, p. 59-68.

ABSTRACT — The results are given of a recent survey of the utilization of geothermal energy produced in low-temperature areas in Iceland. About 70 percent of Icelanders enjoyed geothermal district heating in 1979 and in the next 3-5 years this percentage should increase to about 80%. Most of the district heating systems receive hot water from low-temperature (reservoir temperature less than 150°C) geothermal areas. In late 1980 the thermal power above 15°C used for district heating amounted to 850 MW while the total low-temperature use was about 950 MW-thermal.

Huxtable, D., R. Szymanek and B.A. Housse, 1980, Direct use of deep low enthalpy fresh waters for district heating in France: Geothermal Resources Council, Transaction, v. 4, p. 573-575.

ABSTRACT — Two geothermal-power projects were undertaken in 1976 in south-western France, coming into production in 1977. They extract the heating energy from fresh water at approximately 60° C, without reinjection, from two different natural reservoirs; karst limestones or conglomeratic sandstones between 1850 and 1600 m deep. The two wells also correspond to two different types of application: supplying several consumers previously equipped with conventional heating plants: military base, residential units and hospital; and supplying a vast residential complex pre-equipped with a view to the use of geothermal energy.

Lienau, P.J., 1981, Design of the Klamath Falls geothermal district heating network: ASHRAE Transaction, v. 87, pt. 2.

ABSTRACT — The Klamath Falls Known Geothermal Resource Area (KGRA) presently provides heat to over 600 structures on an individual basis and has been developed for a Commercial Business District heating network. Design of the district network consists of a single pipe carrying 218°F geothermal fluid 4,060 feet from two production wells to a central heat exchanger. An injection well is used to circulate heated city water to Phase I (6.2 MW), fourteen government buildings and 120 homes of a planned 54 city block (41.8 MW) central business district heating system. Geology, district heating boundary determinations, details of the district design and economics are presented.

Lineau, P.J., 1984, Geothermal district heating projects: IDHA District Heating Journal, v. 70, no.1, p.28-35.

ABSTRACT — Geothermal district heating potential for western cities is very large. An inventory identifies a total of 1,277 hydrothermal sites within five miles of 373 cities in eight

western states, with a combined population of 6,720,347 persons. Summaries of operating geothermal district heating projects are presented for Boise, Idaho; Idaho Capitol Mall Project; Elko, Nevada; Klamath Falls, Oregon; Pagosa Springs, Colorado; Philip, South Dakota; San Bernardino, California; Susanville, California; and California Correctional Facility at Litchfield. The characteristics of these projects indicate that a reasonable resource temperature of at least 170°F and large temperature drop across the system are critical for project success. A reasonable district heating size, in the order of 30 billion Btu's of delivered heat annually, and large heat load density are desirable to keep the costs per unit of energy delivered competitive with conventional fuels. Experience at the nine geothermal projects indicates that low temperature geothermal resources can provide a reliable and economic source of energy for district heating systems. However, cities or private developers wishing to develop geothermal energy still face a number of obstacles. Legal clarification of their right to control water resources and local hydrology must be studied carefully before proceeding in order to avoid environmental problems. Cities willing to undertake these problems will find their efforts rewarded with a low cost, dependable energy supply which can spur economic development and provide energy savings to private citizens, businesses and municipalities.

Rybach, Ladislaus, 1979, Urban heating from geothermal aquifers in the Paris Basin: Geothermal Resources Council Special Report No. 5, p. 55-58.

ABSTRACT — A total of 10,000 apartments are heated at present by combining the geothermal source with auxiliary boilers and heat pumps in an area of normal geothermal conditions (average geothermal gradient 33°C/km = 1.8°F/100 ft.). The geothermal contribution which supplies domestic hot water as well amounts to about 70% of the total heat consumed. The resource consists of a deep aquifer (porous Dogger limestone). Due to the high salinity of the formation water (up to 25 g/L) produced, reinjection is necessary. This is performed by the "doublet" system which consists of a twin well (production-reinjection). Typical production rates are 100 m³/h (440 gpm) at 60-70°C (140-158°F). Noticeable temperature drawdown at the production well is not expected before 30 years. Economic analysis shows that the geothermal system is slightly less expensive (at 1977) fuel prices) than conventional fossil-fuel schemes. The French authorities strongly support this development (the risk of the production well is covered by the government) which aims at 800,000 geothermally-heated apartments in the Paris basin by 1990.

Zoega, J., 1974, The Reykjavik municipal district heating system: Multipurpose use of geothermal energy, Klamath Falls, Geo-Heat Center, Oregon Institute of Technology, p. 121-145.

ABSTRACT — The Reykjavik District Heating System uses natural heat resources, found in the city and its vicinity, to heat 11,000 houses, serving some 88,000 inhabitants.

The natural hot water used is obtained by drilling in known thermal areas, and in areas found by various geophysical methods to be promising.

The water used is chemically clean, directly potable and contains only a small amount of dissolved solids, it is also non-corrosive to steel, and ordinary black steel pipes are used throughout in the system. Load density in the city is low, the average being 20 MW/km² and 1.9 MW/km of distribution mains.

The maximum heating load is 350 MW and the available energy 370 MW including a 35 MW oil fired heat peak power plant.

The climate in southern Iceland is mild considering latitude, the mean temperature in July being 11°C, and in January it is 0.4°C, and the consumption in January is only two to three times that of July; thus, due to the relatively cold summers and warm winters, the equivalent hours at peak power for natural heat alone are 4500 per year. (Load factor 51%). Water meters are used for billing and the cost of heating averages 30% of the cost of individual fuel oil boiler heating.

The growth of the city, as well as the supply of neighboring communities having 26,000 inhabitants, will in the near future necessitate exploration and development of thermal areas further from the city where high temperatures (up to 280°C) have been found. This project enables combined production of heat for the district heating system and electricity.

It is shown that the production cost of both electricity and heat is lower than it would be in separate plants. The heat cost will be lower than from the present fields due to higher borehole temperature and larger size of the projected plant.

GENERAL

Gudmundsson, J.S., 1985, Direct uses of geothermal energy in 1984; Geothermal Resources Council, International Symposium Volume, p. 19-29.

ABSTRACT — District heating is the largest sector of geothermal energy direct use in the world. It holds great promise for further development, especially when operated in conjunction with district cooling. At the end of 1984, the installed thermal power of all direct use projects in the world was about 7072 MW and the associated flow rate, 57,803 kg/s. The thermal energy used was found to be 23,957 GWh, in most instances above a reference temperature of 35 to 40°C. The amount of oil saved by geothermal energy direct uses worldwide was estimated to be about 2.8 million tonnes per year.

Gudmundsson, J.S., 1983, Geothermal in Iceland: It's only natural: Geo-Heat Center Quarterly Bulletin, Fall 1983, p. 3-11.

NO ABSTRACT — "The purpose of this essay is to review, in semi-technical terms, the current geothermal energy situation in Iceland."

Gudmundsson, J.S., and G. Palmason, 1982, World uses of lowtemperature (<150°C) geothermal resources in 1980: Geothermal Resources Council, Transactions, v. 6, p. 441-444.

ABSTRACT — The results of a recent world survey of low-temperature geothermal energy utilization are reported. It was found that 44 countries have low-temperature geothermal resources, 24 countries are involved in exploration, 12 countries are utilizing low-temperature geothermal energy and 9 countries have carried out assessment studies. The survey showed that about 8700 MW-thermal (above 15°C reference temperature) were installed at the end of 1980.

Kenkeremath, Deepak C., Robert E. Blackett, James V. Satrape and Gene V. Beeland, 1985, The current status on geothermal direct use development in the Unites States: Geothermal Resources Council, International Symposium Volume, p. 223-236.

ABSTRACT - Information obtained on commercial, agricultural, industrial, institutional, and residential projects in the United States that utilize low- to moderatetemperature geothermal water as an energy source is presented in this paper. The annual thermal energy use of a total of 263 projects either on-line, under construction, or under expansion has been estimated to be over 1861 x 10⁹ Btu. Of the total annual utilization, space and water conditioning projects (473 x 10° Btu) account for approximately 25 percent; district heating projects (426 x 10° Btu) are estimated to account for 23 percent; commercial fish farms (396 x 10° Btu) comprise 21 percent; commercial greenhouses (328 x 109 Btu) contributed 18 percent; while projects involving small resorts (120 x 10⁹ Btu) and industrial process heat (118 x 10⁹ Btu) combine to make up the remainder. All but one of the identified active projects are located in states west of the Mississippi River, with the bulk of the geothermal energy direct heat utilization occurring in California, Idaho, Oregon, Nevada, and New Mexico. The possible influence of various federal and state incentive programs on geothermal direct use development is discussed.

Lidal, B., 1973, Industrial and other applications of geothermal energy (except power production and district heating), *in* Armstead, H.C. H. (ed.), Geotheraml Energy: A review of research and development: Paris, UNESCO, Earth Sceinces, v. 12, p. 135-148.

NO ABSTRACT — Paper discusses the use of geothermal fluids in the fields of industry, agriculture, balneology and recreation.

Reistad, G.M., 1980, Direct application of geothermal energy: NTIS Report No. DOE/ET/20501-T1, 73 p.

ABSTRACT — An overall treatment of direct geothermal applications is presented with an emphasis on the aboveground engineering. The types of geothermal resources and their general extent in the US are described. The potential

market that may be served with geothermal energy is considered briefly. The evaluation consideration, special design aspects, and application approaches for geothermal energy use in each of the applications are considered. The present applications in the US are summarized and a bibliography of recent studies and applications is provided.

Ungemach, P. and J.L. Fouasse, 1985, The status of geothermal direct uses in Europe. Production related problem areas:

Geothermal Resources Council, International Symposium Volume, p. 415-426.

ABSTRACT — An updated status of European geothermal direct uses is presented. Production problem areas, particularly those related to (i) injection into clastic sedimentary reservoirs of the heat depleted brine, (ii) submersible pump reliability, (iii) corrosion and scaling of tubular goods and down hole pumps, and (iv) reservoir management issues, are reviewed with special reference to the Paris basin, the most recently developed resource to date. The prospective impact of the so-called hydro-energy route aimed at exploiting, via heat pumps, very low temperature sources, which contribute to diversifying the conventional geothermal heating spectrum, are also discussed.

GREENHOUSES, AGRIBUSINESS AND AQUACULTURE

Boren, K.L., 1979, The use of geothermal fluids to heat a large greenhouse complex: Geothermal Resources Council Special Report No. 5, p. 69-70.

ABSTRACT — Geothermal fluids are being used to heat 30 greenhouses near Susanville, in northeastern California. Cucumbers and tomatoes are grown in a hydroponic system requiring no root medium such as dirt or gravel. A high quality ground water supply is used for irrigation, while a shallow geothermal well supplies hot water for the heat-exchange type heaters. Thermostats and humidistats control the greenhouse environment. Nutrient are supplied in the irrigation water circulated through the root system that is contained in polyethylene growing tubes. A high quality fruit is produced and sold in the Los Angeles market. The complex has been planned for expansion to 205 greenhouses, and the next units are scheduled for construction this year.

