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Introduction

These Proceedings contain 299 papers that resulted from the Second United Nations Symposium on the Development and Use of Geothermal Resources, which was held in San Francisco, California, USA, from **20** through **29** May **1975.** The Symposium brought together approximately **1200** specialists and students of geothermal energy to appraise the status and examine the state of the art of, the exploration for, and the development and use of, geothermal energy. Participants came from 58 countries in addition to the United States and were primarily associated with national and local governments, industry, and universities. The expertise of the participants and the subject matter of these papers cover a wide range which includes the various geological sciences, drilling and production technology, energy utilization, environmental engineering, economics, and law.

The first United Nations Geothermal Symposium took place in Pisa, Italy, in the fall of **1970.** The Proceedings of that Symposium appeared in Special Issue 2 of ***Geothermics,*** the international journal of geothermal research published by the International Institute for Geothermal Research, in Pisa. After the Pisa Symposium, international interest in geothermal energy intensified, exploration efforts were increased, and new fields came into production. In **1973,** United Nations officials decided that increased worldwide scientific interest and advances in geothermal technology warranted a second symposium. In October **1973** the United Nations formally asked the Government of the United States to host the Second United Nations Symposium on the Development and Use of Geothermal Resources. The United States officially accepted this invitation in December of that year.

The United States Department of the Interior was designated lead federal agency responsible for implementing and hosting the Symposium. Additional federal assistance in hosting the Symposium was provided by the United States National Science Foundation, the United States Energy Research and Development Administration, and the Department of State. Other hosts of the Symposium, in addition to the United Nations, were the State of California through its Resources Agency, and the University of California. The organization of the Symposium in the United States and the publication of these Proceedings were under the direction of the United States Organizing Committee-a group **of 21** individuals representing government, academic, and industry interest in geothermal development.

Lawrence Berkeley Laboratory of the University of California prepared the Symposium publications: the Abstracts and this three-volume Proceedings. Abstracts of **358** papers were published in English, French, and Spanish at the time of the Symposium. While the supply lasts, the abstract volume is available for US$lO from the Geothermal Resources Council, P.O. **Box 1033,** Davis, California **95616,** USA. Please specify whether you want the English, French, or Spanish edition. The authors of **274** of the abstracts submitted full papers which are published in these Proceedings. In addition, these Proceedings contain 25 papers which were received too late for inclusion in the Abstracts.

The papers in these Proceedings are divided into **12** sections, each dealing with a different aspect of geothermal energy. The abstract volume had only **1** I sections, but the abstracts' Section **111** has been divided into two sections, I11 and IV, in the Proceedings. Section **I11** is now Geochemical Techniques in Exploration, and

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Section IV is Geophysical Tehniques in Exploration. Technical rapporteurs have summarized the contents of each section, and these 12 summaries are grouped together just before the beginning of Section I in this volume. Each volume of the Proceedings has a complete Table of Contents, Author Index, and Subject Index covering the entire three-volume set. Page numbers run consecutively through the three volumes.

Manuscripts for the Proceedings were accepted in English **(275),** French **(8),** and Spanish **(16)** and are printed in the languages submitted. All French or Spanish papers are followed by English versions of the text. In those cases where authors did not provide an English translation, the United States Organizing Committee had the manuscript translated, and these translated versions have been printed without review by the authors.

In order to hasten publication of these Proceedings, a minimum of editorial changes and corrections were made, and authors were not given the opportunity to proofread their manuscripts prior to final publication. Therefore, the responsibility for editorial or typesetting errors is borne by the United States Organizing Committee.

January **1976** R. 0. Fournier
Executive Director
U.S. Organizing Committee, Inc.

Acknowledgments

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The United States Geological Survey, using funds provided by the United States National Science Foundation, issued a grant to the United States Organizing Committee, Inc. (USGS Grant No. 14-08-0001-(3-161) for editing, translation, and preparation of camera-ready copy to be used in printing the Proceedings.

Other financial contributors to the Symposium were:

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The officers and directors of the United States Organizing Committee, Inc., who were responsible for the financial management of the Symposium and publication of the Proceedings are:

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Summary of Section I
Present Status of Resources Development

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INTRODUCTION

The first two years after the 1970 United Nations geothermal symposium in Pisa, Italy, saw a slow but steady growth in geothermal development and exploration, mainly based on decisions made in the late 1960s. This period was highlighted by the increase of electrical capacity at The Geysers, California, USA, from 78 megawatts electrical (MWe) in 1970 to 237 MWe by the end of 1972 (Worthington, 1975). This period also saw the beginning of construction at Cerro Prieto, Mexico, and the continued development of space-heating and agricultural systems in Iceland, the USSR, and Hungary. Geothermal exploration increased steadily from 1970 to 1972, with substantial efforts in Italy, Japan, Iceland, USA, Indonesia, the Philippines. and Mexico. In addition, the continuing efforts of the United Nations supported exploration in Chile, El Salvador, Ethiopia, Kenya, Nicaragua, and Turkey. Also during these years, an increasing popular and governmental awareness developed of the nature and possible importance of geothermal energy.

The slow, steady increase in geothermal activity accelerated abruptly in 1973 when imported oil became difficult for many countries to obtain and petroleum prices rose sharply. This price rise, combined with a belated awakening to the fact that oil and gas resources are indeed limited, led private industry and governments to pay much more attention to alternate energy sources, particularly in those countries dependent on imported oil. This attention has been manifested in accelerated exploration, increased drilling, and marked expansion of geothermal research and development. The status of geothermal electricity generation in 1975 is shown in Table **1.** Geothermal exploration efforts are not listed in Table I but are outlined below. Also, Table **1** does not reflect the continuing growth in the use of geothermal energy for space-heating and agricultural purposes.

ITALY

The status of geothermal development in Italy is covered in admirable detail by Ceron, Di Mario, and Leardini (p. 59). As of March 1975, the total installed geothermal electrical capacity in Italy was 417.6 MWe, of which 380.6 was in the Larderello region, 15 at Travale, and 22 in the Monte Amiata region (Fig. **1).** Net geothermal power production in 1974 amounted to 2.29 x **IO9** kWh, which represents an average utilization of 64% of total installed capacity. Although 20 productive new wells were drilled in the Larderello region between December 1969 and March 1975, the production of old wells decreased notably, resulting in a net decrease of 9.1% in steam production. In part this decrease was offset by replacing atmospheric turbines with more efficient condensing turbines.

In the Monte Amiata region, steam production from December 1%9 to March 1975 decreased 28%, in part due to rapid inflow of recharge water into the Bagnore field.

Extensive exploration in the Travale region since 1969 has extended the old field (Cataldi et al., 1970) northeast where five wells have been drilled and a sixth was in progress in May 1975 (Burgassi et al., p. 1571). Although all of the wells encountered high temperatures (up to 270'0, only three are productive (T22, R4, and probably CI). Dry steam from well T22 has been used since July 1973 to supply a 15-MWe power plant (Burgassi et al.. p. 1571).

Extensive exploration is being carried out throughout the pre-Apennine belt by the Ente Nazionale per I'Energia Elettrica (ENEL) in cooperation with the Consiglio Nazionale Ricerche (CNR). In the Monte Sabatini region (Baldi et al., p. 8711, a well drilled at Cesano in January 1975 discovered a geothermal reservoir that produced a brine of 356 OOO ppm total dissolved solids, primarily SO;, Na+, and **K'** (Calamai et al., p. **305).** Temperatures at depth are at least 210°C and may exceed 300°C. At Torre Alfina in the Monte Volsini region, a hot-water geothermal system at a production temperature of 120 to 140°C has been discovered (Ceron, Di Mario, and Leardini, p. 59; Cataldi and Rendina, 1973); and in the Monte Cimini region a hot-water system at 60 to 80°C reservoir temperature was discovered (Ceron, Di Mario, and Leardini, p. 59). Exploration is being carried out in the Naples region (Cameli et al., p. **315;** Baldi, Ferrara, and Panichi, p. 687), near Siena (Fancelli, Nuti, and Noto, Abstract III-23)', and in the Roccastrada, Colli Albani, Roccamonfina, and Vulture areas (Ceron, Di Mario, and Leardini, p. 59). According to Barelli, Calamai, and Cataldi (Abstract **I-3),** the electrical energy potential of the pre-Apennine belt is 130 to 660 MW-centuries.

'The Abstract number refers to the numbering in the abstract volume for this symposium.

Table 1. World geothermal generating capacity in megawatts (electrical), 1975.

Countrv	Field	Operating	Under construction
United States	The Geysers	502	21 6

Italy Larderello 380.6
Travale 15
Monte Arniata 22
New Zealand Wairakei 192
Kawerau 10
Otake 13
Onurna 10
Onikobe 25
Hatchobaru 50
Takinoue 50
Cerro Prieto 75
Japan Matsukawa 22
Mexico Path6 3.5
El Salvador Ahuachapdn 90
Krafla 55
Philippines Tiwi 100
Soviet Union Pauzhetsk 5
Turkey Kizildere 0.5 2.5
Total 1278.8 563.5
Ice1 and Nknafjall 2.5
Paratunka 0.7

USA

The status of geothermal development in the USA is summarized by Koenig, Anderson, and Huttrer (p. **139).** Geothermal electrical capacity at The Geysers, California, has increased rapidly from **78** MWe in **1970** to **502** MWe in **1975.** Additions of approximately **100** MWe per year are planned through **1980,** although it appears that the installation timetable will be delayed by protracted regulatory and environmental hearings.

Although no other geothermal areas in the USA are currently producing electricity, the past five years have seen greatly accelerated exploration by private industry, in great part stimulated by the increased costs of fossil fuel. In addition, the Geothermal Steam Act of **1970** finally was implemented in **1973,** and the vast areas of geothermal potential on federal government land are gradually being made available for exploration by private industry. Signifi-

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Figure 1. Map showing geothermal regions of Italy (after Ceron, Di Mario, and Leardini, p. 59).

cant geothermal discoveries have been made at the Valles Caldera, New Mexico; Roosevelt Hot Springs, Utah; Carson Desert of western Nevada; and the Heber, East Mesa, and Brawley areas of the Imperial Valley in southern California (Fig. **2).** Step-out drilling has extended both The Geysers and the Salton Sea geothermal fields, and there has been continued exploratory drilling at Beowawe, Nevada, and Surprise Valley, California. Exploratory drilling, however, met with little success in California at Honey Lake, Sierra Valley, and Mono Lake; in Oregon at La Grande and Lakeview; in Nevada at Tipton; in Idaho at Mountain Home; in Utah at Brigham City; and in Arizona at Casa Grande and Chandler (Koenig, Anderson, and Huttrer, p. **139).** With the exception of the Casa Grande area (Dellechaie, **p. 339),** virtually none of the data from these drilling ventures have been released by the private companies involved.

The past five years have also seen an upsurge in geothermal research and development financed by the federal government.

The Energy Research and Development Administration (ERDA), created in January **1975** from the old Atomic Energy Commission, is funding research and development in all aspects of the geothermal cycle. Major efforts include the development of technology to extract heat from Got dry rock (Smith et al., p. **1781),** investigation of new conversion technologies (particularly binary cycles and impulse turbines), development of new drilling technologies (for example, Altseimer, **p. 1453),** and investigation of representative geothermal areas, including the Raft River area in Idaho, the area just west of the Valles Caldera in New Mexico (Smith et ai., p. **1781),** several sites in western Nevada (Beyer, Morrison, and Dey, **p. 889),** and the Cos0 Mountains of California. The National Science Foundation (NSF) also carried out a substantial geothermal program in **1973** and **1974,** including site investigations at Marysville, Montana (Blackwell and Morgan, p. **895),** at Kilauea Volcano, Hawaii (Zablocki et al., **1974;** Furumoto, p. **993),** and at Roosevelt Hot Springs, Utah (Ward, Rijo, and Petrick, Abstract 111-90; Whelan, Nash, and Petersen, Abstract 11-55).
Since **1971** the U.S. Geological Survey (USGS) has had an extensive program of investigations aimed at the nature and distribution of geothermal resources, including major investigations at Long Valley (February **1976,** Journal of Geophysical Research), The Geysers (McLaughlin and Stanley, p. **475;** Hearn, Donnelly, and Goff, p. **423;** Donnelly and Hearn, Abstract 111-18; Isherwood, p. **1065),** the Cos0 Mountains, California (Duff ield, Abstract **11- 12;** Duff ield, **1975;** Lanphere, Dalrymple, and Smith, **1975),** southeastern Oregon (MacLeod, Walker, and McKee p. **465),** Raft River, Idaho (Williams et a]., p. **1273),** and Yellowstone (White et al., **1975;** Eaton et al., **1975;** Fournier, White, and Truesdell, p. **731).** In addition, the USGS recently produced a substantial report evaluating the geothermal resources of the United States (White and Williams, **1975).** The Bureau of Reclamation has also carried out geothermal research, primarily aimed at self-desalination of geothermal fluids from the East Mesa area, southern California (Mathias, p. **1741** ; Fernelius, p. **2201** ; Swanberg, p. **1217).**
The geopressured resources of the Gulf Coast are attracting increasing attention (Jones, p. **429;** Wilson, Shepherd, and Kaufrnan, p. 1865). These deposits have a huge energy potential (Papadopulos et al., **1975)** consisting both of thermal energy and dissolved methane.
Geothermal heat is being used directly for space heating on an increasing but still small scale in the United States,

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Marysville
WASHINGTON
MONTANA
P O R T L A N D L a Grande
Yet lawstone
Nationol Park
OREGON IDAHO
WYOMING
***Mountain Home**
Raft River
La kevt ew 0

I

\ * T h e Geysers

Surprise Volley

I Beowawe

*Honey Lake
* S i e r r a Valley
I .Carson Desert
NEVADA
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*Mono Lake
*Long Valley
Brigham City
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Figure 2. Map showing locations of geothermal drilling in the United States and northern Mexico.

primarily at Klamath Falls, Oregon (Lund. Culver. and Svanevik, p. **2147),** and at Boise, Idaho (Kunze et al.. **p. 2141).** Geothermal waters are also **used** for greenhouse heating at scattered localities in the western United States.

Development of the extensive geothermal resources of the USA continues to be plagued by institutional problems (Koenig, Anderson, Huttrer, **p. 139;** Aidlin, p. **2353:** Eisenstat, p. **2369;** Finn, p. **2295;** Schlaugh and Worcester, **1974;** Olson and Dolan, 1975). These problems include ownership considerations (surface vs subsurface), leasing delays, uncertainties about tax status (with respect to depletion allowance and intangible drilling deductions), legal definition of geothermal resources (mineral, gas, water, or ***sui gener-is),*** overlapping and multiple regulatory bodies, and environmental litigation.

JAPAN

Geothermal exploration and development in Japan experienced rapid acceleration since **1970,** primarily in response to the **1973** energy crisis. The dry-steam system at Matsukawa (Fig. 3) and the hot-water system at Otake continue to produce electricity at **22** MWe and **13** MWe respectively, and there are plans to expand Matsukawa to 90 MWe (Mori, p. **183).** A IO-MWe installation has been operating at the Onuma hot-water system since **1973** (UN, Centre for Natural

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TOKYO
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Figure 3. Map showing major geothermal areas of ,Apan.

Resources, Energy, & Transport, p. 31, and a 25-MWe installation has been put into service at the Onikobe caldera (Yamada, p. 665). Drilling is in progress at Takinoue (7 km southwest of Matsukawa) where a 50-MWe plant is to be completed by 1977 (Mori, p. 183). A geothermal power plant of 50-MWe capacity is also under construction at Hatchobaru (Yamasaki and Hayashi, p. 673; Aikawa and Soda, p. 1881). Intensive exploration is being carried out on northern Honshu and on Hokkaido (Mori, p. 183). If these exploration ventures are successful, the geothermal electrical capacity of Japan could well exceed 1000 MWe by 1982.

In addition to the exploration and development efforts described above, the government of Japan has instigated an aggressive program of geothermal investigations, aimed at establishingperhaps 50 *OOO* MWe of geothermal generating capacity by the year 2000 (Mori, p. 183). This program is part of the “Sunshine Project” (Sakakura, p. 2431) and includes extensive regional evaluation by the Japanese Geological Survey (for example, Baba, p. 865; Sumi and Takashima, p. 625).

ICELAND

Geothermal development in Iceland during the past five years is highlighted by the development of the Krafla field (Fig. 4). Production wells have been drilled, and a 55-MWe power station is to be completed in 1976 (Phlmason, Ragnars, and Zoega, p. 213). In addition, the Svartsengi area (235°C reservoir temperature) has been drilled to 1.7-km depth and will be used via a heat exchanger to provide 80 megawatts thermal (MWt; I MWt = **IO6** joule/sec) for house-heating in communities on the western part of the Reykjanes peninsula and at the Keflavik international airport (Arn6rsson et al., p. 2077). The Krisuvik area has also been explored (Arn6rsson et al., p. 853) and could supply perhaps 500 MWt for **100** years.

Geothermal energy in Iceland continues to be used primarily for space heating, but with some electrical generation and process use. Warm water from the Reykjavikand Reykir thermal areas supplies 340 MWt and meets nearly all the heating requirements of Reykjavik and neighboring towns (Tbmasson, Fridleifsson, and Stefhsson, p. 643; Arn6rsson et al., p. 853; Thorsteinsson, p. 2173). New district heating systems using water from which steam has been flashed were installed at Nhafjall (2 MWt in 1971) and Hveragerdi (8 MWt in 1973; Th6rhallsson et al, p. 1445). These geothermal systems are at temperatures of 200 and 215°C respectively, and the district heating systems are consequently plagued with silica-scaling problems. At Nhafjall, the geothermal steam is used to dry diatomite and to generate 2.5 MWe of electricity. A plant for drying seaweed is being constructed at Reykh6lar (Bjornsson and Gronvold, Abstract 11-3; Ludviksson, Abstract IX-7), and studies are being carried out with a view to producing NaCl and **MgCl** from the saline Reykjanes geothermal area (Linda], p. 2223; Bjornsson, Arnbrsson, and Tbmasson, 1972).

Owing to its ideal location on the mid-Atlantic Ridge, Iceland has a very large geothermal potential, both for electricity generation and for space heating. Bodvarsson (p. 33) estimates that the high-temperature areas of Iceland have a production potential of 3200 MWt for 50 years, and that the heat content of recoverable low-temperature resources may amount to the equivalent of 4 x **IO9** tons of petroleum.

MEXICO

Geothermal development in Mexico has been primarily at Cerro Prieto (Fig. 2) where electricity has been generated at 75-MWe capacity since November 1973 (Alonso, p. 17). The **15** wells that supply the power plant produce a watersteam mixture from depths of 900 to 1500 m (Isita S., Mooser H., and Soto P., Abstract 1-17). Plans are being implemented to expand the generating capacity to **150** MWe (Guiza, p. 1973). and the potential of the field is estimated by Tolivia M. (p. 275) to be between 33 and 235 years at a production rate of 150 MWe. Alonso (p. 17) estimates a minimum

ICELAND

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Figure 4. Map showing explored and developed geothermal areas of Iceland.

:osta Rica, and Guatemala, and geothermal energy could

The most noteworthy geothermal advance in Central America since 1970 has been the development of the Ahuachapin field in El Salvador (Fig. *5),* where 16 production wells have been drilled (Romagnoli et al., p. 563). In 1975.30 MWe were to be installed with *60* MWe additional by 1977 (Einarsson, p. 2363). A reservoir study carried out in 1971 estimated the geothermal reserve as at least 50 MWe-centuries (UN, Centre for Natural Resources, Energy, & Transport, p. 3). Ahuachapin is also notable for the apparently successful demonstration of reinjection into the reservoir as a means of effluent disposal (Einarsson, Vides R., and CuCllar, p. 1349).

Geothermal development is also proceeding in Nicaragua,

capacity of 450 to 500 MWe, and Mercado G. (p. 487) estimates a capacity on the order of IO00 MWe for several decades. Isita S., Mooser H., and Soto P. (Abstract 1-17) note that a recent well (M-53) achieved a reservoir temperature of 344°C and produced separated steam at 117 tons per hour at 11 bars wellhead pressure, and suggest that there may be important extensions of the Cerro Prieto field east of the presently exploited area.

Geothermal exploration has taken place at many areas in Mexico (Alonso, p. 17), and extensive investigations including exploratory drilling have been carried out at Ixtlan de las Hervores and Los Negritos (Fig. 5). In addition, intensive geological surveys have been carried out at Los Azufres, La Primavera, and San Marcos. Alonso (p. 17) estimates the geothermal potential of Mexico to be roughly 4000 MWe.

CENTRAL AMERICA AND THE CARIBBEeN

allow Central America to become independent of petroleum imports for power generation by 1980 (Einarsson, p. 2363). Investigations in Nicaragua from 1969 to 1971 under the auspices of the United States Agency for International Development revealed two promising areas, San Jacinto-Tisate and Momotombo, but development efforts were set back several years by the disastrous Managua earthquake of 23 December 1972. Temperatures of 209°C were recorded at 210 m at Momotombo (F. Morlock, oral commun., 1975).

In Costa Rica, reconnaissance geothermal exploration has been carried out for several years by the Costa Rica Institute of Electricity. Current attention is focused on Guanacaste Province where geological and geophysical surveys beginning in July 1976 may lead to the siting of exploration wells later in the year (J. Kuwada, oral commun., 1976). The Guatemalan government expects to begin geothermal drilling at Moyuta in 1976.

Although little geothermal exploration has been carried out in Panama, MCrida (Abstract 1-26) reports the recent discovery of a field having “great possibilities.”

On Guadeloupe in the French West Indies, a drilling program carried out at Bouillante resulted in one well with high production of water and steam from a zone at 338 m and a temperature of 242°C (Demians d’Archimbaud and Munier-Jolain, p. 101). Three other wells, to depths of 800 m, 850 m, and 1200 m, did not achieve significant production. It appears that an extensive reservoir might exist at greater depth. and further drilling is proposed (Demians d’Archimbaud and Munier-Jolain, p. 101).

SOUTH AMERICA

Beginning in 1968. the United Nations Development Program and the Government of Chile conducted an intensive

Figure 5. Map showing geothermal areas being explored or developed in Central America.

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Figure 6. Map showing major geothermal areas of Chile, Peru, and Bolivia.

geothermal exploration program at El Tatio in northern Chile (Fig. **6).** Geological, geochemical, and geophysical investigations, carried out in great part by New Zealand scientists, led to the drilling of six exploration wells (IO-cm diameter) and in 1973-1974 to the drilling of seven production wells (20-cm diameter) to a maximum depth of **1.8** km (Lahsen and Trujillo, p. 157; UN, Centre for Natural Resources, Energy, & Transport, p. 3). The principal producing zone is at 800 to 900 m and has a temperature of 265°C (Lahsen and Trujillo, p. 157). The wells produce a mixture of steam and water, with the water containing appreciable lithium, arsenic, and cesium (Cusicanqui, Mahon, and Ellis, p. 703). Steam equivalent to **18** MWe is obtained from three wells at El Tatio, and a pilot desalination plant has been installed on one well.

In addition to the intensive work at El Tatio, geothermal exploration has been carried out elsewhere along the Andes Mountains of South America, most notably at Puchuldiza and Polloquere in northern Chile (UN, Centre for Natural Resources, Energy, & Transport, p. 3). **In** addition, the Andes in southern Peru and western Bolivia are likely to have similar geothermal potential; Parodi **I.** (p. 219) emphasizes the potential around the Ubinas volcano in Peru, and Carrasco C. (p. 43) describes areas of geothermal potential in the Cordillera Occidental and Altiplano of Bolivia.

TURKEY

During the past five years, the Mineral Research and Exploration Institute of Turkey (MTA) has carried out extensive geothermal exploration (Kurtman and $5milgil, p. 447). primarily in western Turkey (Fig. 7). Geothermal energy is likely to supply 10% of the Turkish electrical energy requirements in the year 2000, and geothermal exploration and development have a prominent place in the **1975** to 1979 five-year economic plan (Alpan, p. 25).

Development of the Kizildere field (Tezcan, p. 1805) has proceeded slowly, owing in great part to serious CaCO, scaling problems. Six out of fourteen existing wells are considered productive (Alpan, p. 25), with a maximum subsurface temperature of 207.4"C. The MTA has built an 0.5-MWe pilot generating plant, and has plans for an 11.4-MWe facility (Alpan, p. 25). In addition, a pilot greenhouse is in operation.

Exploration and drilling are being carried out in the surroundings of Ankara and Afyon, primarily to supply hot water for space heating. At Afyon a well to 905 m recorded a bottom-hole temperature of 106°C and produced at 20 **1** /sec (Tan, p. 1523). Near Ankara, three geothermal areas are under exploration: the Kizilcahamam graben, the Murtet graben, and the Cubuk graben (Kurtman and Shmilgil, p. 447; the Cubuk graben apparently is the same as the Meliksah area of Keskin et al., Abstract **111-51).** The Na:K ratio at Kizilcahamam suggests a reservoir temperature **of** greater than 195"C, and accordingly the area is being considered for the possible production of electricity as well as for space heating.

Exploration and shallow drilling in the Seferihisar and Tuzla regions of western Turkey have discovered areas promising for the production of electricity from hot-water geothermal systems. The Seferihisar area is characterized by many Quaternary rhyolite domes, and chemical geothermometers suggest a reservoir temperature greater than 200°C (Kurtman and Siimilgil, **p.** 447); a temperature of 137°C was measured at 70 m in well (3-2 (Egder and SimSek, p. 349). At Tuzla, post-lower Pliocene dacite domes are associated with sinter-depositing springs, and Na-K-Ca geothermometry suggests temperatures of approximately **215°C** (Kurtman and $5milgil, p. 447). One shallow drillhole has produced a water-steam mixture, with a measured bottomhole temperature of 145°C (Ongur, Abstract **11-36).**

NEW ZEALAN D

Although approximately 8% of the electrical energy used in New Zealand comes from geothermal sources, Wairakei and Kawerau (Fig. 8) remain the only two producing areas. Installed capacity at Wairakei remains constant at **190** MWe, but modifications of the steam collection system to allow multiple flash resulted in a gain in electrical output equivalent to a 20-MWe increase in electrical capacity (Bolton, p. 39). At Kawerau, geothermal fluids continue to supply approximately 11% of the total energy required by the Tasman

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Figure **7.** Map showing geothermal areas being explored in Turkey and Greece.

NEW ZE

Figure 8. Map showing major developed geothermal areas of New Zealand.

Pulp and Paper Company mill (Bolton. p. **37).** Geothermal fluids also are used extensively in Rotorua for heating homes (Burrows, **1970)** and for the air conditioning of a hotel (Reynolds , **1970).**

Geothermal drilling was suspended in New Zealand from **1971** to **1973,** largely because of the expectation that substantial quantities of electricity would be generated from a large offshore natural gas field. In **1973** a program of four wells per year was reactivated at Broadlands. and in **1974** the worldwide energy crisis stimulated a similar drilling program to establish the full potential of the Kawerau field. Twenty-eight wells have now been drilled in the Broadlands field, and seventeen of these wells produce fluid sufficient to sustain a 165-MWe plant. The New Zealand Power Planning Committee has recommended a 150-MWe station to be commissioned in **1981** (Bolton. p. **37).**

Bolton (p. **37)** estimates that the New Zealand geothermal fields could produce approximately **1.45** x 10'o kWh/yr. from an installed capacity approaching2000 MWe. Hochstein (Abstract 1-16) gives a similar estimate for proved and “semiproved” reserves. Bolton (p. **37)** notes that only 1556 of the estimated geothermal potential is proven. and accordingly it has been difficult to incorporate geothermal energy into national energy planning.

EAST AFRICA

Since **1970.** the French government has carried out geothermal exploration in the French Territory of Afars and Issas, primarily in the Asal Rift (Fig. **9).** This exploration has led to the conclusion that optimum sites for geothermal wells are not in the central part of the rift but on the margins where any geothermal systems will be sealed (Stieltjes. p. 613). Two wells were drilled in 1975. One of the$e wells had a temperature of 253°C at 1050 m and produced a brine of salinity greater than **190** 000 mg/l (A. C. Gringarten and L. Stieltjes. data presented at the Workshop on Geothermal Reservoir Engineering, Standford University. Dec. IS- **17. 1975).**

Geothermal exploration in Ethiopia has been carried out since **1970** under the United Nations Technical Assistance program. and promising areas were identified in the Lakes District. the Awash Valley, and the northern Danakil Depression (Fig. **9:** UN. Centre for Natural Resources, Energy.

& Transport. p. 3). There are proposals for further work in the Lakes District. possibly leading to a IO-MWe power station.

Of the many hot-spring areas in the Rift Valley of Kenya, only Olkaria, Eburru. and Lake Hannington have been explored (Fig. **9).** At Olkaria, two wells were drilled to 502 m and **942** m in **1957** to **1958** (Noble and Ojiambo, p. **189).** but no further exploration took place until a joint program of the United Nations Development Program and the East African Power and Lighting Company began in **1970.** In addition to bringing the deeper Olkaria hole into intermittent production. the program drilled four additional holes at Olkaria to depths of **1.3** km (Noble and Ojiambo, p. **189)** and temperatures up *to* 287°C. Although the Olkaria field appears to be large, output of the wells drilled to date is restricted by the great depth to the water table and by low permeability. Deepening of the existing wells at Olkaria to **1.7** km is planned, along with further drilling in the Olkaria area and possibly the Lake Hannington and Eburru areas. In an area of high-power costs such as Kenya, even wells of only moderate output such as Olkaria **3** and **4** appear to be economically attractive (Noble and Ojiambo, p. **189).**

Geothermal exploration in the western rift of Uganda was renewed in **1973** by the Uganda Geological Survey and Mines Department. with limited resistivity and microearthquake surveys conducted at Sempaya, Kitagata, and Lake Kitagata (Fig. **9).** From chemical and resistivity data, Maasha (p. **1103)** estimates a subsurface temperature of at least 160°C at Sempaya. the most promising of the three areas.

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9. Map showing geothermal areas in East Africa.

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Figure 10. Map showing major geothermal areas under exploration in Java and Bali, Indonesia.

INDONESIA

Extensive geothermal exploration has been carried out in Indonesia during the past five years, primarily on the islands of Java and Bali (Fig. **IO).** This exploration is highlighted by the confirmation of the Kawah Kamojang area as a vapor-dominated geothermal system of large potential (Hochstein, p. 1049). As of May 1975, four holes had been drilled to depths of 500 to ***800*** m, and at least two of these wells produce dry steam (Hochstein, p. 1049; Kartokusumo, Mahon, and Seal, p. 757).

The Dieng area of central Java was investigated from 1970 to 1972 by the Indonesian Power Research Institute with initial assistance from the United States Government (Truesdell, 1971; Muffler, 1971). Five holes were drilled in 1972 to depths ranging from 84 to **183** m. Maximum temperature encountered was 173°C at 139 m (Radja, p. 233, as quoted from Danilchik, 1972). Unlike the Kawah

Kamojang area, the Dieng geochemistry suggests the presence of a hot-water geothermal system at depth (Truesdell, 1971).

Exploration has also been carried out at Kawah Derajat, Kawah Cibeureum, Cisolok-Cisukarame, and Tambanan (Bali) jointly by the Geological Survey of Indonesia and Geothermal Energy of New Zealand, Ltd. (Akil, p. I1 ; Radja, p. 233). In addition, the North Banten area has been investigated by Pertamina (the Indonesian oil and natural gas company) and Kyushu University of Japan (Radja, p. 233). Reconnaissance evaluation of the Indonesian islands (Radja, p. 233) indicates substantial geothermal potential throughout the nation.

CANADA

The' regional geothermal potential of Canada has been evaluated in an excellent study by Souther (p. 259). Significant geothermal potential in Canada appears to be concentrated near young, silicic volcanic centers in British Columbia, most prominently Mt. Edziza and Meager Mountain (Fig. **1** I). The latter has been studied in detail by the British Columbia Hydro and Power Authority, and a 347-111 hole has found 69°C water (Nevin and Stauder, p. **1161).** The chemistry of thermal waters in the area suggests a subjacent reservoir of over 185°C (Souther, p. 259).

INDIA

Geothermal reconnaissance has been carried out throughout Indiaduring the past five years, with emphasis on tectonic setting and the interpretation of hot-spring chemistry in terms of subsurface temperatures (Krishnaswamy, p. 143; Subramanian, p. 269; Gupta, Narain, and Gaur, p. 387). The region of most immediate potential appears to be the Himalayan arc in northwestern India (Fig. 12), but the Konkan area, and the Sanha, Cambay, Narbada-Tapti, and Godavari grabens may have significant potential.

Exploration efforts through 1975 have concentrated in the Puga, Chumathang, and Parbati Valley areas of northern India. In the Puga area, six wells at depths up to 80 m recorded temperatures up to 135°C and flowing steam and water; chemical geothermometers suggest a base temperature of 220 to 270°C (Shanker et al., p. 245). At Chumathang, 20 km north of Puga, a temperature of **109°C** was recorded at 30 m, and geochemistry of fluids suggests a reservoir temperature of 145 to 184°C (Shanker et al., p. 245). In the Parbati Valley (which contains the Manikaran area), geochemistry of fluids suggests reservoir temperatures of over 200°C (Jangi et al., p. 1085; Gupta, Saxena, and Sukhija, p. 741; Chaturvedi and Raymahashay, p. 329). In all three areas, scaling by CaCO, appears to be a significant production problem (Subramanian, p. 269; Chaturvedi and Raymahashay, p. 329).

In the Cambay graben, high temperatures and pressures (up to 170°C and **100** kg/cm2) have been found at depths of up to 3.4 km (Krishnaswamy, p. 143), suggesting the

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Figure 11. Map showing geothermal areas being explored in British Columbia, Canada.

CHINA

Figure 12. Map showing geothermal areas and regions *of* geothermal potential in India.

presence of a geopressured resource similar to that in the Gulf Coast of the United States.

Geothermal exploration in India is likely to progress rapidly in the next few years as a new cooperative program between the Ministry of Energy and the United Nations Development Program gets under way in the Parbati Valley and the West Coast (Krishnaswamy, p. 143; Subramanian, p. 269). In addition, further exploration is planned by the Geological Survey of India in the Puga, Chumathang, and Sohna areas (Krishnaswamy, p. 143).

FRANCE

Geothermal development in France has been highlighted since 1969 by the utilization of 70°C water from Jurassic rocks at a depth of 1.8 km in the Paris Basin to heat apartments at Melun (Maugis, 1971; BRGM, 1975; Fig. 13). A similar installation is now being constructed at Creil. 50 km north of Paris (P. Coulbois, oral commun., 1975). Aquifers of temperature greater than 50°C have also been identified in other sedimentary basins of France, in particular the Aquitanian Basin and Alsace (BRGM, 1975). Geochemical exploration for geothermal resources has also been carried out in the Massif Central (Fouillac et al., p. 721).

GREECE

Since 1970, reconnaissance geochemical exploration has been carried out in six areas of Greece (Dominco and Papastamatoki, p. 109): the Sperchis graben, Sousaki, Methane, Lesbos, Nisiros, and Milos (Fig. 7). The most promising area of the six appears to be the island of Milos, where a 70-m hole drilled in 1972 discharged steam and water and had a bottom-hole temperature of 138°C (Dominco and Papastamatoki, p. 109). A program of deep test drilling on

Creil

- Melun

PARIS

F R A N C E

Massif

Aquitanian Central

Basin

Figure 13. Map showing areas of geothermal development and exploration in France.

Milos is planned. Greek thermal waters appear to be a mixture of sea water and meteoric water, with salinities as great as, and locally exceeding, that of sea water (Dominco and Papastamatoki, p. 109).

EASTERN EUROPE AND THE USSR

The temperature map given by termhk, Lubimova, and Stegena (p. 47, Fig. 6) shows that temperatures greater than 40°C at 1 km exist over much of southeastern Europe. The Pannonian Basin of Hungary and the basins immediately

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Figure 14. Map showing geothermal areas and regions of eastern Europe.

north and south of the Caucasus have temperatures greater than 50°C at I km, and geothermal resources have been developed for space-heating and agricultural purposes in all three areas.

In Hungary, thermal waters are produced from highly permeable upper Cenozoic sandstones at depths up to 2.5 km and temperatures up to 150°C (Boldizsir and Korim, p. 297). Most of the geothermal production is from southeastern Hungary, in a belt extending northeast from Szeged to Debrecen (Fig. 14), with some utilization in northwestern Hungary and at Budapest (Boldizsir and Korim, p. 297, Fig. 1; Balogh, p. 29). At the end of 1974, there were 433 wells in Hungary producing water at greater than 35°C wellhead temperature. These 433 wells produced 461 m3/min, giving 1010 MWt (Boldizsir and Korim, p. 297). Balogh (p. 29) estimates that 5 to 30 x 1010 m3 of thermal water can be recovered from depths of 1.5 to 2.5 km beneath Hungary. Boldizsir and Korim (p. 297) estimate the water recoverable from the main reservoir (the iower Pliocene sandstones) to be 28 x 1 O ' O m3, with a usable heat content

Geothermal resources similar to those of Hungary also occur in the surrounding countries, but there has been little utilization to date. Figure 1 of Boldizshr and Korim (p. 297) shows clearly that the area of high geothermal gradients in southeast Hungary extends into Romania (see also C. Opran quoted in Geothermics, 1974, v. 3, p. 82), and that the area of high gradients in northwestern Hungary extends northeast into Czechoslovakia. Figure 6 of Cermak, Lubimova, and Stegena (p. 47) suggests that temperatures of greater than 50°C at 1 km occur in Austria and Yugoslavia.

Geothermal investigations have been carried out in the Slovakian Socialist Republic (Franko and RaEickf, p. 131) and are beginning in Bohemia (the Czech Socialist Republic; T. PaTes, oral commun., 1975). In Slovakia, the most promising region is the central depression of the Danube Basin, southeast of Bratislava, where water at 138°C has been found at 2.5 to 3 km (Franko and RaEickf, p. 131).

Although heat-flow and geothermal gradients are not as high in Poland as in the countries to the south, there still may be opportunities for geothermal utilization in southwestern Poland (Dowgiao, p. 123). Water up to 60°C has been produced from drillholes into granite at depths of 660 and 750 m at Cieplice, and water up to 46°C has been produced in a drillhole into granite at a depth of 700 m at Ladek. The silica content of the Cieplice water suggests that temperatures at depth exceed 100°C. Thermal waters also have been found in drillholes into Mesozoic sediments beneath Silesia; one well has produced 19.4 1 /sec of 595°C water (Dowgiao, p. 123).

From all indications, the use of geothermal energy in the USSR continues to expand rapidly, although very few specific data were presented to the United Nations Symposium. Kharahashiyan and Khelkvist (Abstract 1-18) state that 28 geothermal fields in the USSR are in industrial operation, mainly supplying heat to houses, industries, and agricultural operations, and that 200 000 m of exploratory geothermal wells have been drilled since 1966. According to Fomin et al. (p. 129), geothermal resources in the USSR could supply greater than 10^{18} J/yr. Mavritsky and Khelkvist (p. 179) estimate the "reserves" (potential yield?) of thermal waters with temperatures of 40 to 250°C in the USSR to be 22×10^6 m^3 per day. These "reserves" consist of "steam-water deposits" (> 100°C reservoir temperature?) in of5 x 1019~.

Kamchatka and the Kuril Islands, and "thermal water deposits" in Kamchatka, the Caucasus, Middle Asia, Kazakhstan, and Siberia. Hydrothermal convection systems with temperatures up to 257°C in Kamchatka have a natural heat discharge of 3.8×10^9 J/sec, enough to support an electrical generating capacity of 350 to 500 MWe (Fedotov et al., p. 363).

PHILIPPINES AND TAIWAN

Extensive drilling has taken place in the Tiwi area of southeastern Luzon, the Philippines (Fig. IS), and a **100-** MWe geothermal plant is to be completed by 1977, with an additional **100** MWe to follow soon thereafter (UN, Centre for Natural Resources, Energy, & Transport, p. 3). In addition, drilling indicates that the Los Banos area, also

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Figure 15. Map showing geothermal areas in Taiwan and the Philippines.

on Luzon, is of considerable promise. Exploration and some drilling have also been carried out at Tongonan on Leyte, and exploration has been proposed for several promising sites on Negros and Mindanao.

Although no information on Taiwan could be presented at the United Nations Symposium, two geothermal fields have been explored (Chen, 1975). The Tatun field (Fig.

15) has reservoir temperatures up to 293"C, but acidity of the water (pH ***2)*** has precluded development to date. A well drilled to 240 m in the Tuchang field found temperatures of 173°C and a sodium bicarbonate fluid of pH 8.5.

AZORES (PORTUGAL)

Geothermal exploration has proceeded in the Azores, albeit somewhat inadvertently, since 1970. One hole was drilled to 981 m on the north flank of Agua de Pau volcano on the island of S5o Miguel by Dalhousie University (Halifax. Nova Scotia, Canada) as part of an investigation into the processes of formation of oceanic islands. Although the drill hole was not intended for geothermal exploration, temperatures of over 200°C were found at depths greater than 550 m (Meucke et al.. 1974). Further exploration and development are planned for the area (V. Forjaz. 1975. oral presentation at the Workshop on Small Geothermal Power Plants, Furnas, the Azores, September 8-14. 1975).

CONCLUSION

The acceleration in geothermal development since 1973 has not yet had a major effect on the world's installed geothermal capacity (Table **1)** owing to the lag of two to five years between discovery of a field and commercial utilization. Also, the electrical capacity figures do not reflect the continuing steady growth of direct utilization of geothermal heat. The upsurge in geothermal exploration and production drilling, the dramatic expansion of geothermal research and development. the continuing high petroleum prices. the dwindling supplies of petroleum and natural gas. and the increased awareness of the need for environmental protection are combining to bring geothermal energy from **a** minor curiosity to a significant source of electricity and heat throughout the world.