Bressler, S.E., 1980, Potential for geothermal direct use in the greenhouse, lumber, chemical, and potato and onion processing industries: Geothermal Resources Council, Transactions, v. 4, p. 763-765.

ABSTRACT — It has generally been assumed that rising energy costs in industries with high energy needs for low-temperature process heat will induce increasingly widespread geothermal direct use, so long as technical feasibility and cost advantage can be demonstrated. However, few systematic attempts have been made to

determine how industry management and technical personnel within these industries view this possibility in light of factors they deem important to their own firms' energy supply choices. This paper discusses that subject in relation to potential commercial geothermal use in the greenhouse, lumber, chemical, and potato and onion processing industries. It is based upon extensive interviews with decision-makers in over 50 firms representing various segments of these industries and is a selected synthesis of material complied into reports on each industry.

Gudmundsson, J.S., 1983, Geothermal soil heating in Iceland: Geothermal Resources Council, Transactions, v. 7, p. 601-606.

ABSTRACT — The climate of Iceland is such that only hardy vegetables can be grown in the summer. Common crops are potatoes, carrots, cabbage and cauliflower. Soil heating using geothermal water has been practiced in Iceland for several years. Growing on naturally warm land in geothermal areas has, however, been known for a much longer time. Vegetable growing on warm land has proven to be very attractive and several new systems have recently come into operation. The practice is to heat the soil with lowtemperature geothermal water that flows in plactic pipies buried at 50-80 cm depth and spaced 120-200 cm apart. An engineering study was undertaken to quantify the main parameters that govern heat transfer from parallel pipes in soil. Measurements from operational geothermal soil heating systems were compared to model calculations. Design guidelines have been prepared.

Hayes, A. and W.C. Johnson, 1980, Geothermal aquaculture: A guide to freshwater prawn culture: Oregon Institute of Technology, Geo-Heat Utilization Center, 25 p.

ABSTRACT — Biological data of the Malaysian prawn, Macrobrachium rosenbergil, are summarized. A history on its rearing techniques is given, but through the use of geothermal water or industrial warm water effluent, its range can be expanded. The use of wasted geothermal water at the Oregon Institute of Technology for prawn ponds is noted. Pond management and design; the hatchery design and function for larval culture; and geothermal applications (legal aspects and constraints) are discussed.

Higbee, C.V., and G.P. Ryan, 1981, Greenhouse heating with low temperature geothermal water: Geothermal Resources Council, Transactions, v. 5, p. 651-654.

ABSTRACT — Greenhouse heating systems can be designed that supply 100% of the annual heat requirements using geothermal water with a temperature as low as 81°F. The heat is extracted using a forced air system with finned coil heaters in the air ducting. Design and evaluation was based on an energy efficient semicircular arching roof type with double polyethylene covering. The one acre of greenhouses were located in the LaGrande area of Oregon where 81°F water exists at a shallow depth. Three cases were considered in the

economic evaluation, which savings were calculated, based on displacing 39,300 therms of natural gas annually. The three 20 year life cycle cost analyses generated rates of return on capital investment of 21.8%, 30.3% and 17.1%. The highest rate of return (30.3%) is for the new greenhouse where an existing geothermal well and water disposal system exists. Lowest rate of return is for the retrofit situation where wells are needed and capital credit cannot be taken for the conventional hydronic system.

Howard, S.M., 1983, Direct utilization of geothermal energy in western South Dakota agribusiness. Final report: NTIS Report No. DOE/ET/28419-7, 98 p.

ABSTRACT — This project involved the direct utilization of geothermal energy for (1) space heating of farm and ranch buildings, (2) drying grain, and (3) providing warm stock water during the winter. The site for this demonstration project was the Diamond Ring Ranch north of Midland, South Dakota. Geothermal water flowing from an existing well into the Madison Aquifer was used to heat four homes, a shop, a hospital barn for cattle, and air for a barn and grain dryer. This site is centrally located in the western region of South Dakota where geothermal water is available from the Madison Aquifer. The first year of the project involved the design of the heating systems and its construction while the following years were for operation, testing, demonstrating, and monitoring the system. Required modifications and improvements were made during this period. Operating modifications and improvements were made during this period. Operating experience showed that such application of geothermal resources is feasible and can result in substantial fuel savings. Economic analyses under a variety of assumptions generally gave payback periods of less than ten years. Numerous technical recommendations are made. The most significant being the necessity of passive protection from freezing of remote geothermal systems subject to winter shut downs caused by power or equipment failure. The primary institutional recommendation is to incorporate a use for the geothermal water such as irrigation or stock watering into agribusiness-related geothermal development.

Lienau, P.J., 1978, Agribusiness geothermal energy utilization potential of Klamath and western Snake River basins, Oregon. Final report: Klamath Falls, Geo-Heat Center, Oregon Institute of Technology, 202 p.

ABSTRACT — Resource assessment and methods of direct utilization for existing and prospective food processing plants have been determined in two geothermal resource areas in Oregon. Ore-Ida Foods, Inc. and Amalgamated Sugar Company in the Snake River Basin; Western Polymer Corporation (potato starch extraction) and three prospective industries—vegetable dehydration, alfalfa drying and greenhouses—in the Kalmath Basin have been analyzed for direct utilization of geothermal fluids. Existing geologic knowledge has been integrated to indicate locations, depth, quality, and estimated productivity of the geothermal reservoirs. Energy-economic needs and balances, along with

cost and energy savings associated with field development, delivery systems, in-plant applications and fluid disposal have been calculated for interested industrial representatives.

Ray, Leo, 1979, Channel catfish (Ictalurus punctatus) production in geothermal water: Geothermal Resources Council Special Report No. 5, p. 65-67.

ABSTRACT — Fish Breeders have been raising Channel Catfish (Ictalurus punctatus) in geothermal facilities for six years. The product produced is superior to other catfish on the market.

Concrete facilities and 6,000,000 gallons per minute of water allow densities of five to ten pounds per cubic foot of space and 10,000 pounds per second foot of water. Oxygen and ammonia are the principle factors limiting production. Disease is related to these factors.

Identifying the resource, facility design, financing, construction, production, processing, marketing and distribution are the main problem areas preventing expansion of geothermal fish farming.

Schaevitz, Robert C. and Paul Rodzianko, 1979, Geothermal applications in agriculture: Mushroom farming in the western United States: Geothermal Resources Council, Transactions, v. 3, p. 629-632.

ABSTRACT — The relatively high energy costs of large, surface-sited mushroom farms has prompted a study to investigate the feasibility of constructing what is believed would be the world's first mushroom farm to utilize geothermal water as its primary energy source. As presently conceived, this moderate-sized facility would combine a highly automated growing operation with the use of geothermal wells to provide all heating and cooling energy requirements. An analysis utilizing order-of-magnitude capital and oeprating cost estimates reveals that extensive benefits may result from the use of geothermal energy. Several factors contribute to a project's financial feasibility; however, it is the use of geothermal energy that transforms what might otherwise be an undistinguished business venture into a potentially profitable operation. The authors conclude that the remote possibility of a geothermal resource failure is far outweighed by energy cost savings potentially equal to many times the total capital cost of a geothermal energy system.

INDUSTRIAL PROCESSING

Fettkether, L.M. and J.C. Austin, 1979, Direct application of geothermal energy for industrial processing: Geothermal Resources Council, Transactions, v. 3, p. 205-208.

ABSTRACT — Geothermal water at 300°F could provide approximately 50 percent of certain industrial process energy

requirements, where sufficient quantity water is available. A federal government cost-sharing program has facilitated a major frozen food processor's development of geothermal energy in the Northwest. The geothermal energy will be used to heat low temperature process water by utilizing heat exchangers and retrofitting the process equipment. The planned geothermal system includes two production wells, a transmission main, a complex of plate heat exchangers, and a deep injection well. The cascade principle is employed to extract the usable energy from the geothermal water.

Hornburg, C.D., 1978, Feasilibity of developing geothermal energy industrial complexes: NTIS Report No. CONF-780133, p. 121-130.

ABSTRACT — The overall purpose of this study was to provide economic, technical and other related information on developing industrial complexes to utilize geothermal energy. The basic concept was to select processes of production that may utilize large amounts of moderate temperature energy and group them together at specific geothermal sites for synergic production of products in an optimum economic manner. The study plan consisted of executing seven technical tasks in near sequential order to successively screen the alternate possibilities of: products to produce and processes: energy recovery systems and; reservoir types and locations. This was done in such a manner so as to arrive at selection of those products and processes matched to energy recovery systems and sites that offer the highest potential for economical utilization of geothermal energy. A preliminary design was made; capital and operating costs estimated and; the overall possibilities and problems in developing Geothermal Energy Industrial Complexes assessed.

May, S.C., E.H. Houle and D.J. Basuino, 1978, Applications of geothermal resources in the evaporation/crystallization industry: NTIS Report No. CONF-780133, p. 91-95.

ABSTRACT — A survey of major industries utilizing the evaporation/crystallization process was carried out in order to select three industries for consideration for utilization of geothermal energy. From among each of the selected industries, an example case was chosen for technical and economic evaluations. This evaluation included use of the feed-and-bleed process for energy extraction from the low-temperature geothermal brine. This study concludes that, under certain conditions, geothermal energy could be used economically in the evaporation and crystallization industry. The factors that would most affect cost include geothermal resource characteristics; the energy extraction process chosen; and the duration of the evaporation/crystallization operation.

Peterson, Eric A., 1979, Possibilities for direct use of geothermal energy: ASHRAE Transactions, v. 85, pt. 1, p. 231-251.

ABSTRACT — Thermodynamic guidelines for utilization of the geothermal resource are discussed and it is shown that

there is the potential for use of geothermal energy in preheating, thus supplying a greater percentage of the process heat required at a particular temperature.

Sherwood, P.B., 1978, Economic feasibility of utilizing geothermal heat for an agricultural chemical plant: Geothermal Resources Council, Direct Utilization of Geothermal Energy: A Symposium, p. 97-101.

ABSTRACT — The engineering and economic feasibility of utilizing geothermal heat from the Heber KGRA for industrial processing purposes at the Valley Nitrogen Producers, Inc., El Centro, California, agricultural chemical plant was investigated. The analysis proceeds through the preliminary economics to determine the restraints imposed by geothermal modification size on internal rates of return, and through the energy utilization evaluation to determine the best method for substituting geothermal energy for existing fossil fuel energy. Finally, several geothermal utilization schemes were analyzed for detailed cost-benefit evaluation. An economically viable plan for implementing geothermal energy in the VNP Plant was identified and the final conclusions and recommendations were made based on these detailed cost-benefit analyses. Costs associated with geothermal energy production and implementation were formulated utilizing a modified Battelle Pacific Northwest Laboratories' GEOCOST program.

Wilson, R.D., 1974, Use of geothermal energy at Tasman Pulp and Paper Company Limited, New Zealand, in Lienau, P.J., and J.W. Lund (eds.), Multipurpose use of geothermal energy: Proceedings of the International Conference on Geothermal Energy of Industrial, Agricultural, and Commercial-Residential Uses: Geo-Heat Utilization Center, Oregon Institute of Technology, p. 79-100.

ABSTRACT — The sites for the integrated newsprint, pulp and timber mills of the Tasman Pulp and Paper Company Limited and the associated town of Kawerau, were selected in 1952 in proximity to an area of thermal surface activity. Investigation and subsequent drilling in the area produced usable quantities of geothermal steam. The steam/water mixture produced by the geothermal bores is generally separated at the well heads into its two fractions. The steam is piped to the mill and hot water discarded.

Geothermal energy is used by Tasman for timber drying, black liquor evaporation, pulp and paper drying and for electric power generation.

Recent surveys of the area and an investigation drilling program planned by the Ministry of Works and Development to commence in 1975, if approved, are expected to determine the extent and future development of the Kawerau field. The present energy crisis has placed further emphasis on the important part geothermal energy plays in Tasman's operations.

The site (Figure 1) of the integrated mills of the Tasman Pulp and Paper Company Limited producing newsprint, kraft pulp

and sawn timber, and the town site of Kawerau, were selected from several alternatives in 1952 because of the close proximity of the mill site to an active hydrothermal area then known as Onepu Springs and now known as the Kawerau geothermal field. The Tasman mills have undergone two major expansion programs since production commenced in 1955. The second of these programs will be complete with the commissioning of No. 3 newsprint machine in mid 1975. This will bring the mills annual production capacity to 345,000 long tons of newsprint, 160,000 long tons of kraft pulp and 80 million board feet of timber.

Completion of this expansion program will increase the mills demand for process steam to approximately 820,000 lb/hr. This steam will be supplied from two entirely different sources: 620,000 lb/hr will be generated in a conventional steam plant comprising two chemical recovery boilers and four power boilers. These six units will burn black liquor, hog fuel and oil to produce steam at 650 lb/in² guage² and 750°F.

The remaining 200,000 lb/hr of process steam requirement will be supplied by a group of steam bores located approximately three quarters of a mile from the mill, producing wet saturated steam at 120 lb/in² at the well heads.

This paper describes the development and use of this source of geothermal energy in the Tasman mills where it plays a very important part in the economics of mill operations.

DIRECT UTILIZATION PUBLICATIONS OF GENERAL INTEREST

- Anderson, D.N., and J.W. Lund (eds.), 1979, Direct utilization of geothermal energy: A technical handbook. Geothermal Resources Council Special Report No. 7, variously paginated.
- ______ 1979, Direct utilization of geothermal energy: A layman's guide: Geothermal Resources Council Special Report No. 8, 97 p.
- Geo-Heat Utilization Center Quarterly Bulletin, Klamath Falls, Oregon Institute of Technology.
- Geothermal Resources Council, 1978, Direct Utilization of Geothermal Energy: A Symposium: San Diego, January 31-February 2, 1978, 133 p.
- Geothermal Resources Council, 1979, A symposium of geothermal energy and its direct uses in the eastern United States: Geothermal Resources Council Special Report No. 5, 103 p.
- Geothermal Resources Council, 1980, Commercial uses of geothermal heat: Geothermal Resources Council Special Report No. 9, 143 p.
- Lineau, P.J., and J.W. Lund (eds.), 1974, Multi-purpose use of geothermal energy: Proceedings of the International Conference on Geothermal Energy for Industrial, Agricultural, and Commercial-Residential Uses, Geo-Heat Utilization Center, Oregon Institute of Technology.

SPECIAL REPORT NO. 14

Abstract Sets Printed To Date:

CASE HISTORIES	1-21
DRILLING IN AN UNDER PRESSURED GEOTHERMAL RESERVOIR	25-27
GEOTHERMAL RESERVOIR ENGINEERING	31-38
INJECTION	39-50
GEOTHERMAL WELL LOGGING	51-66
ENVIRONMENTAL CONSIDERATIONS IN GEOTHERMAL DEVELOPMENT	67-76
GEOTHERMAL WELL PRODUCTION	77-84
GEOTHERMAL MATERIALS	85-93
ELECTRIC POWER PRODUCTION	94-103
DIRECT UTILIZATION OF GEOTHERMAL ENERGY	104-112

Special Report 14 Addendum

Economics of Geothermal Energy

Abstracts Reviewed By Thomas A.V. Cassel, Bob Greider and Paul J. Lienau

ECONOMICS

Atlas Corporation, 1983, Can we develop 10,000 MWe? What are the economics?: Seventh Annual Geothermal Conference and Workshop: Proceedings: Electric Power Research Institute Report No. EPRI-AP-3271, p. 7.20-7.21.

ABSTRACT — An overview is presented of the workshop discussions on the question: What are the economics involved in developing 10,000 MWe of geothermal power. It was agreed that economics is the single most significant factor in achieving the 10,000 MWe of generating capacity by the year 2000. The economic objectives for developing the 10 GWe by the year 2000 are discussed.

Altseimer, J.H., F.J. Edeskuty, W.B. Taylor, and K.D. Williamson, Jr., 1984, Evaluation of the St. Lucia geothermal resource: Engineering investigation and cost estimate: NTIS Report No. LA-10209-MS, 52 p.

ABSTRACT — An engineering and economic study of the development of geothermal energy in St. Lucia has given cost estimates for electricity and process heat produced from the geothermal energy, identified additional industries that are worthy of further examination, and developed methods for examining the economic impact of this new energy source. Costs have been estimated for electricity produced from geothermal energy, by diesel engines used only during peak power demand, by diesel engines producing the total electricity requirement, by an oil-fired steam-power plant, and by a coal-fired steam-power plant. Costs have also been estimated for thermal energy to be used for industrial process heat under various conditions of transport distances, capacity factors, and temperature requirements. Several industries that may be attracted to St. Lucia by the development of geothermal energy have been identified.

Amir, E., and L.W. House, 1982, Economic assessment of geothermal plant efficiency improvements in the PG and E system: IEEE Trans. Geosci. Remote Sensing, v. 6, p. 489-492.

ABSTRACT — This study examines the merits of investment in geothermal efficiency improvements in the PG and E system. The study compares the costs, composed of the equipment investment cost and the increased payment to steam suppliers, with the benefits, composed primarily of displacing existing oil-fired generation and cost savings due to geothermal fuel repricing. Two alternative oil cost real escalation rates were examined: 4.7 percent through 1987 and 3.0 percent thereafter, and a zero escalation rate throughout. The analysis found for the higher oil price escalation case that the present value of future savings was about \$17,000/kW of improved efficiency at a cost of \$6,000/kW. Under the lower oil price escalation case, the present value of future savings was less than the investment. Whether or not improving the efficiency of geothermal units is a profitable investment is almost totally determined by future oil prices, given the resource plan used in the analysis.

Barron, William, Peter Kroll, Richard Weissbrod, and W.J. Toth, 1980, Geothermal energy market study on the Atlantic coastal plain, GRITS: A computer program for the economic evaluation of direct-use applications of geothermal energy: Johns Hopkins University, Center for Metropolitan Planning and Research Report No. MCGER-80-002, 84 p.

ABSTRACT — The Geothermal Resource Interactive Temporal Simulation (GRITS) model calculates the cost and revenue streams for each year in the lifetime of a project that utilizes low to moderate temperature geothermal resources. With these two estimates, the net present value of the project can be determined for each year. The GRITS model allows preliminary economic evaluatations of direct-use applications of geothermal energy under a wide range of resource, demand, and financial conditions, some of which change over the lifetime of the project.

Bens, A.R., J.J. McCartan, L.W. Vigrass, and F.A. Curtis, 1982, Use of geothermal energy at the University of Regina: Results of an engineering-economic study: ENERGEX '82 Conference Proceedings, Vol. II/II, p. 1123-1128.

ABSTRACT — An engineering-economic study on the use of geothermal energy combined with conventional energy sources at the University of Regina has been performed. A geothermal retrofit of the campus is considered. Energy savings associated with the retrofit are assessed, and the associated costs are determined. The overall economics of the retrofit are examined and a fifteen year cash flow projection is also developed.

Blair, P.D., T.A.V. Cassel, and R.H. Edelstein, 1982, Geothermal energy: Investment decisions and commercial development, in Alternate Energy: A Wiley Series, New York, NY, John Wiley and Sons, Inc., 195 p.

ABSTRACT — Geothermal energy technology and the investment practices of resource developers and electric utilities in using geothermal resources for the production of electric power are covered. An analytical framework, a decision model, is developed from basic principles of multiobjective decision analysis and probabilistic choice theory for evaluating geothermal investment behavior of both resource developers and power producers. The decision model is used to estimate the potential role of geothermal energy in the US over the next several decades and the relative effectiveness of alternative government incentives or other public policy initiatives for accelerating the development of geothermal electric power production in specific resources areas.

Blake, J.C., 1984, GCFM5.0; Geothermal field and power plant costs (mag tape): NTIS Report No. ANL/NESC-976.

ABSTRACT — GCFM (Geothermal Loan Guaranty Cash Flow Model) is an interactive program which estimates project costs and cash flows for geothermal producer field projects and geothermal electric plant projects during construction and operation. Both the year-by-year cash flow for a project and a levelized busbar cost of electricity or a levelized price for geothermal fluid can be estimated. Maxima of 50 years project life (construction and operation), 50 years loan life, 15 financial cases, 10 power plant designs, 10 field designs. GCFM does not contain provisions for estimating the costs of geothermal direct heat utilization projects.

Bloomster, C.H., and L.L. Fassbender, 1982, GEOCITY: A computer model for systems analysis of geothermal district heating and cooling costs: American Society of Heating. Refrigerating, and Air Conditioning Engineers, Transactions, v. 88, p. 1309-1322.

ABSTRACT — GEOCITY is a computer simulation model developed to study the economics of district heating/cooling using geothermal energy. GEOCITY calculates the cost of district heating/cooling based on climate, population, resource characteristics, and financing conditions. The principal input variables are minimum and maximum temperatures, heating degree-days and cooling degree-hours, population size and density, resource temperature and distance from load center, housing type, and interest

rate. From this input data the model designs the transmission and district heating/cooling systems. From this design, GEOCITY calculates the capital and operating costs for the entire system, including the production and disposal of the geothermal water. The basis for the geothermal energy cost analysis is the unit cost of energy which will recover all the costs of production - capital investment, operating expenses, taxes, and the specified rates of return on capital. The calculation of the unit cost of energy is based on life cycle costing and discounting cash flow analysis. A wide variation can be expected in the range of potential geothermal district heating and cooling costs. The range of costs is determined by the characteristics of the resource, the characteristics of the demnad, and the distance separating the resource and the demand. In this paper, costs were developed for each of the main parts of the production process. The sensitivity of these costs to several significant parameters under a consistent set of assumptions were also determined.

Brown, G.L., 1983, Geothermal wells: The cost benefit of fracture stimulation estimated by the GEOCOM code. Final Report: NTIS Report No. SAND-83-7440, 39 p.

ABSTRACT — GEOCOM, a computer code that provides life cycle cost/benefit analysis of completion technologies applied to geothermal wells, is used to study fracture stimulation techniques. It is estimated that stimulation must increase flow by roughly tons per \$100,000 in order to be cost effective. Typically, hydraulic fracturing costs \$100,000 to \$500,000 per well, and the attempts at stimulation to date have generally not achieved the desired flow increases. The cost effectiveness of hydraulic fracturing is considered for several geothermal reservoirs.