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Summary of Section 11
Geology, Hydrology, and Geothermal Systems

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INTRODUCTION

This rapporteur report summarizes the ideas and data presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources with respect to geology and hydrology of geothermal systems. The report makes no attempt to deal with mathematical models or reservoir engineering; both are treated by Manuel Nathenson in the rapporteur report for Section **VI1** (Production Technology, Reservoir Engineering, and Field Management). The following discussion of geothermal geology and hydrology has three goals: **(1)** to outline generally accepted models, (2) to highlight areas of agreement, controversy, or uncertainty, and (3) to direct the reader to significant original references, both papers submitted to the Second UN Geothermal Symposium and recent papers published elsewhere.

GEOLOGIC ENVIRONMENTS

It is widely accepted in the scientific community that geothermal energy is the natural heat of the earth. This heat is stored in rock and water within the earth and can be extracted by drilling wells to tap anomalous concentrations of heat at depths shallow enough to be economically feasible (usually less than 3 km). Water or steam transfers heat from rock to a well and thence to the surface. Accordingly, a commercially attractive geothermal system **must** have sufficient permeability to allow large quantities of water or steam to be extracted for a prolonged time.

Regions of Normal Heat Flow

Most of the heat stored in the outer 10 km of the Earth is in regions of normal heat flow (1.5 x cal/cm2 sec = 1.5 heat flow units = **1.5** hfu) where geothermal gradients are 20 to 40"C/km (for example, Diment et al., 1975). Utilization of this energy is limited primarily by the great depths and consequent high drilling costs necessary to reach water with temperatures sufficiently high even for space heating, and secondarily by low porosity and permeability of most rocks at such depths. Although possible breakthroughs in drilling technology (for example, Altseimer et al., Abstract **V-I;** Altseimer, p. 1453) and hydrofracturing (for example, Smith et al., p. 1781) could permit widespread commercial extraction of heat from normal-gradient areas, utilization with present technology requires a large, porous, and permeable aquifer at a location where there is demand for fluids at less than 100°C for space-heating or agricultural purposes. These conditions currently are satisfied in the Paris Basin (Coulbois and Herault, p. 2099; BRGM, 1975; Maugis, 1971) and in some areas of the USSR (Mavritsky and Khelkvist, p. 179).

In addition, there are areas of normal heat flow where large, porous aquifers contain water at pressures well in excess of hydrostatic. These "geopressured" reservoirs are best known in the northern part of the Gulf of Mexico basin (Jones, 1970; Jones, p. 429) but are also found in deep, young sedimentary basins elsewhere in the United States, in the Niger delta of Nigeria (Nwachukwu, p. *205),* in the Cambay graben of India (Krishnaswamy, p. 143) and in the USSR (Mavritsky and Khelkvist, p. 179). In the northern Gulf of Mexico basin, geopressured reservoirs are common at depths of ***2.5*** to at least 7 km at temperatures averaging 165°C (Papadopulos et al., 1975) and at pressures sometimes approaching lithostatic. These geopressured systems have the potential to supply immense quantities of both geothermal energy and energy from combustion of dissolved methane (Papadopulos et al., 1975). Although production of geopressured fluids appears technologically feasible, the economics of production have yet to be demonstrated (Wilson, Shepherd, and Kaufman, p. 1865).

Regions with No Associated Young Volcanic Rocks

Production of geothermal energy for space-heating and agricultural purposes has been shown to be feasible in a number of regions where heat flow is significantly greater than the worldwide normal value of 1.5 hfu. Prominent among these regions is the belt of high heat flow that extends along t_he Alpine orogenic zone in eastern Europe and western Asia (Cermik, Lubimova, and Stegena, p. 47). Within this belt, heat flow and thermal gradient maxima occur in the Pannonian Basin of Hungary and in the areas just north and south of the Caucasus Mountains in the USSR. Boldizshr and Korim (p. 297) state that the heat flow in the Pannonian Basin of Hungary is 2 to 3.4 hfu and that thermal gradients averaging 56"C/km persist to the base of the Cenozoic sedimentary section at nearly 6-km depth. It is generally believed that this high regional heat flow is transmitted into the sediments from beneath, but Shvetsov (p. 609) suggests that the heat liberated from compaction and diagenesis of sediments themselves, in areas of rapid sedimentation (for example 2.5 km per million years), can augment the heat flow substantially.

Regionally high heat flow also is found in the northern Basin and Range province of Nevada and Idaho, USA (Sass et al., Abstract **111-80;** Diment et al., 1975). Regional, permeable aquifers like the middle Pliocene Pannonian formation of Hungary do not exist in the Basin and Range province of the USA. Instead, many normal faults allow deep circulation of meteoric water and serve as loci for numerous thermal springs (Hose and Taylor, 1974).

Regions with Associated Young Volcanic Rocks

It has long been recognized that many geothermal systems have a close spatial and genetic relation to young volcanic centers (Healy, p. 415), in particular, to those of silicic composition, In addition, field studies of intrusive rocks of all ages have shown that most large magma chambers in the upper **1C** km of the continental crust are silicic (Smith and Shaw, 1975). Hence, one approach in the search for geothermal resources is to identify silicic volcanic centers young enough and of sufficient size that molten or hot intrusive rocks still exist at depth and can drive overlying convection systems of meteoric water, This approach has been used by Smith and Shaw (1975) to rank geothermal exploration targets and to estimate the magnitude of geothermal resources related to silicic intrusions in the USA.

In Figure **1,** the ages and volumes of igneous intrusions, deduced to underlie young silicic volcanic centers, are plotted against a family of lines showing solidification times of hypothetical-source magma chambers as functions of various boundary conditions. The geothermal potential is greatest for large, young igneous systems (that is, down and to the right on Fig. **1).** Basic data necessary for this approach include: **(1)** geologic mapping and petrology of volcanic rocks to allow calculation of volumes; **(2)** precise dating of volcanic rocks by K-Ar, **I4C,** thermoluminescence, obsidian hydration, or fission-track methods; and **(3)** numerical models for cooling igneous bodies (for example, Smith and Shaw, 1975; Norton and Gerlach, Abstract 11-35).

An example of this approach in the exploration for geothermal resources **is** given by MacLeod, Walker, and McKee, p. 465. K-Ar dating and geologic mapping define two belts of ryholite domes trending northwest across southeast Oregon, USA, and becoming progressively younger from 10 million years (my.) on the southeast to less than **1** my. near Newberry Volcano. The age-volume relations suggest that high-temperature hydrothermal convection systems are likely to exist only at the northwest end of the belt near Newberry Volcano.

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Figure 1.

represent younges; ages and estimated volume for the best known young igneous systems **of** the United States (see Table 7 of Smith and Shaw, 1975).

Graph of theoretical cooling times for various magma bodies (from Smith and Shaw, 1975, Figure 4). Points

Although the use of Figure **1** is restricted *to* silicic rocks, areas of intensive basalt extrusion may also have significant geothermal potential (Smith and Shaw, 1975, p. 78-83). One such area is in southern Washington State, USA, where a major Quaternary basaltic feeder zone is coincident with a pronounced negative gravity anomaly (Hammond et al.,
Intrusion of magma into the upper crust can generate one or all of three types of geothermal systems: **(I)** magma, (2) hot dry rock, (3) hydrothermal convection.
Magma bodies are known at a number of young volcanoes, most notably at Kilauea Volcano in Hawaii, where basaltic lava ponds in pit craters and remains partly molten for years after extrusion (for example, Peck, Wright, and Moore, 1966). The movement of magma within Kilauea Volcano is monitored using seismological and deformation techniques, and prominent self-potential anomalies on the flanks of the volcano are thought *to* indicate the position of subsurface magma pockets (Zablocki, p. 1299). Magma has been tentatively identified by teleseismic P-delay studies at Yellowstone, Wyoming, and The Geysers. and Long Valley, California (Steeples and Iyer, p. 1199) and is likely to exist under many other volcanoes.
The term “hot dry rock” is commonly applied *to* hot rock that is of *too* low porosity or **is** too impermeable *to* allow natural circulation of water at appreciable rates. An example of hot dry rock is in the Jemez Mountains. New Mexico, USA, where temperatures of 200°C have been found at 3-km depth in Precambrian gneiss and amphibolite of very low permeability (Smith et al.. p. 1781: Albright. p. 847; Jiracek, Smith, and Dorn, p. 1095). Experiments are under way at this site *to* fracture the rock hydraulically and set up an artificial convection system. Similar research efforts are under way at the Avachinsky Volcano, Kamchatka, **USSR** (Fedotov et al., p. 363; Sviatlovsky. Abstract VII-24) and are planned for Japan and Italy. Another possible hot dry rock resource is under study in the Cos0 Mountains, California, USA, where Pleistocene rhyolite domes form a discontinuous veneer over Mesozoic granite near the center of a 40-by-20-km area of late Cenozoic ring faulting (Duffield, Abstract 11-12; Duffield, 1975; Lanphere, Dalrymple, and Smith, 1975). Several drillholes ***to*** I-km depth will be put down at Cos0 in 1976.
Igneous intrusions into permeable water-bearing rocks of the upper crust commonly set up overlying hydrothermal convection systems. Meteoric water circulates downward along faults or aquifers, is heated at depth by the intrusion, and rises buoyantly towards the surface in a column of relatively restricted cross section (White, 1968). For many years it was thought that this water had to be heated by conduction through country rock from the molten intrusion. However, recent studies of **I8O** in Tertiary intrusive rocks have shown that meteoric water can circulate along fractures in a cooling intrusion (Taylor, 1971) and may even penetrate into the liquid magma (Friedman et al., 1974). Analytical studies by Lister (p. 459) suggest that heat output of a hydrothermal convection system is maintained by penetration of meteoric water into the solidified margins of an

intrusion along fractures that propagate inward at 0.2 *to* 20 m/y. Fournier, White, and Truesdell (p. 731) speculate that heat is transferred from the magma under Yellowstone to the dilute hydrothermal convection systems via a hot, slowly convecting, highly saline brine.

Data on a number of hydrothermal convection systems
p. 397).
related *to* silicic intrusive or volcanic activity were presented at the Second UN Geothermal Symposium. The Geysers, California, steam field is clearly associated with the Clear Lake Volcanics of late Pliocene (?) *to* Holocene age (Hearn, Donnelly. and Goff. p. 423; Donnelly and Hearn, Abstract 111-18) and with a major gravity low. Isherwood (p. **1065)** considers that the gravity and magnetic anomalies are caused by a young intrusive body centered 10 km below the southwest edge of the Clear Lake Volcanics, and teleseismic P-delay data suggest that this intrusive body may still be partly molten (Steeples and Iyer. p. 1199). **A** gravity ridge separating the main gravity low from a smaller low at The Geysers is most likely due *to* a northeast-dipping dense caprock that directs hydrothermal fluids from beneath the volcanic field southwest *to* The Geysers (Isherwood, p. **1065).**

The new geothermal discovery at Cesano. Italy (Calamai et al.. p. 305). is clearly associated with the late Quaternary Sabatini volcanoes. The Cesano discovery well was drilled in Boccano caldera, the site of very young phreatic volcanism. and penetrated 700 m of hydrothermally altered diatreme breccia (Baldi et al.. p. 871: Calamai et al.. **p. 305) .**

Other areas associated with silicic volcanism include the Seferihisar area, Turkey (ESder and SimSek. p. 349), and the Salton Sea geothermal field, California (Robinson, Elders, and Muffler, 1976). Areas associated with andesite volcanism include the Cerro Prieto geothermal field, Mexico (Reed. p. 539). El Tatio, Chile (Lahsen and Trujillo, p. 157: Cusicanqui. Mahon. and Ellis, **p.** 703; Hochstein, Abstract 111-39), and the Kawah Kamojang area, Indonesia (Hochstein, **p.** 1049: Kartokusumo, Mahon. and Seal, p. 757).

LOCATION OF GEOTHERMAL SYSTEMS

The revolution in earth science that resulted from the theory of plate tectonics (Cox, 1973) was mentioned only in passing at the First UN Geothermal Symposium in 1970 in Pisa, Italy. By 1975, however, it was widely accepted that geothermal fields are localized in areas of young tectonism and volcanism, primarily along active plate boundaries (Muffler. p. 499; Healy. p.415).

Spreading Ridges

Spreading ridges are zones where new crust is created by intensive igneous intrusion and extrusion, and accordingly they are favorable sites for copious discharge of hydrothermal fluids. Williams (Abstract 1-40) notes that 20% of the Earth's heat loss occurs along the 5.5 x **IO4** km of spreading ridges, which comprise only 1% of the Earth's surface area. Lister **(p.** 459) calculates that the probability of finding a major hydrothermal convection system at a spreading zone is a direct function of spreading rate (0.025 per km of rift length per cm/yr spreading rate). According to Lister's analysis. a major hydrothermal convection system might be expected every 20 km on the mid-Atlantic ridge, every 3 km on the fast-spreading East Pacific rise, and every **100** km on aslow-spreadingcontinental rift zone (for example the East Africa rift or the Baikal rift).

By far the most thoroughly studied submarine geothermal area is the Atlantis 11 deep in the Red Sea. Saline brine trapped in this and other deeps along the axis of the Red

Sea has its origin in hydrothermal discharge from the sea floor. Schoell (p. 583) estimates that the hydrothermal brine responsible for the Atlantis I1 brine pool is discharging at 2.4 **x IO4** I/m and has a subsurface temperature of 210°C.

The spreading ridge that extends from the Indian Ocean through the Gulf of Aden to the Red Sea is emergent from the ocean in the Afar Depression (Tazieff et al., 1972). The southernmost emergent spreading element of this ridge is the Asal Rift, characterized by an axial zone 5 km across where new oceanic crust is forming and very young basalts have been extruded (Stieltjes, p. 613). Geothermal exploration wells were sited just to the southwest of the axial valley, which was interpreted by Stieltjes to be too “open” (permeable ?) to support a good hydrothermal convection system. One of the wells drilled in 1975 found a reservoir at **1050** m and 253°C containing a brine of 190000 mg/l salinity (Gringarten and Stieltjes, 1975).

In a general sense, Iceland also represents a mid-oceanic spreading ridge that extends above sea level (PBlmason and Saemundsson, 1974). The neovolcanic zone extending northwest through Iceland is the locus of extensive Quaternary basaltic volcanism, scattered silicic volcanic centers, and at least 17 major high-temperature hydrothermal convection systems (P&lmason, Ragnars, and Zoega, p. 213; Bodvarsson, p. 33: Hermance, Thayer, and Bjornsson, p. 1037; Arn6rsson et al., p. 853).

The best example of a spreading ridge that extends onto a continent is the East Pacific Rise as it passes north up the Gulf of California into the Salton Trough. Spreading segments separated by transform faults occur throughout the Gulf of California (Lawver, Abstract **111-54;** Williams, Abstract 1-40), and similar segments are represented on land by the young volcanoes and geothermal fields at Cerro Prieto and the Salton Sea (Elders et al., 1972).

Intracontinental rifts are also the loci of young volcanism and geothermal fields, but their low rates of extension result in a lower probability of finding major geothermal areas than along fast-spreading oceanic ridges (Lister, p. 459). The best known example of an intracontinental rift is the East Africa rift, with associated geothermal areas in Ethiopia (Demissie and Kahsai, Abstract **1-10),** Kenya (Noble and Ojiambo, p. 189), and Uganda (Maasha, p. 1103).

Subduction Zones

Subduction zones are belts along which two plates move toward each other, resulting in the consumption of lithosphere, commonly by the thrusting of one plate beneath the other. Melting of downthrust crust produces pods of magma that rise into the upper plate and act as heat sources for overlying hydrothermal convection systems. Geothermal

fields clearly related to subduction zones include:
I . Kawah Kamojang, Java, Indonesia (Hochstein, p. 1049; Kartokusumo, Mahon, and Seal, p. 757), related to thrusting of the India plate under the China plate.
2. Puga, Chumathang, and Parbati Valley of the Himalayas of northwest India (Gupta, Narain, and Gaur, p. 387; Subramanian, p. 269; Krishnaswamy, p. 143; Shanker et al., p. 245; Jangi et al., p. **1085),** related to the same subduction zone as Kawah Kamojang, but in a complex zone of convergence between continental crust of each plate.
3. El Tatio, Chile (Healy, p. 415; Lahsen and Trujillo, p. 157; Cusicanqui, Mahon, and Ellis, p. 703), related to subduction of oceanic crust beneath continental crust along the west coast of South America.

Intraplate Melting Anomalies

Intraplate melting anomalies are also the loci of recent volcanism and associated geothermal fields. Examples of these intraplate melting anomalies are Hawaii (Dalrymple, Silver, and Jackson, 1973) and Yellowstone (Christiansen and Blank, 1969; Eaton et al., 1975).

GEOMETRY OF HYDROTHERMAL RESERVOIRS

Regional Aquifer Systems

Many parts of the world are characterized by laterally extensive thick aquifers of permeable rock that can be tapped for geothermal resources over wide areas. Prominent among such aquifers is the upper part of the Pannonian formation (middle Pliocene) of Hungary, where discontinuous sandstones interbedded with siltstone and shale contain approximately 2800 km3 of 80 to 99°C water, of which perhaps 10% is recoverable (BoldizsL and Korim, p. 297). The Pannonian formation also forms a major geothermal aquifer in the central depression of the Danubian basin of Czechoslovakia (Frank0 and Mucha, p. 979). Regional sandstone aquifers are found in Tertiary sediments of the Gulf Coast of the United States, where growth faults have broken sandstone formations into discrete, geopressured reservoirs (Jones, 1970; Jones, p. 429). Many of these reservoirs are found in the Oligocene Frio Formation of south Texas, USA (Bebout and Agagu, Abstract **11-1;** Dorfman and Sanders, Abstract **11-1** 1). In the Salton Trough of California and Mexico, geothermal resources occur in sandstone lenses in a thick sandstone-siltstone sequence that comprises the Colorado River delta (Swanberg, p. 1217; Reed, p. 539). Major regional aquifers are also found in the Paris Basin, where geothermal fluids at 70°C are produced from the Dogger Limestone of Jurassic age (BRGM, 1975; Maugis, **1971).**

Large volcano-tectonic depressions are favorable sites for geothermal reservoirs (Yamasaki and hay as hi,^. 673; Healy, p. 415). Prominent among these depressions are the Taupo depression of New Zealand, a depression trending westsouthwest from Beppu to Unzen in northern Kyushu, Japan, and the Guatemala-Quezaltenango depression of Central America. Large grabens not necessarily related to young volcanism contain geothermal resources in Turkey and India (Kurtman and Similgil, p. 447; Krishnaswamy, p. 143).

local Stratigraphic Reservoirs

Young calderas commonly are favorable sites for hydrothermal convection systems, both because of the underlying igneous heat source and because of the probability of permeable caldera fill. Major calderas described at the Second UN Geothermal Symposium include Yellowstone (Fournier, White, and Truesdell, p. 731; Truesdell et al., Abstract **111-87;** Morgan et al., p. **1155;** see also Eaton et al., 1975), Onikobe, Japan (Yamada, p. 665), and the Valles Caldera, New Mexico, USA (Jiracek, Smith, and Dorn, p. **1095;** see also Smith, Bailey, and Ross, 1970). Geothermal resources in the Long Valley caldera in California have also been described recently in a number of papers published

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in volume 80, no. 5 of the Journal of Geophysical Research (1976).

Basaltic central volcanoes in the Tertiary strata of Iceland have good reservoir characteristics (Fridleifsson, p. 371). The highly permeable basaltic hyaloclastites erupted under glaciers during the Pleistocene also form important aquifers along the neovolcanic zone of Iceland (Thasson, Fridleifsson, and Stefinsson, p. 643; Fridleifsson, p. 371).

Fractured Reservoirs

Although many geothermal reservoirs seem to be associated with porous and permeable sedimentary or volcaniclastic rocks, perhaps a greater number are related to fractures in rocks that are otherwise impermeable. Bodvarsson (p. 903) states that ". . . fractures of various types are the most important conductors of circulating fluids in practically all major geothermal systems." Grindley and Browne (p. 377) emphasize that major production from many geothermal fields is derived not from the most porous stratigraphic units but from fractures in some of the least porous units. This phenomenon is clearly illustrated by the Kawerau area, New Zealand, where major production is from a dense, fractured andesite (Macdonald and Muffler, 1972).

Traditionally, fractures in geothermal areas have been interpreted to result from tectonic stress and the resulting formation of faults, joints, fractures, and breccias. At the Second UN Geothermal Symposium, however, several papers proposed other mechanisms for the development of fractures.

Bodvarsson (p. 903) presents calculations showing the effect of temperature changes on the width of fractures and suggests that fractures along dikes can form by thermal contraction during soldification of the dikes or by inflow of cold water along the dikes, gradually extending downward the open space against the country rock. Increasing temperature due to ascending hot fluids will close cracks at intermediate depths (a fracture of initial width of **1** mm will be closed in 0.5 yr by a 10°C increase in fluid temperature) but will ***cause*** fracturing at higher levels due to overall expansion of the region.

An elegant analysis of fracturing at Broadlands, New Zealand, is given by Risk (p. 1191). who used detailed bipole-dipole resistivity studies to define the fracturing pattern around a buried rhyolite dome. Measuring stations over the center of the dome show no preferential direction of conduction of electricity, but stations over the periphery of the dome show strong preferential conduction of electricity in directions radial to the center of the dome, suggesting the presence of radial fractures. Borehole data and electrical soundings indicate that these fractures are beneath the dome and hence were probably formed during its extrusion.

Grindley and Browne (p. 377) propose that many breccia zones in geothermal fields are produced by natural hydraulic fracturing in situations where (by self-sealing, for example) fluid pressures exceed the least principle stress by an amount equal to the tensile strength of the rock. According to Grindley and Browne (p. 377). rapid extension of a fissure by hydraulic fracturing may sharply reduce fluid pressure in the fissure and cause adjacent impermeable rocks to fail explosively. This theory of fracture formation in geothermal areas is based in great part on papers by Phillips (1972; 1973). Natural hydrofracturing is also referred to by Norton and Gerlach (Abstract 11-35).

Another method of fracturing is proposed by Vartanyan (p. 649), who hypothesizes a substantial decrease in specific volume of rock at depth by degassing during regional metamorphism, thus producing fractures in overlying rock.

Several examples of geothermal reservoirs in fractured rock were presented at the Second UN Geothermal Symposium. Blackwell and Morgan (p. 895) show clearly that flow of hydrothermal fluids at Marysville, Montana, is controlled by fractures in a Tertiary intrusion in Precambrian country rock. In the Larderello and Travale regions of Italy, production of steam isfromfissures in the Upper Triassic to Jurassic limestones that in general have **low** matrix permeability (Petraccoand Squarci, p. 521; Burgassiet al., p. 1571; Celati et al.. 1975). The steam reservoir at The Geysers is in fractured, indurated Mesozoic graywacke in a complex, southeast-plunging antiform broken by young, northwesttrending faults (McLaughlin and Stanley, p. 475). In Japan, fracture control of geothermal fluid production is emphasized by Sat0 and Ide (p. 579, Yamada (p. ***665),*** and Todoki (p. 635). At Ahuachapfin, El Salvador, permeability of the geothermal reservoir (the Ahuachapin andesite) is predominantly due to fractures (Romagnoli et al., p. 563).

Artificial fracturing to increase permeability and thus allow exploitation of hot dry rock has received much recent attention. In the Jemez Mountains of New Mexico, USA, a program is underway to hydrofract Precambrian gneiss and amphibolite found at 3-km depth and 200°C just west of the Valles Caldera (Smith et al., p. 1781). Similar efforts have begun in the USSR (Diadkin and Pariisky, p. 1609; Fedotov, et al., p. 363; Sviatlovsky, Abstract VII-24) and are being considered in Japan (Hayashida, p. 1997).

HYDROLOGY OF GEOTHERMAL SYSTEMS

Movement of Geothermal Fluids

Vertical upwelling of hot geothermal fluids is suggested by the geometry of the Broadlands area, New Zealand, where resistivity studies have shown the field to be nearly circular with vertical boundaries at least to a depth of 3 km (Risk, Macdonald, and Dawson, 1970). Detailed bipoledipole resistivity and I.P. studies by Risk (p. 1185) show that the south boundary zone of the Broadlands field is **100 to 150** m thick and is probably an impermeable barrier created by deposition of hydrothermal minerals, particularly quartz. The broader boundary on the east side of the field may indicate intrusion of cold water through a leaky boundary (Risk, p. **1185),** as required by Macdonald's (p. 1113) model of the field. A tongue of low-resistivity material extending northwest along the Waikato River suggests subsurface outflow of thermal water (Macdonald, p. **1** 113).

Horizontal movement of geothermal fluids has been emphasized by Healy and Hochstein (1973) and Healy (p. **413,** mainly on the basis of extensive hydrologic data available from El Tatio, Chile (Cusicanqui, Mahon, and Ellis, p. 703; Lahsen and Trujillo, p. 157; Healy, p. 415). Meteoric water originating 15 to 20 km east of El Tatio flows westward and becomes heated as it passes under the volcanic crest of the Andean Mountains. This horizontal flow. primarily through the fractured Puripucar ignimbrite, is impeded to the west by relatively impermeable rocks of the Tucle horst. Upward movement of the thermal water in the Tatio basin occurs on northwest- and northeast-trending fractures. Cusicanqui, Mahon, and Ellis (p. 703) interpret

preliminary tritium data to suggest a time of 15 years for passage of water from the recharge area to the El Tatio basin. A similar model seems to apply to the Ahuachapkn area in El Salvador (Romagnoli et al., p. **563).**

Horizontal movement of thermal water over long distances has also been deomonstrated in Iceland (Bodvarsson, p. **33).** Deuterium isotope data and volcanic structure indicate that the thermal water of the Reykjavik and Reykir areas originates as precipitation in the interior highlands of Iceland and flows over 100 km southwest through buried Quaternary hyaloclastite ridges (Tbmasson, Fridleifsson, and Stefknsson, p. **643).**

Predominantly vertical flow of geothermal fluids along faults is common in many areas, for example, the northern Basin and Range province in Nevada and Idaho, USA, an area of regional extension where meteoric water circulates to many kilometers depth along young normal faults (Hose and Taylor, **1974;** Olmsted et al., **1975).** This type of geothermal circulation is well illustrated by the Raft River area in Idaho (Williams et al., p. **1273).** Geothermal wells were sited at the west edge of the Raft River basin at the intersection of the north-trending Bridge fault and the northeast-trending Narrows structure, which is probably an old shear zone in the Precambrian basement. Large flows of **147°C** water were found at the predicted depth and at the reservoir temperature predicted by SiO, and Na-K-Ca geothermometers **(Young** and Mitchell, **1973).** Igneous rocks in the area are too old **(8** m.y.) to be the source of heat for the geothermal system. Heat flow in the area is **2.5** hfu (T. C. Urban and W. H. Diment, oral commun., **1976),** approximately the same as the regional heat flow of the northern part of the Basin and Range province.

Fault control of geothermal fluid movement has also been demonstrated at the East Mesa area of the Salton Trough, California, USA (Swanberg, p. **1217),** in the Parbati Valley of northwestern India (Jangi et al., p. 1085), and at the Sempayaarea in Uganda, where the thermal fluids are clearly related to the Bwamba fault that bounds the western rift valley on the east (Maasha, p. **1103).**

Movement of geothermal fluids along dikes in basaltic terrane has been emphasized by Bodvarsson (p. **33** and p. **903).** Thermal water systems in northwestern Iceland are commonly controlled by flow along dike margins, for example, at Reykholar (Bjornsson and Gronvold, Abstract **11-3).** Flow of thermal fluids along basalt dikes also has been demonstrated in the Konkan region of India (Gupta, Narain, and Gaur, p. **387).**

Cap Rocks and Self-Sealing

Upward movement of geothermal fluids is commonly restricted by relatively impermeable rock (a "cap rock"), allowing accumulation of fluids in a geothermal reservoir directly beneath the cap rock. In some areas the cap rock has been interpreted as an impermeable stratigraphic unit. At Larderello, the cap rock is the allochthonous "argille scagliose" of Cretaceous to Eocene age that overlies the Triassic reservoir rocks (Petracco and Squarci, p. 521). At Wairakei the cap rock is the Huka Falls formation, whereas at Broadlands a cap rock is provided by the Huka Falls formation and various buried rhyolite domes (Grindley and Browne, p. **377).** In the geothermal fields of the Salton Trough, a cap rock is formed by relatively impermeable clays and shales that extend to a depth of **600** to **700** m (Swanberg, p. **1217;** Tolivia M., p. **275;** Mercado G., p. **487;** Paredes A., p. 515). At Kizildere, Turkey, reservoirs appear to be in both Miocene limestone and Paleozoic marbles, each overlain by relatively impermeable cap rocks (Kurtman and SBmilgil, p. **447;** Tezcan p. **1805).**

In perhaps the majority of hydrothermal convection systems, however, the cap rock is produced, by self-sealing (Bodvarsson, **1964;** Facca and Tonani, **1967),** most commonly owing to the deposition of silica, but also owing to hydrothermal formation of clays, zeolites, and other minerals (for example, Kristmansdbttir, p. **441** ; Grindley and Browne, p. **377;** Sheridan and Maisano, p. **597)** or by deposition of calcite as CO, is lost from a fluid. Examples of a cap rock being created by self-sealing include the Dunes geothermal system in the Salton Trough, California, USA (Bird and Elders, p. **285)** and the hot-water geothermal systems of Yellowstone National Park, Wyoming, USA, where self-sealing has produced vertical hydraulic gradients exceeding hydrostatic by **11** to **47%** (White et al., Abstract **11-56;** White et al., **1975).**

Fluid Recharge

Recharge to geothermal systems consists both of heat and water, and the balance between the two is important in determining whether a geothermal system is hot-water or vapor-dominated (White, Muffler, and Truesdell, **1971).** Fluid recharge is of critical importance to convective hydrothermal systems but is poorly understood, owing primarily to lack of deep drillhole data in the recharge parts of geothermal systems (Healy, p. **415).** However, several intensively developed geothermal systems do provide some quantitativedata. At Wairakei, Hunt **(1970),** from an analysis of subsidence data and gravity changes from **1961** to **1967,** showed that only **20%** of the fluid discharged during that time had been replaced by recharge. Bolton **(1970),** however, presented an analysis of the **1968** shutdown of the Wairakei field which indicated an inflow of water equivalent to two-thirds of the field discharge and at a temperature equal to or higher than the maximum measured in the field. At Larderello, Panichi et al. **(1974)** have identified steam derived from recharge from the south by its low and variable **I8O** compared to steam from the center of Larderello region. According to Petracco and Squarci (p. **521),** approximately **30** to **40%** of the steam produced at Larderello comes from these aquifers in the south.

Fluid recharge in some systems, however, appears to be of little importance. According to Boldizdr and Korim (p. **297),** the thermal water of the Pannonian aquifer of Hungary "does not participate in the hydrologic cycle." The geopressured fluids in the northerm Gulf of Mexico basin have been clearly demonstrated by Jones **(1970)** to be derived from diagenesis of sediments rather than from circulation of meteoric water. Jones (p. **429)** describes in detail a model for the formation of the geopressured reservoirs, emphasizing that they result from the compartmenting of sandstone beds by growth faults and the resultant retardation of fluid expulsion through the bounding, low-permeability clays. Fluid pressures will decrease with time as the confined water gradually escapes. Temperatures also decrease with time, as shown by comparison of paleotemperatures (determined by the electron spin resonance of kerogen) with modern temperatures in Cretaceous rocks at depths of **3** km in south-central Texas (Pusey, **1973).** Inasmuch as the deposi

tional axis of the Gulf Coast deposits migrates gulfward with time, one would expect the locus of the geopressured deposits also to migrate gulfward with time (Jones, p. 429).

GEOTHERMAL RESOURCE ESTIMATION

Several methods of geothermal resource estimation are currently in use, with little agreement on which method is best. Heat stored in water in the geothermal reservoir is used by Alonso (p. 17) and Tolivia (p. 275) to estimate the geothermal resources of Cerro Prieto, and by Swanberg (p. 1217) to estimate the geothermal resources of East Mesa, California, USA. On the other hand, many authors have calculated the heat stored in both water and rock and have calculated (or assumed) an extraction efficiency. Recent examples of this approach include Bodvarsson (p. 33) in Iceland; Macdonald and Muffler (1972) at Kawerau, New Zealand; Macdonald (p. **11** 13) at Broadlands in New Zealand; Muffler and Williams (1976) in Long Valley, California, USA; and Renner, White, and Williams (1975) and Nathenson and Muffler (1975) for geothermal systems of the United States. Healy (p. 415 and 1976). however, considers that estimates of resources and reservoir life based on stored heat calculations are unreliable, since no reservoir may in fact exist. That is, the permeability distribution of rock in the "reservoir" is such that most of the heat is inaccessible to circulating fluids and thus cannot be transmitted to the wells. This possibility is also explicitly recognized by Muffler and Williams (1976).

A second method of estimating the power potential of a new hydrothermal convection system is to compare the area of surface alteration in the new field with the altered area in a developed field, under the assumption that the area of surface alteration is proportional to the power potential. A refinement of this method used in Japan involves careful determination of the areal extent, type, and age of surface alteration and correlation with the age of associated volcanism (Sumi and Takashima, p. 625).

The total natural heat flow can also be used *to* estimate the geothermal potential of a hydrothermal convection system. Healy (p. 415) notes that estimates based on natural discharge are minima because experience at several geothermal fields (particularly Wairakei) has shown that natural discharge can be increased several times for many years. Accordingly, one can estimate field production by comparing natural discharge with that of another field whose capacity is known. Using this approach, Healy and James (1976) have estimated that heat discharge from Kawerau might be increased to four times natural discharge (that is, to 420 megawatts thermal = 420 MWt); this compares to 350 to 600 MWt for 50 years calculated from the 0.55 to 0.95 x **10IR** J of extractable heat estimated by Macdonald and Muffler (1972) for Kawerau.

Dawson and Dickinson (1970) have estimated the natural heat discharge from Broadlands to be 84 MWt. Using the same fourfold factor, derived from the Wairakei example for increase of production over natural heat discharge (Healy and James, 1976), the productive capacity of Broadlands is calculated to be 336 MWt. This compares to 2350 MWt for 50 years estimated from the stored heat in the Broadlands system (Macdonald, p. 11 13). Clearly, development of the Broadlands geothermal area will provide an important case history for evaluating the accuracy of the two contrasting methods of geothermal resources estimation.

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Summary of Section 111 Geochemical Techniques in Exploration

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I NTROD UCT ION

Considerable advances have been made in the knowledge of the chemistry of geothermal fluids in the five years between the first and second United Nations Geothermal Symposia held in Pisa **(1970)** and San Francisco **(1975).** At the Pisa Symposium. Donald E. White reviewed the entire field of geothermal geochemistry. He emphasized the distinction between hot-water and vapor-dominated geothermal systems and carefully reviewed the application of quantitative and qualitative geothermometers to each type of system. Geothermal chemistry was also recently reviewed by Sigvaldason **(1973).** Ellis **(1973, 1975).** and Mahon **(1973).** In reportingon fluid chemistry papers from the San Francisco Symposium, I shall build on these earlier reports and include Symposium papers and abstracts with g,eochemical data, as well as some recent papers not submitted to the Symposium. The literature in this field is expanding so rapidly that some worthy papers were probably missed.

Geothermal fluid chemistry finds its widest application in exploration, and it is this aspect that will be stressed in this report. Recent exploration activities have resulted in new chemical data on thermal fluids from springs and wells in Afars and Issas, Canada, Chile, Columbia, Czechoslovakia, El Salvador, Ethiopia, France, Greece, Guadeloupe, Hungary, Iceland, India, Indonesia, Israel, Italy, Japan, Kenya, Mexico, New Britain. New Zealand, the Philippines, Poland, the Red Sea, Rhodesia, Swaziland, Switzerland, Taiwan, Turkey, the United States, the USSR, and Yugoslavia. New methods for estimating subsurface temperatures have been proposed based on chemical and isotopic analyses of surface and well discharges. Chemical indices based on trace constituents of spring fluids and deposits, altered rocks, soils, and soil gases have been proposed as aids to geothermal exploration. Chemical models of interaction of geothermal fluids with reservoir rocks have been constructed. Studies of alteration in geothermal systems have aided exploration and exploitation. Finally, studies of geothermal rare gases suggest that although most are atmospheric in origin, excess)He in some systems may come from the Earth's mantle.

Although not covered in this report, chemical studies also assist in the exploitation of geothermal resources. Analyses of produced fluids indicate subsurface temperatures and production zones. Problems of scale deposition, corrosion of piping, and disposition of environmentally harmful chemical substances in geothermal fluids have been studied and solved in some applications. Plans continue for the recovery of valuable chemicals from geothermal fluids.

CHEMICAL COMPOSITION OF FLUIDS

Summaries of analytical data on selected thermal spring and well discharges, indicated geothermometer temperatures, and references to data sources are presented in Table I . Most data are from papers submitted to this Symposium. The classification of geothermal system type in Table **1** is based on the assumed genesis of their anomalous heat and follows, in a general way, classifications proposed by

Mahon (p. **7551,** Arnorsson **(1 9 7 4** ~lv anov **(l967),** Kononov and Polak (p. **767).** and White **(1970).** Volcanic systems (where the heat sources are inferred to be recent igneous intrusi0ns)dominated by hot water or steam are distinguished from nonvolcanic systems in which the heat source is normal or elevated regional heat flow and the waters are heated by deep circulation along faults or by their position in broad downwarped sedimentary basins. There are many chemical studies of volcanic geothermal systems because these are most easily exploited with current technology; fault-related and sedimentary systems are poorly understood chemically, although these may yield large quantities of heat for nonelectrical uses. Additional data on nonvolcanic geothermal systems may be found in the Proceedings of the Symposium on Water-Rock Interactions held in Prague in **1974** (Cadek, **1976).** Because of their distinctive and relatively uniform chemistry, **1** have treated seawater systems separately and discussed them in a special section.

Mahon's Classification

Mahon (p. **775)** characterizes geothermal fluids as originating from volcanic and subvolcanic geothermal systems, which may be either water or steam systems, and from nonvolcanic geothermal systems. Volcanic water systems are usually characterized at depth by waters of the neutral sodium chloride type which may be altered during passage to the surface by addition of acid sulfate, calcium, or bicarbonate components. The concentration of chloride may range from tens to tens of thousands of ppm. The origin of the water itself is dominantly meteoric, and the concentrations of readily soluble components such as CI, B, Br. Li. Cs. and As are related to their concentrations in the rock, to the subsurface temperature, and possibly **to**

contributions from deep fluids related to the volcanic heat source. Other less soluble constituents such as SiO,, Ca, Mg, Rb, **K,** Na, SO,, HCO,, and CO, are controlled by subsurface temperature, mineral solubility, mineral equilibria, and pH. Gases in these systems normally include CO,, H,S, H,, CH,, N,, and inert gases, with CO, predominant, and constitute **0** to ***5%*** by weight of the deep fluid.

The near-surface fluids of volcanic steam (vapor-dominated) systems are low in chloride (except for fundamentally unrelated high-temperature volcanic fumaroles with HCI). They contain only elements soluble in some form in lowpressure steam (SO, as **H,S,** HCO, as CO,, B as HBO,, Hg, NH,). The gases are similar to those in volcanic water systems. Because of their relative rarity and because vapor rather than liquid is produced (although liquid may predominate at depth), the geochemistry of these systems is not well understood.

Nonvolcanic geothermal systems have a wide range of water compositions and concentrations, from dilute meteoric waters to connate waters, metamorphic waters, and oil field brines. The controls on their compositions are less well known than those of volcanic waters.

Arnorsson's Classification

Arnorsson **(1974)** classifies Icelandic thermal fluids as related to (I) temperature, (2) rock type, and (3) influx of seawater. Low-temperature waters (**< ISOOC)** are the result of deep circulation in regions dominated by conductive heat flow (up to **4** to 5 hfu, which is above average for most of the world) and are characterized by low dissolved solids contents (200 to **400** ppm) and gases dominated by nitrogen. Higher temperature waters (*>20O0C)* result from intrusions of igneous rocks and are characterized by higher dissolved solids contents **(700** to **1400** ppm) and by gases with large amounts of CO,, H,S, and **H,.** Fluids in silicic rocks tend to be higher in CI and other dissolved solids than fluids of the same temperature in basaltic rocks if seawater is nor involved.

Classifications of Ivanov and Kononov and Polak

Ivanov **(1967)** proposed a classification of thermal fluids based ongas contents, which has been expanded by Kononov and Polak **(p. 767).** Fluids directly related ,to volcanic processes are characterized either by H,S-CO, gases and acid sulfate or acid sulfate-chloride waters in the oxidizing zone, or by N,-CO, gases and alkaline sodium chloride waters in the reducing zone. Fluids related to thermometamorphic processes have high C0,gases and carbonated waters, which may in part be connate. Fluids of deep circulation but outside of volcanic and thermometamorphic zones have N, gases and dilute sodium chloride-sulfate waters. Kononov and Polak further divide volcanic fluids into "geyseric" with H,-CO, gases and "riftogenic" with H, gases, which occur in spreading centers and characterize the highest temperature (>300"C)geothermal systems. It isonly in "riftogenic" fluids that anomalous contents of -\He and H,S with **634S** near zero are expected. Parts of this classification are applied in detail to Icelandic thermal fluids by Arn6rsson, Kononov, and Polak **(1974).**

Although this classification may need modification based on the chemistry of fluids in drilled systems, it has the advantage of focusing attention on geothermal gases, which deserve more study. The occurrence of excess ,He in the hydrothermal fluids of Kamchatka (Gutsalo, p. **749,** Lassen, and Hawaii (Craig, **1976)** and of Yellowstone ***Ei3,S*** values near zero (Schoen and Rye, **1970)** suggests these fluids are "riftogenic" when, in fact, they are far from present spreading centers.

Classifications of White

Reviews by **D.** E. White of mineral and thermal water chemistry **(1957a.** b, **1968,1970,1974)** havegreatly influenced most workers in this field. Space does not allow adequate description of his water classification schemes, which have evolved as more chemical and isotopic data became available. **In** brief, ***meteoric*** waters dominate shallow crustal circulation and mix with more saline deep waters of all types. Meteoric waters may also circulate deeply under the influence of magmatic heat and receive additions of NaCI, CO,, H,S, and other substances from rock leaching, thermal metamorphism, and possibly magmatic fluids. These moderately saline sodium chloride deep waters of ***volcanic*** association undergo near-surface rock reactions and atmospheric oxidation to form the range of observed surface volcanic waters. ***Oceanic*** water is incorporated in marine sediments and, by extended low-temperature reactions, becomes ***evolved-connate*** water. Deep burial and higher-temperature reactions cause expulsion of highly altered ***metamorphic*** waters from rocks undergoing regional metamorphism. ***Magmatic*** water has been dissolved in magma but may have various ultimate origins. The existence of ***juvenile*** water new to the hydrologic cycle is certain, but its recognition is doubtful. Recent work by White and his coworkers has elaborated the chemical distinctions between hot-water and vapor-dominated systems (White, Truesdell, and Muffler, **1971:** Truesdell and White, **1973)** and demonstrated the existence of thermal water of nonmeteoric origin in the California Coast Ranges (White, Barnes, and O'Neil, **1973).**

VOLCANIC HOT-WATER SYSTEMS

Deep Fluids

Hot-water geothermal systems with volcanic heat sources have been very thoroughly studied. The deep fluids of these systems are, in general, waters of dominantly meteoric origin with chloride contents of 50 to **3000** ppm, unless seawater, connate water, or evaporites are involved. Components of these fluids, such as Na, K, Ca, Mg, and SO,, that are present in major amounts in most volcanic reservoir rocks almost certainly originate from rock-water reactions. Other fluid components, such as CI, **F,** B, CO,, and H,S, are present in these rocks only in trace quantities and have been explained as magmatic contributions (Allen and Day, **1935;** White, 1957a). Experimental rock-leaching studies (Ellis and Mahon, **1964, 1967)** have shown, however, that these soluble components may be extracted from most rocks at moderate temperatures **(200** to 300"C), and isotope studies (see below) have failed to detect magmatic water in geothermal systems. Rock leaching as a sole source of chloride has been criticized by White **(1970)** because it appears to require unreasonable rock volumes or unreasonable original rock chloride contents to maintain the chloride **flux** of old geothermal systems, such as Steamboat Springs, Nevada (age **1** to **3** m.y.; Silberman and White, **19751,** or Wairakei,

New Zealand (age 500000 years; Banwell, **1963;** Healy, p. **415,** suggests half this figure).

Recent isotope studies of fresh and altered Wairakei rocks suggest that the apparent water:rock mass ratio of drilled parts of this system is at least **4.3:1** (Clayton and Steiner, **1975).** Since the C1 contents of possible rocks at depth in this system are less than IO00 ppm (Ellis and Mahon, **1%4),** a mechanism other than simple leaching would appear necessary to produce the 1400-ppm-C1 Wairakei deep water. More probably, however, the rock leached of chloride was at much deeper levels as in the deep reservoir hypothesized by Hochstein (Abstract **1-16)** and at those levels the water:rock ratio was much lower. However, a lower water:rock ratio requires a larger volume or rock which. if the predrilling flux of chloride **(2.5 x IO'"** g/year; Ellis and Wilson, 1955) has been maintained over the life of the system, requires more than *5* x **IO3** km7 of leached rock; this is more than ten times the possible volume of the system estimated by Hochstein (Abstract **1-16).** To resolve this problem, Wilson (1966) and Ellis (1966) suggested that flow ingeothermal systems is intermittent and that present activity is much greater than that of the past. Ellis (1970) suggests this cycle might have a period of **IO5** years with the active part of the cycle complete in **IO'** years. Experimental and model studies of nonuniformly heated fluid in porous media by Horne and O'Sullivan (1974) produced intermittent flow. which may support this suggestion. However, the numerous dormant geothermal systems *(9%* of the total) required by this model would be easily recognizable by fossil sinter deposits and have not been found.

The efficacy of rock leaching as a source of dissolved constituents in geothermal waters must depend on the availability of fresh rock surfaces. Heat transfer and leaching from established fractures should be rapid. and solute concentrations and temperatures would be expected to decrease rapidly. This may not occur because the growth of thermal stress fractures (Harlow and Pracht, 1972; Smith et al., 1973;, L ister, Abstract 11-27) would provide fresh rock surfaces and heat transfer at the same rate so that the chemical and thermal properties of convecting fluids would be uniform in time. Studies of fluid inclusions from Broadlands, New Zealand, suggest that changes of fluid concentration and temperature may have been small over the IO'-year life of this system (Browne, Roedder, and Wodzicki, 1976). Careful chemical and physical modeling is needed to further test the rock-leaching hypothesis.

The opposite hypothesis, that small quantities of magmatic fluids of high salinity supply a significant part of geothermal solutes, has been defended by White (1957a, 1970). Recent fluid inclusion and isotopic studies (reviewed by White, 1974; see also later issues of ***Economic Geology)*** indicate that two fluids were involved in the generation of many ore deposits. Initial fluids of porphyry copper, epithermal base metal, and other ore deposits were probably magmatic in origin, and later fluids were local meteoric waters. However, magmatic waters have not yet been positively identified in epithermal gold-silver deposits, which are most closely related to active geothermal systems. The presence of mantle-derived 3He in geothermal fluids (Kononov and Polak, p. 767; Gutsalo, p. 745; and Craig, 1976) may not indicate direct contribution of other juvenile or even magmatic components because of the possibility that helium may migrate independently of other fluids or may be contained in some volcanic rocks (Lupton and Craig, 1975) and enter geothermal fluids from rock leaching.

Perhaps the most persuasive evidence for the participation of at least small amounts of magmatic components in geothermal fluids is the close temporal and spatial relation and analogous geochemical behavior of certain volcanic and geothermal systems. The volcanic zone in Taupo. New Zealand. with numerous geothermal systems. has the active volcanoes of White Island at its north end and Ruapehu and Ngauruhoe at its south end. Chemical studies of White Island have shown that fumarole discharges alternate between typical high-temperature (to 800°C) volcanic emanations with high su1fur:carbon ratios when flows of volcanic gases are not impeded. and nearly typical geothermal steam at temperatures below 300°C with low su1fur:carbon ratios when the gases are forced to pass through surface waters (Giggenbach. 1976). Some fluids of geothermal systems associated with near-active volcanoes of the Tatun Shan, Taiwan (Chen and Chern, written commun., 1975) and of Tamagawa (Iwasaki et al.. 1963) and Hakone (Noguchi et al.. 1970). Japan. may be similar to the drowned volcanic emanations of White Island. Hydrolysis of sulfur or nearsurface oxidation of H,S cannot produce the HCI acidity proven at Hakone and Tamagawa and indicated at Tatun (analysis Ta *I*, Table 1. from New Zealand Dept. Sci. Ind. Res., quoted by Chen and Chern) which must originate from high-temperature. probably magmatic, processes (White and Truesdell, 1972; R. 0. Fournier and J. M. Thompson, unpub. data). Magmatic fluid contributions to these geothermal systems appear probable, but proof *is* lacking. More work is needed on this problem, possibly through more extensive isotopic studies of elements dissolved in geothermal waters. However, fractionation during crystallization and re-solution of trace constituents is expected to be small, so leached material may be indistinguishable from direct magmatic contributions.

Near-surface Alteration of Hot Waters

Near-surface processes producing the varied compositions of geothermal waters of volcanic systems include steam separation during adiabatic cooling, mixture with cold shallow meteoric waters, and chemical reactions involving rock minerals, dissolved gases, dissolved constituents of diluting waters, and atmospheric gases. Many indicators of subsurface flow (see below) depend on the effects of these processes on ascending geothermal fluids. Fluid component ratios that are not affected by these processes, such as CI:B, are useful in indicating the homogeneity of subsurface fluids and thus the continuity and size of geothermal systems (Stefhnsson and Arnorsson, p. 1207; Cusicanqui, Mahon, and Ellis, p. 703).

Subsurface reactions with dissolved gases and rock minerals control the contents in the water of most components present in excess in the rock or in the dissolved gas. Most of the bicarbonate and part of the sodium and potassium are produced by reaction of dissolved CO, with the rocks to produce mica or clay minerals and bicarbonate and alkali ions (Fournier and Truesdell, 1970),

CO, + H,O + (Na,K) silicate = HC0,- + (Na+,K+) + H silicate.

The coupled increase in HC0,:CI and decrease in C0,:other gases during lateral flow through a near-surface aquifer has

been demonstrated for Shoshone Geyser Basin, Yellowstone (analysis US30), where near-surface rocks are glacial sediments composed of rhyolitic glass (Truesdell, 1976a). Crystallized rhyolite and ash flow tuff are not as reactive as glassy rocks, so CO, is converted to HCO, less rapidly, as at Norris Geyser Basin, Yellowstone, where waters flowing in devitrified ash flow tuff are low in HCO, (analysis US34).

Mixture of deep hot water with cold meteoric waters produces variations in the concentrations (but not the ratios) of CI, B, and other components not involved in lowertemperature rock reactions. The resulting temperatures in subsurface aquifers where mixture takes place (Truesdell and Fournier, p. 837) affect all temperature-sensitive equilibria such as quartz solution and exchange of dissolved cations with aluminosilicate minerals. With sufficient dilution, subsurface boiling may be prevented and a high partial pressure of CO, retained in waters at temperatures well below 200°C. Under these conditions, the solubility of calcite is relatively high (Holland, 1967) and calcium can be leached from volcanic rocks. When these dilute high P,,-high Ca solutions emerge at the surface, they lose CO, and deposit travertine as well as silica.

Steam separation produces changes in water chemistry because most salts are nearly insoluble in low-pressure steam (Krauskopf, 1964) and remain entirely in the liquid phase, while gases partition strongly into the vapor (Ellis and Golding, 1963; Kozintseva, 1964). The result of these processes is an increase in nonvolatile salts and a decrease in dissolved gases (principally CO, and H,S) in the liquid phase. The loss of gas produces an increase in pH from about 6 at depth to near 9 at the surface (Ellis, 1967; Truesdell and Singers, 1971) through the reaction

HC0,- + H' = CO, + H,O.

The effect of CO, loss is greatest in waters with large contents of bicarbonate such as those from Shoshone Geyser Basin, Yellowstone (analysis US30) or Orakeikorako, New Zealand (analysis NZ7), so these waters become very alkaline whereas waters with little bicarbonate (for example Norris waters, analysis US34 remain near neutral.

Sulfate can originate from oxidation of **H,S** by atmospheric oxygen dissolved in meteoric water of deep or shallow circulation. The amount of sulfate ion that can be formed in this manner is 22 ppm from rain water percolating underground after equilibrating with air at 0°C (Truesdell, 1976). This is close to the observed sulfate contents in water not affected by near-surface oxidation of H,S in volcanic rocks with low sulfate contents, such as those in the Yellowstone caldera (analyses US29-34) and the Taupo volcanic zone (analyses NZ 1-10). Higher contents of sulfate in volcanic hot water probably originate from leaching of sulfate contained in some volcanic rocks. Sulfate in lowtemperature waters in basalts probably has this source (analyses IC 1-3). In high-temperature areas the self oxidation of SO, to H , S and SO, must also be considered. The sulfate contents of thermal waters in sedimentary aquifers are usually much higher as a result of solution of sedimentary sulfate from the rock (for example Kizildere, Turkey, analyses TI-2).

Acid waters with very high sulfate contents are produced by direct superficial atmospheric oxidation of **H,S** to sulfuric acid in areas of drowned fumaroles or steaming ground (White, 1957b). The acid-sulfate-chloride waters at Waimangu, New Zealand, and Norris, Yellowstone, probably result from percolation of this acid sulfate water into near-surface reservoirs where it mixes with chloride water from below.

The change from deep, slightly acid chloride waters, to neutral CI-HC0,-SO, waters, to acid sulfate waters with decreasing depth in the Onikobe caldera has been described by Yamada (p. 665).

Roots of Volcanic Hot Water Systems

Knowledge of the deepest parts of geothermal systems must come chiefly from refined geophysical studies and from fossil geothermal systems exposed by erosion; but experimental studies of the thermodynamic chemistry of water and rock minerals provide important constraints for modeling.

From chemical and isotopic compositions of surface fluids and the phase chemistry of water and silica, Truesdell et al. (Abstract 111-87) have proposed that a 3- to 6-km-deep reservoir of dilute (IO00 ppm NaCI) water at 340 to 370°C underlies much of Yellowstone. This reservoir may correspond to the deep (also 3 to 6 km) reservoir proposed by Hochstein (Abstract 1-16) on geophysical evidence to underlie the Taupo volcanic zone, New Zealand. Fournier, White, and Truesdell (p. 731) proposed that the solubility maximum of quartz (at 340°C for dilute steam-saturated water; increasing with salinity and, to a lesser extent, pressure) acts as a thermostatic mechanism for deep waters because circulation to higher temperatures would cause rapid quartz deposition and permeability decrease. Circulation of fluids through the zone of quartz solubility maximum should produce additional porosity by solution.

STEAM (VAPOR-DOMI NATED) SYSTEMS

Certain geothermal systems (Larderello and Monte Amiata. Italy; The Geysers, California; Matsukawa, Japan; Mud Volcano, Yellowstone; and others) are characterized by production of saturated or slightly superheated steam without liquid water. Despite intensive search, few examples of this type of system have been found. Two new discoveries, the Kawah Kamojang and Salak fields of Indonesia, have been reported to this Symposium and another likely candidate has been identified in Mt. Lassen National Park, California (Renner, White, and Williams, 1975).

Although known systems have been intensively drilled, the character of the reservoir fluid, the mechanism of steam production, and the origin of these systems have been highly controversial and at least seven major models have been proposed. The latest of these models (White, Muffler, and Truesdell, 1971) hasutilized the chemistryof superficial fluids and deep pressure and temperature measurements to conclude that both steam and water are present in these reservoirs. The model was elaborated and the mechanism of superheated steam production explained in a later paper (Truesdell and White, 1973).

New data on the Kawah Kamojang, Indonesia, field (Hqchstein. p. 1049; Kartokusumo, Mahon, and Seal, p. 757) indicate that it is vapor dominated. Drillholes to 600 m showed the reservoir temperature below 550 m (390 m below the water table) to be 238"C, close to that of steam of maximum enthalpy (236°C). as predicted for these systems (James, 1968). Production initially was a steam-water mixture

that changed to saturated steam and finally superheated steam. Surface drainage and borehold fluids are nearly chloride-free (<2 ppm in hot waters; 3 to **6** ppm in drainage waters), as expected in a system with only steam flow from depth. The resistivity to 500-m depth is 2 to 5 ohm.meters, indicating a near-surface water-saturated zone above the reservoir. Deeper resistivity is **> 10** ohm. meters, probably indicating the presence of steam. This resistivity structure is similar to that found in the vapor-dominated Mud Volcano, Yellowstone, geothermal system (Zohdy, Anderson, and Muffler, 1973). Deeper drilling is needed at Kawah Kamojang to confirm the presence of the predicted low "vapostatic" pressure gradient. The Salak, Indonesia, field is also considered to be vapor dominated, as indicated by surface fluid chemistry (Kartokusumo and Seal, Abstract 111-49).

Isotope chemistry of Larderello, Italy, steam has shown that increased production has drawn fluids from recent inflow at the sides of the reservoir and from deeper levels inthecenter(Celatietal., 1973;Panichietal., 1974). Marginal inflow was also indicated by a hydrologic balance (Petracco and Squarci, p. 521). Steam from the central area has been shown to carry up to **60** ppm chloride associated with ammonia and boron (F. D'Amore, oral commun., 1975), which may indicate boiling from a high-chloride brine water table. Reassessment of original pressures of this system has indicated that, in general, they conform to the vapordominated model (Celati et al., p. **1583).**

NONVOLCANIC HOT-WATER SYSTEMS

Earth temperatures increase generally with depth, and although most normal thermal gradients average 25"C/ km, there are broad regions where thermal gradients are 40 to 7S°C/km or higher (White, 1973). **In** these regions, hot water may be exploited by drilling in sedimentary basins or along fault zones where deep circulation occurs. Chemical data on these waters are sparse. but thermal water in sedimentary basins appears similar to nonthermal waters in similar geologic situations. The fault-controlled waters are similar to, but more dilute than, volcanic waters. The recent review of the chemistry of subsurface water by Barnes and Hem (1973) may be useful.

Examples of thermal systems that are considered nonvolcanic in Czechoslovakia. France, Iceland, India. Israel, Japan, Switzerland, Turkey, the United States, and **Yu**goslavia are given in Table I . The waters of the Pannonian and related sedimentary basins of Czechoslovakia, Hungary, and Yugoslavia appear to be crudely zoned, with bicarbonate predominating near the top of the aquifer and chloride at greater depths (for example analysis Czl; Frankoand Mucha, p. 979; Boldizsir and Korim. p. 297; Petrovik, p. 531). Waters in carbonate aquifers (analysis HI, **Y2?)** have relatively high contents of bicarbonate, calcium, and magnesium as might be expected, and gases appear to contain more CO, than in sandstone aquifers, which have more nitrogen. Methane is also present. Sedimentary basins in Russia are reported to yield water at 40 to 105°C with **1** to IO **g/l** salinity at depths of 2500 to 3000 m without further chemical data (Mavritsky and Khelkvist. p. 179). More studies are needed on thermal waters of sedimentary basins.

Waters heated by deep circulation along faults may be very dilute with only atmospheric dissolved gases if their temperatures are low (analysis **US4)** and become much more concentrated with more CO, and H2S as their subsurface temperatures approach those of volcanic systems (analysis US26 for example). The water source is meteoric and salts are probably leached from rock, although evaporites may be associated with some fault-heated waters. Wollenberg (p. 1283) suggests that uranium may accumulate at depth in some of these systems owing to reducing conditions.

SEAWATER GEOTHERMAL SYSTEMS

Many geothermal systems in coastal areas have remarkably similar thermal fluids which are mixtures of local meteoric waters and thermally altered seawater. The effect on seawater of high temperature reaction with rock is marked increase in calcium and smaller increase in potassium and occasionally chloride, with marked decreases in magnesium, sulfate, and bicarbonate, and often a smaller decrease in sodium. These changes are apparently due to formation of montmorillonite, chlorite, and albite from calcic feldspars, which releases calcium and causes consequent precipitation of anhydrite and calcite (Mizutani and Hamasuna, 1972; Bischoff and Dickson, 1975). The salinity is affected by dilution and subsurface boiling. Chemical and isotopic studies have shown the presence of altered seawater in coastal thermal areas of Fiji (Healy, **1%0),** Greece (analyses *GI-?* Dominco and Papastamatoki, p. 109; Stahl, Aust, and Dounas, 1974), Guadeloupe (analysis Gu ***1;*** Demians d'Archimbaud and Munier-Jolain, p. 101). Iceland (analyses lc7-IO; Bjornsson. Arnorsson, and Tomasson, 1972; Arnors**son.** 1974; Arnorsson et al., p. 853). Israel (analysis **IsI;** Eckstein, p. 713). Italy (analyses Itl-2; Baldi, Ferrara, and Panichi. p. 687), Japan (analyses J 1-2; Mizutani and Hamasuna, 1972; Matsubaya et al., 1973; Sakai and Matsubaya, 1974). New Britain (analysis NB I; Ferguson and Lambert, 1972). New Zealand (Crafar, 1974; Skinner, 1974), and Turkey (analyses T3 and T6; Kurtman and SLmilgil, p. 447). The composition of normal seawater is given in Table **1** for comparison (analysis SW ***I).***

The application of chemical and isotopic geothermometers to seawater thermal fluids has some unusual features. Silica geothermometers apparently behave normally, but may reequilibrate more rapidly upon cooling because of the high salinity. thus indicating lower temperatures (Fournier, 1973). Cold seawater and partly altered seawater in low-tomoderate-temperature thermal systems indicate anomalously high temperatures, near 100°C from Na:K and 170°C from NaKCa. The sulfate-water isotope geothermometer also indicates temperatures near 180°C for cold and partially altered seawater. These high-temperature indications may be relics of partial equilibration in submarine geothermal convection systems located along spreading centers (Lister, p. 459; Williams, Abstract 1-40), with the seawaters resisting reequilibration in moderate-temperature coastal geothermal systems because of insufficient rock alteration to affect their high ion contents. Seawater-rock interaction experiments now in progress (Hajash, 1974; Mottl, Corr, and Holland, 1974; Bischoff and Dickson, 1975) will provide more data on this problem and may suggest new geothermometers for these systems. Where thermal seawaters have higher chlorinities than local seawaters and there is **no** evidence of evaporite contribution. I have calculated the subsurface temperatures required to produce the observed concentrations by boiling (analyses G7, Ic7, NB *I*, and T6). The indicated subsurface temperature of the Reykjanes, Iceland, seawater geothermal system agrees with that ob

served. Chloride leached from rocks and conductive heating would tend to increase apparent temperatures and mixing with dilute waters would tend to lower them.

CEOTH ERMOMETERS

Where fluids from geothermal convection systems reach the surface in springs or wells, the chemical and isotopic compositions of these fluids may indicate the subsurface temperature and flow patterns, as well as the recharge source, type of reservoir rock, and other important parameters of the system. Component concentrations or ratios that can be related to subsurface temperatures are called geothermometers. Chemical geothermometers may be quantitative, so that specific subsurface temperatures may be calculated, or qualitative, so that only relative temperatures may be inferred. Important advances in the application of quantitative and qualitative geothermometers have been made since the first UN Geothermal Symposium in Pisa in 1970.

Quantitative Chemical Ceothermometers

The theory of quantitative chemical geothermometers has been discussed by Fournier, White, and Truesdell (1974). These thermometers depend on the existence of temperature-dependent equilibria at depth which are quenched or frozen during passage to the surface.

At the time of the Pisa Symposium (1970), the quartz-saturation geothermometer (Mahon, 1966; Fournier and Rowe, **1966),** which depends on the near-universal equilibrium with quartz in geothermal fluids above **100** to 150°C, and on the relative reluctance of quartz to precipitate from supersaturated solutions, was widely used in exploration and in monitoring well discharges. Temperatures above 200 to 230°C are seldom indicated by this geothermometer from spring analyses because reequilibration above 200°C is relatively rapid and solutions initially saturated with quartz at higher temperatures can precipitate amorphous silica during passage to the surface (Fournier, 1973; Truesdell and Fournier, p. 837). Lower-temperature waters may be saturated with chalcedony rather than quartz (Fournier and Truesdell, 1970), with some Icelandic waters suggesting chalcedony saturation at temperatures as high as 180°C and others suggesting quartz saturation as low as 110°C (Arn6rsson. 1970, 1974, 1975). Examples of many thermal waters with probable quartz or chalcedony saturation are given in Table **I ,** and equations (data from Fournier, 1973, 1976) for quartz saturation with conductive and adiabatic (maximum steam loss) cooling and for chalcedony saturation are given in Table 2. Adiabatic cooling is probably most common in high-temperature geothermal systems (M. Nathenson, unpub. calculations), but loss of silica from reequilibration during upward flow may make conductive quartz temperatures appear to indicate reservoir temperatures more accurately (White, 1970). Systems with both adiabatic and conductive cooling have been discussed by Fournier, White, and Truesdell (p. 731).

The other geothermometer widely used ***5*** years ago was the Na:K ratio. The empirical calibration of this geothermometer does not agree with experimental studies of feldspar and mica equilibria, and in 1970 there was wide divergence between calibration scales. Syntheses of available data (mostly from the Pisa Symposium) by White and Ellis (quoted in White, 1970) and by Fournier and Truesdell (1973) have produced two slightly different scales, which are approximated by equations given in Tab!- 2. Since the White-Ellis curve is more widely used, it has beel, adopted for calculations in Table I .

Because the Na:K geothermometer fails at mnperatures below **100** to 120°C and yields improbably high temperatures for solutions with high calcium contents, an empirical NdKCa geothermometer was proposed by Fournier and Truest'ell (1973). NaKCa temperatures have been found to be close. to quartz-saturation temperatures for thermal springs of Nevada by Hebert and Bowman (p. 751). but Na:K temperatures appear to be equally accurate for 200 to 300°C low-calcium well discharges (Table I) , and may correctly indicate fluid temperatures and movement in drilled systems (Mercado, p. 487).

The cation (Na:K and NaKCa)geothermometers are useful in initial evaluations of the geothermal potential of large regions because they are less affected by reequilibration and near-surface dilution than are the silica geothermometers. Cation geothermometers have been used in regional evaluations in Canada (Souther, p. 259), Iceland (Stefinsson and Arn6rsson. p. 1207), India (Krishnaswamy, p. 143; Gupta, Narain, and Gaur, p. 387), Israel (Eckstein, p. 713), Italy (Fancelli and Nuti. 1974), the Philippines (Glover, 1974a. b, 1975). and the United States (Young and Mitchell, 1973; Swanberg, 1974,1975; Mariner et al.. 1974a, b; Renner, White, and Williams, 1975; Reed, 1975).

Cation geothermometers. although empirical, apparently depend on equilibria between thermal waters and aluminosilicate minerals original to the host rock or produced by alteration. If equilibrium is not achieved, or if the mineral suite is unusual, misleading temperatures may be indicated. Thus, cation geothermometers must be used with caution in geothermal systems involving seawater, because in many of these, equilibrium with rocks probably is not reached because of the resistance to chemical change of the concentrated solution; and apparent temperatures are close to those indicated by cold seawater (analysis SW I-t..:,. I00"C and **tNaKCa.** 170°C). However, in some high-temperature geothermal systems, seawater does appear to have nearly equilibrated with rock and indicated temperatures are close to those observed in drillholes (analyses Ic7-9 analyses J ***1-2).*** Acid sulfate springs in which silica and cations are leached from surface rocks are not suitable for chemical geothermometry, although acid sulfate chloride waters of deep origin give reasonable indicated temperatures (analyses J ***/2,*** Ta ***1-2).*** Cation (and silica) geothermometers may also give misleading results when applied to waters in highly reactive volcanic rocks (Fournier and Truesdell, 1970; Baldi et al., 1973;

Arn6rsson. 1975), especially those rocks with high contents of potassium (Calamai et al., p. 305), or to warm waters that emerge in peat-containing soils (Stefinsson and Arn6rsson, p. 1207). Paces (1975) has suggested a correction factor for the NaKCa geothermometer when applied to high-CO, waters.

Although many other high-temperature chemical equilibria exist, most of these equilibria are affected by subsurface conditions other than temperature, reequilibrate rapidly, or are affected by other reactions during ascent to the surface. These equilibria can. however, be used as qualitative geothermometers (see below) and, in specialized circumstances, as quantitative geothermometers.

The content of magnesium in thermal waters varies inversely with temperature, but it is also affected by C02

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pressure. Experimental calibration by Ellis (1971) allows magnesium contents to be used as a quantitative geothermometer if CO,.pressures can be otherwise calculated.

Waters with high calcium and sulfate and low bicarbonate contents, such as thermally altered seawater (see discussion above), may be saturated with anhydrite at depth and become undersaturated during ascent because of the inverse temperature dependence of anhydrite solubility (analyses **J** 1-2; Sakai and Matsubaya, 1974). The contents of calcium and fluoride in geothermal waters are in part controlled by equilibrium with fluorite (Nordstrom and Jenne, Abstract 111-70). but reequilibration apparently is rapid.

The reaction CO, + 4H, = CH, + 2H,O may occur in geothermal reservoirs (Craig, 1953; Hulston, **1964;** but see Gunter and Musgrave, 1966, 1971), and the amounts of these gases in surface discharges may indicate subsurface temperatures. Temperatures calculated from Wairakei borehole gases (analysis NZI; Hulston and McCabe, 1962a; Lyon, 1974) are reasonable, but Arnorsson et al. **(p.** 853) have applied this method to fumarole discharges with somewhat ambiguous results.

Mixing Models

Although mixing of thermal waters with cold near-surface waters limits the direct application of chemical geothermometers, the dilution and cooling resulting from mixing may prevent reequilibration or **loss** of steam and allow the calculation of deep temperatures and chemical conditions. The chloride contents and surface temperatures of springs were used to calculate minimum subsurface temperatures in early New Zealand geothermal surveys (Mahon, 1970). More recently, models have been proposed based on surface temperature and silica contents of cold and warm springs (the warm spring mixing models in: Truesdell, 1971 ; Fournier and Truesdell, 1974; Truesdell and Fournier, 1976), and on the temperature, chloride, and silica concentrations of mixed boiling springs and the chloride concentrations and temperatures of cold springs and nonmixed boiling springs (the boiling spring mixing model in: Truesdell and Fournier, **p.** 837, Fournier, White and Truesdell, **p.** 731). **A** mixing model using chloride-enthalpy relations of cold, warm. and boiling springs was proposed by Glover (l974a) for Tongonan, Philippines, geothermal waters (analysis Ph ***I) .*** Related diagrams of chloride and enthalpy (or temperature) have been used to analyze subsurface processes in drilled systems (Giggenbach, 1971 ; Mahon and Finlayson, 1972; Cusicanqui, Mahon, and Ellis, p. 703).

The warm spring mixing model depends on the assumption of conservation of enthalpy and silica and on the nonlinear temperature dependence of quartz solubility. The boiling spring mixing model depends on assumed conservation of chloride and enthalpy and reequilibration with quartz after mixing. Proper application of these mixing models depends therefore on the fulfillment of a number of assumptions, the validity of which should be considered in each case.

Mixing model temperatures have been calculated for appropriate spring and well analyses in Table **I .** The accuracy of mixing model calculations depends ***to*** a great degree on measurement or accurate estimation of the chemistry and temperature of local cold subsurface water. For these calculations, as well as for isotope hydrology (see below), collection and analysis of cold waters should be an important part of a geochemical exploration program. The warm spring mixing model was applied by Gupta, Saxena, and Sukhija (p. 741) to the Manikaran, India, geothermal system and by Young and Whitehead (1975a,b) to Idaho thermal waters.

Components other than silica and chloride may be used in mixing models. The temperature and salinity of a hypothetical concentrated high-temperature component have been calculated by Mazor, Kaufman, and Carmi (1973) from **I4C** contents and by Mizutani and Hamasuna (1972) from sulfate and water isotopes (analyses **Is3** and J *I)* .

Qualitative Geothermometers

Qualitative geothermometers were reviewed at the first UN Geothermal Symposium by Mahon (1970), Tonani (1970), and White (1970). These geothermometers may be applied to spring waters and gases, fumarole gases, altered rock, soils, and soil gases. Ratios and contents of dissolved hot-spring constituents and gases resulting from hightemperature reactions. but not susceptible to quantitative temperature calculation. are useful for indicating subsurface flow paths when siting wells (Mahon, **p.** 775).

Substances carried in steam are important in the study of systems without hot springs and may indicate subsurface flow paths more effectively than liquid water discharges, which are more subject to lateral flow (Healy, **p.** 415; Healy and Hochstein, 1973). Gas discharges were used by Glover (1972) to indicate upflow zones in Kenya geothermal systems. where hot water discharges were lacking or grossly contaminated with surface waters. Gas ratios were also useful at **El** Tatio. Chile (Cusicanqui, Mahon. and Ellis, **p.** 703), where extensive lateral flow of hot water occurs (see discussion below). Ammonia and boron have been used as indicators in thermal seawaters which are otherwise unresponsive to subsurface temperature (Dominco and Papastamatoki, **p.** 109).

New studies using sensitive analytical methods have shown that soil gases in geothermal areas have anomalous concentrations of mercury (Koga and Noda, **p.** 761) and helium (Roberts et al.. 1975), and contain CO, with anomalously

high 13C:”C ratios (Rightmire and Truesdell, 1974).
Volatile substances dispersed from geothermal fluids may accumulate in soils and altered rocks, and patterns of soil mercury (Matlick and Buseck, **p.** 785) and **of** mercury, arsenic, and boron in altered rocks (Koga and Noda, p. 761) may indicate subsurface fluid flow, as may alteration patterns (Sumi and Takashima, **p.** 625).

The most important application of qualitative geothermometers is in preliminary exploration over large areas. “Blind” convection systems may exist or surface fluid flows may be inconspicuous or difficult to distinguish from nonthermal sources. In these cases, it may be possible to analyze surface fluids for distinctive “geothermal” components. Lithium in surface waters of central Italy has been tested as a geothermal indicator by Brondi, Dall’Aglio, and Vitrani (1973); and, in a study of the same area, criteria for distinguishing river sulfate of geothermal origin (from H,S oxidation) from sulfate resulting from solution of evaporites or from oxidation of sulfide minerals have been developed by Dall’Aglio and Tonani (1973). Much anomalous boron in surface waters (other than those in closed basins) is probably of geothermal origin (Morgan, 1976). and Larderello steam has been shown to contribute large quantities of boron to surficial waters (Celati, Ferrara, and Panichi, Abstract **111-1 I) .** Anomalous arsenic from natural and exploited geo

thermal systems has been found in the Waikato River, New Zealand (Rothbaum and Anderton, p. 1417), and in the Madison River, Montana (Stauffer and Jenne, Abstract IV-14). Fish in the Waikato River appear to accumulate mercury of geothermal origin (Weissberg and Zobel, 1973), but Yellowstone fish do not (L. K. Luoma and E. A. Jenne, oral commun., 1976).

Geothermal waters of meteoric origin may exchange oxygen isotopes with rock during deep circulation, and this “oxygen shift” has been used as a positive or negative qualitative geothermometer (Fancelli, Nuti, and Noto, Abstract 111-23; Fouillac et al., p. 721).

Although sampling is difficult, gases and solids can also be used in regional exploration. In a reconnaissance study of much of central and southern Italy, Panichi and Tongiorgi (p. **815)** found carbon isotopes in CO,, and travertine associated with known and prospective geothermal areas, to be distinctly heavy compared with those from other sources. The use of other isotopes in regional exploration (”Sin air gases for instance) should be investigated. Mercury vapor has been found in the atmosphere of the Beppu, Japan, geothermal system (Koga and Noda, p. 761) and might be detectable in a regional survey.

ISOTOPE HYDROLOGY AND THERMOMETRY

Isotope compositions and rare gas contents of geothermal fluids have been used to indicate sources of recharge, time of circulation, fluid mixing, and subsurface temperatures. Geothermal isotope and nuclear studies have been the subject of symposia at Spoleto, Italy (Tongiorgi, 1%3), Dallas, Texas (Hall, 1974). and Pisa, Italy (Gonfiantini and Tongiorgi, 1976). and were extensively reviewed by White (1970, 1974). Many papers on nuclear hydrology with application to geothermal studies were recently presented at Vienna (International Atomic Energy Agency, 1974).

Hydrology

A major discovery resulting from early measurements of the oxygen-18, deuterium, and tritium contents of thermal fluids was that local meteoric water overwhelmingly dominates recharge of most geothermal systems (Craig, Boato, and White, 1956; Craig, 1963; Begemann. 1963). More recent studies (reviewed by White, 1970) agree with the early data with a few exceptions. New **I8O,** deuterium and tritium measurementsof cold and thermal fluids of Larderello, Italy, demonstrate local meteoric recharge with both long and short circulation times (Celati et al., 1973; Panichi et al., 1974). Meteoric water dominance has also been demonstrated for thermal fluids of El Tatio, Chile (Cusicanqui, Mahon, and Ellis, p. 703), Kawah Kamojang, Indonesia (Kartokusumo, Mahon, and Seal, p. 757). the Massif Central, France (Fouillac et al., p. 721), Iceland (Arnason, 1976; Tbmasson, Fridleifsson, and StefLnsson, p. 643). Lake Assal, Afars and lssas (Bosch et al., 1976), Broadlands, New Zealand (Giggenbach, 1971), Yellowstone, Wyoming (Truesdell et al., Abstract 111-87), Long'Valley, California (Mariner and Willey, 1976), and southwestern Idaho (Rightmire, Young, and Whitehead, 1976). In most of these systems (El Tatio, Yellowstone, Iceland, Idaho, and Long Valley), hot-spring waters are a mixture of a local cold meteoric component and a hot thermal water component, also of meteoric origin but from higher elevation and somewhat distant from the hot-spring area.

Mixing of local cold water with hot seawater has been demonstrated by 180 and deuterium studies of coastal geothermal systems of Greece (Stahl, Aust, and Dounas, 1974). Italy (Baldi, Ferrara, and Panichi, p. 687), and Japan (Mizutani and Hamasuna, 1972; Matsubaya et al., 1973; Sakai and Matsubaya, 1974). Thermal connate and metamorphic waters were shown to mix with meteoric water in the California Coast Ranges by White, Barnes, and O'Neil (1973). Meteoric thermal waters are interpreted to mix with cold saline lake waters at Lake Assal, Afars and Issas, by Bosch et al. (1976), although the high salinity of borehole waters from this area (Gringarten and Stieltjes, 1976) suggests a more complicated system.

Tritium measurements have been used to demonstrate mixing with young near-surface waters. Gupta, Saxena,'and Sukhija (p. 7411, using this approach, calculate hot-water fractions for spring waters of Manikaran, India, that agree with those calculated from the warm-spring mixing model.

In general, radioactive isotopes have not been successful in indicating the circulation times of geothermal systems. This results from the generally long circulation times involved (except for some Larderello steam discussed above), which are usually beyond the range of tritium dating; from the large quantities of metamorphically produced old CO, , which prevent use of **I4C** measurements; and from the common admixture of young near-surface waters with old deep waters in surface thermal discharges. Recent improvements in low-level tritium analysis may improve the situation.

The radioactive 39Ar isotope has a half-life of 269 years, which allows a dating range of SO to **1000** years, and has been used successfully to estimate a <70-year age for water in a Swiss thermal spring (Oeschger et al., 1974). This analysis, although difficult, should also be possible for drilled high-temperature geothermal systems.

Ceothermometry

Certain isotope geothermometers equilibrate more slowly than chemical geothermometers and are capable of indicating temperatures in the deeper parts of geothermal systems. By considering a number of chemical and isotopic geothermometers with various rates of equilibration, it may be possible to calculate the temperature history of a thermal water. This calculation would depend on the existence of considerably more rate data than are now available.

At the time of the first UN Geothermal Symposium, only the distribution of carbon isotopes between CO, and CH,, (A'3C[C02,CH,]), had been tested as a geothermometer. Analyses of well discharges of Larderello (analysis I t 8 Ferrara, Ferrara, and Gonfiantini, 1963) and Wairakei (analysis NZI; Hulston and McCabe, 1962b) indicated temperatures in good agreement with measured reservoir temperatures. These indicated temperatures were based on fractionation factors calculated by Craig (1953) which have been shown to be somewhat in error by Bottinga (1969). Using the corrected fractionation factors, indicated temperatures are increased by SO to 75°C and the new temperatures are higher than those found in the reservoir. Experimental work is needed on this geothermometer to confirm the new fractionation factors, but the indicated temperatures may be real and exist in these systems below drilled depths. C0,-CH, temperatures at Broadlands, New Zealand (analysis NZ3), range from 385 to 425°C (Lyon, 1974) considerably above the reservoir temperatures (-270°C). although tem

peratures in a deep Broadlands drillhole reached 307°C. New measurements at Larderello (C. Panichi, oral commun., 1975) indicate subsurface temperatures that vary with, but are higher than, observed reservoir temperatures. Temperatures for hl3C(CO2, CH,) have also been calculated for geothermal fluids from Indonesia (analysis Ids I), Kenya (analyses K I-3), and the United States (analyses US5 and US36).

Hydrogen isotope geothermometers, AD(H2,CH,) and AD(H,,H,O). have been tested in a few systems in Kenya; New Zealand; the Imperial Valley, California; and Yellowstone; but appear to reequilibrate rapidly and in most cases, indicate temperatures that approximate those of collection (analyses K2, NZ3, US5 and US36). Recently, Horibe and Craig (in Craig, 1976) have experimentally calibrated the H,-CH, geothermometer, which should encourage more isotopic analyses of these gases.

Although gas isotope geothermometers are the only ones available for vapor-dominated systems, they leave much to be desired as practical exploration tools for hot-water systems. Equilibrium may be achieved only below drillable depths (C0,-CH,) or continue up to the sampling point (H,-CH,, H,-H,O), and most geothermal gases (especially from hot springs) are so low in methane that collection and separation are difficult.

For hot-water systems the most useful proven isotope geothermometer may be the fractionation of oxygen isotopes between water and its dissolved sulfate, which appears to equilibrate in geothermal reservoirs at temperatures as low as 95"C, and to reequilibrate so slowly during fluid ascent to the surface that evidence of temperatures above 300°C is preserved in some hot-spring waters. Experimental equilibrium and kinetic data have been measured by Lloyd (1%8), Mizutani and Rafter **(1969).** and Mizutani (1972). Equilibrium has been demonstrated between dissolved sulfate and borehole water from Wairakei (analysis NZ ***I ;*** Mizuntani and Rafter, 1969: Kusakabe, 1974). Otake, Japan (analysis 56: Mizutani, 1972), Larderello (analysis It8; Cortecci, 1974). and Raft River and Bruneau-Grandview, Idaho (analyses US15 and US17 Truesdell et al., unpub. data, 1975). The application of this geothermometer to boiling springs of Yellowstone, correcting for the effect of steam loss on **I8O** content of the water, was made by McKenzie and Truesdell (Abstract 111-65). and unpublished measurements have been made on several other United States spring systems (analyses US7, USIO, US/& US24, US26-27). Estimates of subsurface temperatures in Japanese geothermal systems without deep drillholes and uncorrected for steam loss appear reasonable (analyses J ***1-5;*** Mizutani and Hamasuna, 1972; Sakai and Matsubaya, 1974).

Two other geothermometers need more testing. The first, A34S(S0,,H2S), which has recently been calibrated experimentally by Robinson (1973). indicated unreasonably high temperatures for Wairakei bore fluids (analysis NZ2. Kusakabe, 1974) and for Mammoth, Yellowstone, water (analysis US35; Schoen and Rye, 1970). The second, AI3C(CO,,HCO,) may indicate the temperature of bicarbonate formation at Steamboat Springs, Nevada, and Yellowstone (analyses US24, US30, and US32), but experimental data in this system need reevaluation (O'Neil et al., Abstract 111-71).