Carson, C.C., 1982, Geothermal drilling problems and their impact on cost: NTIS Report No. SAND-82-0261C, 18 p.

ABSTRACT — Historical data are presented that demonstrate the significance of unexpected problems. In extreme cases, trouble costs are the largest component of well costs or severe troubles can lead to abandonment of a hole. Drilling experiences from US geothermal areas are used to analyze the frequency and severity of various problems. In addition, average trouble costs are estimated based on this analysis and the relationship between trouble and depth is discussed. The most frequent drilling and completion problem in geothermal wells is lost circulation. This is especially true for resources in underpressured, fractured formations. Serious loss of circulation can occur during drilling — because of this. the producing portions of many wells are drilled with air or aerated drilling fluid and the resulting corrosion/erosion problems are tolerated — but it can also affect the cementing of well casing. Problems in bonding the casing to the formation result from many other causes as well, and are common in geothermal wells. Good bonds are essential because of the possibility of casing collapse due to thermal cycling during the life of the well. Several other problems are identified and their impacts are quantified and discussed.

Cassel, T.A.V., C.B. Amundsen, and P.D. Blair, 1983, Geothermal power plant R and D: An analysis of cost-performance tradeoffs and the Heber Binary-Cycle Demonstration Project: NTIS Report No. DOE/CS/30674-2, 174 p.

ABSTRACT — A study of advancements in power plant designs for use at geothermal resources in the low to moderate (300 to 400°F) temperature range is reported. In 3 case studies, the benefits of R and D to achieve these advancements are evaluated in terms of expected increases in installed geothermal generating capacity over the next 2 decades. A parametric sensitivity study is discussed which analyzes differential power development for combinations of power plant efficiency and capital cost. Affordable tradeoffs between plant performance and capital costs are illustrated. The independent review and analysis of the expected costs of construction, operation and maintenance of the Heber Binary Cycle Geothermal Power Demonstration Plant are described. Included in this assessment is an analysis of each of the major cost components of the project, including (1) construction costs, (2) well field development costs, (3) fluid purchase costs, and (4) well field and power plant operation and maintenance costs. The total cost of power generated from the Heber Plant (in terms of mills per kWh) is then compared to the cost of power from alternative fossil-fueled base load units. Also evaluated are the provisions of both: (a) the Cooperative Agreement between the federal government and San Diego Gas and Electric (SDG and E); and (b) the Geothermal Heat Sales Contract with Union Oil Company.

Cassel, T.A.V., C.B. Amundsen, R.H. Edelstein, and P.D. Blair, 1981, Geothermal well-field and power-plant investment-decision analysis: NTIS Report No. DOE/ET/27242-T1, 168 p.

ABSTRACT — Investment decisions pertaining to hydrothermal well fields and electric power plants are analyzed. Geothermal investment decision models were developed which, when coupled to a site-specific stochastic cash flow model, estimate the conditional probability of a positive decision to invest in the development of geothermal resource areas. Quantitative decision models have been developed for each major category of investor currently involved in the hydrothermal projects. These categories include: large, diversified energy resource corporations; independently operating resource firms; investor-owned electric utilities; municipal electric utilities; state-run resource agencies; and private third-party power plant investors. The geothermal cash flow, the investment decision analysis, and an example of model application for assessing the likely development of geothermal resource areas are described. The sensitivity of this investment behavior to federal incentives and research goals is also analyzed and discussed.

Demuth, O.J., 1984, Effects of vaporizer and evaporative condenser pinch points on geofluid effectiveness and cost of electricity for geothermal binary power plants: NTIS Report No. EFF-M-24083, 6 p.

ABSTRACT — A brief study was conducted in support of the DOE/DGHT Heat Cycle Research Program to investigate the influences of minimum approach temperature differences occurring in supercritical-heater/vaporizer and evaporative-condenser heat rejection systems on geothermal-electric binary power plant performance and cost of electricity. For the systems investigated optimum pinch points for minimizing cost of electricity were estimated to range from 5 to 7° F (3 to 4° C) for the the heater vaporizer. The minimum approach of condensing temperature to wet-bulb temperature for evaporative condensers was estimated to be about 15° F (8° C) in order to achieve the highest plant net geofluid effectiveness, and approximately 30° F (17° C) to attain the minimum cost of electricity.

Dolenc, M.R., F.W. Childs, D.W. Allman, and R.D. Sanders, 1983, Evaluation of direct-use-project drilling costs: NTIS Report No. EGG-M-11683, 5 p.

ABSTRACT — This study evaluates drilling and completion costs from eleven low-to-moderate temperature geothermal projects carried out under the Program Opportunity Notice (PON) and User-Coupled Confirmation Drilling Programs. Several studies have evaluated geothermal drilling costs, particularly with respect to high-temperature-system drilling costs. This study evaluates drilling costs and individual cost elements for low-to-moderate temperature projects. It considers the effect of drilling depth, rock types, remoteness of location, rig size, and unique operating and subsurface conditions on the total drilling cost. This detailed evaluation should provide the investor in direct-use projects with approximate cost projections by which the economics of such projects can be evaluated.

Eldredge, D.L., and J.L. Rasband, 1984, Cost and performance alalysis of wellhead and central geothermal power plant development at Roosevelt Hot Springs: Electric Power Research Institute Report No. EPRI-AP-3686, p. 3.42-3.46.

ABSTRACT — Utah Power and Light Company (U Pand L) has been studying the development of economic alternative power sources to large coal-fired power plants. This effort includes the new 20 MW Milford No. 1 Geothermal Power Plant and future development of the Roosevelt Hot Springs geothermal resource near Milford, Utah. To facilitate further development of Roosevelt Hot Springs, a study was undertaken to evaluate the economics of central plant and wellhead plant development schemes at the resource, compared to U P and L's present coal-fired plants. Major goals of the study were to assess available technology and its application at Roosevelt, as well as appropriate development schemes for comparison. For study purposes, it was decided to compare 100 MW of geothermal capacity from each of the technologies looked at. It was felt that 100 MW of capacity would give a fair representation of the operating costs of each technology at a mature resource. Once technologies were agreed upon, each was assessed for capital cost, operating cost and fuel cost. While these costs would naturally reflect their application at the Roosevelt resource (particularly the fuel costs), some areas of sensitivity were applicable to a wide

range of geothermal resources. Three basic technologies were chosen to investigate: conventional 50 MW central plant, the RST wellhead plant, and two binary wellhead plants.

Gordon, L.C., and T.R. Breton, 1983, Economic assessment of nine geothermal direct use applications. Final report: NTIS Report No. DOE/ET/12099-5, 101 p.

ABSTRACT — This report provides an economic analysis of nine federally supported geothermal direct heat applications which were part of DOE's Program Opportunity Notice (PON) program. Three of the projects analyzed were userowned systems, and six were district heating systems. Five of the nine projects are successful from an economic standpoint and the majority of these projects are in areas where geothermal energy has long been used for heating. The results of this analysis indicate that geothermal energy projects can be economic under certain conditions, but these conditions may not be very widespread.

Greider, B., 1981, Exploration, the economic strategies: Geothermal Resources Council, Transactions, v. 5, p. 643-646.

ABSTRACT — Exploration for a geothermal reservoir is capital-intensive, and requires planning and significant capital. The objectives of exploration are to locate, analyze, and acquire the areas that can produce economic and useful quantities of geothermal energy. Evaluation of the risks of finding adequate producible and useable energy with the available techniques and funds provides the foundation for the exploration plans. Exploration wells now cost about \$200 per foot drilled. Development of a 50 MW field and plant requires more than 76 million dollars. A direct use development requires a minimum of \$1,000,000 if it involves a new industrial installation. A development must provide more than 25% rate of return on the investment to compete with low risk investments.

Grossin, R., P. Sagnes, and F. Bussac, 1984, Techno-economic study of energy conversion from geothermal brines using two phase thermodynamic cycle: Commission of the European Communities, Luxemborg, Report No. EUR-8853-EN, p. 229-231.

ABSTRACT — Currently, two processes for electricity production can be used: the flash process and organic Rankine cycles. The ongoing research program presented here concerns a third process, using a two phase turbine expanding directly geothermal brines, which would have the following advantages as compared with other conversion systems: no problems associated with heat exchangers,; conversion of the whole enthalpy containers in the brine; better compromise betweeen cost and efficiency.

Harrison, R., 1984, Cost modelling of low enthalpy geothermal developments — U.K. costs: Commission of the European

Communities, Luxemborg, Report No. EUR-8853-EN, p. 193-200

ABSTRACT — Using the cost model which has been developed at Sunderland, well head unit costs of geothermal heat are estimated assuming that drilling is carried out in the U.K. by the indigenous drilling industry. The sensitivity of unit costs to important reservoir parameters is investigated as also is the importance of "matching" the fluid parameters of temperature and flow with scheme demand and operating temperature characteristics.

Harrison, R., 1984, Economics of low enthalpy geothermal district heating developments, northern France and the U.K.: IEE Conference Publication, v. 233, p. 241-248.

ABSTRACT — In this paper the economic analyses of six geothermal district heating schemes are described. The schemes are all in the Paris Basin, two are in operation and the four others are under development. The study of these schemes provides a real context within which the prospects for more tentative U.K. developments can be discussed. In order to obtain more general indications of the prospects for developments which may have a range of resource and scheme condtions modelling studies have often been used. Economic modelling studies in the geothermal field have been reviewed by Lockwood and also by Lease. This paper reports some results from one of these models and more details can be found in Harrison et al.

Harrison, R., and N.D. Mortimer, 1984, U.K. drilling cost estimation: Commission of European Communities, Luxemborg, Report No. EUR-8853-EN, p. 201-209.

ABSTRACT — A drilling cost estimation procedure has been developed in which physical parameters of drilling time, casing quantity, etc., are estimated and combined with unit costs of rig hire, casing, etc., to determine overall well costs. An important sub-model is the estimation of drilling time; this sub-procedure uses instantaneous rates of penetration at different depths and also bit life estiamtes as input data. With generalized data on instantaneous rates of penetration and bit life this sub-model yields estimates of drilling time which are consistent with experience for the Wessex and Aquitaine basins. From a study of U.K. and U.S. well costs and rig rates it is concluded that official exchange rates are misleading when comparing well costs. Also there may be no significant differences in rig rates in the two countries.

Harvey, C., 1983, Sperry low temperature geothermal conversion system, Phase I and Phase II. Final Report. Volume VI. Economic studies: NTIS Report No.DOE/ET/27125-T2-Vol. 6, 80 p.

ABSTRACT — The basic thrust of the studies represented was to compare the overall economics of the Gravity Head system with that of optimized conventional binary generating plants.

The study is site-specific to the East Mesa geothermal reservoir. The limiting factors at East Mesa are reservoir drawdown and maximum practical brine pump impeller setting depth. Using the 1300 gpm, 360°F resource as a starting point, detailed cost estimates and performance calculations were made for the Gravity Head and various conventional alternative well-head systems. The most cost effective of the conventional alternatives was found to be a 700 psi cycle using R114 as the working fluid (actually optimized at 682 psi). The study is in two parts. In Part I, emphasis is placed on the economic sensitivities of the compared systems to variations in capital cost. O and M cost. avoided energy inflation rates, and brine cost. In Part II, a somewhat more rigorous attempt is made to derive the actual economic performance of the systems under more realistic circumstances with contingencies, cost penalties, and multiple-unit developments added.