In the rather special circumstances where water and steam phases may be separately analyzed, or steam analyzed and water isotopes estimated from other samples, the liquidvapor fractionation of deuterium or **I8O** may be used to estimate temperatures of phase separation. This has been done at Wairakei (Giggenbach, 1971), Campi Flegrei, Italy (Baldi, Ferrara, and Panichi, p. 687). Kawah Kamojang, Indonesia (Kartokusumo, Mahon, and Seal, **p.** 757), and White Island, New Zealand (Stewart and Hulston, 1976).

Rare Cas Studies

Rare gases (He, Ne, Ar, Kr, and Xe) have been analyzed in geothermal fluids and shown to indicate the source of water recharge and, less certainly, the mechanism of steam loss (Mazor. p. 793). Ne, "Ar, Kr, and Xe are not produced in rocks and do not undergo chemical reactions. However, they are affected by phase changes and their distribution between liquid and vapor is temperature dependent. For this reason, their contents in geothermal waters that have not boiled indicate that recharge waters are meteoric and allow calculation of temperatures of last equilibration with the atmosphere. In systems with subsurface boiling, the water phase is depleted in gases and their concentration patterns may indicate dilution and boiling mechanisms.

Other rare gases (,He and **^{40}Ar)** are produced from radioactive decay of rock materials and their concentrations may indicate rate of water movement through the system (Mazor, Verhagen, and Negreanv, 1974). High-temperature thermal waters in young volcanic rocks of Yellowstone and New Zealand apparently do not contain anomalous **,OAr** (Mazor and Fournier, 1973; Hulston and McCabe, 1962b), although young volcanic rocks that have not lost volatile elements have high ^{40}Ar contents (for example, Dalrymple and Moore, 1968). The origin and fate of "OAr in geothermal systems needs much closer study.

Several recent studies have been made of excess ^{3}He in ocean water (Craig, Clarke, and Beg, 1975), volcanic rocks (Lupton and Craig, 1975), and geothermal fluids of Iceland (Kononov and Polak, p. 767), Kamchatka (Gutsalo, p. 745). and Imperial Valley, Lassen, and Kilauea in the United States (Craig, unpub. data, 1975). ^{3}He has been depleted from the atmosphere and crust because it is lost into space at a greater rate than ,He, and its enrichment in waters and rocks associated with spreading centers indicates contributions from the mantle. **As** noted earlier, mantle contribution of this isotope does not necessarily indicate that other mantle-derived components are present in geothermal fluids.

CHEMICAL MODELING AND METHODOLOGY

Modeling

Geothermal systems are chemically very active. Deep minerals are altered in response to the prevailing pressure, temperature, and chemical conditions, and ascending fluids change their physical and chemical properties rapidly over relatively short distances and effect profound mineralogical changes in rocks traversed. Mineralogical changes in these processes were reported by Bird and Elders (p. 285) and Reed (p. 539). It would appear both challenging and rewarding **to** model these changes, but disappointingly few attempts have been made.

Pampura. Karpov, and Kazmin (p. 809) report a chemical model for the changing compositions of ascending fluids of the Pauzhetsk geothermal system. Many of the changes described earlier as occurring during the near-surface alteration of volcanic waters are successfully modeled, but the

absence of potassium in the fluids and of aluminosilicate minerals is a severe limitation. A relatively simple model for computing the downhole character of geothermal fluids (Truesdell and Singers, 1971) has been used to calculate deep pH values.

Using established models for solution and mineral equilibria, mineral alteration has been related to deep fluid chemistry for Broadlands, New Zealand, by Browne and Ellis (1970) and for Cerro Prieto, Mexico, by Reed (p. 539). **In** both these systems, deep waters are in near equilibrium with rock minerals and produced their observed metamorphism. Mass transfers in the Dunes, Imperial Valley, geothermal system were deduced from mineralogical changes by Bird and Elders (p. 285).

Methodology and Data

The geochemical investigations described in this report depend both on the accurate chemical and isotopic analysis of natural fluids and on laboratory measurements of the properties of chemical substances over a range of temperature and pressure. Because analyses of many samples from a geothermal system allow a more complete reconstruction of chemical processes and deep conditions, analytical methods that are rapid and inexpensive or that can be automated are useful. Bowman et al. (p. 699) and Hebert and Bowman (p. 751) describe automated instrumental methods of water analysis that appear *to* be rapid and accurate and can provide analyses for trace constituents not normally measured. Some of these traces may provide geothermometers when their behavior is better understood.

Geothermometer components are necessarily not in equilibrium under surface conditions, and special care must be taken to preserve them for analysis by dilution (SiO,) or filtration and acidification (Ca). Thompson (1975) and Presser and Barnes (1974) report methods for collection and preservation or field analysis of geothermal waters. Akeno (1973) describes methods for preservation and analysis of geothermal gases. Downhole samplers for geothermal wells have been described by Fournier and Morganstern (1971) and Klyen (1973). Collection of geothermal fluids was the subject of a recent workshop (Gilmore, 1976).

Potter (p. 827) and Potter, Shaw, and Haas (1975) have compiled and assessed the status of studies on the density and other volumetric properties of geothermal brine components, and, using critically evaluated data, Haas (1971) has calculated boiling point-to-depth curves for sodium chloride solutions. Compilations of geochemical data are also being made by the Lawrence Berkeley Laboratory (Henderson, Phillips, and Trippe, Abstract 1-15).

It is impossible to review here the many experimental studies of solution chemistry at high temperatures and pressures that are directly applicable to geothermal systems. These studies have been recently reviewed by Ellis (1967, 1970), Franck (1973), Helgeson (l969), Helgeson and Kirkham (1974), and Marshall (1968, 1972). When sophisticated chemical models are constructed for geothermal systems in their natural and disturbed states, these experimental studies will provide vital data.

AN EXAMPLE OF EXPLORATION GEOCHEMISTRY

The role **of** chemistry in geothermal exploration is well illustrated by investigations at **El** Tatio, Chile, reported by Cusicanqui, Mahon, and Ellis (p. 703), Lahsen and Trujillo (p. 157), and Armbrust et al. (1974), that were made in conjunction with geological and geophysical studies (Healy and Hochstein, 1973; Hochstein, Abstract 111-39; Healy, p. 415) by New Zealand and Chilean scientists with United Nations support. El Tatio lies at an altitude of 4250 m in the high Andes. There are over 200 hot springs, most of which boil (at 8S.S"C at this altitude) and deposit sinter and halite. Many of these springs were analyzed for major and minor components and some, along with cold springs and snow samples, were analyzed for **I8O** and deuterium. Fumaroles were analyzed for gases.

The analyzed spring waters showed narrow ranges of CI:B and Na:Li ratios, indicating homogeneous thermal water at depth. Waters of the northernmost spring group were rather uniform in composition, with 8000 &200 ppm chloride, SiO, contents of 260k ppm, and Na:K weight ratios near 8.2. To the south and west, spring waters have lower SiO, contents, higher Na:K ratios, and CI contents of about 4000 to 6000 ppm, indicating mixing with near-surface waters.

Direct application of chemical geothermometers to highchloride spring waters indicated minimum subsurface temperatures averaging 160°C from quartz saturation, 167°C from Na:K ratios, and 205°C from NaKCa relations. Maximum indicated temperatures were 189°C (quartz saturation), 210°C (Na:K), and 231°C (NaKCa). The boiling-spring mixing model of Truesdell and Fournier (p. 837), not yet developed at the time **of** the original investigations, can be applied to these spring waters assuming that those to the north were not diluted and that those to the south and west were mixtures with cold dilute water (t = 4"C, CI = 2 ppm). Average calculated subsurface temperatures are 208"C, but the maximum indicated temperature of 274°C is considered to be a better indication of the maximum aquifer temperature.

Some of the high-chloride **El** Tatio springs issue at temperatures below boiling, and warm-spring mixing calculations, assuming cold waters of 4°C and 25 ppm SiO,, indicate an average subsurface temperature of 269°C (standard deviation 13°C).

The patterns of CI contents, SiO, contents, Na:K ratios, and Na:Ca ratios were interpreted to indicate that cold near-surface drainage from the east was entering a shallow aquifer in the western and southern areas, and diluting high-chloride water rising from greater depths.

Deuterium analyses of the thermal waters agreed with the general picture of near-surface mixing, but suggested that the deep recharge was from higher elevation precipitation with lower deuterium values. Cold-water samples from the higher mountains to the east also tended to have lower deuterium values than local precipitation and were considered possible recharge waters.

Fumarole gas analyses also suggested movement from east to west, but at shallower depths. Eastern fumaroles had much higher contents of CO, and H,S than other gases, and higher ratios of H,S:CO,. Quantitative interpretation of gas concentrations is difficult because of the effects of rock reaction and fractional separation into steam. In general, gases tend to decrease in CO, and H,S content and in H,S:CO, ratio with lateral flow (Mahon, 1970; Truesdell, 1976a). In retrospect, more weight should have been given to the fumarole chemistry in siting exploratory wells.

On the basis of resistivity surveys and spring chemistry, six slim holes were drilled to about 600-111 depth. **In** the west and northwest, holes I , 2, and 4 encountered maximum

temperatures of 212 to 230°C. with temperature inversions toward the bottoms of the wells. In wells 3 and 6. in the southwest, temperature inversions were not found and 254°C was measured in well 3. Seven production wells were located near No. 3, and the best of these (No. **7)** tapped fluids of 263°C. A shallow (about 170-m) aquifer at 160°C was encountered in the Trucle dacite, which is probably where mixing with near-surface water occurs to produce the lower chloride waters of the western and southern springs. Deeper aquifers in the Puripicar ignimbrite (500 to 600 m) and the Penaliri (Salado) tuffs and breccias (700 to 900 rn) were at about 230 and 200 to 260°C. respectively.

Comparison of drillhole and spring analyses indicates that the most concentrated spring waters are undiluted samples of the deep thermal fluids. The quartz saturation, Na:K. and NaKCa geothermometer temperatures are low. indicating considerable subsurface reequilibration. The mixing calculation temperatures are. however, surprisingly accurate.

Lateral subsurface flow from east to west, indicated by water isotopes and fumarole gases, was confirmed by drillhole measurements. Tritium contents of drillhole fluids suggested that the subsurface transit time was **IS** years (unusually short for geothermal waters), but small additions of young near-surface water would also explain the results.

The early resistivity survey did not indicate lateral flow. and a resurvey was made after the exploratory holes were drilled. This showed a much larger anomaly that could be interpreted as due to deep lateral flow.

Two chloride inventories were made to estimate the total heat flow from the heat:chloride ratio of the thermal waters, which was established from drillhole fluid temperatures and chloride contents. These were not very accurate because of salt accumulation at the surface, but indicated a heat flow of 30 to ***SO*** x 1 8 cal/sec.

El Tatio is very favorable for the application of geochemical methods because there are a large number of springs with rapid flow from the thermal aquifer, and the surface chemistry indicated subsurface conditions with reasonable accuracy. Gas and isotope analyses correctly suggested subsurface flow patterns, and chemical geothermometers and mixing models predicted temperatures at increasing depths in the system.

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Table **1.** Chemical summaries and geothermometer temperatures for selected thermal fluids. (See end of table for explanatory notes.)

Area

:2 & :?: '"$$" Other Observed Temp tNaKCa Geothermometers OC

QC (depth)
TDS Gases C'
*C OC
References
Afl
Cal
Ca 2
ca3
Chl
Ch2
Ch3
Ch4
CO1
CZ1
cz2
cz3
cz4

cz5
cz6
cz 7
cza
ESI
ES2
Afars and Issas
Lake Assal, Spr 6 VW s 83 w,i Na>Ca>>K>,Mq 66000
Cl>>SOk>>HCO3
Canada
British Columbia
Tawah Creek (X40) VW s 43 w Na,Mg>K,Ca 2400
HC03>>Cl>>SOk
Meager Creek (X52) VW s 55 w Na>K=Ca,Mq 2000
Cl>HC03>SOt,
Hot Springs 1s1. (#57) W s 76 pw Na>Ca>>K
Chile
El Tatio
spr 181 VW s 84.5 w,tr,i Na>>KICa>>>Mg 7060
C1>>>HC03>>S04
C1>>S04>HC03
Spr 226 s 83 w Na>K>Ca 14000
Well 7 w 85.5 w,g Na>>K>>Ca>>>Mg 15600 C02>>>H2S
Average of 26 springs s 52-85.5
with standard deviation
(a) and maximum
Cl>>>HCO31SOQ
Columbia
Ruiz, Spr A1 WI s 90 pw.i Na>>K>>Ca>>Mq 1570 C02,HzS
Cl>>HC03>SOk
Czechoslovakia
Danube lowland Nvs w inc depth HC03-Na <1o00 N~.CHL,.+CO~
+ HC03-Cl-Na 55COO
Cl-HC03-Na 510000
Stranka N V F W pw
Karlovy Vary N V F w 7 2 p w
Jachymov N V F W PW
Central depression
(Danube lowland)
Chorvotsk? Grob NVS w 46
Topolniky Nvs w 90
Podhdjska Nvs w 80
Levice block,
Liptov depression,
Besenova Nvs w 34
C1-HCOJ-Na 1800
HC03-Cl-Na 3900
Cl-Na 19600
SOt,-HC03-Ca-Mq 3200
156 166
162 177
171 187
138 145
142 149
184 199
257
160 ave
15 o
189 max
174 202 1.165 Na-Ca-Si02 253 (1050 ml Bosch et al. (19761 ; Gringarten
272 WSMM TDS = 190000 and Stieltjes (1976)
210 227
197 211
161 190 205 WSMM
Souther (p. 259); Nevin and
Stauder (p. 11611
69' (347 m)
195 211 229 BSMM
210 230
261 261 262 BSMM 263 (800 ml
Cusicanqui, Mahon and Ellis (p. 703) ;
Lahsen and Trujillo (p. 157); Adrust
et al. (1974)
205 ave 208ave BSMM, 269 ave WSMM 140-170, Truesdell and Fournier (p. 8371
231 max 274max , 283 max 236-263
20 o 270 , 13 a 190-235,
255 234 Arango et al. (1970)
20 Na-K-Ca-C02
73 Chalc
154 188 44 Na-K-Ca-COZ
91 Chalc
137 92 21 Na-K-Ca-CO2
66 Chalc
36 115
38 1000 m Franko and Mucha (P. 979)
gradient
40 (1005 m) Pa8es and b& (p. 803)
72 (6 m)
30 (493 m)
46 (970-1210m) Franko and Rarickf (p. 131)
90 (2040-249Oml
80 (1160-19Ohn)
34 (4209~")

El Salvador
Ahuachapdn
Salitre
Ah-1 231
Sigvaldason and Cu6llar (1970);
Glover and Cu6llar (1970);
Cataldi et al. (11-431
Area
%io2 %io Other ObservOeCd Temp
TDS Gases adla con2 tN$cfi tNa'C KCa GeothemOoC meters (depth1
QC --C
References
El
E2
E3
E4
Fl
F2
F3
F4
GI
GZ
G .?
G4
G5
G6
G7
GUI
GuZ
HI
H2
Ethiopia
East of AwaSa **(Spr** 6-41 **VW**
AlUtO Spr **10**
Tendaho Spr **15**
Lake Afrera Spr 31
France
Massif Central
Chateauneuf,
bain tempere
Chatelguyon.
Alice
Ste. Marguerite,
Rive d'Allier
Royat, Eug6nie
Greece
Kamena Vorla,
Gamma **9**
Thermopylae,
Psoroniria
Edipsos, Damria
Lesbos, Arginos
Nisiros,
Demotika Loutra
Milos,
Mavros Gremos
Sousaki, borehole
Guadeloupe
Bouillante 2
Spr G52.4
Hungary
Pannonian Basin
Triassic dolomite
U-Plio. sandstone
VW
VW
VW
NVF
NVF
NVF
NVF
vsw
vsw
vsw
vsw
vsw
vsw
vsw
vsw
Nvs
NvS
s
S
S
S
S
5
S
S
W
s
s
S
s
W
W
W
s

w
w
87
96.5
100
57.5
37
35.5
29
33
47.9
32.5
78.5
81
48.5
45
73
1.99
59
1007
99?
w, tr
w,tr
W,tI
w,tr
PW
pw,i
pw
PW
w
w,i
w
w
w
5
PW
pw.tr.9
w
w
w
Na>Sa>K
Na,Ca,>K
Na>>Ca2K
Na>>Ca>K
1640
2510
1950
19100
18900
27800
33400
11800
32000
33800
45100 CO_2,HzS
,24600 CO_2>>>HzS
3020
1410
151
159
206
124
143
139
137
126
96
45
110
135
160
172
152
158
168
224
130
155
150
148
136
99
45
112
141
174
185
164
103
107
196 207
158 211
193 204
150 179
154 178
198 183
215 203
215 195

121 169
119 173
120 174
171 **191**
114 167
232 205
249 265
242 232
199 189
181 75
119 164
225 WSMM
208 WSMM
1.50 Na-K-Ca-COZ
130 Chalc
-50 Na-K-Ca-CO2
124 Chalc
1.50 Na-K-Ca-CO2
122 Chalc
"-50 Na-K-Ca-COZ
108 Chalc
67 Chalc
11 Chalc
81 Chalc
113 Chalc
198 WSMM
138
,120 boiling calc. 73
242
200 wsMM2
(70 m)
(145 m)
UNDP (1971); Demissie and
Kahsai **(1-10)**; Gonfiantini, Borsa,
Ferrara and **Panichi**. 1973, Earth
and Planetary Sci. Letters, v. **18**.
p. 13-21.
Fouillac et al. (P. 721)
DominCO and Papastamatokr **(p. 109)**;
Stahl. AuSt and **Dounas** (1974)
(338 **m)** Demians d'Archirbaud and Munier-
Jolain **(p. 101)** ¦Cormy, Demians
d'Archlmbaud and Surcin (1970)
1507 **(950tm)** Boldizsbr and Korim **(p.** 297)
100-150
(2250?ml
~_____

Table **1.** Chemical summaries and geothermometer temperatures for selected thermal fluids ***(continued).***

Area References
IC1
IC2
Ic3
Ic4
IC5
IC6
Ic7
IC8
IC9
IC10
IC1 ***1***
IC12
Idal
Ida2
Ida3
Ida4
Ida5
Ida6
Ida7
Ida8
Ida9
Ida10
Idal ***1***
Ida12
Idal 3
Iceland
Selfoss
Deildartunga
Seltjarnarnes
Lqsuh611
Torfajokull,
Eyrarhver
Geysir
Reyk janes
Reykjanes Well 8
Svartsengi Well 3
Krisuvik Well 6
Nhfjall Well 4
Hveragerdi wall 4
Irdia
Puga, Ladakh ***(NW***
Himalaya subprov. I)
spr 101
Well Gw5
Chumathang. Ladakh

(*NW* Himalaya I)
Spr 40
Well CGWl
Manikaran, Himachal
Pd. (*NW* Him. 11)
spr 4
spr 11
Kasol (NW Him. 11)
Tatwani
(NW Him. 111)
Kopili, Naga-Lushai
Tvral Ratnigiri,
west Coast
Tvwa, carmbsy
Bakreshvar, W. Bengal
(E.I. province)
Dug rell, s o b
NVF
NVF
NVF
NVF
VW
VW
vsw
vsw
vsw
VSW?
vw
VW
VW
VW
VW
W
vw
VW
vw
vw?
vw?
NVS
vw?
NVS?
s
S
s
8
s
s
S
W
W
W
W
W
5
W
S
W
S
s
5
5
S
S
8
8
s
79
99
83
40
95
84
99
270
236
258
258
198
83
100
49
85
81
82
42
57
57
61
63
81
42
w,i
w,i
w,i
w.i
w,i
w,i

w,tr,g
w,i
w.i
w
w.g.i
w.g.i
w
w
w
W.T
w
w
w
w
w
w
w
w
667 NZ>XOz
358
1110
1670 COZ>>Nz
1350
1130
48300 COz>>>NZ>HzS
33650
>O2>>CH4
22460
2600
956 Hz>C02>HzS
>Nz>>CH4
681 COz>>>H2=
H2S>>CHk
2850
2420
1250
1480
595
550
531
611
449
922
3527
468
701
122
145
137
160
194
227
234
149
163
126
150
143
176
209
256
262
270
241
257
261
200
157
171
87 120
86 123
68 109
162 174
148 199
200 220
210 231
234 240
251 245
260 234
262 237
169 187
258 247
248 234
153 166 148 170
161 171 151 171
141
127
105
90
116
119
119
120
94
148
131
111
93

122
125
124
124
97
288 204
268 194
322 195
117 146
108 129
279 207
50 114
192 161
96 Chalc
124 Chalc
115 Chalc
153 Chalc
193 Chalc
91
I I9
262 boiling calc.
270
236
215-240 K(COzKH4) 258
258
182 Chalc 198
Arn6rsson (1974) ; ?.mason (1976) ;
T6masson. Fridleifsson and
StefLnsson (p. 643); Bj8rnsson,
Arnbrsson and T6masson (1972) ;
Arnbrsson et al. (p. 853)
(500 rn)
221 WSHM
231 WSMM
209 WSMM
170 WSMM
224 WSMM
113 WSMM
203 WSMM
165 WSHM
Shanker et al. (p. 245);
chaturvedi and Raymahashay (p. 329) ;
Gupta, Saxena and sukhija (p. 741);
Jangi et al. (p. 1085) ; Krishnaswamy
(p. 143); Gupta, Narain and Gaur Z ::1I 3:i,
(p. 387)
102 (20 m)
max 109 (30 m)
110-151 (270Om)
170 (7340Om)
Area
%io Other ObservOeCd Temp
adia con2 'NVK tNZKca Geothermuneters
oc (depth)
TDS Gases
OC OC
References
Indonesia
Kawah Komojang,
Well 6
Dieng,
Pulosari Spr
Israel
Hamm El Farun
Rift Valley Spr
Hammat Gader
Ids1
Ids2
IS1
IS2
IS3
It1
It2
It3
It4
It5
It6
It7
It8
It9
JI
52
53
54
J5
J6
57
J6
238
55
72
52f
34

88
56
38
37
47
100
97
1
48
100
97
Y99
730 COz"H2S
1340 143
240
153
123
171
113
153
77
232 217
436 250
93 143
175 90
252 217
97 167
,300
760 260
548 521
190 78
169 198
238 (620 m) Kartokusumo, Mahon and Seal (p. 757) ;
Ellis (pers. comun., 1975)
173 (139 m) Truesdell (19711; Radja (p. 233) quoted
from Danilchik (19731
220-230 "Isotope"
260 A1)C (C02,CH4)
203 WSMH2
VS
VW
NVSW?
NVF?
NVF
vsw
vsw
VW
VW
VW
VW
VS
VS
vsw
vsw
NVS?
NVS?
VW
VW
VS
w
8
8
s
s
s
8
8
8
w
s
s
w
8
w
s
S
s
s
W
s
w
NaDDCa>>K D12900
rare gases
1490 N2'02XH4,
rare gases
Eckstein (p. 713)
Mazor (p. 793)
68 14C mixing Mazor, Kaufman and Carmi (19731
Italy
Campi Flegrei
Spr 6D
Spr 5
Stufe d'Nerone
Tuscany, Romans,
Spr 50 (group C)
Cesano Well 1
Tuscany Spr 12836
Acqua Borra

Larderello
Wells
3600
25500
116
161
271 WSMM *,300* (1800 m) Baldi, Ferrara and Panichi (p. 6871 ;
Cameli et al. (p. 315)
130-190 A180-D
(steam-water)
Meidav and Tonani (p. 1143)
82 Chalc Baldi et al. (19731
163 WSMM
210 (1400 m) Calamai et al. (p. 305)
Brondi, Dall'Aglio and Vitrani
Fancelli and Nuti (1974)
(19731
2390 COp>>N2>>>02 108
356000 148
6400 74
>1o600
220-390 A13C(C02,CH4) 5240
152-329 A180(S0,,.H20)
312 84
Panichi et al. (1974); Ferrara.
Ferrara and Gonfiantini (1963) ;
B.S. Michele 357 Cortecci (1974)
Japan
Coastal Waters
Shimoqamo 20 154 174 200 A180(S04-H20) n.a. (179 m) Mizutani and Hamasum (19721 ;
150 CaSOQ sat. Sakai and Matsubaya (1974)
221-335 isotope mixing
V18000
519000 167 200 200 A180(S04-H20)
%ZOO CaS04 sat.
Sakai and Matsubaya (1974);
Matsubaya et al. (1973)
Ibusuki 4
Arima Type
Yashio %34000 183 231 170 A180(SO4-H20)
Greentuff Type
Tottori
Volcanic Type
Bepw
Otaki 8
%4700 76 130 102 A'00(SO~-H20)
232 239 193 At80(SO4-HZO)
227 222 229 220 A180(SOt,-H20) 195 (500 m) Mizutani (1972); Koga (1970)
236 210 223 Nakamura (19691
53800
3190
Otaki Spr 3680
Matsukawa
Well MR3 2760 429 273 Sumi and Maeda (1973)

Table 1. Chemical summaries and geothermometer temperatures for selected thermal fluids *(continued)*.

Area
Other Observed Temp
%i% 20 "/%, a:"' tNaKca Geothennometers OC
OC (depth1
TDS Gases "C
OC ∝
References
I
Japan (continued)
Volcanic Type
Matsukawa
Akagawa
Matsukawa
Onikobe
Mitaki
J9
J1O
J11
J12
K1
K2
K3
MI
M2
NB1
NZ *1*
NZZ
Nz3
42 w
c
54.5 pw
800
20
1540
10800
239 358 232 250 (1100 ml Fujii and Akeno (1970); Baba et al.
(19701
KOga and Noda (p. 761)

Yamada (p. 6651; Hitosugi and
Yonetani (1972)
295 (1300 m)
VW
VW
252 208
Katayama GO-10 *w* 361 270
Kenya
Olkaria X2 v w w
VW? **f**
VW? **s**
240
170
250 360 Al3C(CO2.CHt,) 286 (1300 **m)** Noble and Ojiabo (p. 189); recalc.
,*300* K(CO~CHQI from Lyon, Cox and Hulston (1973
490 A13C(C02,CHt,) a,b); Glover (1972, 1973)
s130 AD(H2,CHb)
47-68 240-500 Al3C(C02,CH41
C1>HC03
Eburru
6000-
14500
Hannington
Mexico
cerro Prieto
Well M5 319 292 288 **BSMM**
249 250 292 BSMM
289 (1300 m) Reed (p. 539); Mercado (p. 4871
228 (1400 m)
27600 C02>>H2S 278
17500 C02>>H2S 228
VW
VW
w
w
99
99
W.P9
Well M9 W.P9
New Britain
Matupi-Rabalankaia vsw 85 Na>>Mg>Ca>K 143 189 >150 boiling calc. Ferguson and Lambert (1972)
c1>>so4
s 34200 C02>>>H2S
New Zealand
Wairakei
Well 44 255 259 360 Al3C(C02,CH41
200 K(COpCH41
6Ar=290
248 Mahon (1973); Lyon and Hulston
(1970) ; Lyon (1974)
Kusakabe (1974)
VW s99
s99
w.i.g
i 305 Al80(SO4,H2O)
400 A3% **(SOq,HpS)**
Well 28
Broadlands
Well 8 311 302 385 A13C(CO~,CH4)
275 AD(CHL.H~I
273 (771 **m)** Mahon and Finlayson (1972);
307 (2160 m) Giggenbach (19711; Seward (19741 ;
in research Ritchie (19731; recalc. from Lyon
well (19741 ; Macdonald (p. 11131
260,265,272 Truesdell and Fournier (p. 837) ;
Mahon (1973, 1972)
VW
183 ave 270 ave BSMM
17 23 **a**
218 max 306 max
NZ4 Springs **s** 179 ave
11 **a**
202 max
Kawerau
NZ5 Well ***8*** 3070 CO~>>>HZS 263 265 283 260
?HC>N~'H~
188 ave
7 0
199 M X
227 ave 225 ave BSMM
8 0 24a
239 max 267 M X
185,218,235
260,265,281
NZ6 Springs

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Table 1. Chemical summaries and geothermometer temperatures for selected thermal fluids (continued).

Area References
Turkey
Kizildere
Demirtas
Well KD-16
TI
T2
T3
T4
T5
T6
T7
US1
us 2
us 3
us4
us 5
US6
us 7
us8
us 9
us10
us11
us12
us13
us14
VW
vsw
VW
VW
VSW?
Nvs
NVF?
VW
NVS?
NVF
VW
VW
VW
NVF?
VW
VW
VW
VW
s
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s
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s
s
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w
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s
s
s
s
s
100
99
82
96
55?
102
87?
55
100
82
61.3
211
180
79
96.5
95.4
55
68.5
52
w I w
w
w
w
w
w
WrP9
w,i
w
w
w.i.14~
w,i
Pw
w,i
w.i,g
w,i
w
3780 C03>>>HzS
4210
19500
5490
2480
58700
4930 C02.HzS.SO2
156
166
175
147
114
107
178
129
194
109
153
170
179
166
179
160
163
175
188
153
120
107
189
137
209
112
63.5
372?
219
143
180
190
180
194
168
177 231
172 226
223 238
166 187
195 201
220 242
158 193

110 146
158 236
39 66
394 4
354 308
207f' 230f
203 238
156 171
118 160
227 229
126 240
132 238
211, 169,
257 215
Dominco and s%oilgil (1970)
(666 m) Alpan (p. 25)
(70 m) Kurtman and $*&lgil (p. 447) ;
Esder and SLmfek (p. 349) ;Tan
(905 m) (p. 1523);OnWr (11-36)
225 BSMM 207
137
198 WSMM 106
176 WSMM
285 boiling calc 145
Seferihisar,
cuma
Afyon,
Gecek H.
Ankara,
Kizilcahamam
Canakkale,
Tuzla
Aydin.
Germencik
United States
Alaska
Pilgrim
Umnak Island
(49 m)
5550
1610
Miller (1973) ;Miller, Barnes and
Patton (1975)
Arizona
Casa Grande
Arkansas
Hot Springs Nat.
Park, Spr 42
California
Imperial Valley
IID X2
2600 81 Chalc 102 (2500 m) Dellechaie (p. 339)
Bedinger et al. (1974)
300 (1110 m) White (1968); Craig (1976)
340 (IID X1)
200 (2400m) Swanberg (19741
259000
Mesa
Long Valley
Magma #5
Little Hot Creek
Spr
Surprise Valley,
Lake City
Morgan Springs
28000*
1700 180 Mariner and Willey (1976); Sorey and
Lewis (1976) ;Truesdell (unpub.
1660 COz>>>Nz>> data, 1975)
02+Ar>>XH4
1210 160 Reed (1975)
213 A180(S0,,H20) White, Hem and Waring (1963) ;
Truesdell, Bowen and Nehring
(unpub. data, 1976)
4590
Clear Lake
Wilbur spr
Elgin Spr
Seigler spr
Thermal waters
205 WSMM2 Berkstresser (1968); White, Barnes and
O'Neil (1973); Barnes, Hinkle et al.
(1973); Barnes, O'Neil et al. (1973);
Goff, Donnelly and Thompson (""pub.
data, 1976)
27200 CO~>>>CHI,
28900
1130 COZ>>>CHL,>N~>
02
rare gases
195 WSMM2
Mazor (p. 793)
Area
tsio tsio Other Observed Temp

adi: c o d 'Neap %$Ca Geothemometers OC
OC (depth)
TDS Gases
OC OC
References
United States lcontinuedl
Idaho
Raft River
Crank Well
Well 11S25E-11
RRGEl 147 Young and Mitchell 11973) ;Young and
11526 **rn)** Whitehead (1975a.b); Williams et al.
lp. 1273) ;Rightrmre, Young and
whitehead 11976); Tmesdell, Nehring
and Thompson lunpub. data, 1975)
us1 5
US16
US17
US18
us19
us20
us21
US22
us23
us24
us25
US26
us27
US28
NVF
NVS?
NVF?
NVF?
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NVF?
NVF?
NVF?
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NVF?
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W?
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s
s
s
s
90
60
65
76
98
93
98
49
77
94
75
76
74
a5
93
w.i.g
W
w,g,i
w,i
W
W
w,tr
W, tr
W
W
W
W
W
W
3360 N2>>COZ>>OZ>>R 131
372 107
324 N2>>02>CH4 129
566 149
136
111
136
157
128
161
214

125
161
201
125
148
136
202
90 139
98 131
40 105
95 141
124 158
143 173
151 194
223 197
234 211
184 207
215 202
198
102 130
273 284
142 A1801S04,H20)
145 WSMM
11058 CAh1a810c1 S04,H20)
228 WSMM
234 A1801S04,H20)
Bruneau-Grandview,
Well 5531-28
Weiser,
Well llN6W-10
Montana
Marysville
Big Creek
Nevada
Beowane
Buffalo Valley
Kyle
Steambaat
690 125
975 154
98 Chalc 98 I1000 m) Blackwell and Morgan lp. 895); Morgan
(written comun., 19761
IP. 553)
223 WSMM Robertson. Fournier and Strong
1140 198
1370 118
2270 152
2370 lea
212 (400 **rn)** Mariner et ai. (1974al; **Bowman** et ai.
lp. 6991; Wollenberg lp. 1283); White
(1968); Truesdell and Nehring (unpub.
data, 1975)
215 WSMM
257 WSMM
2209. A’801S0,,,H20)
190f A18ClC02 .HC031
186 (222 **rn)**
New Mexico
Jemez Mtn.,
Jemez Spr
Oregon
Alvord
3500 122 165 WSMM Trainer 119741
3400 140
850 130
217 WSMM
209 A1801SO~,H201
192 WSMM
196 A1801SO~,H20)
Mariner et al. (1974b); Lund, Culver
and svanevik lp. 2147); Truesdell.
Sannnel, Mariner and Nehring (unpub.
data, 1975)
Klamath Falls,
Olene Gap
Utah
Roosevelt Hot Spr
Wyoming
Yellowstone Park
Shoshone Basin
Area I Sprs
7850 196 260+ Mundorff 119701 ;Swanberg 11974) ;
Beaver County News (1976)
us23
US30
190 ave
10 0
203 max
1250 COZ>>>R>>>H~S 185 199
175 ave 267 ave BSMM
16a ***5 0***
223 max 272 max
110 171 272 BSMM
1296O0t A Al1830C(ISC0042,,HH2C00)3)
Truesdell and Fournier lp. 837, ***o*** =

Std. dev.); McKenzie and Truesdell
(111-65); Thompson et ai. 119751 ;
White et al. (1975); Truesdell
and Fournier (1976b) ;Truesdell
lunpub. data, 1975)
spr 35
Upper Basin
US31 Springs
us32
186 ave 230 ave BSMM
20 *o* 18 *o*
221 max 280 max
122 186 314 A1801S04,H20)
201 A13C1C02,HC03)
v w s 195 ave 181 (152 **m)**
11 *o*
210 max
Ear Spr 206 224
Norris Basin
us33 springs
us34
210 ave
22 *o*
255 max
250 291
251 ave 276 ave BSMM
32 *o* 32 *o*
294 max 374 max
289 272 309 A180(S04,H20)
237.5 1332 m)
Porcelain Terrace

Table 1. Chemical summaries and geothermometer temperatures for selected thermal fluids *(continued)*.

Area
%io2 Other Observed Temp
adia cy$ '".a,/" tNaKCa Geothemmeters QC
C OC OC (depth) TDS Gases
OC
us35
us36
us37
URI
UR2
UR3
UR4
YI
Y2
Y3
United States (continued)
Wyoming
Yellowstone Park
Mammoth
New Highland
Washburn Spr
Research Wells
USSR
Kamchatka
Panzhetka
Well 4
Paryaschy
Bolshe Banny
Well 35
Spr 4
Yugoslavia
Pannonian Basin
Middle Serbia
Crystalline and young
tectonic areas
VW
VS
VW
VW
VW
NVS
NVS
NVF?
References
73.5 w,i,g Ca>Na>K>Mg
82 w,trg,i
HCO3>SO4>,CI
2270 C02>>>H2S>>R 103 105 421 96 300 A34S(S0,,H,S) 73 (15-113 **m)** Schoen and Rye (1970); Robinson (1973)
74 ChalC
CO~>>CH~>>NZ> 380 bl3C(C02,CH4) Recalc. from Gunter and Musgrave
H2>>>02 115 **AD(H2,HzO)** (1966, 1971)
rare gases >boiling rare gases **Mazor** (p. 793)
70 AD(CHk.H2)
? **w** Na>>>K?Ca 1330
SOk>>Cl>HC03
99 **w** Na>>,K>Ca 1200
SOk>>Cl>HCO3
80-90 HCO3-Na.Cl-HCO3-Na. <35000 N2,CHb
C1-Na
HC03-Na-Ca-Mg co2

HCO3-SO4-Na-Ca-Mg <1o00 Np,Op,tRn
193? 209 194 209
160 168 156 186
177? 188 161 177
160 168 167 183
219
171
Vakin et al. (1970); Manukhin (11-29)
Petrovi6 (P. 531)

Note: The following abbreviations are used in Table **1.**

system Type

VW volcanic hot water system

VS volcanic steam (vapor-dominated) system

vsw volcanic system involving seawater

NVSw nonvolcanic system involving seawater

NVS

NVF

S spring

f fumarole

W we1 l

Sampling Temperature is the surface temperature for a spring or a nonboiling well discharge, the temperature of steam separation for well discharges above boiling, or the downhole temperature if a downhole sampler was used or if the analysis was recalculated to downhole conditions.

nonvolcanic sedimentary basin with thermal water

nonvolcanic system with heat from deep circulation along faults

Sample Type

Analyses

W

PW partial water analysis

Pg partial gas analysis

water analysis with all major ions and S i 0 2

adia is the quartz saturation temperature ("C) assuming maximum steam loss during cooling (adiabatic cooling) calculated by the computer program CEOTERM (Truesdell, p. 831), along with tSlo2 cond, **tNaKC-,** WSMM, and BSMM, which are defined below. No allowance has been made for dissociation of dissolved silica. Some spring systems have data indicated as ave. (average), max. (maximum), and u (standard deviation).

t, cond is the quartz saturation temperature assuming no steam loss during cooling (conductive cooling).

t,,,, is the temperature calculated from the ratio of Na to K using the WhiteEllis curve of Table 2.

tNaKDi s the NaKCa temperature calculated using the equation of Table *2.*

Other Ceothwmometers

Na-K-Ca-CO,: The NaKCa geothermometer with correction applied for high C02 contents (Paces, 1975).

Chalc: The chalcedony saturation geothermometer with conductive cooling (Table 2).

CaS0,sat.: Temperature calculated for saturation of anhydrite (see text).

WSMM: The warm spring mixing model described in the text with no steam loss before mixing. Where no other data were available, the cold water component temperature was estimated as equal to the mean annual temperature and the SiO, content was assumed to be 25 ppm.

WSMM2: The warm spring mixing model, assuming steam separation at l0OT before mixing. Same assumed cold water component as above.

BSMM: The boiling spring mixing model described in the text. The cold spring temperature was estimated as above and the CI contents estimated (in the absence of data) as *2* to 15 ppm according to the distance from the ocean.

tr trace water analysis

trg trace gas analysis

gas analysis

water P0.D) or other isotopes B

T,14C tritium, carbon-1 **4**

Water Type is calculated on a weight basis. The symbols mean:

A = B

A > B

A > B

A>>B

A >>> B

A approximately equals B in concentration

A is 1 to 1.2 times the concentration of B

A is 1.2 to **3** times the concentration of B

A is 3 to 10 times the concentration of B

A is more than 10 times the concentration of B

A"C(CO,,CH,): Temperatures indicated by the fractionation of '3C between C02 and CH,. The notation for this and other isotope geothermometers is self-evident (see text).

K(C0, + CH,): Temperature calculated from chemical equilibrium constants for the reaction CO, + 4H2 = CH4 + 2H,O.

Boiling calculation: Temperature calculated from the apparent increase in conientration of seawater due to boiling.

Na-Ca-SO,, isotope mixing, 14C mixing, "isotope", heat balance, CI-E: Special methods explained in the original references.

Observed Temperature is aquifer temperature rather than maximum temperature where aquifers are identified; otherwise, maximum recorded temperature.

References in many cases are grouped where data for a well, spring, or geothermal system are from more than one source. "recalc. from" means that temperatures were calculated from a calibration curve other than that used by the author.

TDS is the sum of the reponed constituents of the analysis in ppm (mg/kg).

Gases are in order of molar or volume abundance with the same symbols as for water type.

Table 2. Equations for geotherrnometers.
Silica *Ceotherrnorneters* (SiO, in **pprn)'**
Quartz, adiabatic cooling (k 2°C from 125-275°C)
Quartz, conductive cooling 0.5"C from 125-250°C) t"C =
Chalcedony, conductive cooling toc =
t"C =
1533.5
5.768 - log 50,
- 273.15
1315
5.205 - log SiO,
1015.1
4.655 - log 50,
- 273.15
- 273.15
NaIK *Geotherrnorneters* (Na, K in ppm)
White and Ellis (see text) (k 2°C from 100-275°C)
Fournier and Truesdell (1973)
855.6
log(Na/K) + 0.8573
t"C = - 273.15
777
log(Na/K) + 0.70
t"C = - 273.15
NaKCa Geotherrnometer (Na, K, Ca in rnoles/liter)
Fournier and Truesdell (1 973, 1974)
p = 413 for m/ Na > 1 and t < 100°C
p= 1/3for-/NA< 1 art,,,> 100°C
1647
log (Na/K) + p log (a / N a) + 2.24
t"C = - 273.15
'Data from Fournier (written cornmun., 1973)

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Summary of Section IV
Geophysical Techniques in Exploration

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INTRODUCTION

Geophysical exploration involves the study and measurement of physical waves, fields, and emissions of the solid earth and the interpretation of these observations in terms of realistic geological models. Geophysics therefore assumes the role of a science which relates physics *to* geology. Thus, whenone realizes that each subfield of physicscan be related to each subfield of geology, there is an appreciation for the potential size and rather complex nature of geophysics. The role of geophysics in the exploration for geothermal resources has been examined and discussed in several review papers (Bodvarsson. 1970: Banwell. 1970, 1973; Combs and Muffler, 1973; and in this symposium by Nakamura, p. 509: Duprat and Omnes, p. 963; McNitt, p. 1127; Meidav and Tonani, p. 1143; and Palmason. p. 1175). Geophysics is a tool which can often provide important information about the nature of a geological feature (such as a geothermal system) as effectively and certainly at a lower cost than can a large number of boreholes. However, some boreholes for direct information about the subsurface physical properties are always necessary before a geophysical survey can be properly interpreted. Nongeophysicists as well as geophysicists must be aware of the fact that particular geophysical techniques and the interpretation of the resulting data can (or cannot) be expected to provide useful results in given circumstances.