Hederman, W.F., Jr., and L.C. Gordon, 1984, Investment in geothermal direct-heat applications: Energy Journal, v. 5, no. 1, p. 85-97.

ABSTRACT — An assessment of eight geothermal direct-heat projects for which confident cost and production data exists indicates that low-temperature geothermal resources can, in certain instances, provide an inexpensive, reliable source of direct-heat energy. The analysis examines the retrofit investment decision separately for private firm and local government investors. It compares the economics of geothermal and conventional energy supplies, and explores the sensitivity of these comparative results to changes in the underlying assumptions. Investors are warned that geothermal direct-heat applications projects have not been uniformly successful. Three of the eight projects do not appear to be economical when compared to conventional alternatives even though all eight are the most advanced of 22 demonstration projects originally funded by DOE.

Herron, E.H., 1982, Estimating geothermal energy costs in the eastern United States: Geothermal Energy Magazine, v. 10, no. 7/8, p. 31-35.

ABSTRACT — The various costs involved in the installation of a typical geothermal production/disposal system in the eastern U.S. can be separated into two groups: one essentially independent of well depth, and one strongly dependent on well depth. Summation of the depthdependent terms produces a total cost per foot that is constant over the range of depths likely in eastern operations. These observations lead to the following formula for estimating the cost of a single-production-well/singledisposal-well geothermal system in 1980 dollars: cost = 380 + (110 x production depth) + (85 x disposal depth), where costs are in thousands of dollars and depths are in thousands of feet. When estimating the cost of a disposal well, it is conservative to assume that the spent geothermal fluids will be reinjected into their original formation. In many instances, however, it may be possible to use shallower formations for disposal. Pumping costs, which depend on well productivity,

may heavily influence the economics of a potential geothermal project. Because well performance is difficult to predict, conservative feasibility studies should acknowledge that up to 700 kW of power may be consumed in circulating geothermal fluids through a production/disposal system. The cost-depth relationship derived here for eastern operations is significantly different from industry's experience in the west. In the western U.S., geothermal service contractors are in place, so setup costs are less and therefore shallow wells cost less. However, the drilling environment is generally more severe, causing western drilling costs to overtake eastern costs as drilling depth increases.

Higbee, C.V., 1984, Life-cycle cost analysis for direct-use geothermal systems: Geothermal Energy Magazine, v. 12, no. 3, p. 7-8.

ABSTRACT — In the midst of our frantic search to discover new renewable energies and our rush to develop the technology of solar and wind applications, the old reliable direct-use geothermal energy continues to surface. There is no need to wait for the development of direct-use geothermal technology. It has been on-line, tried and proven, since the turn of the century. Nearly all the equipment required for direct-use geothermal systems has been available for decades as off-the-shelf items. The only remaining question for direct-use geothermal development is the economic feasibility of the proposed direct-use system. If the resource is proven and the proposed end use is compatible with the temeprature and flow rate of the resource, the only element left for consideration is the economic viability of the project. That is, will the system create sufficient benefits, savings, or revenues to justify the amount of capital investment necessary to bring it on-line. Life-cycle cost analysis is the method generally used to determine economic feasibility. This paper will acquaint the reader with the basic principles of this analysis. Life-cycle costing combines all the techniques of projecting and evaluating total system costs over the expected life of the system. These costs include capital investment, annual costs of operating and maintaining the system, financing costs, taxes and insurance, etc. associated with the system. The end result of all these cost projections is to evaluate the ratio of the annual benefit (revenue or savings) to the cost or required capital investment to determine if the project is worthwhile. Once life-cycle costs have been calculated it is easy to determine the present worth of these cash flows, the internal rate of return on invested capital, and the payback period.

Howard, J.H., 1981, Price estimates of hot-water geothermal energy: NTIS Report No. LBL-11133, 22 p.

ABSTRACT — A generalized price equation for hot water geothermal energy has been developed. The equation is based on analysis of specific quantities of fossil fuels. The equation is useful in starting negotiations for sale of heat from a hot water resource and is necessary in any reserve valuation in the absence of a firm sales contract. The sales price of the only known hot water geothermal energy sales contract is

presently 0.082 mills/1bm and compares with 0.079 mills/1bm according to the proposed equation.

Long, G., and D. McClain, 1983, Economic constraints to the development of geothermal power in the Cascades: Geothermal Resources Council, Transactions, v. 7, p. 263-267.

ABSTRACT — Economic constraints to the development of geothermal power in the Cascades region are composed of limitations which are unique to the region itself and limitations which are generic to the development of all geothermal resources. Lack of knowledge about Cascades resources and the preponderance of volcanic strata will result in high drilling and development costs. The electrical market is constrained by sufficient electrical supplies capable of meeting regional demand through the turn of the century, lack of transmission interties with other regions, and lower avoided cost compared to central and southern California. Perceived lack of proven geothermal technology limits utility interest and raises required rates of return to investors in geothermal resources.

Merz, C.M., and P. Hanson, 1982, Pricing and marketing geothermal energies for space heating in Boise, Idaho: Geothermal Resources Council, Transactions, v. 6, p. 463-466.

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ABSTRACT — The Boise Geothermal System will begin delivering geothermal water for space heating in the fall of 1982. Boise Geothermal represents one of the first district heating systems to become operational from the ERDA and DOE programs to stimulate geothermal development. This paper discusses the economic aspects of the project. The pricing policy and operating cost structure are compared, along with the role of a drilling partnership from the private sector. Also described are Boise Geothermal's marketing activities to date and the obstacles that have been encountered in trying to convince building owners to convert their heating system to use geothermal water. The paper presents actual financial data and describes actual marketing experiences. Although the literature contains many feasibility studies, Boise Geothermal is the first of the new heating districts for which actual data are available.

Miller, R.J., 1982, The influence of decline rates and pressure interference effects on the economic viability of vapor-phase geothermal reservoir development: Geothermal Institute, University of Auckland, Auckland, New Zealand, Report No. CONF-8211142, p. 81-85.

ABSTRACT — The sensitivity of the economic feasibility of development of geothermal reservoirs for electric power generation to decline rate and intra-reservoir pressure interference effects in vapor dominated reservoirs are examined. Decline rate can be shown to be the primary controlling factor in determining economic viability due to the sensitivity of infill drill requirements to variance in decline rate over long-term (30 year) production. The additional influence of intra-reservoir pressure interference between

wells and well-groups is examined to establish: the initial impacts of multi-well production groups on individual well and well-group performance. The long-term influence of inter-well inference from original well groups and infill drilling.

Murphy, H.D., R.H. Drake, J.W. Tester, and G.A. Zyvoloski, 1984, Economics of a conceptual 75 MW hot dry rock geothermal electric power station: NTIS Report No. LA-UR-83-2258, 25 p.

ABSTRACT — Man-made, Hot Dry Rock (HDR) geothermal energy reservoirs have been investigated for over ten years. As early as 1977 a research-sized reservoir was created at a depth of 2.9 km near the Valles Caldera, a dormant volcanic complex in New Mexico, by connecting two wells with hydraulic fractures. Thermal power was generated at rates of up to 5 MW(t) and the reservoir was operated for nearly a year with a thermal drawdown less than 10°C. A small 60 kW(e) electrical generation unit using a binary cycle (hot geothermal water and a low boiling point organic fluid, R-114) was operated. Interest is now worldwide with field research being conducted at sites near Le Mayet de Montagne, France; Falkenberg and Urach, Federal Republic of Germany; Yakedake, Japan; and Rosemanowes quarry in Cornwall, United Kingdom. To assess the commercial viability of future HDR electrical generating stations, an economic modeling study was conducted for a conceptual 75 MW(e) generating station operating at conditions similar to those prevailing at the New Mexico HDR site. The reservoir required for 75 MW(e), equivalent to 550 MW of thermal energy, uses at least 9 wells drilled to 4.3 km and the temperature of the water produced should average 230°C. Thermodynamic considerations indicate that a binary cycle should result in optimum electricity generation and the best organic fluids are refrigerants R-22, R-32, R-115 and R-600a (Isobutane). The break-even bus bar cost of HDR electricity was computed by the levelized life-cycle method, and found to be competitive with most alternative electric power stations in the US.

Oregon Institute of Technology, 1982, Sonoma State Hospital, Eldridge, California, geothermal-heating system: Conceptual design and economic feasibility report: NTIS Report No. DOE/ET/27256-T30, 71 p.

ABSTRACT — The Sonoma State Mental Hospital, located in Eldridge, California, is presently equipped with a central gasfired steam system that meets the space heating, domestic hot water, and other heating needs of the hospital. This system is a major consumer of natural gas — estimated at 259,994,000 cubic feet per year under average conditions. At the 1981 unit gas rate of \$0.4608 per them, an average of \$1,258,000 per year is required to operate the steam heating system. The hospital is located in an area with considerable geothermal resources as evidenced by a number of nearby hot springs resorts. A private developer is currently investigating the feasibility of utilizing geothermally heated steam to generate electricity for sale to the Pacific Gas and Electric Company. The

developer has proposed to sell the byproduct condensed steam to the hospital, which would use the heat energy remaining in the condensate for its own heating needs and thereby reduce the fossil fuel energy demand of the existing steam heating system. The geothermal heating system developed is capable of displacing an estimated 70 percent of the existing natural gas consumption of the steam heating system. Construction of the geothermal fluid distribution and collection system and the retrofits required within the buildings are estimated to cost \$1,777,000. Annual expenses (operation and maintenance, insurance, and geothermal fluid purchase) have been estimated to be \$40,380 per year in 1981 dollars. The proposed geothermal heating system could then be completely paid for in 32 months by the savings in natural gas purchases that would result.

Parker, J.M., and R.A. Maurer, 1983, An economic feasibility study for a geothermal-coal hybrid power plant in Chaffee County, Colorado: Colorado School of Mines Quarterly, v. 78, no. 1, 38 p.

ABSTRACT — The feasibility of a geothermal-coal hybrid power cycle was studied in comparison to a strictly geothermal and a coal-fired plant in the Chalk Creek area, Chaffee County, Colorado. The geothermal reservoir in this area is postulated to be liquid dominated with a temperature ranging from 150°C to 200°C (Pearl, 1978). The thermal waters are very low in dissolved solids (250 mg/l), and, therefore, corrosion problems should be minimal in steam turbines. Development of the geothermal resource in the Chalk Creek area has been limited so far to direct use in greenhouses, swimming pools, and residential space heating. This paper considers the possibility of generating approximately 50 MW of power using the available geothermal energy in a hybrid or geothermal cycle as an alternative to producing electricity from a straight coal-fired plant.

Quitzau, R., and Z. Bassiouni, 1981, Economic potential of geopressured aquifers under different schemes of exploitation: Geothermal Resources Council, Transactions, v. 5, p. 733-736.