Geophysics applied to the exploration for, and delineation of, geothermal resources spans a wide range of subject areas from the measurement of physical parameters of rocks (for example: Watts and Adams, p. 1247; Duba. Piwinskii, and Santor, Abstract 111-19; Goss and Combs. p. 1019) to development of instrumentation and measurement systems (for example: Whiteford, p. 1255; Combs and Wilt, p. 917; Yuhara, Sekioka, and Ijichi, p. 1293) to data acquisition and digital data processing (for example: Hermance, Thayer. and Bjornsson, p. 1037; Isherwood, p. **1065:** lyer and Hitchcock, p. 1075) and to the modeling and geological interpretation of geophysical data (for example: Bodvarsson, p. 903: Risk, p. I191 ;Williams, et al., p. 1273). **A** considerable volume of geophysical data pertaining ***to*** geothermal systems has been developed since the first United Nations Symposium on the Development and Utilization of Geothermal Resources held in Pisa, Italy, in 1970: the proceedings of which were published in the Special Issue 2 of ***Geothermics.*** In addition *to* refinements and increases in the effectiveness of existing geophysical exploration systems, some methods and techniques not previously used ingeothermal exploration have been adopted from crustal geophysical studies as well as from the petroleum and mining industries (for example: teleseismic P-wave delays, Steeples and Iyer, p. 1199; tellurics, Combs and Wilt, p. 917; self-potential-SP, Corwin, p. 937; audiomagnetotellurics-AMT, Hoover and Long, p. 1059) and have been given thorough field tests. Several well-documented geothermal case histories have either been completed through the exploratory drilling phase or are presented as progress reports (for example: Noble and Ojiambo. p. 189: Cameli. et al., p. 315; Arnorsson, et al., p. 853: Blackwell and Morgan, p. 895; Jangi, et al.. p. **1085;** Nevin and Stauder, p. 1161; Swanberg, p. 1217; Williams, et al.. p. 1273).

Considering the large number of contributions to this section and the diverse subject matter, I shall attempt here theonerous taskof summarizing the ideas and data presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources with respect to geophysical exploration for geothermal systems. The intent of my summary will be *to* clarify several concepts associated with geophysical exploration, *to* emphasize the need for realistic geological models that can be tested, *to* summarize the diversity of geophysical information presented, and to direct the reader to significant papers published elsewhere.

PHYSICAL PROPERTIES

A geophysical survey consists of a set of measurements made over the surface of the earth, in the air above and parallel **to** it, and in boreholes within the earth. The measurements are of the variations in space or time of one of several physical fields of force. These fields are determined, among other things, by the nature and structure **of** the subsurface, and because rocks vary widely in their physical properties, at least one of these properties usually shows marked discontinuities from place **to** place. These physical properties include thermal conductivity, electrical conductivity, propagation velocity of elastic waves, density, and magnetic susceptibility.

Geothermal systems often give distinctive and fairly easily measured discontinuities in physical properties (such as high heat flow, low electrical resistivity, attenuation of highfrequency elastic waves). Clearly the ease with which discontinuities can be detected depends on the degree of contrast in the physical properties between the rocks com

prising the geothermal system and the surrounding subsurface. An accurate and unambiguous interpretation of geophysical data is only possible where the subsurface structure is simple and known from drillhole data, and even then it is by no means always achieved.

Geothermal reservoirs usually have irregular shapes and occur in rocks of complex structure and varying type. The emphasis in geophysical exploration is therefore upon detection of geothermal systems and the determination of their relative physical properties, rather than on precise quantitative interpretation. Nevertheless some indication of the quality, size and depth of a geothermal system may often be obtained. In other words, geophysical surveys are conducted in order to provide data for the location of geothermal systems and the estimation of geothermal drillhole locations.

Considerable volumes of rock at high temperatures are known to exist below all major geothermal areas (Healy, p. **415;** Muffler, p. **499;** Eaton, et al., **1975).** Almost any type of rock, igneous, metamorphic or sedimentary, may be involved. Although there can be little doubt that some types of recent igneous intrusions in the shallow crust and the associated cooling magmas constitute the ultimate heat sources for all high-temperature geothermal systems, little is known about the form of the intrusions. When the permeability due to fractures or pores is sufficient, meteoric water can circulate downward through the hot rock, extract and convect some of its heat content, and return to the surface through springs or boreholes as thermal water or natural steam (White, **1968; 1973).**

The Geysers geothermal field in California represents a good example of the abovementioned phenomena. The steam field is undoubtedly associated with the Clear Lake volcanic field of late Pliocene (?) to Holocene age (Hearn, Donnelly, and Goff, p. **423;** McLaughlin and Stanley, p. **475;** Donnelly and Hearn, Abstract **111-18)** and with a major gravity low which Chapman **(1966)** suggested was produced by a magma chamber at depth. From a detailed analysis of the gravity and magnetic data of The Geysers, Isherwood (p. **1065)** postulated that the gravity and magnetic anomalies are caused by a young intrusive body centered **10** km below the southwest edge of the Clear Lake volcanic field. Teleseismic P-delay data indicate that the postulated intrusive body may still be partly molten (Steeples and Iyer, p. **1199). A** gravity high separating the main gravity low from a smaller gravity low is most likely due to a dense cap rock that directs hydrothermal fluids from beneath the volcanic field southwest to The Geysers (Isherwood, p. **1065)** through a fault zone (McLaughlin and Stanley, p. **475)** that remains permeable because of continued microearthquake activity (Hamilton and Muffler, **1972).**

It is evident that geothermal reservoirs and their immediate surroundings have certain specific physical characteristics that are susceptible to detection and mapping by geophysical methods. The temperature within the reservoir, that is, the base temperature (Bodvarsson, **1964; 1970), is** the most important physical characteristic of a geothermal system. Simply stated, the base temperature is the highest temperature observed in the thermally uniform part of a geothermal reservoir. The physical and chemical processes within the geothermal reservoir depend critically on this quantity, and the technique of heat extraction has to be selected with regard to these temperature conditions.

Additional important characteristics of geothermal reservoirs that can be determined to some extent by geophysical exploration are the probable dimensions of the reservoir, its depth, and the necessary physical conditions prevailing within it. From theoretical calculations, Banwell **(1963)** and Goguel **(1970)** indicate that a reservoir with a base temperature of **250°C** would need to have a volume of **2** to **3** km3 in order to justify exploitation for electric power production with present-day economics and technology. This then is the size of the target to be sought by geophysical exploration, although some of the larger geothermal systems already explored have volumes which may be from **5** to 10 times larger.

The geothermal reservoir rock must have an adequate and suitably distributed permeability. A good geothermal well should produce at least 20 t/hr of steam; many wells produce at much higher rates (Budd, **1973;** Tolivia, p. **275;** Grindley and Browne, p. **377;** Mercado, p. **487;** Petracco and Squarci, p. **521;** Barelli, et al., p. **1537;** Burgassi, et al., p. **1571;** Fukuda, Aosaki, and Sekoguchi, p. **1643;** Katagiri, Abstract **VI-25).** The maintenance of high flow rates implies a high degree of permeability in the reservoir, with porosity performing only a secondary part. Permeability is not a reservoir characteristic that is easy to measure using geophysical techniques (Risk, p. **1185).**

The principal geothermal heat carrier, water, must be available in adequate quantities. As hot geothermal fluids are withdrawn from wells or from surface manifestations, the hydrological balance of the system **is** restored, or partially restored, by the inflow of new or recharge water (White, Muffler, and Truesdell, **1971).** Knowledge of water movements in geothermal systems can be obtained with geophysical techniques (Hunt, **1970;** Bodvarsson, p. **33;** Tolivia, p. **275;** Gupta, Singh, and Rao, p. **1029;** Macdonald, p. **1113;** Risk, p. **1185).**

Retention of heat is increased and the upward movement of fluids from a geothermal reservoir is restricted by a cap rock which is simply a layer of rock of low permeability overlying the reservoir. The cap rock may be formed by a stratigraphic unit (Tolivia, p. **275;** Grindley and Browne, p. **377;** Kurtman and S2milgil, p. **447;** Petracco and Squarci, p. **521;** Swanberg, p. **1217).** A cap rock may also be produced by self sealing due to the deposition of minerals from solution, mainly silica, or by hydrothermal alteration of rocks to clays and/or zeolites (Bodvarsson, **1964, 1970;** Facca and Tonani, **1967:** Bird and Elders, p. **285;** Grindley and Browne, p. **377;** Kristmansd6ttir. p. **441;** White, et al., Abstract **11-56),** Cap rocks provide a recognizable geophysical exploration target because of the considerable contrast in physical properties.

The maximum depth at which a geothermal system might be found and exploited is limited on the one hand by the probability of decreasing porosity and permeability and on the other hand by drilling costs. A provisional upper limit under present economic and technological conditions is perhaps **2** km depth to the top of the geothermal reservoir.

Since the base temperature constitutes the most important physical characteristic of a geothermal system, thermal exploration methods, such as geothermal gradient measurements in boreholes and heat-flow determinations, are of primary importance. Thermal exploration techniques provide the most direct method for making a first estimate of the size and potential of a geothermal system with surface geophysical exploration. Although geophysical methods other than thermal methods only provide an indirect deter

mination of the base temperature of a geothermal reservoir, they provide an estimate of depth, lateral extent, permeability, water supply, and cap rock distribution which cannot be obtained using thermal techniques.

The application of any geophysical method, other than thermal methods, in geothermal exploration is based on the fact that the physical property of the rock that is being measured is affected to some degree by an increase in temperature (Birch and Clark, 1940; Birch, 1943; Hochstein and Hunt, 1970; Keller, 1970; Murase and McBirney, 1973; Spencer and Nur, 1976; Watts and Adams, p. 1247). In the geophysical exploration for geothermal reservoirs, the most reliable indicator of abnormal subsurface temperatures is the direct determination of an anomalous heat flow. Any alternative geophysical indicator is less reliable since it provides an indirect determination of temperature.

For example, the application of electrical and electromagnetic methods in geothermal exploration is based on the fact that the electrical conductivity of wet porous rocks increases rapidly with increasing temperatures. Variations in electrical conductivity may be due to changes in salinity or porosity (Keller, 1970; Duba, Piwinskii, and Santor, Abstract **111-19)** rather than the temperature. There is no unique relationship between temperature and the electrical conductivity of the subsurface.

MODELS AND GEOPHYSICAL SURVEYS

From the foregoingdiscussion, it isevident that geothermal reservoirs and consequently geothermal fields owe their existence more to deep-seated tectonic processes and physical conditions than to any particular near-surface geological environment. However, it must be recognized that the total surface area thus far sampled by geothermal exploration is a very small fraction of the surface of the earth and the selection of exploration sites has been strongly biased towards areas with obvious surface thermal rnanifestations-near hot springs, geysers, fumaroles, and pools of boiling mud. Surface manifestations may or may not reflect conditions at depth depending on the extent to which the thermal system is masked by overlying nonthermal groundwater horizons.

Moreover, the presence of surface thermal manifestations implies that a geothermal reservoir has been breached by fault movement or erosion, and its contents are being dissipated by this natural leakage. The larger the outflow and the longer period of time that the discharge has been continuing, the less are the chances that a commercially useful geothermal reservoir still remains.

Geothermal exploration, however, is moving beyond this stage of reservoir detection, and has turned towards the search for deeper-seated and well-sealed geothermal reservoirs which are unmarked by any surface evidence (for example: Cataldi and Rendina, 1973; Arnbrsson, et al., p. 853; Baldi, et al., p. 871; Blackwell and Morgan, p. 895; Combs and Rotstein, p. 909; Swanberg, p. 1217; Williams, et al., p. 1273). New geothermal systems are being found by a process of geological analogy supported by geophysical measurements. However, the strategy of geothermal exploration is quite often hampered by the variability of the geological environment, by a lack of understanding of the geothermal systems, by the lack of reasonable geological models to be tested by geophysical surveys, and by a confusion about what results can be obtained from particular geophysical surveys.

The known geothermal fields of the world are all associated with various forms of volcanic activity (Healy, p. 415; Muffler, p. 499) and with faulting, with graben formation, and with tilting, uplift, and subsidence of crustal blocks, all of which are probably the result of processes in the upper mantle. The rock types present and the character of the volcanic rocks ejected are no more than a reflection of the composition of the crust in the immediate vicinity.

This close spatial and genetic relationship of many geothermal systems to young volcanic centers (Healy, p. 415) has formed the basis for a new rationale for the search for geothermal resources. This approach, developed by Smith and Shaw (1975), is to identify large, young, silicic volcanic centers which may be molten or have hot intrusive rocks at depth that can function as a heat source for the overlying convective systems of meteoric water. Although this approach has been restricted to silicic rocks, areas of intensive basalt extrusion may also have a significant geothermal potential (Smith and Shaw, 1975). For example, a major Quaternary basaltic feeder zone in southern Washington state is indicated by a pronounced negative gravity anomaly (Hammond, et al., p. 397) which would indicate that the basaltic feeder zone is partially molten if the gravity low is interpreted in the same manner as the major gravity low over The Geysers (Isherwood, p. **1065;** Steeples and Iyer, p. 1199).

Since the intrusion of magma into the upper crust can produce the necessary heat source for a geothermal system, we are concerned with the identification and development of geophysical methods to determine the depth and areal extent of these large volumes of molten rock within the crust. Because of their considerable depth of penetration, electrical, electromagnetic, and seismic techniques are the types of geophysical surveys which are particularly suited for locating deep magma chambers.

In the central volcanic region of the North Island of New Zealand, where the Broadlands, Rotokaua, Tauhara, and Waiotapu thermal areas are situated, Keller (1970) conducted a large-scale regional electrical depth sounding using the time-domain/coil technique. With this electromagnetic survey, Keller (1970) located an apparent deep heat source which has been interpreted to be a slab of basalt with a partially molten interior (Banwell, 1970). From an extensive magnetotelluric survey of the neovolcanic zone in Iceland, Hermance, Thayer, and Bjornsson (p. 1037) have found a systematically lower resistivity than was found in the older crust and have interpreted the lower resistivity to be partially caused by a small (several percent) melt fraction of basalt in the deep crust. Zablocki (p. 1299) has used the prominent self-potential anomalies found at Kilauea Volcano in Hawaii to determine the position of magma pockets on the flanks of the volcano.

Magma chambers and movement of magma within volcanoes have been recognized using seismological techniques, such as in the seismic prospecting carried out by Hayakawa (1970) at Showa-Shinzan in Japan and by Fedotov, et al. (p. 363) at the Avachinsky Volcano on Kamchatka; the use of seismic body waves from microearthquakes by Matumoto (1971) to identify the magma chamber underlying Mount Katmai Volcano in Alaska; and the use of teleseismic P-delay studies by Steeples and Iyer (p. 1199) to postulate magma chambers at Yellowstone National Park, The

Geysers, and Long Valley, California in the United States. Since magmas in the crust provide the necessary heat source for geothermal systems, large-scale exploration for hidden high-temperature reservoirs can be recommended in regions of volcanism. However, most, if not all, hightemperature geothermal areas show a close connection with eruptive centers that have produced silicic lava. This is most conspicuous in Iceland where the volcanism is predominantly mafic. Only about 5% of the lava erupted is of the silicic type; nevertheless, three or four of the largest high-temperature areas in Iceland are located near volcanic centers which have had a very recent history of silicic eruptions (Bodvarsson, 1970).

The general location of geothermal systems is therefore determined by the location of these deep igneous masses which are the probable heat source driving the overlying meteoric convection system (White, 1968). Furthermore, the detection of such systems, even if completely sealed against convection to the surface, should not be difficult. Calculation of the conductive temperature distribution over a reservoir of modirate temperature and size with its upper surface at a depth of **2** km indicates that the resulting temperature anomaly would approximately double the normal geothermal /gradient over an area of a few square kilometers. Thu!, surface thermal gradient measurements and heat-flow d+terminations in shallow boreholes penetrating below the level of the local groundwater disturbance should suffice /to locate this type of geothermal reservoir.

There is a large variety of other geophysical methods that can, in princiile, be used to map the subsurface temperature distribution. ,'The problem is to select the most suitable method f r o ~ ' t hpeo int of view of field operations, processing of data, and the interpretation of the results in terms of realistic ge$ogical models.

During the early development of petroleum exploration, almost evtry type of geophysical survey was used; however, it has been found that certain ones provide the necessary information for detecting petroleum reservoirs. A similar developbent is evolving in the application of geophysical techniques to geothermal exploration. In the past, there has frebuently been some confusion over the precise purpose for which a given geophysical survey has been undertaken, and surveys of both conventional and innovative types, often made at considerable expense, have produced data and maps whiih now appear to have little bearing on the central problem of finding and delineating geothermal reservoirs.

Refinements in the geological models (Tolivia, p. 275; T6-mpsson, Fridleifsson, and StefLnsson, p. 643; Bodvarsson, p;. 903; Macdonald, p. 1113; Morgan, et al., p. 1155) of the geothermal reservoir which are being sought will be of value for suggesting geophysical targets, for calibrating the response of our geophysical instrumentation, for explaining some of the nonrelevant anomalies in the geophysical patterns and for constructing siGnificant residual anomaly maps. In order to interpret the geophysical anomalies obtained, it is essential to convert the geological models and subsurface geological formations into their equivalent physical patterns of thermal conductivity, electrical conductivity, seismic velocity, density, magnetic susceptibility, porosity and/or permeability by laboratory measurements on actual rock samples where available; otherwise by the use of data for similar geological materials. Finally, if a geophysical survey of any kind is undertaken, it is very important to be quite clear as to the precise reasons for doing the survey and, more importantly, whether or not the particular geophysical survey is likely to make any material contribution to the detection and delineation of the geothermal system and whether or not the results of the survey can provide useful modifications to the proposed geological model of the geothermal reservoir.

GEOTHERMAL CASE HISTORIES

It is now apparent that geothermal reservoirs and their immediate environments have certain specific physical characteristics that are susceptible to detection and mapping by geophysical methods. This section of my summary will discuss various geophysical surveys currently used in geothermal exploration which can provide direct information about geothermal reservoirs. No mention will be made of the other geophysical techniques which have been used in

past geothermal surveys or have been recommended from time to time. These include methods such as gravity, magnetics, active seismics, seismic noise, airborne infrared, microwave radiometry, and satellite imagery. None of these techniques will be mentioned because none of them appear to be required to bring a geophysical investigation to the point where a deep exploratory geothermal borehole can be planned and sited. In an actual survey, problems might arise which some of these techniques could help to resolve, and some anomalies in the temperature of electrical resistivity patterns might be accounted for, but the choice of technique, and the justification for using it at all, must arise in and be defined by the progress of the original survey.
Thermal-gradient measurements and heat-flow determinations may be useful in large-scale regional surveys, as well as in specific reservoir studies, since anomalous conductive surface heat flow can be used as an indicator of hydrothermal activity at depth (for example; Cermak, Lubimova, and Stegena, p. 47; Demians d'Archimbaud and Munier-Jolain. **p.** 105; Dowgiao, p. 123; Franko and RaEick9, p. 131: Krishnaswamy, **p.** 143; Shanker, et al., p. 245; Boldizsir and Korim, **p.** 397; ESder and SimSek, p. 349: Gupta. Narain, and Gaur, p. 387: Kurtman and SBmilgil, p. 447; Mongelli and Loddo, p. 495; PetroviC, p. 531 ; Stieltjes, p. 613; Baba. **p.** 865; Sass, et al., Abstract **111-80;** Urban, et al.. p. 1241; Morgan, et al., p. 1155). As geophysical exploration techniques for guiding the site selction for deep drilling, shallow thermal surveys are of limited value because of their rather low effective depth of penetration and the masking effects of shallow groundwater circulation. The measurement of temperatures in deep boreholes (Albright, p. 847) is the only reliable method of providing information on the base temperature of a given geothermal reservoir.
Although under favorable conditions an electrical resistivity survey can provide penetration to depths of 1 km or more, the physical property that it measures is related not only to temperature but also to porosity and formation-fluid chemistry, and this makes geological interpretations of resistivity data difficult. **A** considerable number of different electrode configurations (Wenner arrays, constant-spread Schlumberger arrays, Schlumberger soundings, collinear arrays, dipole-dipole profiling, roving dipole arrays, bipoledipole arrays, rotating dipole arrays) have been used in direct current resistivity surveys (Keller and Frischknecht, 1966; Beyer, Morrison, and Dey, p. 889; Furgerson, Abstract 111-29; Garcia, p. 1003; Gupta, Singh, and Rao, p. 1029; Hochstein, p. 1049; Jiracek, Smith and Dorn, p. 1095;

Maasha, p. 1103; McNitt, p. 1127; Risk, **p.** 1185 and p. 1191; Stefhnsson and Arnorsson, p. 1207; Tezcan. p. 1231).
Electrical resistivity studies have provided data for the detection and mapping of geothermal systems, for subsurface geological and structural interpretation, and for monitoring of groundwater flow patterns. Geophysical surveys, based only on electrical methods, have been used to determine the extent of the geothermal reservoir of the El Tatio geothermal field of Chile (Lahsen and Trujillo, p. 170; Hochstein, Abstract 111-39). United Nations project experience

(McNitt, p. 1127) indicates that the most suitable geothermal exploration technique is dipole-dipole resistivity profiling since this type of electrode array is easy to maneuver in rugged country and it provides the results that are simplest to interpret geologically. Risk (p. 1191) has presented an excellent analysis of fracturing at Broadlands. New Zealand using detailed bipole-dipole resistivity studies. In another study, Risk **(p. 1185)** has shown that the inflow of cold water to the Broadlands geothermal field can be determined by regular monitoring of the position of the reservoir boundary using electrical resistivity surveys.

During the last few years, there has been a serious effort made to test various electromagnetic methods which are designed to monitor the naturally occurring electric and magnetic fields that are observed at the surface of the earth (Beyer, Morrison, and Dey, p. 889; Combs and Wilt, p. 917; Cormy and Musk, p. 933; Hermance, Thayer. and Bjornsson, p. 1037: Hoover and Long. p. 1059; Maas and Combs, Abstract 111-56; Whiteford, p. 1255; Williams. et al., p. 1273). The development and testing of the telluric and magnetotelluric methods in geothermal exploration has been motivated partly in an attempt to find ***a*** rapid and low-cost method for reconnaissance surveys of relatively large areas and partly in an attempt to increase the depth of penetration under the conditions of high near-surface electrical conductivities which usually occur in geothermal areas.

Geothermal activity may generate significant self-potential anomalies by thermoelectric coupling or by generation of streaming potentials caused by the motion of subsurface fluids. Therefore. self-potential (SP) surveys can be used to determine the presence of zones of thermal activity and 10 identify possible shallow subsurface channels for the movement of geothermal fluids (Zohdy, Anderson. and Muffler, 1973; Combs and Wilt, p. 917: Corwin. p. 937; Jangi, et al.. p. 1085; Williams, et al,. p. 1273: Zablocki. p. 1299).

It has been known for some time that high-temperature geothermal areas are characterized by a relatively high level of microearthquake activity (Ward, 1972; Combs and Rotstein, p. 909; Maasha, p. 1103). The study of these microearthquakes, and their precise hypocentral locations provide the data necessary to determine any active fault zones in a geothermal area, which may be functioning **as** subsurface conduits for the geothermal fluids. In addition, the results of a microearthquake survey can be used to speculate on the subsurface physical characteristics of the geothermal system (Combs and Rotstein. p. 909). Palmason (p. 1175) has suggested that the main use of microearthquake surveys, at the present time, may be to try to predict the depth of water circulation in geothermal systems. something which cannot easily be accomplished with other geophysical methods.

Published case histories of geothermal fields are few and are generally incomplete. However, at least eight excellent geothermal case histories have been presented at this symposium, in addition to the four presented by McNitt (p. 1127). The eight include three from the United States, the Mesa Geothermal Anomaly in California (Swanberg,

p. 1217). the Marysville Geothermal Area, Montana (Blackwell and Morgan, p. 893, and the Southern Raft River Valley Geothermal Area. Idaho (Williams, et al., p. 1273); two from Italy, the Cesano Geothermal Field (Calamai, et al.. p. *305):* one in Iceland, the Krisvik High-Temperature Area. Reykjanes Peninsula (Arnorsson, et al., p. 853), one in India. the Parbati Valley Geothermal Field, Kula District, Himachal Pradesh (Jangi. et al., p. 1085) and one in Kenya, the Olkaria Geothermal Field (Noble and Ojiambo, p. 189). I will not attempt to either highlight or summarize them here.

The papers covered in Section **IV** are extremely diverse: from the evaluation of geophysical exploration methods and techniques. to the collection of field data, to laboratory techniques and measurements, and to geothermal case studies using a myriad of geophysical surveys. Nevertheless, the unifying theme throughout is the attempt of each of the investigators to develop a better method of identifying the geothermal systems that are the target of the search and of defining potential drilling sites for exploratory geothermal boreholes. Geophysical surveys should not, however. be discontinued when the discovery well is completed but should be continued with a change in direction **as** pertains to the target being sought. That is. they should begin ***to*** examine water recharge and the nature of the heat source. to consider the prediction of permeable zones for future production-well drill sites. and to aid in the ongoing environmental monitoring.

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:Summary of Section V Environmental Factors and Waste Disposal

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INTRODUCTION

Until fairly recently, the general attitude towards geothermal pollution has been one of **laissez-fuire.** The reasons for this are not far to seek. In the first place. geothermal energy has been widely acclaimed by its enthusiasts as “clean,” and it cannot be denied that, for **a** given scale of heat exploitation, it is generally far less a cause of pollution than fuel combustion. Secondly, Nature herself is often a polluter in unexploited thermal areas; so. it is asked, who are we *to* compete with Nature? Thirdly, we have tolerated for generations (and continue *to* tolerate) the polluting effects of fuel combustion on a vast and ever-increasing scale. Hence, one argument is that the influence upon the environment from the miniscule energy contribution made by geothermal heat has, on the whole, been slightly beneficial. so that no trouble arises. This somewhat natural tendency to sweep a problem beneath the carpet of persuasive excuses is understandable; but in recent years public awareness of the hazards of all forms of environmental pollution has belatedly been aroused, and we can no longer permit ourselves to look the other way.

Stringent antipollution laws have now been enacted in certain countries. While such laws are welcome in some respects. as a step in the right direction, it has sometimes been argued that their stringency is acting as a serious and very costly brake upon the tempo of geothermal development.

It has now been virtually proved that an antidote of acceptable efficiency can be found for nearly every possible source of geothermal pollution. The more recently constructed geothermal power plants in The Geysers field, California, are models of nonpolluting exploitation in which the designers may take justifiable pride. Nevertheless. the antidotes cost money and (more important) take time to apply. It is this delaying factor, rather than the directly incurred costs, which has been the subject of some criticism. for delays are themselves extremely costly. It can be shown that every kilowatt of base-load geothermal power feeding a composite integrated power network can save about ***2*** tons of oil fuel per year. Thus, with oil fuel at a price of about $7S/ton. the cost of delaying the construction of No. 12 unit-106 MW (net)-at The Geysers would approach $16 million for one year's deferment. This sum would appear as an invisible burden on the national balance of payments. If the cost of delay were expressed as about $lSO/yr/kW and compared with the estimated construction cost of No. 12 unit, which according *to* Dan et **al. (p. 1949)** is S141.3/kW. it will be seen that one year's delay would more than double the true construction cost. Nor is that the end of the sad story, for during that year, the basic construction costs will have risen in the present inflationary climate.

These figures. although specifically applying to No. 12 Geysers unit. illustrate the urgency that applies to all geothermal power construction programs in oil-importing countries. The question arises whether strict compliance with the antipollution laws may not be too high a price to pay for achievingnear-perfection too quickly, and whether some temporary relaxation of the law would better serve the national interest. These are not only the views of the author. Axtmann (p. 1323) has suggested that some regulations under the antipollution laws should be eased, if not actually repealed. in order *to* aid the rapid expansion of geothermal development.

However. this should be a relatively short-term problem. In future installations it should be possible to synchronize the provision of the necessary pollution antidotes with the con\truction period of the remainder of the plant. Moreover, ***a s*** pointed out by Allen and McCluer (p. 1313) and Axtmann (p. **1323).** it is far cheaper to design a plant with built-in antidotes than to fix the antidotes as an afterthought to a completed installation. as has been necessary where antipollution legislation has been enacted after plants have been in service for some time. In the future, the enforcement of rigid antipollution laws probably will prove to be entirely beneficial and not unduly expensive. It may well be true that certain natural phenomena-for example, the hot springs at Yellowstone Park-are themselves "breaking the law" by polluting the environment *to* a greater extent than is permitted legally. But although we cannot prosecute Nature. there can be no harm in trying to improve her.

PROBLEMS

The problems of environmental pollution may best be considered one by one.

Hydrogen Sulfide

The gases accompanying geothermal fluids almost invariably contain H S. This noxious gas. in moderate and harmless concentrations. has a characteristic and rather unpleasant smell: but when more strongly concentrated, it paralyzes the olefactory nerves and thus becomes odorless. Therein

lies its danger. When it is present in lethal quantities, it gives no warning of its presence. It is also 17.5% heavier than air at the same temperature and is therefore apt to collect in low-lying pockets. Fatalities have occurred on rare occasions in the vicinity of fumaroles, but no incidents have yet been reported from this hazard in geothermal exploitation plants. This is probably largely attributable to the care of designers in providing adequate ventilation in cellars and basements. H, S also attacks equipment-for example, electrical contacts and commutators-and it may have adverse effects on crops and river life.

The gas can escape to the environment by all or any of the following paths: **(1)** from the condenser gas ejector discharge; **(2)** with warm vapor and air rising from cooling towers; **(3)** from wells discharging to waste when undergoing test or when a plant is unable to absorb all the steam from the bores connected thereto; **(4)** from "wild" bores; ***(5)*** from traps and drains; (6) in solution in the surplus condensate where cooling towers are used; **(7)** in solution in the main body of cooling water where river cooling is adopted for turbine condensers; and **(8)** in solution in the water phase in wet fields, when the water is discharged into rivers or streams (relatively small).

Until fairly recently, the general attitude to H, S pollution has been that with (I) , **(2), (3),** and **(4)** the combination of temperature buoyancy and, in the first two cases, a high discharge altitude ensures sufficiently wide dispersal to render the gas harmless; with (5) and **(8)** the quantities of gas are negligible; with (6) the fluids usually enter streams already infected naturally with **H, S** from hot-spring discharges; and with **(7)** adequate dilution is likely to be afforded by large river flows (as at Wairakei). This tolerant attitude may have been justified in the early days of geothermal exploitation, but the scale of development has now grown ***so*** rapidly in certain fields that H,S pollution can no longer be disregarded. Axtmann (p. **1323)** has estimated that the H,S discharged daily from Cerro Prieto *(75* MW) is about 55 tons; and if 200 MW were to be developed at Broadlands, New Zealand, the daily amount would be about **30** tons. Reed and Campbell (p. **1399)** give an estimate of **28** tons/day for the 500 MW now installed in The Geysers field. Such quantities cannot be ignored; and California legislation now insists on the removal of nearly all of this gas to bring the concentration down to less than the threshold of odor, so that if the gas can be smelled the law is being broken.

At The Geysers, escape paths (I) , **(2),** ***(5) .*** and (6) are being steadily and efficiently tackled by methods described by Allen and McCluer (p. **1313).** The ejector gases contain sufficient combustibles for them to be burnt so as to convert the H_2S into SO_2, which is then scrubbed by the coolingtower water. As a result of the "Claus reaction," elemental sulfur is precipitated. At the same time, a metal catalyst such as a nickel or iron salt is added to the cooling water, and this too has the effect of precipitating sulfur by oxidizing the H_2S. A certain amount of natural oxidation of this gas also occurs in the cooling towers. The elemental sulfur is filtered out as a sludge and the surplus cooling water is reinjected into the ground. As the sulfur sludge is contaminated with catalyst, rock dust, and ***so*** on, it is not at present marketable and is therefore being dumped in a disposal site pending the outcome of efforts to refine it or find a useful application for it. Traps and drains are being piped to the cooling towers where they share the same treatment as the condensate and cooling water. These methods are very effective, though there are certain corrosive side effects. Further research is being carried out to effect even greater H_2S abatement if possible and to reduce the corrosive action. Axtmann (p. **1323)** proposes hybrid power and chemical plants based on the Claus reaction which could render H_2S emission control profitable. Allen and McCluer **(p. 1313)** suggest it might be possible to remove the H_2S from the steam before it reaches the plant.

There appears to be no answer to **(3)** beyond insistence that, when a plant is shut down for more than a short time, the wells should be throttled back to reduce the effluent. Nor is there a solution **to (4)** beyond the avoidance of "wild" bores by taking great care when drilling. It is difficult to see a simple solution to escape-path **(7),** where river flows are not very copious and are far from the sea, other than substituting cooling towers in place of direct river cooling. It is already being claimed that at Wairakei the fisheries and weed growth may be suffering from H_2S emission into the river. The answer to **(8)** could be reinjection. Mercado (p. **1385)** states that at Cerro Prieto, although reliance is mainly placed on the conventional use of high ejector stacks for wide dispersal of H_2S, additional protection against accumulation of the gas at ground level (especially on windless days) is provided by means of extraction fans and long ducting towards the settling-pond area. H_2S detection and alarms are also installed to protect personnel against dangerous local concentrations of the gas.

Carbon Dioxide

The greater part of the incondensable gases that accompany the bore fluids consists of CO_2. This can escape into the environment by the same eight paths listed above. The fact that fuel combustion usually produces far greater quantities of this gas than geothermal exploitation on the same thermal scale has generally been regarded as an excuse for inaction, particularly as the gas is not toxic. However, in certain high-gas-content fields, such as Monte Amiata, the CO_2 discharged to the atmosphere may be much greater than that from fuel-fired plants of comparable size and duty. It is believed that thegrowingCO_2content of theatmosphere, mainly due to fuel combustion, may be having a gradual adverse effect on the world climate; while high CO_2 content in waters discharged into rivers can aggravate weed growth. It if undesirable that geothermal exploitation should contribute towards these effects, and suggestions have been made for the commercial extraction of CO, from geothermal effluents. The production of dry ice, carbonic acid for beverages, and methyl alcohol have all been considered but no commercial propositions have yet been advanced. Meanwhile the emission of large quantities of ***CO,*** from geothermal installations seems inevitable. The problem is not yet one of urgency, but if geothermal development grows dramatically-as it probably will in the near future-it will soon have to be tackled.

Land Erosion)

At The Geysers field, heavy rains and steep slopes of incompetent rock often cause natural landslides and high erosion rates. The artificial leveling of ground for the accommodation of field works, roads, and power plants has sometimes aggravated erosion by creating steep local

gradients and removing vegetation. These hazards have been stressed by Reed and Campbell (p. 1399) who state that close control, replanting shrubs and trees, more careful site selection, and improved construction methods are helping to solve this problem. Close spacing of several wells within a single leveled area, combined with directional drilling, can also help in this respect.

Waterborne Poisons

The water phase in wet geothermal fields sometimes contains poisonous elements-notably boron, arsenic. ammonia, and mercury-which, if discharged into streams or rivers, cancontaminate downstream waters used for farming, fisheries, or drinking. This hazard has been emphasized by Axtmann (p. **1323),** Rothbaum and Anderton (p. 1417). and by Andersen (p. 1317) who quotes actual concentrations of boron and permissible concentrations for various crops. Although not strictly "poisonous," high-salinity bore waters can also be harmful. A few suggested solutions are: reinjection: disposal into the sea (if not too remote) through ducts and channels: using evaporator ponds, as in Cerro Prieto (see Mercado, p. 1385): and storing the water during the dry season with subsequent release into rivers in spate during the wet season. Rothbaum and Anderton (p. 1417) propose to remove the arsenic simultaneously with the silica by preoxidizing it to the pentavalent state and subsequently dosing it with slaked lime. They also mention other possible chemical remedies.

Airborne Poisons

From ejector exhausts, from the upward effluents from cooling towers. from silencers, drains and traps. from discharging bores under test, from "wild" bores. and also from control vent-valves, various harmful elements sometimes escape into the air at geothermal exploitation sites. These can include H,S (see above), mercury, and arsenic compounds and radioactive elements. Certain quantities of noxious. though not poisonous, emissions such as rock dust and silica-laden spray (see below) may also be airborne. Mercado (p. 1385) mentions that during the initial development and cleaning of bores, the vertical discharge of fluids can foul the power plant and neighboring agricultural lands with salt. Horizontal well discharge **in** a controlled direction is being considered as a solution to this problem. Authors in general have not alluded much to airborne poisons other than H,S, but other toxicants are seldom of serious proportions. Nevertheless, systematic monitoring is advisable to keep a careful watch on possible future dangers.

Noise

The noise of escaping steam at high pressure can be very distressing to the ears, and workers on new wellhead sites have to wear ear plugsor muffs lest their hearing be damaged. Even after exploitation, when the bore steam normally flows fairly silently through insulated pipes to the plant, there will often be fluids escaping noisily to waste through any of the following paths: **(I)** newly commissioned bores or other bores undergoing test: (2) “wild” bores-fortunately rare occurrences: (3) pressurized hot water in wet fields discharged to waste and flashing in the process: (4) small quantities of steam vented to waste in order to control pressures and flows; *(5)* large quantities of steam vented to waste when a plant is shut down either inadvertently or for maintenance.

The last three of these noise sources can be greatly mitigated by means of effective mufflers which destroy the kinetic energy of the discharging fluids, reduce the volume of noise and deflect it skywards, and (more important) lower the pitch to a frequency level less painful to the ears. At the Wairakei Hotel, situated only a few hundred meters from some of the bores and vent valves, the noise-mostly from (3)-resembles that of a waterfall and has, it is sometimes claimed, a soporific rather than a distressing effect. The first two sources of noise are virtually incurable except by erecting temporary sound barriers, and can be mitigated only by reducing blowing times to practical minima and taking all possible precautions against the appearance of ”wild” bores. The third source of noise could sometimes be overcome by reinjection. Drilling operations can also be noisy. but they do not persist for very long.

Reference to noise and its reduction is made by Mercado (p. 1394). Reed and Campbell (p. 1399), Swanberg (p. 1435), Jhaveri (p. 1375). and Andersen (p. 1317). Jhaveri and Andersen give details of comparative noise levels. Jhaveri extends his study to include vibrations and Andersen includes a study of the effects of noise upon animals.

Noise in and near power-plant buildings also occurs from machinery. This is difficult to control and is generally no worse than in conventional power plants. Control rooms and office5 can be soundproofed. Legislative action against harmful noise levels has been taken in the USA and other countries, and though strict enforcement may sometimes be difficult. these lawc should act as a powerful incentive to designers to overcome the nuisance.

Heat Pollution

The necessary adoption of moderate temperatures for geothermal power production results in low generating efficiencies and the emission of huge quantities of waste heat. Where cooling towers are used, this waste heat escapes into the atmosphere and into the surplus condensate: where direct river cooling is adopted, it is mostly spent in raising the temperature of the river water. **In** wet fields, another enormous source of heat waste can arise from the reinjection of very hot unwanted bore water into rivers and streams (as at Wairakei) or into storage ponds and thence into the atmosphere (as at Cerro Prieto). One possible way of reducing this heat waste may be the reinjection of the surplus cooling-tower water and rejected bore water into the ground. Other possible ways are to generate additional power by means of binary cycles or to establish dual or multipurpose plants which usefully extract low-grade heat from the turbine exhausts or from rejected bore waters. Where none of these practices are adopted. as at Wairakei, huge quantities of heat may be dissipated into rivers, with consequent hazards to fisheries and perhaps with encouragement to the growth of unwanted water-weeds. At Wairakei, the normal river flow is fortunately sufficiently high to dilute the hot and warm wastes so that the average river temperature rise, after complete mixing has been effected, is limited to about **1 .S”C.** Although there is a high local degree of heating near the point of hot-water discharge, the danger zone is confined to a comparatively small area which the fish learn to avoid.

At times of low river flows, however, temperature rises of up to 6°C may occur. Fish kills have been reported and trout hatching appears to have suffered, though it is possible this has been partly due to other influences such as H,S.

At Cerro Prieto, waste heat is dissipated in a large evaporation pond (Mercado, p. 1385).

The ill effects of heat pollution have been stressed by Swanberg (p. 1435). In the discussion, Armstead deplored thedischarge of huge quantities of very hot water into rivers, as an unnecessary and “criminal” waste of heat in an energy-hungry world. Reinjection, he said, could perhaps be the answer. But alternatively, it should be possible to find a profitable market for vast quantities of free (or at least very cheap) heat. If medium-grade heat is copious enough it should always pay to ship the raw materials and labor required for an energy-intensive industry to remote sites where very cheap energy is available, even across national frontiers, and to transport the end products to the markets. The aluminum industry has proved this to be so. Moreover, the transportation of hot water (though not steam) was economic over considerable distances, as had been proved in Sweden.

Swanberg (p. 1435) also suggests that the escape of heat and moisture from cooling towers may affect local climate (to a greater extent than with highly efficient fuel-fired plants), particularly in the matter of forming fog and ice. On the other hand, he admits that the increased atmospheric humidity could sometimes have a beneficial effect.

Silica

One of the most troublesome products of wet geothermal fields is the silica content of the bore water, often in saturated solution at depth. With the temperature reductions as flashing occurs in the bores and in subsequent stages of exploitation, the silica will either precipitate immediately, or it will remain for a limited time in a state of supersaturation, according to the form and conditions in which it occurs. Axtmann (p. 1323) mentions that the chemistry and physical behavior of silica is not yet fully understood. Although silica precipitation on bore casing and in wellhead equipment is not unknown, usually it is delayed by supersaturation and comes out in discharge ducts. At Wairakei, for example, much effort and expenditure (about $26 000/yr according to Mahon) has to be spent in cleaning the silica deposits from the open bore water discharge channel from the field to the river. Mercado (p. 1385) reports that at Cerro Prieto, waste bore waters are ducted to a large evaporation/ settlement pond (pending the construction of a new canal to lead the waste fluids to the large Laguna Salada, or perhaps to the Sea of Cortez), and that precipitation in the ducts to the pond is not excessive. In district heating installations, however, where the bore water remains contained for a long time within pipes and heat exchangers, silica scaling can become a serious problem, especially on galvanized surfaces, as described by Thorhallsson et al. (p. **1445).** Dilution with colder fresh water has proved to be beneficial in such cases, as a less troublesome alternative to frequent cleaning with wire brushes.

The fear of subterranean silica precipitation has often acted as a deterrent to reinjection (see below), and this has been stressed by Cuellar (p. 1337). Axtmann (p. 1323) mentions the possibility of passing supersaturated silica solutions through a sand-filled fluidized bed heat exchanger, in which the fall in temperature, in combination with sand nucleation centers, should effectively precipitate and remove the silica; while Rothbaum and Anderton (p. 1417) describe a pilot plant for treating supersaturated silica solutions with slaked lime to produce useful calcium silicates. Both these proposals could perhaps effectively remove the silica from the bore water before reinjection. The Rothbaum and Anderton proposal could simultaneously remove any arsenic that might be present (see above). The resulting calcium silicates may be dried with geothermal heat and used for building materials, insulants, ceramics, and perhaps for pretreating soils. Axtell, in the discussion, asked how much enthalpy would be lost by the treatment advocated by Rothbaum and Anderton (p. 1417). Mahon, on behalf of the authors, said that a **9** and an 8°C temperature drop had been observed at Wairakei and Broadlands respectively. The use of settlement ponds, as at Cerro Prieto, can be a partial solution to the problem of precipitating silica by aging before reinjection.

CuCllar (p. 1337) discusses the chemistry and behavior of silica and describes certain tests performed at Ahuachapin in order to ascertain the best method of waste-water disposal. It has been demonstrated that reinjection at or above 150°C can be effected without any silica deposition in the reinjection bore or in the underground fissures, but for lower temperatures encrustation will occur after a lapse of time as the water cools. This means that water separated at the wellheads at more than 150°C would have to be carried to the reinjection points through insulated pipes, or if open channels were used, periodic cleaning would be necessary. Also, if lower temperature water is rejected, silica will be precipitated in the pipes or ducts by which such water is removed. It has been found thata retention pond of adequate capacity effectively removes much of the silica by encouraging polymerization so that deposition in channels or pipes after retention would be reduced if not entirely eliminated. Further tests are to be done to study the effects of silica on reinjection at lower temperatures after retention; but it is understood that nevertheless it has been decided to construct a 70-km open channel to the sea, capable of carrying at least **1** m3/sec by gravity.

Another nuisance from silica can be caused by the deposition of fine spray from blowing bores or field silencers on automobile windshields or windows of nearby buildings. Unless quickly wiped off, the deposit becomes very hard and difficult to remove. Spray from the same source can also kill local vegetation. Timber was thus destroyed at Wairakei, and problems arose in El Salvador from this cause, where the bores are sited among coffee plantations. Damage of this sort is usually confined to relatively small areas and must be accepted as inevitable. The payment of compensation to landowners may sometimes be necessary but this should form a negligible fraction of the production costs.

Subsidence

The withdrawal of large quantities of subterranean water from a wet field can cause substantial ground subsidence. This can cause tilting and stressing of pipelines and surface structures, and perhaps could lead to serious damage or even disaster, though large local differential movements are fortunately rare. Stilwell, Hall, and Tawhai (p. 1427) mention vertical movements having been observed of up to **4.5** m

in 10 years at Wairakei and **6** m since **1962.** In addition, horizontal movements of up to **0.225** m have been detected in **8** years, these movements being towards the area of maximum subsidence, which does not necessarily coincide with the area of maximum fluid discharge. Damage at Wairakei has been confined to fractures in the main bore water drainage channel. The power plant itself is fortunately sited well away from the area of maximum subsidence. Dry fields appear to be immune from this trouble (except for tectonic subsidence).

Where wet fields are exploited it is important at the very outset to establish an accurate reference grid of bench-marks and triangulation, extending well into undisturbed areas, so that all ground movements within the exploited area may be carefully monitored. Swanberg (p. **1435)** states that as an alternative check to direct mensuration, gravity surveys offer an approximate indication of water-depleted zones. He also mentions that extensometers are being used in the Imperial Valley, California, to differentiate between deepseated and shallow movements arising from aquifer depletion and ground-water pumping respectively. Stilwell. Hall, and Tawhai (p. **1427)** say that the introduction of extensometers in New Zealand is proposed in order to detect rock strains.

In the discussion, Dominguez asked Stilwell whether distinction could be made in wet fields between tectonic and water-removal subsidence; but the speaker said this was not yet possible.

One theoretical remedy to ground movement. proposed by Swanberg (p. **1435),** would be to install downhole heat exchangers instead of extracting the natural thermal fluids. This would seem to pose underground circulation problems, and in any case an economic solution is not easily foreseen. Another more obvious remedy would be to recharge the field, partly by reinjecting the thermal water after flashing, and partly by means of supplementary water to make good the deficit lost in steam. It has been observed that a discharging field (for example, Broadlands, New Zealand) after "resting" will "rebound" to a large extent as a result of natural recharge, so that this method would almost certainly be effective. In a built-up area it could well be mandatory. In the discussion, Barnea asked Stilwell whether the New Zealand authorities had been deterred from reinjection by the hope that the field would ultimately yield dry steam. The speaker replied that owing to conflicting opinions as to the efficacy of reinjection there had been reluctance to risk spoiling the performance of the field.

Seismicity

Fears have sometimes been expressed that prolonged geothermal exploitation could trigger earthquakes, especially if reinjection is practiced in zones of high shear stress where fairly large temperature differentials could occur. These fears arise because all existing geothermal exploitations are in naturally seismic areas, and it could be that any interference with nature could precipitate seismic shocks. Swanberg (p. **1435)** cites examples in Colorado where fairly big shocks have been induced by the reinjection of waste fluids. Conversely, he says, withdrawal of fluids from an aquifer is likely to have the reverse effect of reducing seismic activity. Cameli and Carabelli (p. **1329)** report a controlled experiment, performed in Italy over a period of **40** days of reinjection, in which careful seismic and microseismic measurements were taken before and during reinjection. No effects were observed.

Ridley and Taylor (p. **141**])give warning that the extraction of heat from artificially fractured hot rocks by injecting cold water could well cause seismic activity. **On** the other hand. the main purport of their paper is conversely orientated; that is to say, it stresses the dangers of natural seismicity to geothermal installations and warns that detailed seismic studies should always precede exploitation and that all possible precautions should be taken for the protection of plant, pipelines, and other surface equipment.

Reinjection (see below) is a comparatively new practice which seems likely to become more widespread, and further experience on this potentially important matter is likely to be gained. Looking to the more remote future when vast quantities of deep-seated heat will probably be exploited by new techniques, it is possible that the risks of seismic effects could become more serious. Incredibly large quantities of heat could be won by cooling the planet through a miniscule average temperature drop. But the tiniest average temperature drop could be achieved only by fairly large local temperature drops at the points of exploitation; and this could give rise to high local stresses, perhaps with unfortunate seismic results. Although this is a long-term problem, it should be carefully studied well in advance.

Escaping Steam

As already mentioned above, the escape of moisture from cooling towers could sometimes cause fog. Of more serious impact can be the huge volumes of flash steam escaping from hot bore water rejected from silencers and from flow control vent valves. as at Wairakei. Dense fogs can result from these discharges, which may drift across nearby roads and cause traffic hazards. Traffic warning signs and diversionary routes can of course mitigate the trouble, but the best palliative is to use the hot bore water productively or to reinject it into the ground. A similar problem arises where bores, newly opened or under test, have to be blown directly into the atmosphere. This is unavoidable at times, but in a well-exploited field the proportion of openly discharging bores will be small and the hazard not serious.

Scenery Spoliation

Thermal areas often occur in natural beauty spots, highly valued by the local population and frequented by tourists. Conservationists may sometimes oppose geothermal development on the grounds that scenic amenities are thereby destroyed. This could be an exaggeration, though it is true that man-made engineering works can seldom compete with natural scenic beauty. Certainly the power plants at The Geysers, California, have been most tastefully camouflaged. The pipelines have been colored to blend in with the background; scarcely a puff of steam is visible; the power plants are inconspicuous; and the dry climate quickly absorbs the plumes of vapor rising from the cooling towers. In New Zealand, where the scarred ground surface has been rehabilitated by careful "landscaping" and damaged trees have been removed so that only the healthy forest is visible, visitors flock to see the geothermal development in greater numbers than those who frequented the area before exploitation. In fact, the Wairakei scene can claim a certain majesty of its own. Even the billowing steam from the

wellhead silencers-itself a form of "pollution"-contributes an aesthetic quality.

It is true that geothermal development can interfere with natural surface thermal manifestations. **In** New Zealand, for instance, the activity of the geysers and hot springs in the once-famous Geyser Valley (close to Wairakei) has virtually ceased. The question of scenic amenities is one that can only be judged subjectively on a balance of considerations, by weighing the value of energy against that of tourist attractions and national heritage. This judgment must be an emotional one and cannot be strictly quantitative. The declaration of an area such as Yellowstone Park, as a zone of outstanding beauty and interest, not to be exploited for energy development, would be a value judgment: there can be no absolute standards in such matters. However, it is only fair to say that a geothermal power plant which produces no smoke, has no unsightly chimney stacks, no ungainly coal- or ash-handling equipment, no coal storage yards or oil storage tanks, and no boiler house can be far more pleasing to the eye than a fuel-fired plant of the same capacity. For similar reasons, industrial establishments using geothermal heat are likely to be far less obtrusive than those that rely upon fuels. On balance, it may justly be claimed that geothermal exploitation is far less a cause of scenery spoliation than fuel combustion, and we must have electricity and industry.

This question has briefly been referred to by Swanberg (p. 1435). whose comments are generally in conformity with what has been said here.

Ecology

There remains one other aspect of the environment that could perhaps be disturbed by geothermal developmeqt, though it has scarcely been mentioned by the authors apart from a passing reference by Mercado (p. 1385) and an implication by Andersen (p. 1317). That aspect is the ecological balance of local flora and fauna. This has been the subject of study in New Zealand, and nodoubt elsewhere. The discharge of chemicals into the air, streams, and rivers and thence into the ground water, small but appreciable changes of local temperature and humidity, noise, and a degree of deforestation: all those factors could, and probably do, disturb the natural balance of nature prevailing before exploitation. Protectors of wildlife and of fisheries would do well to encourage more intensive research in this direction.

REI N J ECTI ON

Reinjection of fluids into the ground has been repeatedly mentioned, either as a proposal for overcoming some particular pollution problem, or as a practice already being adopted. There can be little doubt that the successful reinjection of cooling tower effluents and of rejected bore waters could provide answers to several of the problems discussed. This fact has been recognized for many years, but there was a timidity of approach towards reinjection. Would the introduction of cooler waters into the permeable substrata interfere with the useful output of heat from the producing wells? Would excessive power be absorbed in forcing the unwanted fluids into the permeable substrata? Would the underground permeability be destroyed by chemical deposition? Would reinjected waters outcrop elsewhere, thus simply transferring the pollution problem from one place to another? Would reinjection trigger seismic shocks?

At the UN Geothermal Symposium at Pisa in 1970, reinjection was mooted as a subject worthy of study. By 1975 quite a valuable amount of empirical data had been gained. The “pros” and the “cons” of reinjection cannot yet be established beyond all doubt, but practical experience now offers promisi-ng evidence that reinjection could often be an excellent solution to environmental problems, though clearly there may be occasions where local conditions would render it impractical-at least without prior chemical treatment or settling facilities.

Einarsson. Vides, and Cuellar (p. 1349) describe successful experiments performed in 1970 and 1971 at the Ahuachaphn field in El Salvador, where the most serious environmental problem was how to dispose of bore water from a wet field containing boron. These waters could not be discharged into riverbeds without contaminating downstream farming and drinking water supplies. During theexperiment, 2 million m3 of water at 153°C were reinjected into a bore 952 m deep at rates of up to 164 I/sec without recourse to pumping (the substrata being very permeable), simply by making use of gravity and vapor pressure. No scaling problems were observed, nor was any significant interference detected (by means of tracers) between the reinjected water and the producing bores or ground-water wells. The author recommends that reinjection bores should be about 1.5 km or more from producing bores-at least for Ahuachaph conditions. The total cost **of** reinjection at this site has been estimated by Einarsson at about **1 US** mill/kWh. **In** view of the success of this experiment, it is not clear why the 70-km open channel to the sea, referred to by CuCllar (p. 1337), is considered necessary unless large quantities of cooler bore water have to be disposed of. **In** any case, it would seem wise to await the outcome of the reinjection tests after retention before embarking on the construction of this costly channel which is understood to cost about $10 million, representing $333/kW if borne fully by the first 30-MW installation and $SO/kW even if the field were ultimately developed to 200-MW capacity. Moreover, since Ahuachaphn is situated 800 m above sea level, it seems that an opportunity has been missed-that of generating 5 or **6** MW of base-load hydro power, or considerably more peak load if storage with or without pumping were also used.

Kubota and Aosaki (p. 1379) describe how **8** million tons of hot bore water have been reinjected into the aquifer at Otake since March 1972, through three injection wells. The present rate of reinjection is about **400** t/hr. The reason for doing this is to avoid thermal and chemical pollution. The distances of the reinjection wells from the nearest production bores range from **150** to ***800*** m. No fall in temperature or in output of the producing wells **has** been observed, no contamination of the ground water has been detected, and no seismic effects have been noticed. **On** the other hand, the authors claim that the performance of the producing wells has improved. The station output, which declined from **1 1** to 8.7 MW before reinjection was initiated, has since recovered to **10** MW. The only adverse occurrence has been the deposition of silica on the walls of the reinjection wells (and perhaps in the subterranean fissures) which has reduced the disposal capacity of these wells.

Gringarten and Sauty (p. 1370) refer to the exploitation in France of normal temperature gradients for space heating,

as described by Coulbois and Herault (p. 2099) and as mentioned in the Rapporteur's report on Section **IX.** Surface disposal of the thermal waters after use is precluded because of chemical and heat pollution. Reinjection overcomes these problems and at the same time enables subterranean pressures to be maintained and ground subsidence to be limited; it also provides a means of recharge of both water and heat. Nevertheless, since heat is continually being removed from the aquifer, exhaustion of the exploited zone must ultimately occur, and care must be taken so to space the reinjection and production wells as to give a maximum useful life to the zone. The authors examine the problem mathematically, under certain assumed properties of the aquifer, and deduce a series of curves showing the number of years taken for the reinjected water to reach the production bores by different streamline paths for assumed well spacing, and the expected rate of temperature decline in terms of time. Chasteen **(p. 1335)** reports on reinjection experience in three American fields. (There are discrepancies between the figures quoted in his summary and in his paper. Here the paper is assumed to be correct.) The author states that the purposes of reinjection are partly to recover rock heat and partly to dispose of unwanted bore waters or surplus condensate in a manner that avoids polluting surface water courses. Reinjection has been and is being practiced at The Geysers and Imperial Valley. California, and also at Valles Caldera, New Mexico. At the vapor-dominated field of The Geysers, **4.2** x **IO’** US gal of liquid have been reinjected since 1969. With the present plant installation of about 500 MW, **4.7** million US gal are being injected daily. The liquid contains some ammonia, boron, and some suspended solids. The flow is held up for a short time in concrete settling tanks with wooden baffles for the precipitation of the insolubles, and the fluid is then distributed to six reinjection bores, and is deaerated before entering them so as to avoid casing corrosion. The flow is metered. The wells used were originally steam producers. Slotted liners are provided where the reinjected fluid passes through the injection zone so as to prevent wall collapse when wet. The liquid descends the bores by gravity without pumping. Reinjection bores are placed as far as possible from and are sunk deeper than the production bores (to 5380 ft). In five years no interference has yet been detected between the two classes of bore. Some difficulty was experienced with declining injectivity due to the clogging of the fractured zone with elemental sulfur, but this was simply overcome by shutting in the bore and allowing the temperature **to** rise. **As** sulfur melts at **238°F** and the reservoir temperature is **475°F.** this soon removed the obstruction. Seismicity and subsidence effects are constantly being monitored but none have been observed. **At** Valles Caldera and in the Imperial Valley, both of which are liquid-dominated fields, **100** million **U.S.** gal have been reinjected during more than a year of testing in the former case, and 126 million U.S. gal in one year **(1%4/65)** in the latter case. In the Imperial Valley, the pressure of a static well was about **200** psig. This at first had to be overcome by pumping, but after a while, the column of cooler liquid enabled gravity to take charge. Reinjection at the Imperial Valley has been at a rate of 600 US gal/min. No loss of injectivity or reservoir response has been observed at either of these fields.

Reinjection is understood also to have been successfully practiced at Larderello. In no case of practiced reinjection has pumping been necessary except initially in the Imperial Valley, as reported above. The case for reinjection cannot perhaps yet be regarded as fully proven, but there is much promising evidence in its favor. Silica would seem to be the commonest obstacle: it could mean that the life of reinjection bores could be uneconomically short, or even that underground permeability could be destroyed. Chemical treatment-preferably on a profitable basis, as proposed by Rothbaum and Anderton (p. **1417)-or** settling ponds and filtration could cure or at least mitigate this problem.

Of the other doubts expressed earlier in this section, the most important is the avoidance of short-circuiting between the reinjection points and the production bores. Clearly, reinjection close to the producing horizons of service bores would sooner or later cause a drop in temperature of the bore fluid (though experience in Otake has been encouraging in this respect). On the other hand, reinjection at a strategic distance from the producing bores could well increase the field life by imposing a warm barrier against the ingress of cold waters from outside the field. Again, reinjection at great depth could perhaps displace deep thermal waters upwards, thus "sweeping" the aquifer of most of its original hot-water content, at the same time extracting heat from the hot rock **up** through which the reinjected water must flow. In short, while reinjection could have its dangers, it could also prove to be a valuable tool for good field management by recycling both water and heat. More extended experience is needed before proper judgment can be given.

OTHER ASPECTS

Axtmann (p. **1323)** rightly points out that when comparing the environmental effects of geothermal development with those of other forms of energy exploitation, account should be taken of all related activities. Thus when comparing a geothermal power plant with a nuclear plant of the same useful capacity, the environmental effects of uranium mining, fuel enrichment and reprocessing, and radioactive waste disposal should all be considered in addition to the actual power plant. Geothermal plants, having no such remotely situated sister activities, then appear at a relative advantage. However. the author goes on to point out that when assessing the polluting aspects of a geothermal installation, we should not only consider normal operating conditions, but also those during drilling, well testing, maintenance, shutdown, and the occurrence of "wild" bores, when pollution may be far worse.

Swanberg (p. **1435)** states that high-enthalpy fields are generally less polluting than low-enthalpy fields. This distinction could perhaps have been better expressed as between dry and wet fields. Land subsidence, silica, heat pollution of rivers, and waterborne poisons are generally features of wet fields which, by comparison with dry fields, are of relatively low enthalpy.

Most of the authors stress the importance of monitoringboth before and after exploitation-so that a careful watch may be kept **on** incremental pollution and distinction made between natural and man-made pollution, and between geothermal disturbances and those arising from other human activities such as ground-water pumping. This need for monitoring applies to all of the **13** possible sources of pollution listed above except scenery spoliation, which cannot be "measured." In the discussion, Bradbury asked Axtmann whether he could quote costs for monitoring trace

elements. The speaker said he could not quote actual figures but that it was less than for nuclear plants.

Several authors mention that unexploited natural thermal areas are often highly polluting; and in the discussion, Barnea suggested that this was worthy of study ***so*** that the ill effects of man-made geothermal development could be kept in proper perspective.

Certain rare trace elements can be not only a possible source of pollution but also a potential source of wealth; and in removing "poisons," valuable materials may simultaneously be won. Mercado (p. 1385) talks of the possibility of ultimately recovering chlorides of potassium and lithium from waste water. In the discussion, Barnea suggested that a total analysis be made at all developed fields with a view to studying multipurpose plants.

CONCLUSION

Since the **1960s** there has been a change of mood toward the environmental aspects of geothermal development from one of unreasoning optimism to one of sober realism. Gone is the pious belief that geothermal exploitation is entirely "clean" and does not infect the environment. Nevertheless, despite a keener awareness of the dangers, there is now a well-justified belief that geothermal development is far less culpable than fuel combustion of fouling the human nest, and that an antidote can be found to almost every source of geothermal pollution. Timely legislation in certain countries has enforced attention to this very important matter even though it could have been less drastic **in** its pace of enforcement. The advances made in environmental studies during the last five years have been impressive, and the good work is expected to continue.

Summarv of Section VI $.

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INTRODUCTION

Papers in this section deal with various aspects of drilling geothermal wells. Some papers describe current drilling practices (Altseimer. **p.** 1453; Tan, p. 1523) and improvements in current drilling practice (Jonsson. p. 1501; Dominguez and Vital, p. 1495; Cigni, Fabbri, and Giovannoni. p. 1471 ;and Maurer. p. 1590); see also Dominguez and Bermejo de la Mora (p. 1619) in Section **VII.** Other papers describe advanced technology research (Altseimer. **p.** 1453; Maurer. p. 1509). The magnitude of the drilling program needed to reach 20 000-MW capacity in a IO-year program in the U.S. is estimated to be about 8000 wells using 100 drill rigs (Kennedy and Wolke, p. 1503).

SUMMARY

Kennedy and Wolke (p. 1503) discuss the magnitude of drilling resources needed to develop 20 *000* MW of electricity. If the exploratory success ratio is one in six, some *600* wildcat wells would be needed to locate 100 fields of 200-MW capacity. If each production well yields 5 MW, and there is one injection well for each two production wells, then 4000 successful producing wells, IO00 unsuccessful field-development wells, and **2000** injection wells would **be** drilled, in addition to the ***600*** wildcat wells-a total **of** nearly 8000 wells. If these wells were to be drilled in 10 years, 100 drill rigs would be needed. Detailed cost breakdowns for drilling to 10 000 ft for a range of diameters are given.

Altseimer (p. 1453) summarizes data about current drilling experience in the geothermal environment. Histograms of well depth and overall penetration rate are presented for 33 wells in Imperial Valley and 99 wells at The Geysers, California. Plots of overall average penetration rate as a function of depth for The Geysers show that there is little correlation in the depth range between 1 to 2.5 km, where penetration rates vary from about **1** to about 3 m/hr. A I-km well thus seems to have about as much potential for slow drilling as a 2.5-km well. Altseimer describes the development of rock-melting penetrator equipment (subterrenes), designed to produce self-supporting glass-lined holes by a bit that progressively melts its way into the rock. Various field tests have been run, such as melting a 5-cm hole to a depth of **26** m in a volcanic tuff.

Maurer (p. 1509) summarizes the characteristics of different elements used to drill conventional geothermal wells. These include drill bits, blowout preventers, perforating, and packers. He then goes on to discuss some recent developments in the characteristics of different bits used to drill the Los Alamos Scientific Laboratory's well in New Mexico and to briefly describe some of the novel drilling techniques currently being researched.

Jonsson (p. 1501) describes the use of water in geothermal drilling in Iceland. At the high rates of circulation used, a **loss** in circulation washes the cuttings into the formation: lost circulation does not seem to be a problem. With only water available, high liquid overpressures can be difficult to control. Water circulation at high rates has permitted journal-bearing tricone bits to be used because the sealing rubber, which is limited to 120 to 150°C, is kept below its failure temperature. Bit life is 200 to ***300*** hr, and this permits drilling 500 to IO00 m without changing bits. Water is injected after drilling, using **a** packer to stimulate production by opening up existing fissures.

Cigni, Fabbri, and Giovannoni **(p.** 1471) discuss advances in techniques for cementing casings. Casing failures are generally produced by temperature cycling, and the coupling near the cementing collar often becomes disconnected. In a good cementing, the casing is uniformly anchored to the surrounding rock and thermally induced stresses can be absorbed. The properties of the cement and the technique used for cementing determine uniformity of filling of the annulus and the quality of the cement bond. Italian experience indicates that good practices are efficient mud removal, precise centering of the casing in the hole, and reciprocating the casing to avoid channeling of the cement. Several cements have been tested for rheological properties, compressive strengths, thickening time, and other properties in order to choose the best mixture for existing conditions.

Dominguez and Vital (p. 1483) discuss problems of casing and cement failure and their repair for wells at Cerro Prieto, Mexico. Failures have occurred at 10 wells, a high frequency caused by reservoir temperatures as great as 344°C. Failures occurred in all wells where a single string of casing was used to serve both as the production casing and to support the borehole walls. In subsequent drilling, the failure rate

has been much lower. Repair of the wells has been done using systematic measurements to determine the nature and type of failure and cementing additional casing to cover failures. Only one of the failed wells had to be abandoned: six are currently supplying steam to the power plant. A major blowout in Well M-13 in 1972, caused by casing fracture at 200-m depth, has been controlled by inserting a tube to a depth of 502 m to fill the well with mud and

then installing four cement plugs.

In order to lower the failure rate of casings at Cerro Prieto, a procedure described by Dominguez and Bermejo - failures. de la Mora (p. 1619, Section VII) has been developed for the slow, controlled, opening of the wells; since sudden starting of a well subjects the casing, cement, and rock formation to large temperature gradients, and gives rise to large stress gradients. If the well is opened slowly, temperatures can equilibrate. Wellhead pressure, temperature logs of the shut-in well after the heating period, amount of casing expansion, percentage of sand produced, and caliper logs are used to check the condition of the well to detect any

Tan (p. 1523) describes the drilling of a 905-m-deep production well for home heating at Afyon, Turkey. Bottom-hole temperature is 107"C, and the well produced 29 I/sec at 86°C wellhead temperature. Temperature and pressure distributions were measured in the well at the end of drilling and again after several days of production.

Summary of Section VI1 *f* (& z i Z e c h n o l o g y , Reservoir t nginee)r ing, and Field Management

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INTRODUCTION

The reservoir engineering and production technology of geothermal resources cover a wide range of subjects. In an attempt to bring related papers together. **I** have grouped these papers under six headings.

1. “Hydrothermal Reservoirs” discusses papers giving reservoir and geophysical data for several systems.
2. “Well Operations and Analysis” contains topics such as analysis of pressures in shut-in and flowing steam wells. short-time pressure response of shut-in wells, properties of two-phase flow in wells in hot-water systems, stimulation of hot-water wells by injection under pressure. a new platinum-resistance thermometer for logging. and the use of radon as a diagnostic in reservoir studies.
3. “Reservoir Modeling” discusses work that analyzes nonisothermal flow of single- and two-phase fluids in reservoirs, to understand various aspects of undisturbed and producinggeothermal systems, and includes some laboratory data releated to reservoir modeling.

4. "Fluid Transmission" deals with problems of orifice plates, steam-water flow in horizontal pipes, and the scrubbing of chlorides from water that is entrained in a steam flow.
5. "Corrosion and Deposition" describes recent investigations into materials problems.
6. "Forced Recovery," the final section. describes work on these schemes.

HYDROTHERMAL RESERVOIRS

Burgassi et al. (p. 1571) discuss resistivity, gravity, and heat-flow surveys used to site the new wells at Travale, Italy. The 5-pcal/cm2.sec heat-flow contour defines an area of some 7 or 8 km2. Five wells ranging from 691-m to greater than 1800-m deep have been completed. but only two have found adequate permeability. Well Travale 22, drilled in 1971, had a shut-in pressure of 60 kg/cm2 and flowed 314 t/hr (87 kg/sec) of steam at a wellhead pressure of 8.1 kg/cm2 with a gas-to-steam ratio of 9: 100 by weight. Well R4 had a flow of only 108 t/hr (30 kg/sec) because of lower permeability, but this well had a gas-to-steam ratio of 64: 100, indicating rather different bottom-hole conditions from Travale 22. Katagiri (Abstract VI-25) reports that seven wells at Matsukawa, Japan, produce 240 t/hr (yielding an average flow per well of IO kg/sec) of superheated steam.
Hitchcock and Bixley (p. 1657) report measurements taken during a three-year closed-in period for the Broadlands, New Zealand, field after intermittent production over a five-year period. Pressures in the main production borefield fell during production and rose once the wells were shut in. Pressures outside the production field continued to decrease after withdrawal ceased; this pressure trend indicates a general flow toward the producing field to equalize pressures.
Mathias (p. 1741) describes the drilling of five wells at East Mesa, California, that range in depth from 1816 to 2442 rn and in bottom-hole temperature from 154 to 204°C. Bottom-hole pressure drops range from 1 1 to 60 bars to produce flows ranging from 13 to 27 kg/sec. Because long-term testing has not been performed, the trends of downhole pressures have not yet been established.
Tezcan (p. 1805) presents surveys of resistivity, geothermal gradient, and temperatures at 100-m depth for the field at Sarayhkoy-Kizildere. Turkey. Plots of temperature with depth combined with measured water levels (equivalent levels calculated for wells with positive wellhead pressures) for various wells are used to argue that there should be a steam zone located around the dry hole KD-XI1 because its temperatures exceed the reference boiling point curve, although no fluids exist in this well.
Wilson, Shepherd, and Kaufman (p. 1865) present an economic. power-plant, and reservoir study for producing electricity from geopressured resources. The measured temperatures at depth in the two areas of study are 196°C at depths of 4500 to 5600 m. Wells are assumed to flow at 51 OOO barrels of brine per day (approximately 85 kg/sec) ina 17.8-cm-diameter casing. Power costs are 26.8 mill/kWh for a two-stage flash system if a credit of 0.85 m3 of natural gas per barrel of water is assumed and the use of mechanical

energy from the high wellhead pressures is neglected.
Vides (p. 1835) discusses resistivity, gravity, and temperature-gradient surveys done for the Ahuachaphn, El Salvador, field. Reservoir temperature is 232°C and four wells produce 1080 ton/hr (yielding an average flow of 75 kg/sec). Water levels in some wells are 200 m below ground level. making the initiation of production somewhat difficult. although it should be possible to sustain two-phase flow in the wells if adequate permeability is available.

Kavlakoglu (p. **1713)** provides a formula relating reservoir temperature to porosity, water resistivity at surface temperature, and reservoir resistivity. He suggests that reservoir temperatures be calculated using this formula.

WELL OPERATIONS AND ANALYSIS

Celati et al. (p. **1583)** have analyzed historical and current water-level data for the Larderello, Italy, field in order to establish the pressure distribution as a function of depth. As drilled depth increases, the pressures at depth increase along a hydrostatic curve until the vapor-dominated reservoir is reached in which the pressures become nearly constant. Somewhat surprisingly, they found that a column of water in a drilled well could sometimes be supported while the well was in the vapor-dominated reservoir. In wells that tap high-permeability zones, blowout takes place soon after the drill has reached the zone, sometimes even while still drilling. The data for the Travale field show the pressure for the early shallow wells lying on a hydrostatic curve. The vapor-dominated reservoir was found only when deeper drilling was done, because the high pressure in the vapordominated zone of some **60** kg/cm2 requires a minimum drilled depth of about **650** m.
Nathenson (Abstract **VI-34;** U.S. Geological Survey open-file report **75-142)** analyzes historical data for the Larderello field. Bottom-hole flowing properties of temperature and pressure are calculated from measured wellhead data. Bottom-hole temperatures at a particular time with varying flow and as a function of time at nearly constant wellhead pressures can show quite different patterns depending on which well is being analyzed. Data on shut-in pressures and total mass produced for the northeast zone of Larderello are plotted to show field-average decline and to estimate the initial mass in place.
Pressure-transient analyses of geothermal wells can be used to determine critical parameters such as drainage volume, porosity, permeability, mean formation pressure, and the condition of the formation just outside the wellbore. Ramey (p. **1749)** reviews the history of pressure transient analysis and discusses the uses and merits of the different types of build-up curves. Data for three steam wells at The Geysers are used to illustrate the method. One of these wells has a negative skin effect indicating that it is stimulated while another has a positive skin effect indicating that it is damaged. One of the problems with applying the method is that if the permeability-thickness product of the reservoir is very high, then the slope of the build-up curve has a low value, and it is difficult to determine the permeability.

Ramey and Gringarten (p. **1759)** use a new solution for the pressure transient obtained from a well tapping a vertical fracture of high internal volume to reanalyze data for a well at The Geysers. The permeability-thickness product is found to be about **7** darcy-meters and the well is found to have a large storage coefficient.

Barelli et al. (p. **1537)** have analyzed a number of wells at Larderello, Italy, using the various pressure-transient methods. Permeability-thickness products range from **1** to **200** darcy-meters, skin coefficients range from 0 to **-5,** and wellbore storage coefficients indicate large open volumes connected to the wells. The data can frequently be matched by solutions for wells tapping fractures. Bottom-hole data calculated from measured wellhead data of flow as a function of pressure indicate that there is non-Darcy flow in the reservoir.

James (p. **1693)** presents data measured in flashing hotwater wells at **El** Tatio, Chile, and Cerro Prieto, Mexico.

In each case, pressure and temperature as a function **of** depth were measured in a flowing column of steam-water mixture. Clock-driven pressure gauges were then placed at the well bottoms to measure pressures at various flow rates. A plot of aquifer pressure minus bottom-hole pressure as a function of flow is then used to distinguish between flow through porous media in one case and flow in a horizontal fracture in the other case.

James (p. **1689)** has measured the temperature and pressure in a flowing well at Kizildere, Turkey. Some of the wells in this field have a large quantity of dissolved gases in the pressurized hot water. Even though these wells were kept under sufficient pressure to prevent steam formation from pure water, dissolved gases cause bubbles of gas and steam to form. Using partial-pressure relations, James is able to deduce the ratio of gas to steam. Since the flow is large the mixture enthalpy is conserved in flowing up the well. The observed temperature drop can then be used to deduce the ratio of steam to water. This method works only where gas content is large enough to affect the temperature of the upflowing water.

Fukuda, Aosaki, and Sekoguchi (p. **1643)** have done calculations for flashing flow in hot-water geothermal wells and have matched wellhead data obtained at Otake and Hatchobaru, Japan. Their data demonstrate that at normal flow rates in two-phase flow in geothermal wells, the mixture enthalpy is constant. Coury (Abstract **IV-11)** uses the available knowledge of two-phase vertical flow to design geothermal production wells.

James (p. **1685)** uses the formula correlating critical lip pressure and mass flow to obtain formulas for the rapid estimation of the electric power produced by a geothermal well. Because of the weak dependence of the electric-power formulas on mixture enthalpy in the range of **400** to **600** Btu/lb, and if one assumes the conversion efficiency to be approximately constant over the range of interest, it is not necessary to know the enthalpy for a hot-water well in order to estimate the electric-power potential. If the well produces dry steam, a different formula is required. The choice of formula is governed by observing the jet to see

if it is dry steam or a steam-water mixture.
Tomasson and Thorsteinsson **(p. 1821)** report using a packer to allow stimulation of drill holes by injection of fluids under pressure. Injection rates vary from **30** to **100** I/sec under pressures of a few to **70** kg/cm2. Zones for injection are chosen on the basis of lithologic **logs,** circulation losses, and temperature profiles taken during drilling. Since the drill water is much cooler than the formation, cooling is greatest where the formation takes in the most water. Improvements in well productivity are attributed to cleaning out drilling debris at the wellbore radius, removing zeolite and calcite vein deposits, and increasing the permeability of the hyaloclastic rocks in the near-well region. During injection, water level response in nearby wells can be used to help understand the hydrology.
Ushijima et al. (p. **1829)** report using a platinum resistance thermometer to measure temperatures in geothermal wells. The cable and head were tested in the laboratory to a temperature of **213°C** at atmospheric pressure at which the
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cable covering began to degrade. At **90** bars pressure and room temperature, the seal of the cable head to the cable did not leak. Field tests to 176°C and 220 m of head (20 bars pressure) at Otake, Japan, showed that the thermometer worked well. These workers point out that in deeper wells, the likely failure location is the mechanical seal of the cable to its head.
Stoker and Kruger (p. 1797) review the theory for the generation and transport of radon in reservoirs. Measurements have been made at The Geysers, East Mesa, and Salton Sea, California. Although radon-to-condensate ratios for one well at The Geysers were constant to within a few percent over a 24-hr period, radon-to-CO, ratios varied by two orders of magnitude over the same period.

RESERVOIR MODELING

Chengand Lau (p. 1591) investigate the convection pattern in a geothermal aquifer bounded above and below by isothermal no-flow boundaries. Recharge is permitted through outer vertical boundaries, and the aquifer is cylindrical in one case and a two-dimensional vertical slice in the other case. The problem is solved for steady convection with and without discharge from a sink (well) in the aquifer. As the amount of discharge increases, the size of the mushroom top becomes progressively smaller as the flow gets sucked into the sink.
Faust and Mercer (p. 1635) have used a computer program to solve the equations involving two-phase flow for some geothermal reservoir problems. The model neglects gravity segregation and the flow is in one dimension in an initially liquid-filled system that is producing at one end. Saturation and pressure distributions are obtained as a function of time. A similar system in which the pores are initially filled with 25% liquid water and the remainder steam is solved. Saturation profiles after 1.6 years of production in reservoirs with different permeability values are given. For low permeability, steam production by boiling is concentrated in the region near where the steam is being withdrawn, whereas at higher permeabilities, more of the reservoir is influenced

by the withdrawal of steam. Results are presented for a low-permeability two-dimensional areal system that is initially filled with liquid and becomes a two-phase system as mass is withdrawn.

Garg, Pritchett, and Brownell (p. 1651) have used a computer program to solve the equations involving twophase flow for some geothermal problems. They simulated Arihara's experiments with a porous cylinder filled with liquid water and then produced from one end into the two-phase region. Pressure and temperature profiles were available for matching, and the simulation results were used to give saturation profiles. A two-dimensional areal reservoir with injection and production is simulated with varying ratios of injection to production such that the reservoir is either all liquid or has a two-phase zone.

Gringarten and Sauty **(p.** 1365, Section V) describe **solu**tions for sets of injection and production wells in an aquifer. Vertical heat conduction from the confining beds is taken into account, but conduction along the beds and along the aquifer is neglected ***so*** that the thermal wave can be treated as a sharp front. An illustrative problem with two injection and three producing wells in an aquifer 100 m thick is solved to yield the temperature behavior of each of the production wells and the location of the temperature front at various times.

Hunsbedt, London, and Kruger (p. 1663) describe experiments in which a volume initially filled with water and rock is produced by lowering the pressure at the top. The model has a high porosity and permeability such that pressure gradients needed to drive flow are small. As the liquid level falls, a steam zone is created at the top while the water zone boils throughout its depth. Temperature profiles as a function of time and distance inside rocks and in the steam and liquid zones are given.

James (p. 1681) analyzes the pressure distribution in a horizontal crack tapped by a geothermal well in order to estimate the distance from the well at which the pressure perturbation is 1% of the pressure drop from the well to the formation pressure. The analysis indicates that at 225 well diameters, the pressure perturbation is about 1%. This spacing represents a minimum value as the field pressure decline due to mass withdrawal can place limits on the proper well spacing.

Kassoy (p. 1707) discusses several aspects of heat and mass transfer in undeveloped hydrothermal convection systems. Using the dimensionless form of the governing equations and assuming that there is an inherent balance between the physical phenomena of buoyant forces, Darcy flow velocity, and pressure gradients, he finds that the characteristic order-of-magnitude parameters for convection are a velocity of **1** cm/day and a pressure drop of **10** bars. Calculation for the onset of convection, including the effects of viscosity varying with temperature, show that the critical Rayleigh number defined with a cold temperature reference state changes as the magnitude of the temperature difference changes. Lower viscosity in the hot part of the system tends to yield higher velocities in the hot convection zone than with constant viscosity. An analysis of flow in a thin vertical conduit of porous material bounded by impermeable walls with a vertical temperature gradient is presented. For narrow conduits, the flow is entirely vertical, but increased width brings zones of upflow and downflow.

Lasseter, Witherspoon, and Lippmann (p. 1715) have developed a computer program to solve problems of twophase flow in geothermal reservoirs. Preliminary results of two simulations illustrate the types of problems that the program is designed ***to*** **solve.** Narasimhan and Witherspoon (Abstract IV-IO) discuss the development of a computer program to solve the nonisothermal flow equations coupled with the one-dimensional consolidation theory in order to analyze land subsidence in geothermal systems.

Lowell and Bodvarsson (p. 1733) use a finite difference code to analyze the wellhead temperature behavior **for** a well that starts to flow at time zero with some temperature at the well bottom. The early time behavior is governed by the time required to remove the volume of fluids initially in the wellbore. For a step change in flow, the change in surface temperature is estimated to see if surface temperature measurements can be used to estimate changes in flow rate.

Ramey et al. (p. 1763) summarize research at Stanford University on geothermal reservoir engineering. In addition to results described elsewhere in this report, data are given on the change in absolute permeability in a water-saturated core with changes in pressure and temperature. At a confining pressure ***of*** 4000 psi, the permeability decreased by about

30% in going from **70** to 300°F. At lower confining pressures, the permeability is less sensitive to temperature changes. The enhancement of temperature sensitivity of permeability by confining pressure has not been found for oil- or gas-saturated samples but only for water-saturated samples. In fact, absolute permeability using oil or gas was found to be essentially independent of temperature.