ABSTRACT — A calculation technique was developed to evaluate the economic potential of a geopressured aquifer for numerous conditions that could allow the exploitation of this unconventional gas resource. This technique allows for the evaluation of both wells drilled with the sole intent of producing the geopressured resource and of unsuccessful conventional hydrocarbon wells completed in geopressured intervals. The calculation technique allows also for the consideration of different water disposal methods and different taxation schemes. The technique was applied to a typical Gulf Coast geopressured aquifer. From this application is it apparent that for certain likely conditions the conversion of an unsuccessful conventional hydrogen well into a geopressured brine well is economically feasible, provided that any associated environmental and legal problems can be overcome.

Sanyal, S.K., and M. Che, 1982, A sensitivity study of the economic parameters for The Geysers geothermal field, California: Geothermal Resources Council, Transactions, v. 6, p. 43-46.

ABSTRACT — This paper analyzes the sensitivity of the revenue to be derived by the developer at The Geysers to the variations in fifteen most important variables. The "cost" variables considered were drilling cost per well, redrilling cost per well, facilities cost per drilled well, facilities cost per redrilled well, gathering system cost per production well, disposal system cost per injection well and operating cost per well. The "rate" variables considered were deliverability decline rate, rate of drilling success, rate of redrilling success; rate of well loss per year due to mechanical causes, plant factor, steam price escalation rate, inflation rate and discount rate. Harmonic decline in well deliverability was assumed, based on the observed production decline and reported theoretical results. The results showed that cumulative revenue is most sensitive to the drilling cost per well among the cost variables, and to the steam price escalation rate among the rate variables.

Sifford, A., and E. Allen, 1983, Comparison of geothermal direct-use pricing terms in seven western states: Geothermal Resources Council Bulletin, v. 12, no. 1, p. 11-13.

ABSTRACT — A comparative survey of pricing terms in 21 direct-use projects in seven western states is summarized. The survey was undertaken to determine the character of pricing strategies which are currently in place or proposed for direct-use projects. A majority of projects are shown to base their geothermal price on a discounted natural gas rate. The average discounted rate for non-profit projects is calculated to be 56% of current gas rates; for profit projects the average is 66% of gas rates. The average delivered geothermal price for all projects basing rates on gas and oil was \$3.80/MMBtu as of March 1982.

Struhsacker, D.W., 1981, Variation of direct-heat geothermal economics with project size: Geothermal Resources Council Bulletin, v. 10, no. 9, p. 3-14.

ABSTRACT — A comparison of the economics of large, intermediate, and small direct-heat geothermal projects is presented. An attempt is made to define which types of direct-heat geothermal projects are most cost-efficient and produce the most energy for the least amount of money. The potential energy contribution of fourteen different sizes of direct heat projects is used to determine the number of projects of a given size required to produce 1 Quad of energy. The cost of developing 1 Quad of direct-heat geothermal energy from large, intermediate, and small projects is compared to the cost of 1 Quad of energy from conventional sources. The engineering and development of large-scale projects is stressed as the way in which direct-heat geothermal energy can make the most significant contribution to the nation's energy requirements.

Todd, J.H., 1984, Capital cost and performance of alternative wellhead power systems: Electric Power Research Institute Report No. EPRI-AP-3686, p. 3.29-3.32.

ABSTRACT — Much interest has been shown by contractors, equipment suppliers and the utilities, in the use of geothermal energy to generate electricity. The interest has spawned many ideas on how this could best be accomplished. Various conversion concepts and unit sizes were offered by enterprising individuals as well as corporations, each offering their unique benefits. As the various concepts matured, the question of unit size gained more interest. The small wellhead units were promoted by some while the larger central units were viewed by others as the more economically viable way to develop large geothermal fields. A study was conducted to determine performance and cost trends for various size wellhead units. The study considered various concepts and unit sizes for different resource temperatures. The objectives, study methodology and scope of the project are presented.

US/China Conference on Energy, Resources and Environment, 1982, Cost effective safe disposal of geothermal fluid, in Kaczynski, V.W., and S.W. Yuan (eds.), Energy, Resources and Environment: New York, Pergamon Press, p. 303-307.

ABSTRACT — Results of a generic research study to determine the potential of disposing of spent geothermal fluids via wetlands treatment are presented. Costs are compared with those for reinjection of the spent fluids into the geologic reservoir. Effluent application criteria and

general guidelines for wetland disposal are presented. Results indicate that the wetlands disposal alternative has general merit and can be environmentally safe. Some pretreatment of effluents may be required before wetlands disposal. High technology pretreatment or high effluent disposal rates plus a zero discharge requirement are not cost competitive to effluent reinjection. Under all other conditions, wetland effluent disposal is economically attractive.

Ziman, G.M., and L.S. Rosenberg, 1983, A comparison of economic evaluation models as applied to geothermal energy technology: Energy, v. 8, no. 10, p. 797-811.

ABSTRACT — Several cost estimation and financial cash flow models have been applied to a series of geothermal case studies. In order to draw conclusions about relative performance and applicability of these models to geothermal projects, the consistency of results in this study were net present value, internal rate of return, or levelized breakeven price. The models used were VENVAL, a DuPont, Inc. venture analysis model: the Geothermal Probabilistic Cost Model (GPC Model) and the Alternative Power Systems Economic Analysis Model (APSEAM), which were developed at the Jet • Propulsion Laboratory (JPL); the MITRE Corporation's Geothermal Loan Guarnatee Cash Flow Model (GCFM); and the GEOCOST and GEOCITY geothermal models developed by Battelle Pacific Northwest Laboratories. The case studies to which the models were applied include a geothermal reservoir at Heber, CA; a geothermal electric power plant to be located at the Heber site; an alcohol fuels production facility to be built at the Raft River, ID; and a direct-use, district heating system in Susanville, CA.

Special Report 14 Addendum

Legal, Regulatory and Institutional Aspects of Geothermal Energy

Abstracts Reviewed by Jack J. McNamara and Owen Olpin

LEGAL

Bronder, L.D., and R.T. Meyer, 1981, Evaluation of state taxes and tax incentives and their impact on the development of geothermal energy in western states: NTIS Report No. EGG-GTH-5450, 168 p.

ABSTRACT — The economic impact of existing and prospective state taxes and tax incentives on direct thermal applications of geothermal energy are evaluated. Study area is twelve western states which have existing and potential geothermal activities. Economic models representing the geothermal producer and business enterprise phases of four industrial/commercial uses of geothermal energy are synthesized and then placed in the existing tax structures of each state for evaluation. The four enterprises are a commercial greenhouse (low temperature process heat), apartment complex (low temperature space heat), food processor (moderate temperature process heat), and small scale energy system (electrical and direct thermal energy for a small industrial park). The effects of the state taxations on net profits and tax revenues are determined. Tax incentives to accelerate geothermal development are also examined. The magnitudes of total state and local tax collections vary considerably from state to state, which implies that geothermal producers and energy-using businesses may be selective in expanding or locating their geothermal operations.

Elmer, D.B., 1977, A comparison of scientific and legal definitions of geothermal energy resources: Geothermal World Directory, 1977/78 edition, p. 360-368.

ABSTRACT — Paper discusses legal case histories and definition disputes associated with the proceedings.

Energy Research and Development Administration, 1978, Legal and institutional impediments to geothermal energy resource development: A bibliography: NTIS Report No. TID-3365, 108 p.

ABSTRACT — This bibliography contains 485 references to literature on the subject of legal and institutional constraints to the development and use of geothermal resources. In addition to government-sponsored reports, journal articles, and books, the bibliography includes specific state and Federal laws and regulations, court cases of interest, and conference proceedings. For each reference, abstract or a listing of subject descriptors is given along with the complete bibliographic citation. Corporate, author, subject, and report number indexes are included.

GRIPS Commission, 1981, Geothermal policy development program.

Geothermal issues that cross county lines: NTIS Report No. DOE/ET/27194-T3, 60 p.

ABSTRACT — The principal issues related to geothermal resources for the production of electricity, which cross county lines, as well as issues which may not cross county lines but which are of common concern to the four counties in The Geysers-Calistoga KGRA are identified and described briefly. As this compilation makes clear, the generation of electricity at The Geysers does not occur in a trouble-free environment—rather, it occurs under difficult circumstances componded by jurisdictional fragmentation. These factors are recognized by grouping the issues according to whether they are Environmental, Administrative, or Planning in nature.

GRIPS Commission, 1981, Geothermal policy development program analysis of county general plans, specific plans and zoning: NTIS Report No. DOE/ET/24194-T2, 45 p.

ABSTRACT — This study evaluates the local geothermal permitting practices of the four Geysers-Calistoga KGRA counties (i.e. Lake, Mendocino, Napa and Sonoma), in California, and the ways in which these processes could be expedited. The detailed analysis of local permitting processes undertaken in the course of this project revealed great variation in procedural approach, types of conditions imposed,

phrasing of conditions and lengty of time it takes to process use permits; and these variations are described in the report. The analysis also revealed a number of interesting techniques employed by one or the other of the counties, or by Imperial County, to improve the process. These techniques are also described. Finally, four alternative approaches to expediting the local government permitting process are identified.

GRIPS Commission, 1981, Geothermal policy development program: Expediting the local geothermal permitting process: NTIS Report No. DOE/ET/27194-T4, 216 p.

ABSTRACT — For a number of years, concerns have been raised about the length of time and the complexity involved in obtaining required permits in order to develop the geothermal resource at The Geysers. Perhaps the most important factor is jurisdiction. At The Geysers, all three levels of government - local, state, and federal - exercise significant authority over various aspects of geothermal development. In addition, several agencies within each governmental level, play an active role in the permitting process. The present study is concerned primarily with the local permitting process, and the ways in which this process could be expedited. This report begins by looking at the local role in the overall permitting process, and then reviews the findings and conclusions that have been reached in other studies of the problem. This is followed by a case study evaluation of recent permitting experience in the four Geysers-Calistoga KGRA counties, and the report concludes by outlining several approaches to expediting the local permitting process.

JM Energy Consultants, 1978, Legal and institutional problems facing geothermal development in Oregon and Washington: NTIS Report No. SAN-2121-7, 36 p.

ABSTRACT — The energy supply and demand picture of these two states is sketched. The perceived legal and institutional problems facing geothermal are shown against the backdrop of this broader, energy policy portrait. The following are discussed: the Bonneville Power Administration regional power broker; other key institutional players; industrial users, public utilities, two state governments, and one regional commission; and a legal/institutional agenda for the Pacific Region team.

JM Energy Consultants, 1978, Legal and institutional problems facing geothermal development in Hawaii: NTIS Report No. SAN-2121-6, 34 p.

ABSTRACT — The problems discussed confronting future geothermal development in Hawaii include: a seemingly insoluble mismatch of resource and market; the burgeoning land claims of the native Hawaiian community; a potential legal challenge to the State's claim to hegemony over all of Hawaii's geothermal resources, regardless of surface ownership; resistance to any sudden, large scale influx of mainland industry, and questionable economics for the largest potential industrial users.

JM Energy Consultants, 1978, Legal and institutional problems facing geothermal development in Alaska: NTIS Report No. SAN-2121-4, 47 p.

ABSTRACT — The major players and the major difficulties each presents to geothermal development in Alaska are sketched. The following are included: the Alaskan natives, the posture of the state of Alaska, and the federal lands.

JM Energy Consultants, 1979, Site-specific legal and institutional analysis of the barriers to geothermal hydrothermal commercialization present at target prospects in the five Pacific rim states: NTIS Report No. DOE/ET/27241-T9, 52 p.

ABSTRACT — The specifics of the permitting process, land access, power plant siting, water law, and other legal or institutional barriers or conflicts are presented for each of the most highly regarded target electric prospects in the five Pacific Rim States: California, Hawaii, Alaska, Oregon and Washington.

JM Energy Consultants, 1980, State water rights law and geothermal hydrothermal commercialization in five Pacific rim states: NTIS Report No. DOE/ET/27241-T6, 53 p.

ABSTRACT — The water rights of the Pacific states - California, Oregon, Washington, Alaska, and Hawaii - and their possible impacts on geothermal development are discussed.

JM Energy Consultants, 1980, Tracking federal land management: Report No. 3 on federal land management actions impacting geothermal commercialization at selected target prospects in five Pacific Rim States: NTIS Report No. DOE/ET/27241-T7, 5 p.

ABSTRACT — Generic land management actions affecting geothermal commercialization in Pacific rim states are reviewed. Specific federal land management actions affecting geothermal prospects in California and the Pacific Northwest are described.

JM Energy Consultants, 1981, Study and analysis of selected legal, institutional, and public-policy problems effecting hydrothermal geothermal commercialization in the five Pacific rim states. Final technical report: NTIS Report No. DOE/ET/27241-TI, 9 p.

ABSTRACT — Summaries and updates of sixteen technical reports issued on this project are included. They cover: in depth analyses of the Federal land management-related problems present at major target prospect KGRA's throughout the Pacific rim states; financial incentives; transmission line access; substantive environmental requirements in air, water, and solid wastes; water law; and the geothermal-impacting activities of the legislative and regulatory agencies of the State of California.

McDevitt, P., and Wells, D., 1982, Energy-market impacts of the legal definitions of geothermal energy in the Western United States: Natural Resources Journal, v. 22, no. 2, p. 391-406.

ABSTRACT — An analysis of the energy-market impacts of temperature-based statutory definitions of geothermal energy during the 1985 to 1995 period and using three temperature minima leads to three conclusions: (1) The market potential is a function of the minimum temperature selected, and states should designate the highest-possible minimum temperature to avoid conflict between traditional and energy water demand. (2) The restrictive impacts of minimum temperature upon geothermal energy development are felt in the earliest years following enactment legislation. (3) The market impacts of proposed temperature-based definitions will vary markedly across states. These impacts result from the site-specific nature of the resources and users as well as existing energy-market conditions in each locale. While the assumption that no resources with temperatures below the minimum will be developed for energy purposes will not hold in all cases, competition with traditional water uses will diminish the market potential of geothermal energy.

McNamara, J.J., 1979, Federal land-use planning and the future of geothermal resources development in the U.S.: an unfolding history: Geothermal Resources Council, Special Report No. 6, 14 p.

NO ABSTRACT — This paper examines the specifics of the more important federal land programs:

- The Forest Service's RARE II ("Roadless Area Review & Evaluation") program;
- II: The BLM (Bureau of Land Management) "Wilderness Program;"
- III: The "Alaskan National Interest Lands" bill now before the Congress;
- IV: The National Park Service's "Desert Trail" proposal;
- V: The recent congressional expansion of many national parks and recreation areas;
- VI: The crucial role of a rejuvenated national historical preservation policy.

Muscelli, L.W., 1984, Taxation of geothermal energy resources: Land and Water Law Review, v. 19, no. 1, p. 25-41.

ABSTRACT — This article contains a comprehensive discussion of the current federal income tax treatment of geothermal energy projects. Particular attention is given to the post-1977 amendments to the federal tax laws which have affected geothermal energy taxation. The author also discusses the current tax issues in the geothermal energy area.

Natural Resources Lawyer, 1982, Geothermal energy: the institutional maze and its changing structure: Natural Resources Lawyer, v. 14, no. 4, p. 589-740.

This volume contains the following papers:

GEOTHERMAL ENERGY AND NATIONAL ENERGY POLICY
Donald N. Zillman and Steven Naumann

GEOTHERMAL SALES CONTRACTS

Robert L. Humphrey and Clayton J. Parr

WATER LAW AND THE DEVELOPMENT OF GEOTHERMAL RESOURCES

Owen Olpin and Barton H. Thompson

FEDERAL LANDS AND GEOTHERMAL RESOURCES MANAGEMENT PROGRAMS

Robert D. Conover

GEOTHERMAL LEASING FROM THE DEVELOPER'S POINT OF VIEW

E. Dale Trower

ENVIRONMENTAL PROBLEMS AND GEOTHERMAL PERMITTING

Peter F. Windrem and Gary L. Marr

INCOME TAXATION OF GEOTHERMAL RESOURCES
Peter C. Maxfield

CAPITAL FOR GEOTHERMAL ENERGY PROJECTS
Theodore E. Worcester and Catherine J. Boggs

USE OF LANDS PATENTED UNDER THE STOCK-RAISING HOMESTEAD ACT FOR CONSTRUCTION AND OPERATION OF GEOTHERMAL POWER PLANTS

Tony J. Tanke and C. Delos Putz, Jr.

Olpin, Owen, 1968, The law of geothermal resources: Rocky Mountain Mineral Law Foundation, Fourteenth Annual Institute, Boulder, Colorado, p. 128.

NO ABSTRACT — Paper discusses federal income taxation and other important legal issues pertinent to geothermal resources.

Olpin, O., Tarlock, A.D., and Austin, C.F., 1980, Geothermal development; the relationship between western water law and geothermal resources development: Energy Law Monograph No. 70, Landman, v. 25, no. 5, p. 40-62.

NO ABSTRACT — A discussion of legal aspects of geothermal development in western states as compared to relevant water law.

Rocky Mountain Mineral Law Foundation, 1985, American law of mining (2nd edition): Rocky Mountain Mineral Law Foundation, Boulder, Colorado, v. 1 and 4.

NO ABSTRACT — Both volumes offer discussions on geothermal wells, geothermal resources, leases, agreements and various legal aspects of private and commercial leases.

Sifford, A., 1981, Legal treatment of geothermal resources in BPA marketing area states: Transactions, Geothermal Resources Council, v. 5, p. 619-662.

ABSTRACT — The Bonneville Power Administration (BPA) marketing area encompasses all of three states and portions of five others with identified geothermal resources. Heightened awareness of geothermal energy as a contributor to the region's energy mix has led to the creation of new geothermal statutes in the BPA area. Each state in the BPA has enacted different geothermal ownership statutes. These statutes are examined, and potential impacts on geothermal development in the BPA marketing area discussed.

Stone, C.D., and McNamara, J.J., 1975, Geothermal energy and the law. I. The federal lands management program: NTIS Report No. NSF/RA/S-75/050, 287 p.

ABSTRACT — The development of geothermal-based electricity has been hampered by a broad range of problems in the legal and institutional environment. This report examines the following topics: (1) Pre-leasing procedures, public vs. private assessment; (2) Exploratory permits and related strategies; (3) The rate of geothermal leasing, past and future; (4) Competitive and non-competitive bidding procedures; (5) Lessee qualifications; (6) Lands available for leasing; (7) Noncompensatory lease terms; (8) Ongoing lease-hold and production requirements; (9) Problems of secondary geothermal uses; and (10) Water law conflicts.

Wagner, S.C., and Stepkin, Charles, 1982, Update on federal taxation of geothermal energy: Transactions, Geothermal Resources Council, v. 6, p. 525-528.

ABSTRACT — We are presenting a brief overview and update of federal taxation of geothermal energy. In our oral presentation at the Technical Session we will discuss how these tax laws interrelate and apply to a variety of taxpayers.

REGULATORY

Beeland, G.V., 1984, Survey of environmental regulations applying to geothermal exploration, development, and use: NTIS Report No. EPA-600/2-84-082, 251 p.

ABSTRACT — Federal, State, and local governmental laws and regulations that apply to geothermal energy development are summarized. Most attention is given to those regulations which deal with air pollution, water pollution, solid wastes and impact assessments. Analyses are made of the regulations with respect to resource definition, pollutants currently not controlled, duplicity and overlap in permit and impact assessment requirements, the lack of uniformity of regulations between states, and the probable future approaches to the regulatory problems.

Buck, J.V., D. Gluck, D. Hagman, J. Krier, and S. Thompson, 1977, Regulatory, planning and policy aspects of geothermal energy development in Imperial County, California: NTIS Report No. DLRI-18; NSF/RA-77-737, 228 p.

ABSTRACT — The political and legal aspects of various possible county regulations that could apply to geothermal development in Imperial County, California are examined. The need for regulation, the political environment of Imperial County, relevant energy development experience in other areas, and legal and jurisdictional aspects of geothermal development in Imperial County are considered. Fifteen policy choices are presented relating to the regulation of geothermal development, increasing the benefits of geothermal development for local residents, maintaining county influence over regulatory process and making it more efficient, maintaining an efficient county government, and increasing interactions with local citizens and local governments. The relevance of the research to other jurisdictions, additional research needs, and the Federal role are also discussed. Included are selected election data for Imperial County, a questionnaire and summary of replies on geothermal developments, Imperial County's authority to prepare a geothermal element to its general plan, powers of various levels of government in California to control property and utilities, and summaries of state and regional agency responsibilities as well as summaries of Federal legislation relating to geothermal development.

California State Lands Commission, 1981, Geothermal resource development for direct heat applications: The impact of regulation: NTIS Report No. PB82-208414, 84 p.

ABSTRACT — The laws of 17 western states are reviewed. Interviews were conducted in four states with regulators, drillers and users to determine the economic impact of regulation on development and utilization of geothermal energy for direct heat applications. Four recommendations are made to encourage greater direct heat applications while maintaining reasonable regulation of the drilling and utilization of the resource.

New Mexico Energy and Mineral Department, 1980, New Mexico handbook for geothermal resource development: State and local government regulations: NTIS Report No. DOE/ID/12017-2, 69 p.

ABSTRACT — The regulatory aspects of a wide range of potential projects and sequences within the projects are covered, such as: exploration, demonstration, construction, commercialization, and operation. Such topics as environmental studies, water rights, district heating, taxation archaeological clearances, and construction permits are addressed. Other general information is provided which may assist a prospective geothermal developer in understanding which state and local agencies have review responsibilities, their review procedures, and the appropriate time frame necessary to complete their review process.

Gilmore, C.C., and D.B. Hunsaker, Jr., 1982, Implications of the Clean Air Act and other air-quality regulations on geothermal development in the United States: NTIS Report No. DE82014872, 17 p.