Robinson and Morse (p. **1773)** studied a one-dimensional reservoir that is initially filled with water and has zero, small, and large recharge of hot water. Production varies from small to very large. **All** reservoirs are assumed to have "an infinite heat source . . . located at the base of the reservoir." Total heat produced and the ratio of steam to water are given as a function of time for various production rates.

FLUID TRANSMISSION

James (p. **1697)** provides formulas for sizing chokes made by clamping an orifice plate (usually a mild-steel plate with a hole drilled in it) between flanges on the horizontal discharge pipeline. The choke is used to control exit pressures of steam or two-phase flows to enable design conditions to be simulated before wells are connected to the power plant. The use of chokes to control flows protects expensive valves from damage. Orifice plates are also used to measure single-phase flows with the addition of appropriate pressure taps. James (p. **1703)** gives formulas for the use of orifice plates and discusses some of the problems in using them. Small amounts of water in steam lines cause small errors, but small amounts of steam in hot water lines cause large errors. Pressure drops in the water line that cause steam to form can be remedied by using short pipe lengths and avoiding sharp bends. The major cause of steam in the water lines is vortex formation in the steam-water separator that can induce steam to be drawn into the water line. This problem has been eliminated in the newer separators which reduce vortex formation and keep a bigger water head on the liquid discharge line. The presenck of steam in the water line affecting orifice flow measurements can be verified by measuring the flow using the critical lip-pressure method.

Soda, et al. (p. **1789)** have studied the transient behavior of two-phase flow in a pipeline due to sudden valve closure caused by turbine tripping. The valve took approximately 0.15 **to0.35** seconds to close. There was no noticeable sound or vibration of the pipe and the pressure wave propagated at about twice the sound speed calculated on the basis of a model of a homogeneous mixture of steam and water. Pressure rise was approximately 20% less than predicted by a homogeneous model. Continuous-flow experiments obtained pressure-drop data for two-phase flow.

McDowell (p. **1737)** has analyzed the scrubbing of chlorides dissolved in carry-over water (-0.5%) in the steam from geothermal well separators. **As** the steam flows along the pipe, more steam is condensed due to heat losses to the atmosphere. As drain pots placed at intervals allow the water to be rejected, the chloride becomes progressively diluted. Data on chloride dilution and drain discharge were taken for a series of five drains. Calculations for discharge based on condensation agree well with measured discharge and discharge calculated from dilution data. James (p. **1699)** analyzes this problem, assuming that pots extract 70% of the liquid water at each location. He suggests that orifices rather than steam traps be used to vent the water to the atmosphere and provides a formula for sizing these orifices.

Lengquist and Hansen (Abstract **VI-28)** discuss the steam piping system at The Geysers, California. The heat-loss factor with **3** in. of fiberglass insulation is 0.15 Btu/hr.ft2 oF. The pipe is made of low-carbon steel. Cast-steel slab gate valves are used with stainless steel trim and stems.

CORROSION AND DEPOSITION

Tolivia, Hoashi, and Miyazaki (p. 1815) report on extensive tests of the corrosion of materials in the geothermal steam environments. Test of stress corrosion and corrosion fatigue were run at different flow velocities. **As** corrosion varies with the chemistry of the fluids at a particular site, results from a particular field can only act as a guide to studies that should be made whenever the design of a plant at a new site is contemplated. Some of the conclusions from this study are: **(1)** aerationof steam and high velocities of steam condensate enhance corrosion rates; (2) in separated steam, carbon steel is usefully resistant, but in condensate allowance must be made for its high rate of corrosion or it must be coated with epoxy; and **(3)** aluminum and deoxidized copper are unserviceable for heat exchanger tubes because of their poor corrosion resistance in condensate.

Loresen, Walkup. and Mones (p. **1725)** have tested polymeric and composite materials **for** their stability at high temperatures and their ability to resist erosion and scale deposition at high flow rates. Tests have been run in ***300°C*** brine, and nozzles and wear plates have been run in flowing two-phase mixtures. In the flow tests, a fluorocarbon polymer showed favorable resistance to both erosion and scale deposition.

Wahl and Yen (p. **1855)** have designed a test unit for measuring scaling. A coolant is circulated in a test probe and the brine is circulated along the length of the outside of the probe. The change in coolant temperature with time is related to the rate of scale deposition. Tests witha synthetic brine showed that silica was deposited at an exponential rate. Tests done at Well **6-1** at East Mesa, California, showed that calcite was the predominant scale and that the rate of deposition did not depend on time.

Yasutake and Hirashima (p. **1871)** report on improvements in the cooling water system in the plant at Otake, Japan. The oxidation of hydrogen sulfide to sulfuric acid in the condensed steam was isolated as the cause of corrosion in the condenser. The addition of caustic soda to the condensate to take its pH from **4.5** to **-6.8** was found to considerably reduce this corrosion. Make-up water supplied to the cooling tower at the rate of 30 t/hr was found to contain waterweeds and bacteria, and the temperature in the cooling tower provided an ideal medium for their growth. The supply of make-up water was stopped, and this ended the problem. Anticipated difficulties, such as concentration of salts in the cooling system or gradual build-up of temperature in the cooling system in the hot summer, did not develop.

FORCED RECOVERY

Smith, et al. (p. **1781)** report field experiments to develop the recovery of geothermal energy from very low permeability rocks by using hydraulic fracturing techniques to

provide a continuous passage between an injection well and a production well. At an experimental site just outside the Valles. New Mexico, caldera, shallow heat-flow holes indicated 5 to 6 pcal/cm2.sec, but deeper drilling has shown that the temperature regime isdisturbed by water movement. Heat flow below the zone of water movement has been found to be 3 to **4** pcal/cm'.sec. Rock temperature of 250°C. then, will require a hole drilled to a depth of **3.8** km. Experimental hole GT-I was drilled to a depth of 785 m with a 100°C bottom-hole temperature. and GT-2 reached a depth of 2928 m depth with a bottom-hole temperature of 197°C. Several hydraulic fracturingexperiments have been performed. For example, with a packer set at 2917 m in GT-2. a single hydraulic fracture was created at a surface pumping pressure of **120** bars with a calculated radius of 57 m. The rock permeability of freshly fractured rock is estimated to be 0.3 microdarcy. The experiment will be continued with the drilling of a deeper hole in order to set up a demonstration system for energy extraction.

Diadkin and Pariisky (p. 1609) discuss technical and economic problems concerning the recovery of geothermal energy from hot-rock resources for generation of electricity or process-heat use. Underground explosions and hydraulic fracturing are considered to be the most promising stimulation techniques. Formulas for estimating the radii of the cavity, crushing. and fracture zones from an underground explosion are based on actual explosions and laboratory experiments. The permeability distribution in such a zone is also estimated. The temperature pattern in a rubble zone with heat conduction from the sides has been analyzed and curves of the solution presented. Aladiev, et al., (p. 1529) present some data on injecting heated water into strata containing a zone that was explosively stimulated. Bernard and Evano (p. 1547) propose the use of nuclear fracturing in the ocean floor. The temperature regime in a fractured medium is analyzed to show how the power decreases as the distance between fractures increases. A preliminary economic analysis is presented.

Bodvarsson and Reistad (p. 1559) discuss the possibility of using open horizontal contacts in flood basalts and near-vertical dikes and fault zones as flow conductors for obtaining geothermal energy for process heat use. From an economic analysis using a value function for the thermal water. assumed temperature-depth profiles, and a function for drilling cost as a function of depth, optimum depths under varying assumptions can be estimated.

Colp and Brandvold (p. 1599) describe a program to obtain energy from molten magma. Initial studies are concerned with source location and definition, methods of source tapping. properties of magma and compatability with engineering materials and methods of energy recovery and conversion. Jacoby and Paul (p. 1673) propose the recovery of geothermal heat from salt domes using solution mining and other methods. Minucci (Abstract VI-33) proposes the recovery of geothermal energy using fully cased wells as heat exchangers with a double pipe system.

Summary of Section VI11 : *I*

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I NTROD UCTI ON

In 1961, at the time of the UN Rome Conference on New Sources of Energy, the total installed geothermal power capacity in the world was about 420 MW. When the UN Geothermal Symposium was held in Pisa in 1970 this figure had risen to about 675 MW, an average annual growth rate of 5.4% over nine years. This was approximately in step with the world growth rate in electricity production. Now in 1975, about 1310 MW of geothermal power plant is in service, and this represents an average annual growth rate of 14% in the last five years. At first sight this is an impressive achievement; but it is a sobering thought that even now only about one-thousandth part of the world‘s electrical need is being supplied geothermally-approximately threequarters of a century after the Italians first pioneered the generation of power from earth heat. We shall have to do much better than this before we-the “geothermal fraternity”- can claim to be making a really significant contribution towards the solution of man’s energy problems. Nevertheless, there are hopeful signs that we may be on the verge of a “geothermal renaissance” that could enormously improve the present gloomy energy outlook. Many hundreds of additional geothermal megawatts are definitely in the planning stage; several new countries are now taking active interest in geothermal exploration; and dramatic new exploitation techniques look as though they may come within our grasp in the fairly near future. Even the growth in numerical participation at the three consecutive UN conventions of 1961, 1970, and 1975 is indicative of the rising interest and increased application of human ingenuity to the development of what is known to be a vast source of economic wealth.

The five years that have elapsed since the Pisa symposium have shown a healthy growth in the capacity of geothermal power plant in service. They have also shown an intensification of interest in novel ideas, some of these were discussed at Pisa but have now become the subject of lavish research or have even been adopted in practical service. Further refinements of design are also in evidence.

DESCRIPTIVE PAPERS

Several papers are purely descriptive. Such papers perform a most valuable function as part of the growing literature of detailed factual information about geothermal power plants in service. They not only give examples of good engineering practice, they sometimes provide timely warnings of pitfalls to be avoided by the designers of later installations. They also sometimes give empirical evidence of the practical applications of ideas which only a few years ago were novel and unproven.

Aikawa and Soda (p. 1881) give an excellent description of the design of the 50-MW plant at Hatchobaru, which is expected to be in service in 1977 and which has certain novel features-notably two-phase fluid transmission. It will also feature an original condenser design and a novel gas-exhausting system (see below). The plant will make use of the “double flash” cycle. It is well here to clear up a possible ambiguity of terms. The first stage of flashing occurs within the bores, so that there is only one further stage of flashing when the pressure of the separated hot water is dropped so as to provide low-pressure flash steam for a pass-in feed to the turbines. Some people might prefer to call this a “single flash” system. In the experimental hot-water transmission scheme at Wairakei-since abandoned through lack of bore water from the selected wellsthe pressure of the separated bore water was dropped in two further stages, and the cycle was usually referred to as “double flash”; but if bore flashing is to be included, it should have been called “treble flash.” To avoid ambiguity, the Hatchobaru system will hereinafter be referred to as “double flash” and the now-abandoned Wairakei system as “treble flash”). Aikawa and Soda mention a specially developed flash vessel that produces 99.93% dry steam, but unfortunately they do not describe how this differs from a wellhead centrifugal separator in principle.

Dan et al. (p. 1949) describe the planning and design of a typical generating unit at The Geysers, Californiaalready the most highly developed field in the world. The rise in oil prices has made the Pacific Gas and Electric Company (PG&E) embark upon a geothermal expansion program at the rate of about 100 MW /yr, but the enforcement of environmental restraints is retarding this program (see Summary of Section V). The ultimate goal is to develop about 2000 MW of geothermal plant at The Geysers, but it is doubtful if this field will ever contribute more than about 10% of the PG&E system demand. Under contracts with the various steam suppliers, PG&E undertakes to install about 100 MW/yr of power plant if the suppliers can prove steam availability five years in advance. A bar-chart shows a typical five-year plan for developing a 110-MW unit; it covers government formalities, plant component design, manufacture, erection and testing. and civil works construc-

tion. The overriding time factor is the three-year supply period for the turbogenerating units. The considerations affecting the choice of design parameters. plant arrangements, controls, and safeguards are discussed, as are the procedures for placing contracts. Certain cost figures are also given (see below).

Guiza (p. 1973) gives a very clear and concise description of the 75-MW installation at Cerro Prieto, Mexico, which taps a wet field at an average depth of 1300 m; the fluid enthalpy averages about 320 kcal/kg. Of 32 drilled wells only 2 were cold. One or two blowouts and casing failures occurred during the drillingoperations, but were successfully controlled. Wells are spaced at 150 m, and no interference between them has been observed, nor has ground subsidence been detected. The field is operated at wellhead pressures of about 7.5 ata. The installation is of more or less conventional geothermal design and at present uses only the bore steam and rejects the bore water into storage ponds. Later, it is intended to use flash steam from the hot bore water in the design of future extensions, and perhaps to reinject the residual hot hater after flashing. Certain troubles have been experienced with silica scale in bores and on turbine blades, the latter causing a decline of 4 or 5 MW of output in a year's operation and necessitating periodic blade cleaning. This trouble has resulted in the attainment of an annual plant factor of only 70% since the plant was first commissioned in 1973. Corrosion of the hydrogen generator coolers and lubricating oil coolers, which at first had aluminum tubing, was experienced as a result of sulfur bacteria polluting the cooling water system. The use of biocides and the substitution of titanium and stainless steel for aluminum has overcome this trouble. At present Cerro Prieto is contributing about 1% of Mexico's megawatt demand (though a higher proportion of its generated kilowatt-hours as it is operated on base load). A plant extension program to raise the total geothermal capacity at Cerro Prieto to 400 MW, including a 30-MW flash unit to exploit the hot water from the first 150 MW of direct-steam plant, has been planned for completion by mid-1982. The field, as now exploited, is believed to have an assured potential of at least 5000 MW-yr without relying on recharge. A neighboring area has revealed a bottom-hole temperature of 344°C at 2000-m depth, and a yield equivalent to 5 MW from a single well; so the potential of the whole district appears to be very substantial.

Matthew (p. 2049) describes 14 years of operating experience at The Geysers plants. All plants have been designed for unattended operation with “shut safe” devices that warn an operator located about 40 miles from the plants. A single two-man 8-hr shift of operating/maintenance personnel is provided at each plant for 5 days per week, but after the installation of six units it was thought advisable to provide a 24-hr roving operating service in addition. **Soon,** a computer-based information and control center will be established and manned continuously. The system dispatcher will take appropriate action in coordination with local staffs for starting up, shutting down, and effecting load and voltage adjustments, based on transmitted signals and alarms. If a unit trips off load, the connecting wells are allowed to blow to waste through mufflers until it has been ascertained that the unit cannot soon be restarted. The first 11 units (with a total capacity more than 500 MW) are controlled and maintained by a total stgf of only 45, including supervisors and clerical employees. For heavy plant overhauls a few extra people are drafted in from elsewhere. Suitable transport, with two-way radio communication, is provided and can negotiate the field road system in all weather. Limited workshop facilities are now available at the plants, but for major overhauls the parts must be sent to the San Francisco area. **In** 1976 a new central workshop is to be provided in the field area. During 56 turbine-years there have been only 12 enforced outages, averaging 3 weeks each, and a few load curtailments-mainly due to blading failures from corrosion/erosion. **For** the older units, spare blading is provided; complete turbine rotors are held as spares for the 55- and **1** IO-MW units so as to improve their availability factor. Corrosion of relay and instrument contracts from the action of **H,S** has been overcome by using gold and platinum contracts. **H,S** attack on commutators has led to the adoption of brushless commutation. The action of ammonia on cooling-tower concrete has been countered by using epoxy **or** rubberized coatings. Turbo units need overhauling at 2- to 3-yr intervals (as against *5* to **8** years for conventional plants) but the outage time is only 2 to 3 weeks (as against 8 to 12 weeks). Operating costs per kilowatt are nearly double those of conventional thermal plants but only about 13% higher per kilowatt-hour. The cheap “fuel” more than compensates for this.

Villa (p. 2055) gives a short history of geothermal development in Italy and describes the evolution of the plant designs and the various troubles encountered and the remedies applied. Zancani (p. **2069)** summarizes **30** years **of** experience in selecting thermal cycles for geothermal plants. His paper is somewhat autobiographical in form but is of general interest. To some extent it overlaps with Villa’s paper, but it also covers plants designed for Mexico and **El** Salvador.

NEW DEVELOPMENTS AND IDEAS

Reinjection

This was the subject of some speculative discussion at the Pisa Symposium, at which time some experimentation had been and was still being done in New Zealand and

Japan. Now reinjection is a fact at The Geysers and at Otake, and much more empirical knowledge has been gained during the last five years. Reinjection has been discussed at some length in the Section V papers. It may be mentioned, however, that if carefully managed, reinjection could perhaps lengthen field life and thus, indirectly, improve the overall power generation cycle efficiency by providing the equivalent of "boiler feed".

Two-phase Fluid Transmission

This subject too was discussed at Pisa as a possible method of encouraging the use of hot water and of economizing hardware. Now it is definitely to be adopted at Hatchobaru, as described by Aikawa and Soda (p. **1881),** who point out that although the pressure drop is greater than when transmitting either steam or hot water separately, a "dividend" is won in the form of additional flash steam resulting from this drop. The advantages of the system are that wellhead equipment can be greatly simplified by the elimination of individual separators; single mixed-flow pipes from the various wells can be merged as they proceed towards the power station regardless of ground level differences;

the complexities of separate hot-water transmission with individual well pumps and carefully regulated flow control are avoided (alternatively. the inefficient transmission of low-pressure steam that would be involved if flashing were undertaken at each wellhead is eliminated); large separators and flash vessels sited close to the power station derive the benefits of scale and can be more cheaply maintained than many small pieces of equipment scattered over the field; only a single hot-water waste channel is needed; and the temperature of the hot water immediately upstream of the point of discharge is lower than when rejection is at the wellheads. The authors claim that no scale or erosion troubles have been experienced in test rigs, nor has water hammer occurred even under conditions of rapid valve movement. They nevertheless warn that two-phase transmission should be adopted only after careful consideration of the well characteristics. the distances between the wells and the power plant. and local gradients. The Hatchobaru steam/water transmission system was tried out successfully on a computer before a decision was made to adopt it. Hopefully, this system will be successful in practice, and the designers are to be congratulated on their enterprise.

Binary Cycles

Yet another subject that was treated in papers and in discussion at Pisa is the use of secondary fluids for power generation with low enthalpy or chemically "hostile" geothermal fluids as the primary source of heat. Continued and increased interest in this subject was evinced in San Francisco. The theoretical advantages of the binary cycle are:

1. They enable more heat to be extracted from geothermal fluids by rejecting them at lower temperature.

2. They can make use of geothermal fluids at much lower temperatures than would be economical for flash-or directsteam use.

3. They use higher vapor pressures that enable a very compact self-starting turbine to be used, and avoid the occurrence of subatmospheric pressures at any point in the

cycle.
There are, however. certain disadvantages:
I . They necessitate the use of heat exchangers which are costly. wasteful in temperature drop, and can be the focus of scaling.
2. They require costly surface condensers instead of the cheap jet-type condensers that can be used with normal geothermal steam turbines.
3. They need a feed pump, which costs money and which absorbs a substantial amount of the generated power.
4. Secondary fluids are volatile, and sometimes toxic. and must be very carefully contained.
5. Makers are generally inexperienced. and high development costs are likely to be reflected in high plant prices until such plants are in high demand.
Arosio et al. (p. 1915) describe the gravimetric loop type of plant and give a mathematical analysis of a conceptual **I-MW** unit (0.85 **MW** net) using various secondary fluids. The basic principle of the cycle is to impart buoyancy to the water contained in one vertical leg. about *50* m high and 2 m diameter, of a hydraulic loop, by injecting an immiscible vapor. At the top of this vertical leg the vapor is separated from the water. which descends down a parallel vertical leg containing a hydraulic turbine at the base. The greater density of the descending water, by comparison with that of the ascending water/vapor "froth," provides the turbine with a working head. The separated vapor from the top of the rising column is condensed, heated geothermally and thus vaporized. ready for a repeat cycle. FII and F21 are recommended as secondary fluids. The cycle efficiency, essentially low because of the small available heat drop. is about *6%.* The authors estimate the cost, excluding cooling tower. at **$2300** to $2500 per kilowatt. They nevertheless consider the cycle to be competitive with diesel power at prevailing fuel costs.
Austin (p. 1925) states that several variations of the binary cycle are under study in the USA and mentions that the use of consecutive flasher/scrubber stages for the primary circuit should greatly ease the chemical problems and enable fluids with high concentrations of noncondensable gases to be handled with ease. He examines the thermodynamics of binary cycles and concludes that the supercritical cycle appears to be superior to others. Nevertheless, he estimates that binary cycles are incapable of producing as much power per ton of geothermal fluid as the double-flash or total-flow systems.
James (p. **2007)** analyzes and compares the electric power output from five different cycles for the same assumed heat input. lsobutane and water are considered as secondary fluids; and two of the cycles are not binary at all. but are two-stage flash systems-with and without deep-well pumps. The author postulates the availability of an efficient deep-well pump; and while admitting that no such device yet exists for operation at a depth of **1** km and at *250°C,* he expresses optimism that it will soon be obtainable. (One speaker, during the discussion, confirmed that two or three such pumps were under design and development and should be available in the market before the end of 1975.) The advantages **of** using a deep-well pump are that by pressurizing

the geothermal fluid, its passage through the heat exchanger of a binary cycle could take place without the emission of steam or gas and without calcium scaling but with the full depth temperature. James concludes that the use of isobutane with a deep-well pump has a slight thermodynamic advantage with well-water temperatures ranging from 150 to ***200°C.*** and that outside this range a binary cycle using a deep-well pump and water as the secondary fluid has \he advantage. He points out, however, that a free-flowing well can produce about twice the output of a pumped well, and concludes that the case for binary cycles is somewhat marginal.

Hankin. Beaulaurier. and Comprelli (p. 1985) describe the conceptual design of a **IO-MW** (net) binary-cycle generating unit and an experimental establishment for testing binary fluids. materials. and equipment under field conditions at Heber in the Imperial Valley, California. The aim of the **IO-MW** unit is to extract power from the hot brines beneath Heber (380°F. **14** *OOO* ppm, pH *6.2)* and thereby to gain experience for more extensive binary-cycle developments in the future. Various flash and binary cycles were first studied. and a supercritical binary Rankine cycle using isobutane was found to give the maximum power output per pound of brine and also to have environmental advantages over the various alternatives considered. The brine

will be supplied by four bores, **4000** to 6000 ft in depth, each yielding 500 to 650 klb/hr of brine with the use of deep-well pumps. The cooled brine from the heat exchangers, together with the cooling tower purge, will be reinjected through two other bores. The brine will be circulated at a pressure of about 50 psi above saturation pressure so as to prevent flashing and to inhibit scaling in the heat exchangers. The turbines will run at **14** 000 rpm and will give a gross output of 12.3 MW and a net output of 10 MW. The feed pump will have an isobutane turbine drive. The cycle efficiency is estimated at 9.1%, and the cost of the power unit is estimated at $16.2 million, or $1620/kW at January 1975 price levels, including a 20% contingency allowance but excluding the costs of bores and brine piping to and from the development site, land costs, electrical transmission, and interest during construction. This is not regarded as a commercial proposition, however, but rather as a development prototype. The construction time is estimated at 34 months. If the costs of the testing establishment, to be constructed simultaneously, is also included with those of the IO-MW plant, the total cost of the whole venture is estimated at $23 million in January 1975 dollars.

Kihara and Fukunaga (p. 2013) point out that the low efficiency necessarily associated with low-enthalpy heat sources implies the use of very large heat transfer surfaces per kilowatt of output. The authors make a parametric study **of** a hypothetical IO-MW plant with assumed heat-source and sink temperatures of 350 and 80°F respectively, and they examine the merits of various secondary fluids. Isobutane and **R-I14** are favored as the most promising secondary fluids.

Kunze. Miller, and Whitbeck (p. 2021) mention the drawbacks of the binary cycle, including the need for a very large heat exchangers, discuss the relative merits of the boiling and supercritical systems, and suggest isobutane ***to*** begenerally the most suitable secondary fluid. The authors make a comparative study of IO-MW flash-steam and dualboiling cycles for using the low-enthalpy geothermal fluid (150°C) from the Raft River area in Idaho state, and they conclude that the latter offers some advantage in efficiency and cost over single flash, but that significant gains in well performance or reductions in well costs could swing the advantage the other way.

Kutateladze, Moskvicheva, and Petin (p. 2031) argue that as fossil fuels become scarcer and the limited number of high-grade geothermal fields become exploited, there will be a growing need to develop power from low-grade heateither from industrial waste or from geothermal fields of comparatively low temperature. For this purpose the authors consider the binary cycle well suited. They maintain that for fluid temperatures less than 170 to 180°C the binary cycle is more economical than the conventional steam cycle. The authors describe a 750-kW (nominal) experimental plant, using Freon 12 as the secondary fluid. at the Thermophysics Institute of the Siberian Department of the USSR Academy of Sciences. It is not quite clear whether this unit is the same as, or merely similar to, the 750-kW (nominal) experimental plant at Paratunka which was described by one of the authors (V. N. Moskvicheva) at the 1970Pisa symposium. The diagram of the thermodynamic circuit is more complex than that which accompanied the Pisa paper, but is basically similar; it is therefore possible that the Pisa diagram was deliberately simplified for ease of description. Both papers mention a short fall of output due to differences between the design terminal temperatures and those provided by nature, and at the San Francisco symposium the authors claim an output of 684 MW. It is not clear, however, whether this is a gross figure from which the auxiliary power consumption must be deducted, or a net power. (According to Austin, p. 1925, the high parasitic losses of the Paratunka plant resulted in a net output of only 440 kW.) A turbine efficiency (as distinct from a cycle efficiency) of 82% was attained. Interesting measurements of Freon leakage show a loss of only 0.12 kg/hr with a charge of **12** tons-that is,a loss of only O.OOl%/hr, which would exhaust the charge after 100 *OOO* hr, or nearly 11.5 years. This is regarded as acceptable. The plant is said to be simple to operate and easily supervised by a single machinist. Experimentation will now be directed towards larger and more efficient plants. For units of 10 to 15 MW (3000 rpm) multistage axial or radial blading is favored.

McCabe, Aidlin, and Falk (p. 2045), after stressing the great success achieved by the developers of The Geysers field, state that on present evidence future geothermal discoveries in the USA are likely to be wet fields with comparatively low downhole temperatures- **150** to 215°C. Flashing systems for such moderate temperatures are inefficient, so the arguments for using binary cycles **are strong.**

The authors refer in particular to the “Magmamax” power process, which is patented, usingdownhole pumps to prevent flashing and to inhibit precipitation in heat exchangers, and reinjecting the cooler geothermal fluid. They state that IO00 US gal/min of water at 175°C can yield 3.5 MW of power. The Magma Power Company is now designing 10-and 50-MW plants, and the authors see a promising future in binary-cycle power generation. They do, however, make a plea for risk funds to be made available and for the environmental laws to be more flexibly applied so as to avoid costly delays. They state that there is no lack of willingness to undertake extensive geothermal exploration and appear confident that suitable downhole pumps will soon become available.

To summarize, it would seem rash to regard the case for the binary cycle as yet fully proven, though there could be conditions where it could be economical. It may be significant that in the island of Ischia a small 20-kW binarycycle unit using ethyl chloride as the secondary fluid and installed in 1952 has now been abandoned; and that a fuel-fired mercury vapor plant installed many years ago in the eastern USA was in operation for only a short time. The simplicity of water is an advantage that must be weighed against the sophistication of more exotic secondary fluids. (It is. of course, possible to use water as a secondary fluid in a binary cycle-see James, p. 2007.) Moreover, if the art of reinjection should ever become so perfected as to ensure that discharged hot geothermal waters can usefully serve as "boiler feed" to the underground heating cycle, then the advantage of a lower rejection temperature is somewhat weakened, and the merits of rejecting cooled bore water could become somewhat dubious. Nevertheless, computer models (below) have a close bearing upon the whole subject of binary cycles, and an open mind ***is*** advisable for the present as to the usefulness of binary cycles until more studies have been made and until a significant amount of operational experience has been gained.

Total Flow Prime Mover

The difficulties of extracting a maximum of heat from the hot-water phase of wet-field fluids has led to the concept of the "total flow" machine in which both the steam and

the hot water are subjected to the full available heat drop as limited only by the supply pressure and the locally determined "sink" temperature. The basic idea is not new, but its practical adoption has been inhibited by the expected difficulties which stem basically from the widely different thermodynamic properties of steam and hot water. The isentropic heat drop through a given range of temperature is very much greater for saturated steam than for saturated hot water at the same initial temperature; and since the maximum velocity attainable in an ideal expansion nozzle is proportional to the square root of the heat drop, it follows that the steam would try to attain a much higher velocity than the water. If both fluids were passed through the same nozzle, the difference between these velocities would be expected to appear as "drag," retarding the steam and accelerating the water; and although the resulting friction would raise the dryness fraction of the mixture, the drag would essentially lower the nozzle efficiency. In other words, two-phase fluid expansion through a single nozzle would

be expected to have a larger isenthalpic and a smaller isentropic component than the expansion of dry saturated steam alone. Another difficulty is that expansion in a single stage from a convenient stop-valve pressure down to vacuum conditions would give rise to such high nozzle velocities that the kinetic energy could not be efficiently captured without adopting impractically high blade tip speeds. In theory, this difficulty could be overcome by multistaging; but the cumulative evaporation of the water phase as the mixture passes through the turbine would result in greatly increased specific volumes which would be difficult to handle. These apparent fundamental difficulties, however, have not deterred a few engineers from pursuing the idea. (The perfection of the reinjection process could reduce the urgency of extracting a maximum of heat from geothermal fluids. This argument might perhaps be used against the development of the total flow prime mover; but it can equally well be argued that "a bird in the hand is worth two in the bush," and the development of the total flow machine should certainly not be abandoned on such slender grounds.)
Austin (p. 1925) shows that the total flow turbine ***is*** thermodynamically the best of all possible cycles in theory, as would be expected. He considers impulse/reaction turbines, the multiple disc turbine which relies on skin friction between the fluid and the discs for the generation of torque, positive displacement machines including the Keller Rotor Oscillating Vane (KROV) machine and the helical expander, and pure impulse turbines with axial and tangential flow. The KROV machine is mechanically complex, would be physically large, and has yet to be demonstrated as practicable. The helical rotor expander is really a helical compressor run in reverse; a demonstration prototype is operating in the Imperial Valley, California. It has the merit of being self-cleaning but the disadvantages of low efficiency and large physical size. More research must be performed on it before it can be properly judged as a competitor in the total flow class of prime mover. On balance, Austin favors the pure axial flow impulse turbine, which shows possibilities of high efficiency, mechanical simplicity, and size advantage.
Weiss and Shaw (p. *2065)* describe a test laboratory for studying two-phase flow nozzles and turbine blades and the behavior of various materials under erosive and corrosive influences, in order to utilize the hot brines beneath the Salton Trough region of California. The work undertaken there may be of great value in the development of the total flow concept.
Armstead (p. 1905) describes the basic design of a total flow turbine from a different standpoint. His aim is not high efficiency but low capital cost, and the turbine he proposes is intended for use as a pilot generating plant for recovering some cheap energy from the first production bores of a new field, where hot fluids would otherwise be blown to waste. The turbine is essentially a noncondensing bladeless Hero engine and can be used either with dry steam or with water/steam mixtures. In the latter case, the rotor itself acts as a separator and the two phases are ejected separately through nozzles at different radii, chosen to suit the available heat drops of each fluid. The self-regulating

characteristics of nozzles passing boiling water would control variations of water flow. To avoid excessive tip speeds the author deliberately sacrifices some efficiency. The turbine would be mechanically simple, and a standard design could be adapted to different well conditions simply by changing fixed nozzles. Since every kilowatt of geothermal base load feeding an integrated power network can save about 2 tons of fuel oil per year, a cheap turbine of this sort which could be built very quickly should pay for itself in a very short time.

Alger (p. 1889) reports tests of supersonic expansion through convergent-divergent nozzles of water/steam mixtures of various qualities and pressures and at varying back-pressures, with thrust measurements. Surprisingly, he reports nozzle coefficients of 0.92 to 0.94, with consequent nozzle efficiencies (proportional to the square of the coefficient) ranging from about 8S% to 88%. Fog flow, with droplets of less than 2-micron size, is believed to occur.

Why are the high nozzle efficiencies reported by Alger surprising? This may best be explained by means of a numerical example. Assume that a water/steam mixture (**4** parts water to **1** part steam) at 300°F expands through a single nozzle to conditions slightly above atmospheric (214°F). It can be shown that the steam, if expanding isentropically without the presence of the hot water, would attain an ideal jet velocity of 2332 ft/sec; while the hot water, also if expanding alone isentropically, would attain a jet velocity of only **SO1** ft/sec. The combined kinetic energy of **1** Ib of the mixture, if each phase could attain its own ideal jet velocity, would be **644** *OOO* ft. .Ib. But the relative velocity of 2332 to **501,** or **1831** ft/sec would act as a drag, or windage, tending to equalize the velocities of the two phases. If the water and steam did in fact attain the same velocity, this would be determined by the quotient of their combined momenta divided by their combined mass, that is, **[(4** x **501) + (I** x 2332)]/5, or 867 ft/sec, and the kinetic energy of the mixture would be 375 840 ft:lb/lb. Thus the total elimination of drag by friction would reduce the efficiency of the nozzle to 375 **840/644** *OOO,* or 58.4%, even assuming no nozzle wall friction.

It can be shown that if the mixture were expanded over a wider range, down to **4** in. Hg vacuum, this efficiency would rise to about 73%. but it is difficult to understand how such high nozzle efficiencies as those observed by Alger can have been achieved, unless the ideal were taken as the “no-slip’’ condition; but that would be putting the process in a falsely optimistic light, for two-phase nozzle flow expansion would seem on first principles to be an inefficient process. The more finely the water atomized in the nozzle, the more closely will “no-slip” conditions be approached. If the slip were not entirely eliminated in the nozzle expansion, then the nozzle efficiency would undoubtedly be higher, but the problem would then be

transferred to the turbine blades, which would be struck by two fluids moving at different speeds.

Tapping Direct Volcanic Heat

Hayashida (p. 1997) explains that there are no hot dry rocks in Japan, such as are known to exist in the **USA.** He therefore appears to advocate the direct tapping of heat from active volcanic zones by pumping water through artifically created fissures in the hot rocks immediately adjacent to the volcanoes. He mentions some of the problems and possible hazards and stresses the need for field experiments. His thesis is not very clearly expressed, but at this stage he appears to be advancing only broad ideas, and he appeals for cooperation from other interested scientific workers.

Geothermal Peaking Plants

Armstead (p. 1897) demonstrates that in theory geothermal energy could be used to supply cheap kilowatts as an alternative to cheap kilowatt-hours, and geothermal energy could therefore provide peak-load power. This would be economical, however. only if steam were conserved during off-peak hours, but the inability of bores to adapt to widely fluctuating flows precludes the exclusive application of a field to peak-load duty. Nevertheless, a small proportion of noncondensing plant capacity. in conjunction with a large proportion of condensing base-load plant, could perhaps supply a useful ‘‘slice’’ of secondary peak load-that is, a band of load occupying a position in the duration curve below the extreme peak but above the band of medium load-factors plants-without excessive pressure disturbance. so that bores should retain their stability. **As** an alternative, if an industrial, or other nonpower use for off-peak steam could be found, perhaps in conjunction with thermal storage. larger amounts of peak load could perhaps be supplied geothermally.

Hybrid Application of Geopressurized Reservoirs

House, Johnson, and Towse **(p.** 2001) have made a study of the geopressurized reservoirs which occur at depths ranging from SO00 to 20 000 ft in the Texas and Gulf Coast region of the USA, where trapped subterrahean hot waters are bearing part of the weight of the overburden. Such waters possess thermal and hydraulic energy and also contain quantities of dissolved natural gas. Total flow, flashed steam. and binary cycles have been studied. with and without reinjection. **Also** three separate topographical zones have been considered. The authors conclude that the development of power and gas production is technically feasible though only marginally profitable under existing conditions. Two of the zones would have to contain natural gas nearly to saturation for their exploitation to be economical for both power and gas production: the third zone might be profitable for gas production only. Only one zone appears profitable for power generation if no gas is present. Changes of future market and price levels and improvements in energy conversion efficiency could alter the situation.

By-product Hydro Power

Armstead (p. 1897) points out that where bore waters are rejected to waste and not reinjected-regardless of whether or not their heat content has first been usefully extracted-and where a geothermal field is situated high above sea level, substantial quantities of by-product hydro power could sometimes be generated. This, in fact, is happening fortuitously in New Zealand, where the bore waters of the Wairakei field are discharged into the Waikato River and pass through a series of hydro plants on their way to the sea. In doing so they generate about 2.5 MW of continuous base load-worth about 5000 tons of fuel oil or its coal equivalent per year. By-product hydro power could be used to supply base load, or (by providing suitable storage) peak load, or even augmented peak load (pumped storage) if the land configuration offers the possibility of a high-level reservoir.

Novel Condenser Arrangement

Aikawa and Soda (p. 1881) describe a condenser for the Hatchobaru plant which is integral with the turbogenerator foundation block. The authors claim that about 5 m of building height is thereby saved. The foundation block is hollow and lined with polyester resin. Use is made of the space beneath the alternator as well as that beneath the turbine.

Novel Cas-Extraction System

Aikawa and Soda (p. **1881)** also describe a hybrid gas-extraction system to be used at the Hatchobaru plant. **A** combination of steam ejectors and rotary exhausters, it is claimed. would consume only about half as much steam as a simple steam ejector system; at the same time, the use of mechanical gas exhausters only for the second-stage boost avoids the mechanical troubles sometimes associated with very high-speed high-vacuum rotary exhausters.

MISCELLANEOUS

cost

Only limited cost information has been given by authors, which is not surprising in view of the inflationary and unstable condition of the markets. Dan et al. **(p.** 1949) give capital-cost estimates for the newest existing and planned power plants in The Geysers field up to 1978-based, presumably, upon some expected future rate of inflation. These costs, excluding steam supplies but including substations and electrical transmission. are shown in Table I .

The same authors give a 1973-based estimate of production costs for Unit 14 at 9.7, 9.2, and 8.8 mill/kWh delivered, for annual plant factors of 70%. 80%. and 90% respectively. These costs include the purchase of steam and the cost of reinjecting the surplus condensate, which were assumed to be 4.8 and 0.5 mill/kWh respectively in 1973 (but which in 1975 are 6.89 and 0.S mill/kWh respectively).

Matthew (p. 2049) quotes comparative 14-yr average production costs for the period **1961** to 1974. These show that the cost of geothermal power in California has averaged 5.612 mill/kWh as compared with 8.256 mill/kWh for fuel-fired plants (68%). When adjusted to the same plant factor as the fuel-fired plants, the geothermal costs become 7.36 mill/kWh (89%).

Barr (p. 1937) deals with costs from a different angle. for he seeks to deduce comparable prices for fuel oil, gas,

Table **7 .** Capital-cost estimates for power plants at The Geysers.

Unit number	Actual or expected year of completion	Net power (MW)	Cost ($/kW net)	Remarks
9 and 10				
11				

12
14
15
13
1973
1975
1977
1977
1977
1978
106
106
106
110
55
135
127.5 2 x 53 MW units
135.2 single unit
141.3 single unit
148.5 single unit
206 single unit
153.5 single unit
Source: Dan **et** al. **(p. 1949).**

coal, and geothermal steam which would give the same "fuel" cost per kilowatt-hour generated. He also gives some recent and typical capital costs for nuclear and conventional thermal power plants, but unfortunately expresses them in $/kWh instead of $/kW. He then proceeds to estimate capital costs and production costs exclusive of fuel (late 1973 basis) for three geothermal plants-one (The Geysers) fed from a dry-steam field and two (Otake and Cerro Prieto) fed from a hot-water field-all adjusted to a standard capacity of **110** MW. His method of scaling for adjusted kilowatt capacity seems to be rather arbitrary, and it is not clear why the costs of The Geysers plant has been exempted from the cost of condenser-cooling towers. By expressing steam flows in pounds per hour in terms of kilowatt-hours he is trying to compare the incomparable (power with energy). Barr does not appear to have carried his thesis to its logical conclusion-a direct comparison of total production costs for different generation methods for various prices of fuel and steam. Incidentally. a common turbine admission pressure is implicitly assumed.

Computer Applications

Green and Pines (p. **1%5)** describe a computer-based process program for making comparative studies of various possible power generation cycles-flash steam. total flow. binary, and hybrid-from the combined aspects of thermodynamics and cost optimization. The program can rapidly estimate thermodynamic efficiencies under various assumed terminal conditions for the different cycles. including binary cycles with different secondary working fluids. The program can also size the principal working components such as heat-exchanger surfaces, pump and fan capacities. cooling tower ratings, and so on. The program is highly sophisticated and can simulate the effects of off-design operating conditions (for example, fouled heat-exchanger surface). changes in pinch-point temperature differences, variations in the noncondensable gas content, and alterations in the assumed basic parameters. The large number of variables favors a computer solution to such problems. Examples of the process are quoted. For binary cycles the authors conclude that if the best conditions are chosen for each, there is little to choose between the thermodynamic merits of the various secondary fluids already studied, but further investigations are proceeding. Supercritical temperatures and pressures at turbine entry are conductive to good performance: and fluids of low molecular weight involve less pumping work, smaller piping, and more compact turbines. Such considerations as toxicity, inflammability, and compatibility with lubricants must be separately judged.

Gas Extraction: General

Dal Secco (p. **1943)** presents a parametric analysis of gas extraction design considerations in terms of the mass flow of noncodensable gases, the condenser vacuum, and the cooling water flow and temperature. He lists the gas-extraction systems used at the various geothermal power plants now in operation-steam ejectors. water jet ejectors, rotary exhausters, and reciprocating air pumps-and he describes the latest compressor designs for Larderello.