ABSTRACT — Generation of electricity by geothermal power results in lower emissions of criteria air pollutants than power generation from fossil fuel combustion. This situation suggests that air quality regulations would not impede the development of geothermal energy resources. However, an in-depth study of the Clean Air Act and state air quality regulations has determined that such regulations have constrained geothermal development in the past, based on hydrogen sulfide (H2S) emissions from geothermal power plants. The federal enforceability provision of PSD (prevention of significant deterioration) regulations has caused some geothermal plants with controlled emissions at low levels to undergo PSD review, thus extending the time needed for permit approval. To determine the potential effects of air quality regulations upon future geothermal energy development, Federal PSD and non-attainment regulations are examined. The proximity of known geothermal resource area to Class I PSD areas and non-attainment areas are determined. Atmospheric modeling of (H2S) emissions from a hypothetical geothermal plant finds that if recently available control equipment is installed, (H2S) emissions do not constrain geothermal development.

Nimmons, J.T., 1981, Current public utility considerations for geothermal power producers and direct heat distributors: Transactions, Geothermal Resources Council, v. 5, p. 611-614.

ABSTRACT — The benefits now available to geothermal power producers under federal law as implemented through recent rulemaking proceedings of the Federal Energy Regulatory Commission (FERC) are reviewed. Some of the problems created for direct heat developer/distributors by existing state regulatory practices are discussed, and a greatly simplified scheme which could spur development and still accomplish the legitimate objectives of traditional regulatory theory is outlined.

Perlmutter, S., and J. Birkby, 1980, Montana geothermal handbook: A guide to agencies, regulations, permits and financial aids for geothermal development: NTIS Report No. DOE/ID/ 12014-T1, 52 p.

ABSTRACT — The handbook is divided into three parts: a list of the permits required for various thermal projects, and an estimate of time needed to obtain them; a brief discussion of the statutes and regulations referred to; (This information was gathered in a survey of state and federal regulations, as well as in conversations with numerous state and federal officials); and a description of the state and federal grant and loan funding available to a prospective geothermal developer. The names and addresses of the relevant state and federal agencies and legal citations are listed in appendices.

Squier, S.E., Robinson, K.S., and Katz, G., 1981, Regulations on hydrogen sulfide emissions from geothermal development at The Geysers: Transactions, Geothermal Resources Council, v. 5, p. 623-626.

ABSTRACT — Current and proposed federal, state and local emission regulations governing The Geysers geothermal resource area are reviewed. The impacts of these laws on field development and delays associated with regulatory problems are significant, and examples of these are given. Permitting requirements for new or modified geothermal sources are examined.

Wells, K.D., Currie, J.W., Price, B.A., and Rogers, E.A., 1981, Cost of meeting geothermal liquid effluent disposal regulations: NTIS Report No. PNL-2991, 107 p.

ABSTRACT — Background information is presented on the characteristics of liquid wastes and the available disposal options. Regulations that may directly or indirectly influence liquid waste disposal are reviewed. An assessment of the available wastewater-treatment systems is provided. A case study of expected liquid-waste-treatment and disposal costs is summarized.

Wells, K.D., Currie, J.W., Weakley, S.A., and Ballinger, M.Y., 1980, Cost of meeting geothermal hydrogen sulfide emission regulations: NTIS Report No. PNL-2802, 93 p.

ABSTRACT - H₂S emission abatement processes considered feasible for control of airborne emissions included two upstream and two downstream treatment techniques. From literature describing the technical aspects of the processes, individual treatment cost functions were developed. These functions were then used to estimate the range of costs that may be encountered when controlling H₂S emissions to meet given standards. Treatment costs include estimates of certain fixed charges and overheads that normally apply to long lived capital investment projects of similar nature. Continuing experience with control technology for H₂S abatement indicates process application may have a significant impact on the total cost of geothermal electricity at sites with H₂S concentrations in excess of 50 pp mw. Approximately four sites of the 38 USGS high temperature hydrothermal systems fall into this category. At Baca, New Mexico the cost of controlling H₂S emissions was estimated to be 5.5 mills per kWh. Calculations were based on a 50 MWe flashed steam plant using the Stretford-Peroxide combination of processes to achieve 99% abatement.

Woller, N.M., 1983, Land use and regulation of Newberry Volcano:

Oregon Department of Geology and Mineral Industries

Open File Report 0-83-3, p. 114-118.

NO ABSTRACT — Paper discusses land use and regulation of Newberry Volcano, Deschutes County, Oregon, based on a survey of potential geothermal exploration sites at the volcano.

INSTITUTIONAL

Aspinwall, C., J. Caplan, R. James and K. Marcotte, 1980, Geothermal institutional handbook for the state of Wyoming: A user's guide of agencies, regulations, permits and aids for geothermal development: NTIS Report No. DOE/ID/12013-2, 48 p.

ABSTRACT — The agencies involved in geothermal development are listed and individually described. A summary of existing geothermal resource laws and their statute numbers are given followed by a discussion on the problems associated with them. The local agencies and their regulations of geothermal development are discussed. The local, state, and federal agencies directly involved in geothermal development and their permitting requirements are tabulated. Some step-by-step instructions for determining what permits are necessary for developing a specific geothermal resource are given. A list of selected references and a list of additional information and referral are included.

Bloomquist, R.G., 1983, Geothermal resources in the Cascades; accessible/developable; the institutional setting: Geothermal Resources Council, Transactions, v. 7, p. 237-242.

ABSTRACT — Institutional barriers have long been recognized as being primarily responsible for the lack of exploration and development activities in the Cascades. Paramount among these barriers has been the almost total lack of access to federal lands managed by the U.S. Forest Service (USFS). The situation, however, is changing. More and more leases are being offered, and the USFS has begun to experiment with Conditional Right Stipulation leases in order to minimize prelease environmental analyses and thus accelerate the entire leasing process. The liberalization of unitization regulations has resulted in a way around the acreage limitation and hopefully minimized the effect of that barrier until Congress is able to enact legislation to increase the acreage limitation. Finally, a major reorganization in the Department of Interior could, if it proves to be successful, significantly streamline the entire leasing and permitting system. However, the increased accessibility of federal lands and the streamlining of leasing and permitting has, to a large extent; been offset by the announcement of a major electrical power surplus in the Pacific Northwest. The announcement of a power surplus has caused major energy companies as well as independent developers to reassess the developability of geothermal energy in the Cascades and their commitment to such development. The surplus, however, may be replaced by a serious deficit by the early 1990s if WPPSS/Nuclear Plants No. 1 and 3 are terminated or if planned additions to the regional power base do not materialize. If the termination should occur as predicted, the developability of geothermal resources could be dependent only upon the quantity and quality of the resource, and a commitment by the geothermal industry.

Coe, B.A., and N.A./Forman, 1980, Colorado geothermal institutional handbook: A user's guide of agencies, regulations, permits and aids for geothermal development: NTIS Report No. DOE/ID/12018-3, 44 p.

ABSTRACT — The following are included: principal state agencies, applicable state legislation, applicable state regulations, local agencies and regulations, federal agencies and regulations, information sources, and agencies and individuals.

Lienau, P.J., 1984, Geothermal district heating institutional factors: Klamath Falls experience: Geothermal Resources Council Bulletin, v. 13, p. 6-11.

ABSTRACT — The city of Klamath Falls Geothermal District Heating System began providing heat to ten government buildings on 20 March 1984. This start is two and one-half years after completion of the system. Construction and this operation is scheduled for only a four month test period. The delay was the result of citizens objecting to pumping from and injecting fluids into the geothermal reservoir and was legally enforced by means of a city ordinance passed by the voters.

Malysa, L., 1980, Arizona geothermal institutional handbook: NTIS Report No. DOE/ID/12015-2, 75 p.

ABSTRACT — The purpose of this handbook is to assist in understanding the various procedures and requirements necessary for the development of geothermal energy in the State of Arizona. It contains the names of key persons and agencies who are directly or indirectly involved in the institutional process. A detailed assessment of all agencies and the role they play in geothermal energy development is provided. The handbook is divided into four sections: State and Local rules and regulations, the Federal rules and regulations, references, and a technical bibliography.

Sacarto, D.M., 1976, State policies for geothermal development. Uncovering a major resource: NTIS Report No. NSF/RA-760230, 104 p.

ABSTRACT — Policies suited to the development of new energy sources and ideas for enhancing the development of geothermal resources are discussed. Reviewed for the states are various technical, economic, and institutional aspects of geothermal development. Research results from numerous specialists are summarized, and present state and federal policies affecting the geothermal industry are outlined. Key policy areas are identified, and several specific actions suggested for the states. Six appendixes are included: (1) State Laws and Regulations Regarding Geothermal Resources; (2) Federal Geothermal Leasing and Development Regulations; (3) Federal Geothermal Lease Summary; (4) Federal Geothermal Steam Act; (5) Federal Geothermal Energy Research, Development, and Demonstration Act; and (6) Regulations for the Geothermal Loan Guaranty Program.

Sifford, A., 1981, An institutional analysis of development at Big Creek hot spring, in Struhsaker, D.W. (ed.), An analysis of geothermal electric power generation at Big Creek hot spring, Lemhi County, Idaho: U.S. Department of Energy Report No. DOE/10/12079-37, p. 59-63.

NO ABSTRACT — An institutional analysis based on geothermal electric power generation at Big Creek hot springs, Lemhi County, Idaho.

Wagstaff, E.W., and S. Green, 1982, Utah geothermal institutional handbook: NTIS Report No. DOE/ID/12016-2, 90 p.

ABSTRACT — Included in the Handbook are lists of the main permits required and the names of agencies and persons associated with the permits; a summary of pertinent laws, regulations, and permits; and charts outlining typical development and permitting procedures.

Washington State Energy Office, 1982, Institutional and financial

guide to geothermal district heating. Serial No. 2: NTIS Report No. WAOENG-82-03, 29 p.

ABSTRACT — General planning considerations which affect nearly every community are reviewed, and alternative operating structures which are available to communities are reviewed, including local governments, nonprofit cooperatives, private enterprises, and joint ventures. The financing options available to publicly-owned and privately-owned district heating systems are then summarized. The geothermal production and distribution activities most appropriate to each type of operating structure are reviewed, along with typical equity and debt funding sources. The tax advantages for private developers are described, as are the issues of customer contracts and service prices, and customer retrofit financing. The treatment is limited to an introductory overview.

SPECIAL REPORT NO. 14

Abstract Sets Separate and BULLETIN Issues Printed To Date

Exploration Strategies	. 1-21
DRILLING (Printed Set 1984) In An Under Pressured Geothermal Reservoir	25-27
RESERVOIR ENGINEERING (Printed Set 1984) Geothermal Reservoir Engineering	31-38
INJECTION (Nov. 1984)	39-50
GEOTHERMAL WELL LOGGING (Dec. 1984)	51-66
ENVIRONMENTAL CONSIDERATIONS IN GEOTHERMAL DEVELOPMENT (Feb. 1985)	67-76
GEOTHERMAL WELL PRODUCTION (March 1985)	77-84
GEOTHERMAL MATERIALS (April 1985)	85-93
ELECTRIC POWER PRODUCTION (June 1985)	94-103
DIRECT UTILIZATION OF GEOTHERMAL ENERGY (Sept. 1985) 10)4-112
ECONOMICS OF GEOTHERMAL ENERGY (Oct. 1985)	3-120
LEGAL, REGULATORY and INSTITUTIONAL ASPECTS OF GEOTHERMAL ENERGY (Dec. 1985)	21-127