Corrosion

Dodd, Johnson, and Ham (p. ***1959)*** describe an extensive corrosion testing program established toguide in the selection of appropriate construction materials for The Geysers plants. Operating experience has shown a need for additional studies of the behavior of mechanical. civil. and electrical materials in the atmospheric, condensate, and steam environments encountered there. Test results are given, and mention is made of the disappointingly low availability factor resulting from repeated turbine blade failures. It has been found that blade and shroud materials are highly sensitive to small variations in heat treatment insofar as their resistance to fatigue and corrosion fatigue are concerned. Active testing and experimentation continues.

Hanck. and Nekoksa (p. **1979)** describe a corrosion monitoring system established at two of The Geysers plants, quote results. and **draw conclusions.** They also state that monitoring systems are to be extended to other plant units and expanded in scope.

Moderate Temperature Utilization

Kunze. Miller. and Whitbeck (p. 2021) underline the importance of moderate-temperature geothermal fluids (for example. 150°C) on the interesting proposition of a probable Poisson distribution curve, from which they draw the conclusion that what lower temperature fluids lack in enthalpy. they make up for in quantity. **As** utilization techniques improve, the authors argue. lower-temperature fluids will become of increasing economic importance. Low-enthalpy fluids are also likely to contain less dissolved solids and gases. On the other hand, they would require more land for a given size of development than would high-enthalpy fluids. and subsidence problems could sometimes be serious. The authors make a particular study of the Raft River thermal area in the state of Idaho, USA, compare various power-plant cycles (see above). and consider the use of moderatetemperature fluids for multipurpose projects.

cx H. **CHRISTOPHER** H. **ARMSTEAD**

Use of Hot Water

Attention wasdrawn at the Pisa symposium to the apparent reluctance of geothermal developers to make use of the hot-water phase in wet fields. There is now evidence of a welcome change of attitude in this respect. It is understood that hot water is being flashed into low-pressure steam at the 30-MW plant at AhuachapLn, **El** Salvador; and this will be done at the SO-MW plant at Hatchobaru in Japan, and also at Cerro Prieto, Mexico, at a later stage of development. Several authors emphasize the advantages of double flash. There is growing interest in the "total flow" machine, in binary cycles, and in multipurpose plants, all of which would extract heat from the hot-water phase. Finally there is the emphasis placed upon reinjection (see above), not merely to avoide certain environmental consequences, but as a possible means of conserving the heat of the hot water, if properly managed.

Summary of Section IX Space and Process Heating

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INTRODUCTION

Until a few years ago there was a widespread tendency to think of geothermal development in terms of electric power only, or at least primarily. This was understandable, because of the versatility, ease of transport. and ready marketability of electricity. Nevertheless, it is important *to* remember that geothermal power generation is essentially an inefficient process owing to inescapable thermodynamic restraints, and that the lower the temperature of the heat source, the lower will be the efficiency of power generation. On the other hand. the direct use of geothermal heat for space heating and domestic hot-water supply. industrial processes, or for husbandry can be highly efficient. since the losses incurred are not imposed by the laws of thermodynamics but only by such imperfections as must inevitably arise from insulation losses, drains, and terminal temperature differences in heat exchangers. These imperfections can be controlled within economic constraints; they are not dictated by natural laws. Another important fact is that the sources of high-enthalpy natural heat at present accessible to man and which are suitable for power generation are believed to be far less abundant than those of lowerenthalpy fluids which can be used for other purposes.

Furthermore, practical applications can be found *to* cover a very wide spectrum of temperature extending down *to* about 30°C for balneology, biodegradation, and fermentation, and even down *to* about 20°C for fish hatcheries. Finally it should not be forgotten that a very large proportion of the world's energy consumption is in the form of heat. rather than electricity. In short, geothermal energy is far too versatile an asset *to* be used for power generation only. **It** is also very much less polluting than heat produced. as is mostly now done, by the combustion of fuel. There is encouraging evidence that these facts are becoming more widely recognized.

The Icelanders have never overlooked these factors. **Just** as Italy led the way in geothermal power generation. so did Iceland pioneer the use of geothermal heat for space heating and domestic hot-water supply on a large scale. The island's economy and climate were important factors that influenced them in so doing. for they lacked fossil fuels and timber. while their weather was never hot. On the other hand they did possess large reserves of geothermal energy. Other countries also, such as Japan. New Zealand, and the USSR, have not neglected the "nonpower" application of geothermal heat, and yet more countries are beginning *to* show interest in such developments. Nevertheless, it is generally true that electric power has been, and still to a large extent is. the prime goal of geothermal development in most parts of the world.

At the UN Geothermal Symposium at Pisa in 1970 the importance of widening the scope of geothermal application was stressed, and it is now becoming clear that the message is reaching more of those people who are in a position *to* influence the direction of geothermal development. The rapid rise in fuel prices since 1973 has provided, and will continue *to* provide, a powerful stimulus *to* the continued advance of all forms of geothermal exploitation and to a widening of its application. Moreover, the growing public awareness of environmental considerations in many countries will also encourage the development not merely of geothermal power but (even more) the exploitation of lowenthalpy fluids which are generally far less polluting and far more widespread than high-enthalpy fluids. A city of about 90 *OOO* inhabitants such as Reykjavik can be almost fully supplied with all its domestic and commercial heating requirements without smoke and by means virtually innocent of any other form of pollution. This is an advantage that is shared by no other form of heat supply except hydroelectric and solar energy.

Space heating and domestic hot-water supply form the principal subject of the papers submitted in Section IX at San Francisco. but other nonpower uses have not been altogether neglected.

SPACE HEATING AND HOT-WATER SUPPLY

Iceland

The volume of building space in Reykjavik heated geothermally has increased from **10.3** million m3 in **1968** to about **15** million m' in 1974-an average growth rate of about 6.4%/yr. The city is now virtually "saturated" with geothermal space heating, only about **1%** of the buildings do not have it. The Reykjavik area alone has a thermal load demand of about 385 **MW,** and the sales of heat energy in 1973 amounted to more than **1.5** x 10' kWh, equivalent to an annual load factor of about **44.5%.** These and other figures are quoted by Einarsson **(p.** 2117) who sketches the 45-yr history of the Reykjavik city heating system from its humble beginnings in **1930** up to 1975. by which time I 1 *OOO* buildings and about 90 000 people enjoyed this public

service. Although new thermal areas have been brought in to meet this tremendous growth, the originally exploited fields are still producing at undiminished capacity after nearly half a century.

The capital city, however, is not the only Icelandic area to be served with geothermal heating. Eleven other independent areas serve about 13 500additional people with domestic heat, while a further 26 *OOO* people will be served during the year 1975/76; and a system is being planned to provide more than **IO** 000additional people with heat **in** the Reykjanes Peninsula under the Svartsengi project. By the time these plans have been executed, more than 137 OOO people will be served with geothermal heat in their homes and the total heat load will be equivalent to nearly **680** MW. By then, more than half the population of Iceland will enjoy the benefits of this service, and it is aimed to extend the proportion to 60 to *65%* within a few years thereafter.

Einarsson (p. 21 17) states that the district heating schemes of Iceland use geothermal waters at 80 to 120°C, though in one case that has been operating for 30 years, the temperature is as low as 56°C. Such low- and moderateenthalpy fields are preferred to high-enthalpy fields, as the fluids generally have much lower mineral and gas content. The Svartsengi project, however, will have to use highenthalpy saline steam and hot water at 167.5"C. A dualpurpose power-heating project is under consideration for Nesjavellir; this project will use a high-temperature field **(260°C** bottom-hole temperature) and will produce **69 MW** of power (net). Einarsson also examines the economics of district heating and shows a parametric graph of costs based **on** water temperature, pipe diameter, and transmission distance. This shows a range of costs (presumably at 1975 levels) from 4.3 to **15** mill/kWh (thermal); the lower figure represents 150°C water at the wellhead (no transmission), and the higher value represents I00"C water transported over 39 km in a 10-in. pipe. Intermediate temperatures, larger pipe diameters, and shorter transmission distances would produce intermediate cost figures. The costs generally compare favorably with fuel oil heatingexcept perhaps where the temperature is low. the pipe diameter small, and the transmission distance great. On average, the price of geothermal heating in Iceland was *SO* to 60% of that of oil heating before 1973 and is now 25 to 30%. Geothermal energy now supplies Iceland with about 2200 GWh (thermal)/yr for space heating; this saves Iceland about 300 000 ton/yr of imported fuel oil. Einarrson also technically describes the heat supply systems of Iceland and examines the climatic factors and means of improving load factor, either by short-term fuel firing or by heat storage. He also touches briefly upon institutional problems and stresses the importance of good building insulation and the effects of high cold winds.

Arn6rsson et al **(p.** 2077) give a technical description of the Svartsengi district heating project for supplying a few population centers in the Reykjanes Peninsula and also the Keflavik International Airport. This project will represent a thermal load of **80** MW (100 MW, according to Einarsson). The wells at Svartsengi produce highly saline water together with steam at about 210 to 230"C, and this is chemically unsuitable for direct heating. Fresh water is therefore heated by the geothermal fluids and is transmitted hot to the load centers, thus obviating most of the chemical problems. **It** is hoped to complete the scheme by 1977 and to supply heat at about one-third of the cost of oil heating.

Four different heating cycles were studied, but one in which steam and fresh water are mixed in two stages and subsequently heated and flashed, so as to degas the mixture, has been chosen as the most suitable. Fifteen kilowatts of electric power for auxiliary supplies is a by-product of the process.

Thorsteinsson (p. 2173) describes the redevelopment of the Reykir hydrothermal system, which has been exploited since 1944 for district heating in Reykjavik, **15** to 20 km distant. Before 1970 this area produced about **300** I/sec at 86°C by free flow and was the principal source of heat of the integrated system until 1959. After the development of two other areas within the city limits, Reykir's share of heat production fell to **38%** of the total. Now the Reykir field is being redeveloped by drilling larger bores (22 to 31 cm) to depths of 800 to 2043 m, and equipping them with submersible pumps. Production had already increased to 850 I/sec at 83.5"C by January 1975, and is expected ultimately to exceed 1500 I/sec, with a fall in water level of **60** to 70 m from the 1970 steady-state level. Drawdown tests have been performed and the characteristics of the aquifer deduced. The effects of tides and earthquakes have also been studied.

USA

Although there are no sizable towns or cities in the USA that use only geothermal heat, there are nevertheless some interesting developments in the western states of Idaho and Oregon. Kunze et al. (p. 2141) point out that nearly 20% of the total energy consumed in the USA is used for space heating, so the market is immense if suitable geothermal resources can be found. They think it not unreasonable to expect that about one-third of this market might ultimately be supplied geothermally. The authors mention that in Boise, Idaho, a small geothermal space heating scheme was established in the Warm Springs residential area as long ago as 1890. At one time this scheme supplied about 400 homes and businesses, but it has recently declined to 170 homes fed with 77°C water pumped from two wells 130 m deep. Now, a study is in progress for establishinga Demonstration Space Heating Project. sponsored by the Energy Research and Development Administration (ERDA) and under the direction of the Idaho National Engineering Laboratory (INEL) and in collaboration with Boise State University and the Idaho Bureau of Mines and Geology, for geothermally heating a group of public buildings in the city of Boise. At present, the annual fuel bill for heating these buildings is $225 000, and this figure is expected to rise. The two wells now feeding the Warm Springs area have shown no decline in productivity in more than 80 years, and the chemical quality of the water is good. The study will cover environmental and chemical aspects, the conversion of existing installations, and various methods of waste disposal including infiltration through sand and gravel pits, reinjection wells, discharge to the existing irrigation system, discharge into the Boise River, and cycling to greenhouses, fish hatcheries, and so on. The cost of the study is estimated at about $2 million.

Lund, Culver, and Svanevik (p. 2147) describe the exploitation of the geothermal waters at Klamath Falls, Oregon-a project which has provided space heating since the turn of the century. About 400 holes of depths ranging from 27 to 580 m are used to heat about *500* buildings

(and incidentally, swimming pools, a milk pasteurization plant, and snow melting facilities for roads). Some of the wells are artesian, with a pressure of about 5 psi. The total heat load is about 5.6 MW. Estimated costs are given for different numbers of households per well and are compared with fuel and electrical heating as alternatives. Initial investment for a single well is usually from ***$5000*** to **$IOOOO,** and the annual operating costs are less than $100. Where several householders share the same well, geothermal heating is shown to be competitive. **A** large-scale district heating project on the lines of the Reykjavik system is being studied, as it is obvious that only a small portion of the total local heat potential is being tapped. Additional uses for the heat, for husbandry and industry, are also being considered. The well temperatures vary from 38 to ll0”C. Downhole “hairpin” heat exchangers are commonly used in order to minimize corrosion, with city water as the circulating fluid; circulation is usually effected thermosyphonically. Four steam wells have been struck, and these too are used with heat exchangers.

France

Coulbois and Herault (p. 2W) state that the French administration is seeking to encourage the use. for domestic heating, of hot waters discovered in the French sedimentary basins in the course of oil prospection during the last **20** years-in particular in the Dogger aquifer near Paris. Since the depths at which these hot waters occur range from 1.5 to 1.8 km and the temperatures vary from 55 to 70°C. it would appear that the areas of interest may be regarded as “nonthermal,” having temperature gradients (assuming surface ambient temperature of 15°C) only of the order of 30”C/km, which can be regarded as “normal.” The water salinity varies from 8 to 30 **g/l** (NaCI) and traces of H,S are present. Heat exchangers are therefore considered necessary so that clean secondary water may be used as the heating medium. Reinjection is necessary in order to avoid surface pollution from the saline well waters after having yielded up their heat, and also to conserve both fluid and heat for recharging the aquifer. The authors examine the problems theoretically from the economic and technical aspects, stress the high capital cost of geothermal heating, and suggest that geothermal energy is suitable for background heating to be supplemented with another heat source for boosting at times of high demand. Their presentation is sometimes rather obscure, and their conclusions could have been stated more clearly.

New Zealand

Shannon (p. 2165) tells us that the extraction of geothermal heat in Rotorua for domestic heating purposes has steadily increased since the first successful bore was sunk there in 1935. There are now more than **700** registered bores in that city, ranging from 50 to **1200** ft in depth and from 2 to 6 in. in casing diameter. Temperatures vary from 49 to 177"C, and pressures are experienced up to 175 psig (which is hard to understand, as this pressure exceeds the saturation pressure at 177°C). These pressures are sufficient to ensure delivery to the places required without pumping. Chemical deposition has been something of a problem, but deep bores generally give less trouble than shallow. After the heat has been extracted from the geothermal fluid. the cooled waters are disposed of in soak bores, vented at high level to dispose of the H,S. Heat exchangers are obligatory in view of the noxious ingredients in geothermal fluids which could escape from valves and pipe joints. The author discusses the choice of suitable materials for the various component parts of the heating system, presents drawings of some of these parts, and discusses controls. He also gives particulars of a scheme for heating a complex of government buildings, representing a total thermal load of nearly 14.6 MW. Finally he gives some interesting cost data which show that although the capital cost of geothermal heating is 16% and 44% higher than for coal- and oil-fired heating respectively, the annual running costs are 30.5 and 71% lower respectively at present fuel price levels. Geothermal heating thus "pays for itself" in 15.5 and 39.5 months when compared with oil and with coal heating respectively.

India

Although India cannot yet claim to be one of the countries in which geothermal space heating is practiced, some experiments are being conducted in two Himalayan areas. The occurrence of geothermal energy in Ladakh coincides with very severe climatic conditions, but unfortunately the natural heat is found at present only in some of the most sparsely populated parts of the world-in particular at Puga in southeastern Ladakh where the population density is only 0.8/km2. Here, at a height of 4500 m above sea level, the winter temperature sometimes falls to -40°C. Nevertheless, steam and hot water are found at depths of only *20* to 30 m. and an experimental test rig has been set up to test the suitability of geothermal space heating. Behl, Jegadeesan. and Reddy (p. 2083) describe the local conditions, the test equipment. and the results hitherto obtained. Some empirical knowledge has been acquired from the tests regarding building insulation and the corrosive properties of the thermal fluids. At present the Ladakhis have to rely on kerosene heaters to make their dwellings habitable in winter. To relieve these people of dependence upon petroleum products would be most desirable; but it is not easy to see how geothermal space heating could become economical, even with such shallow wells, in such an underpopulated area, nor how a viable economy in such an inhospitable climate could be found to justify the establishment of settlements of a size that could be heated economically by geothermal means. Nevertheless, the authors explain how the Government of India has also conducted some successful greenhouse heating experiments at Chumathang, also in Ladakh; so perhaps it might be possible to establish greenhouse cultivation in new settlements of an economical size.

USSR

Dvorov and Ledentsova (p. 2109) recognizing the complexity of the variables which govern the economics of geothermal space heating, have presented an erudite paper in which the component cost factors are analyzed separately-borehole production, local heat distribution, waste disposal, heating systems, and longer distance heat transmission. Different secondary variables are considered in each case as may be applicable-drilling costs, bore yields, bore spacing, bore fluid temperature, pattern of demand, transmission distance, local fuel costs (in competition),

climatic conditions, and ***so*** on. Different heat distribution systems, heating schemes, and devices are also considered. Graphs are given showing the interrelationship of some of these variables. The authors broadly conclude that simple local geothermal heat distribution schemes can at present be competitive with traditional fuel heating only when the thermal fluid temperature is 85°C or more, the temperature change does not exceed 45"C, the local distribution distance does not exceed 5 km, and the ambient air temperature is not less than -8°C. Borehole costs should not exceed 100 OOO to 130 *OOO* rubles, or 150 *OOO* in rare cases. Long-distance transportation can be economical up to 35 to 40 km if drilling costs are exceptionally low-for example, 50 *OOO* rubles per bore. Drilling costs in the range of 80 *OOO* to 120 *OOO* rubles per bore reduce the economical transmission distance to about 5 km-or perhaps 8 to 10 km under very favorable conditions of high well yields and very expensive fuel alternatives. The authors mention the enormous heat reserves in the Soviet Union but point out that in many areas the waters are highly mineralized and sometimes the temperatures are rather low. Different schemes are described for dealing with highly mineralized waters and for moderatetemperature waters; these involve heat exchangers and supplementary fuel heating. The authors also describe a scheme which makes possible the use of low-temperature fluids in combination with a heat pump, and a complex system involving both a boiler unit and a heat pump using the lithium bromide process which permits the **use** of air conditioning in summer. The possibility of recovering rare elements from highly mineralized waters, after yielding up their heat in heat exchangers, is mentioned. The authors stress the fact that high sophistication and complexity may adversely affect the economics of heating schemes and their reliability of operation.

Elsewhere

There are, of course, many other examples of geothermal space heating and hot-water supply to be found in various parts of the world-for example Japan, Hungary, and so on-but unfortunately no papers on these developments were presented in San Francisco.

PROCESS HEATING

The expression "process heating" is used here very broadly to cover all nonpower uses of geothermal energy other than space heating and hot-water supply-even (paradoxically) refrigeration and air conditioning. **As** mentioned in the introduction to this summary there is far more low-enthalpy than high-enthalpy heat available in the world. (This point is brought out by Kunze, Miller, and Whitbeck in a paper in Section **VIII,** p. 2021, and is the subject of comment in the summary of Section **VIII).** Furthermore, a very large proportion of the basic energy needs of an industrialized country is for heating at low to medium temperatures.

Applicability of Geothermal Heat

Reistad (p. 2155) emphasizes these considerations and presents an interesting breakdown of the different uses of energy in the USA economy-electricity generation, residential, commercial, industrial, and transportation. The electricity is then reallocated to the other four sectors according to the requirements of each. Each sector's energy requirements are further broken down into the various applications such as space heating, cooking, refrigeration, process steam, and ***so*** on; and a final allocation is then made to one of two groups-"Potential Geothermal Use" and "Nongeothermal Use." The second group excludes all uses requiring temperatures exceeding 250°C; it also excludes transportation and such applications as cooking, which have intermittent demands. The author's final conclusion is that about 41% of the national energy requirements could be filled by means of geothermal energy, were it available. If the temperature limitation were dropped from 250 to 200"C, the proportion of energy requirements that could be met geothermally would scarcely be affected-a drop merely from about **41** to 40%-because very few processes use temperatures between 200 and 250°C. If the temperature limitation were further dropped to 150 and 100"C, the percentage of national energy requirements falling within the "Potential Geothermal Use" group would become about 30 and 20% respectively. This interesting analysis serves to show that the problem is one of geothermal availability rather than one of applicability, as the uses to which geothermal energy could be put, if it were available, would be enormous.

Howard (p. **2127)** reports on the findings of the Committee on the Challenges of Modern Society Non-electrical Applications Project. The committee first emphasizes that very large resources of low-grade heat can probably be made available by methods already established. They cite the USSR, where it is believed that at least half of the Soviet Union is underlaid with fluids of 50 to **160°C** that are industrially usable. They also state that there are many existing and potential applications for such heat, and support this with extensive tables. The committee believes that the economics of nonelectrical applications of geothermal energy are generally promising and likely to improve as fuel prices rise, but they warn that the disposal of used geothermal fluids can be a consideration of some importance. They stress that cheap energy does not necessarily imply a cheap product, as ***so*** much depends upon the energy intensity of a process. Finally they touch upon institutional and legal aspects of the matter. Much of the paper overlaps with the content **of** Reistad's paper.

Geothermal Heat for Process Steam

Valfells (p. 2181) points out that steam produced by fuel combustion now costs from **$ I** to ***$5*** per ton according to the type of fuel and the location, whereas geothermal heat usually costs less than $O.SO/ton. Temperature and location, however, impose restraints upon the use of geothermal steam. Valfells shows advantages, for a chemical process, of sequential flashing of the geothermal fluid from a wet field, whereby the condensate from each stage of flashing is mixed with the residual hot water from that stage, and the mixture flashed again at a lower pressure. He describes how the system must be optimized together with the heat exchange and recovery system of the plant. If the condensate from the last flashing stage can be sold for space heating, agricultural, or other useful purpose;the net costs would of course be lowered.

Farming, Refrigeration, and Balneology

Geothermal heat can of course be used for a variety of agricultural and horticultural purposes, for fish breeding,

and for animal husbandry-all of which may loosely be termed “farming.” Refrigeration is also closely related to farming as a means of preserving foodstuffs, and this too is a process that can be effected by means of geothermal energy. Much of the application of geothermal energy to farming is no more than a form of space heating, for example, greenhouse and soil warming. The word “balneology” too may be extended to cover its medical counterpart of “crenotherapy .”

Behl, Jegadeesan, and Reddy (p. 2083) describe how the use of geothermal heating under glass has produced very promising results even in the inhospitable climate of Ladakh. The authors also state that a refrigeration plant is being. planned to exploit the Manikaran geothermal field in the Parbati Valley. Himachal Pradesh, in the Himalayas. This district abounds in orchards and potato farms. and it is intended to install a 100-ton cold storage plant, using the ammonia-water absorption process, to preserve the local produce. The residual waters will be used for space heating and to warm swimming pools, as the area is frequented by tourists and by pilgrims. A small hydroelectric plant is to be included in the project so that the whole complex may be self supporting. A small pilot IO- to IS-ton refrigeration plant will form the first step in this project.

Einarsson (p. 21 17) briefly mentions agricultural and balneological applications of geothermal energy. and states that there are now 140000 m2 in Iceland under glass, geothermally heated. He also mentions space cooling. or air conditioning, and mentions that he has proposed the establishment of a district cooling system for Managua. Nicaragua, to be adopted while the city is being rebuilt after its destruction in the devastating earthquake of 1972.

Chiostri (p. 2091) devotes his paper to the medico-balneological applications of geothermal energy. The oldest geothermal “industry” in history is the use of natural hot or warm waters, for pleasure or for alleged medical reasons. The ancients of Greece and Rome made great use of warm and hot springs-and even of cold springs if endowed with certain mineral contents. Such waters were alleged to possess healing and prophylactic properties when applied externally. as in bathing, and sometimes when taken internally or used for douches. The Roman bath became an institution-not

merely as a health center, but also as a kind of social club; and in the eighteenth and nineteenth centuries the idea was more or less revived at the many “spas” and “watering places” that sprang up all over Europe as gathering points both for invalids and for the world of fashion. In Japan. Mexico, and in Maori, New Zealand, thermal waters were also used for health and hygiene. The “hamams” of Turkey are much frequented to this day by sufferers from various ailments and by women hoping for fertility. and ”Turkish baths” are to be found in countless cities all over the world. While some people remain sceptical of the therapeutic value of the waters, modern medical science treats the subject seriously and has coined the word “crenotherapy” as the technique of curing and alleviating diseases by means of thermal waters. For convenience, waters have been classified by the medical profession as follows: (I) cold, less than 20°C; (2) hypothermal. 20 to 30°C; (3) homeothermal, 30 to 40°C; and **(4)** hyperthermal, more than 40°C.
Natural waters vary in their gaseous and soluble solid contents. also in their degree of radioactivity. They are used for drinking, bathing, underwater massage, inhalation, douches, mouthwashes, saunas, and are alleged to cure, alleviate. or inhibit many complaints such as rheumatism, arthritis. skin infections, internal disorders, and diseases of the respiratory tracts. Since a large percentage of potentially useful human activity is frustrated by disease, and much suffering is caused thereby, these alleged properties could-if their efficacy is firmly established-be of immense value to mankind.
Chiostri broadly discusses the whole subject of crenotherapy and clearly believes that it is of very real value.
He mentions that in Italy alone 15 million people were treated at more than 200 thermal clinics in 1971, and that in the USSR more than IO million people are treated annually with thermal waters. Several other countries have also built up impressive “spa” industries. Chiostri points out that where very hot fluids occur, heat could first be extracted for some useful industrial or other purpose and the temperature thus lowered to tolerable body temperature for medical application thereafter. Apart from the health aspects of the matter. there is no doubt that thermal “spas” are responsible for having built up tourism on a large scale in many parts of the world. An international catalogue of all medicinal waters throughout the whole world is proposed.
Gutman (Section **X.** p. 2217). when addressing the symposium participants. stressed the value of geothermal energy in the food industry and described a hydroponic installation in northeastern California situated 4100 ft above sea level, where winter temperatures can fall to -27°F.
The installation uses a natural artesian geothermal well yielding hot water at just below the atmospheric boiling point. An area measuring 3320 ft2 is under “glass.” Domed sheds are placed parallel to one another at 13-ft spacing so that they do not shade one another from the sunlight.
Humidifiers are needed in the summer. Bradbury asked, during the discussion, whether the pliable bubble plastic technique had been considered as a means of constructing the sheds. and whether increased CO, content of the atmosphere had been tried in order to stimulate growth.

To the first question Gutman said that high winds would preclude this method of construction, and that stiff corrugated plastic had been found satisfactory. To the second question he said that the idea was under consideration but had not yet been tried. Gutman also mentioned a proposal for developing a birth-to-death controlled-environment cattle-raising project.

Unfortunately no references were made at San Francisco to other nonpower applications of geothermal energy, although many such are to be found throughout the world.

Summary of Section X
Other Single and Multipurpose Developments

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INTRODUCTION

The papers in this section may be summarized with the observation that geothermal resources may be utilized primarily for electrical purposes and, secondarily, for nonelectrical purposes. Exceptions to this ordering will occur in areas where the geothermal resource is plentiful or where the exploration risks, and hence anticipated costs, are minimal. The electrical-nonelectrical priorities have been assigned in the context of a geothermal resource producing the energy equivalent of tens or hundreds of thousands of barrels of oil per day. The geologic criteria and economic parameters for the generation of electricity are described in the next section.

The electrical generation prerequisite is emphasized by Yuhara and Sekioka (p. 2249); Fernelius (p. 2201); and Palmer, Forns, and Green (p. 2241). The strictly nonelectrical utilization of geothermal energy is reported on by Gutman (p. 2217); Delisle, Kappelmeyer, and Haenel (Sec. XI. p. 2283); and Minohara and Sekioka (p. 2237). The papers by Forbes, Leonard, and Dinkel (p. 2209) and Barnea (p. 2197) discuss both electrical and nonelectrical utilization but give no preference to either. The papers by Linda1 (p. 2223) and Llidviksson (p. 2229) of Iceland describe multipurpose utilization in areas where the resource is both abundant and exploration risks (costs) are minimal.

DI SCU SSI ON

Yuhara and Sekioka (p. 2249) have used linear programming for an economic analysis of multipurpose utilization of a vapor-dominated reservoir in the Siramizu-gawa area near Sounkyo, Hokkaido, Japan. Utilization is shown in three stages. The primary stage is for electrical generation; the secondary stage for space heating, greenhouses, and snow-melting on roads: and the third stage for mineral baths.

The most important elements for the commercialization of a geothermal system are the quality and quantity of geothermal resources, transportation of geothermal fluid, utilization for power generation, utilizations other than power generation, waste disposal, and environmental conservation.

The paper describes the linear-programming model and summarizes the results of the analysis based on actual cost data. Although the authors do not mention mineral recovery. they conclude that utilization is difficult to economically justify without electric power generation.

Water desalinization at the East Mesa field in the Imperial Valley of California conducted by the U.S. Bureau of Reclamation is described by Fernelius (p. 2201). Information is provided on the five deep exploration wells at the East Mesa anomaly, together with results from production tests and information dealing with scaling and corrosion. Two distillation desalting units have been installed at East Mesa, together with a multistage flash unit and a vertical-tube evaporator. The design criterion for this equipment is 200°C; however, the maximum temperature of the geothermal waters is 166°C.

Work to date indicates that electric power generation will most likely be required to supplement the costs for the desalinization program. It is not clear whether the desalinization program would have been economical had the temperatures of the resource been 200°C rather than 166°C.

Palmer, Forns, and Green (p. 2241) consider the concept of locating a geothermal electric power plant on the sea floor at continental-shelf depths. The waste heat would be contained in the sea floor. which in turn would provide a preferred site for certain species of fish and crustacea such as the rock oyster, shrimp, and the "spiny lobster." The basis for the proposition of locating geothermal power plants on the sea floor is derived from studies for siting nuclear power plants in coastal zones. Using the United States as an example. studies indicate that within a coastal belt 80 km wide, **40%** of the population lives on 8% of the land and that land contains job sites for 42.6% of the industrial sector. Because siting a nuclear power plant in a coastal zone precludes multiple uses of this land, it is contended that an offshore. underwater geothermal plant would permit multiple uses of the coastal lands. Offshore experience in oil and gas drilling and heat pipe technology developed by the Hughes Aircraft Company is cited in support of the required underwater technology.

The compatibility of an onshore geothermal power plant with multiple uses may be envisioned from the other papers in this section.

Gutman (p. 2217) describes the use of geothermal waters for the soilless growing technique called hydroponics. No wells were required. The chemical constituents ***of*** the water are described, as is their effect on the types of viruses and bacteria which affect various plants. A chart which describes the impact of boron on different types of crops is included.

Under the heading "Environmental Impacts" Gutman states, "The spent water with some nutrients is discharged into the natural drainage system where it irrigates the natural alkaline soil and induces growth ***of*** grains and grasses from

windborne seed, which previously were unable to germinate due to the toxicity of the alkaline soil." This is particularly thought-provoking when one considers that many of the areas of geothermal potential throughout the world are located near deserts where soil conditions are likely to be similar to those described by Gutman. Because these areas are both toxic and arid, production of geothermal waters or brines which are predominately acidic could serve to neutralize the toxicity and make the lands fruitful. Evaporation of the geothermal waters into the atmosphere could increase rainfall by adding moisture to the air. Soil conditions in many areas of the world, including the United States, could perhaps be enhanced by the drilling and flowing of geothermal wells.

Delisle, Kappelmeyer, and Haenel (Sec. **XI,** p. 2283) list the limiting conditions for economic utilization of geothermal energy. These, combined with the lack of accessible hightemperature geothermal potential in Germany, make major economic development of geothermal energy in Germany appear unlikely at this time, although some exploration to find resources for space heating is under consideration.

The impact of water temperatures slightly higher than normal for the breeding and incubation of crocodilians is described by Minohara and Sekioka (p. 2237). Difficulties were encountered in making direct body-temperature measurements, but this was overcome by using an infrared thermometer capable of remote measuring. The remote sensing device was not described, although it may have application in the exploration for geothermal energy.

The paper by Forbes, Leonard, and Dinkel (p. 2209) illustrates one of the problems often encountered in geothermal development, namely, transportation. While electricity can move long distances between major population centers or from isolated areas to population centers, nonelectrical applications require that the resource be used on-site.

Forbes, Leonard, and Dinkel examine geothermal development in Alaska, where the remoteness of geothermal resources from population centers and the sparseness of the population centers themselves weigh against large-scale development. The potential for geothermal development at Circle and Chena hot springs, Manley Hot Springs, and Pilgrim Springs is described. Additional studies which include space heating, refrigeration, agriculture, controlledenvironment plant systems, sewage disposal, and fish farming are being conducted at the three spring locations cited.

The paper by Ludviksson (p. 2229) explains the concept of multiple uses of geothermal energy for electrical production at temperatures between **180** and 200°C and for processing agricultural products, marine products, and various raw materials using geothermal steam at temperatures ranging from **100** to 180°C. At temperatures from 40 to IOO'C, geothermal hot water may be used for horticulture, animal husbandry, health resorts, and space heating. At temperatures less than 30°C. fish farming may benefit.

Ludviksson presents an operating analysis for an electrohorticultural complex. This includes a market analysis for vegetables, flowers, and ***so*** on, both for domestic consumption and export, and the capital costs for constructing a growing facility. The principal cost of the growing facility is the glass and framework. It may be interesting to learn whether a low-quality glass could be manufactured using the electricity from the complex and the silica precipitate from the geothermal brine. The analysis excludes the costs for electrical generating facilities but assumes that one-half of the electricity produced will be sold in the marketplace. The electrical production **is** considered necessary for artificial lighting. The description of the complex will be drawn upon in the conclusions for this section.

The Reykjanes Peninsula in Iceland is an area of abundant and readily accessible geothermal resources as evidenced by the many surface manifestations. Linda1 (p. 2223) describes the activities of the Sea Chemicals Complex on this peninsula, a project initiated by the National Council of Iceland in 1966. The project was designed to coordinate the exploitation of indigenous Icelandic resources. Principally, these are hydraulic power, heat from geothermal energy, sea water, and industrial raw materials which are found in goethermal fluids. Presently under consideration by the Icelandic government are facilities for the commercial recovery of salt, potash, and calcium chloride from the geothermal brines.

During the last four years of the investigations a well was kept flowing in order to observe production rates and possible changes in the chemical composition of the brine. The depth of the well is not given. The rate of production the first year was 85 kg/sec. The production then declined to 68 kg/sec in the second year, 57 kg/sec in the third year, and remained the same thereafter. The chemical composition did not change. Mineral recovery was achieved through separation by evaporation and fractional crystallization. The minerals present in the brines were found to attain a solid form in the following order: silica, sodium chloride, potassium chloride, and calcium chloride. **An** evaporator was constructed to assist in removing the water in order to concentrate the fluid. Geothermal steam from the **test** well was the source of heat for the evaporator. Silica and calcium sulfate build-up of scale commonly associated with geothermal production is not considered to be a problem. Build-up of scale did, however, inhibit the heat-transfer coefficient in the evaporator when oxygen was permitted to enter the system. By purging the oxygen, the heat-transfer coefficients are expected to remain satisfactory.

The most extensive technical work accomplished by the Sea Chemicals Complex is the preparation of magnesium chloride from sea water as a feed to electrolytic magnesium cells for the ultimate manufacture of magnesium. Inexpensive soda ash processed by geothermal steam is a key component in the manufacturing system envisioned. The production of sodium metal, chlorine, and caustic soda have also been studied. Because magnesium and sodium metal as well as other products such as ammonia can be produced using electrolytic processes, additional attention should be given to electrolysis using power generated by geothermal energy.

GEOTHERMAL DEVELOPMENT COMPLEX

A geothermal development complex conceptualized from the papers contained in this section might consist of an electric-power generating facility, with a portion of the electricity used internally and the balance sold into a transmission grid. The electricity would be used within the complex conventionally by residents and for many energyintensive manufacturing processes such as smelting and electrolysis for the manufacture of ammonia. Some steam could be diverted from the power station for process use or water desalinization. Hot waste water could be used for space heating in buildings, greenhouses, and/or to

hydroponically produce food. Low-quality greenhouse glass could possibly be produced with precipitated silica in electric ovens. Otherwise arid lands could be made tillable with waste waters and ammonia-based fertilizers from the electrolytic processing plant. Perhaps the hot water could be piped under intercomplex roads to keep them snow-free. Mineral baths would be an ideal place for residents to contemplate other productive activities for the geothermal development complex.

While the vision of a geothermal development complex is appealing, the demand (value) for electricity and associated costs may economically preclude multipurpose uses in areas such as the United States. In such areas it may be desirable to reinject the geothermal fluids at their highest temperature in order to maintain or prolong reservoir life. Reinjection would also maximize individual well lives and inhibit production declines. Until more wells are drilled and permitted to flow, this question will remain unanswered.

Summary of Section XI Economic and Financial Aspects

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INTRODUCTION

Capital is a resource more scarce than oil, gas, coal, uranium, or geothermal energy. The marketplace, if permitted to function, and the efficient use of scarce capital will assure adequate supplies of energy in various forms to the common benefit of society as a whole. Geothermal energy for electrical power generation is viewed as competitive with conventional fuels as a source of energy. In order to substantiate this view, geothermal utilization must therefore be developed on a scale equivalent to millions of barrels of oil production per day.

The data presented in these papers to describe the economics of geothermal energy are generally based on experience from activities in the United States. The economic parameters established for operations in the United States are most likely representative of the highest costs to be encountered because of regulatory and environmental constraints and therefore may be used for conservative worldwide economic analysis. World oil prices. the geothermal geologic setting, the means of converting geothermal energy into electricity, and the financial parameters associated with existing and planned additions to electrical generating capacity by the western United States utilities combine to make up the geothermal marketplace in this discussion.

DISCUSS ION

Banwell (p. **2257)** describes the status of world geothermal development by country and by areas of known or probable geothermal potential. To this list we have added daily production of oil based on data published in the December **29, 1975** ***Oil and Gas Journal*** (Appendix I). By adding world oil prices to daily oil production and to Banwell's list of countries with geothermal potential, the international potential social and economic benefits of geothermal energy become more apparent.

Using the western United States as a basis for economic analysis of geothermal energy is appropriate because of the potentially vast size of the resource there. The United States Geological Survey, in a reconnaissance study published as “Geological Survey Circular 726,” has estimated that geothermal energy could supply 11 **700** *MW* of electrical generating capacity using current technology at current prices, 11 **700** MW at higher prices, and up to 154 400 MW for 30 MW-years if proven and undiscovered reserves are taken into account. The significance of this potential is highlighted with the observation that the presently installed electrical generating capacity of the United States is 450 *OOO* MW. The private sector, that is, investor-owned public utilities, own 75% of the generating facilities and sell electricity. The energy to operate the generating facilities is supplied by investor-owned oil, gas, and coal-mining companies, although a number of utilities have their own coal reserves.

The prices for electricity sales are set by the utilities but are regulated by state agencies based on rate-of-return criteria. This method of pricing has led to some misconceptions associated with the construction of new facilities by the utility industry. From the **1920s** to **1970** the utilities enjoyed continuing cost reductions from improved conversion technology. economies of scale from larger power plants. inexpensive fuels, and low interest expenses. These events permitted the utilities to lower prices on a regular basis. This meant that as the utilities increased capital spending. they increased their rate base from which the rate of return was calculated and therefore also increased their profits. The trend to lower prices flattened out in 1970or **1971** and reversed itself with the advent of increased interest costs, construction costs, and lost conversion efficiency arising from environmental constraints. The trend was compounded with the dramatic increase in fuel prices which followed the acceptance of the fact that United States reserves of oil and ***gas*** were declining substantially. This was brought to light by the oil embargo in October of **1973.** Prices for electricity stabilized from 1970 to **1973,** but have increased **20** to **40%** since then, depending upon the geographical area served by the individual utilities and their historic fuel mix. The price increases served their historic role in the marketplace by dampening the rate of growth for electricity in **1975** to 0.6% compared with a historic rate of growth of 6 to 7%.

Greider (p. 2305) compares electrical generation from geothermal energy in the context of electrical generation in the world, and specifically in the United States. He points out first that the growth in total energy consumption will likely **be** held to **2.5** to 3.5% per year for the next decade, but that the energy used in generation of electricity may beexpected to increase between 5.5 and 6.5%. The increased market penetration of electricity will increase to 5.5 to 6.5% because present uses of oil and gas for space heating and cooling will be transferred to electricity. He reports that electricity use is expected to increase because it can be transported cheaply long distances **(0.3** to 0.4 mills per kWh per IO00 miles).

Table 1. Capital costs for electricity generation.

Power **($/kW**	200	300	400	500	600	700	800	900	1 *000*	1100
Enerw (mills/kWh)	4.94	7.41	9.88	12.35	14.82	17.30	19.76	22.23	24.70	27.17

Table 2.

Oil ($/bbl)	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00
Gas ($/103ft3)	0.50	0.66	0.83	1 .OO	1.16	1.33	1 .50	1.66	1.83	2.00
(mills **/kwh)**	5.0	6.6	8.3	10.0	11.6	13.3	15.0	16.6	18.3	20.0
Coal ($/ton)	12.49	16.66	20.83	25.00	29.16	33.32	37.49	41.66	45.82	50.00

Equivalent fuel costs. Each column shows the price of oil, gas, and coal which would result in a particular fuel cost for electrical energy assuming that 1 **O4** Btu are required to generate 1 kWh.

Fuel cost

The market shifts in aggregate electrical energy demand may be expected to seriously strain the financial capabilities of the utilities as viewed in the context of recent developments.

In order to properly compare the cost of geothermal energy with conventional sources of electrical generation, and in order to permit a direct comparison of capital costs with fuel costs, Table **1** shows capital costs at various operating rates in mills/kWh for fixed charges (interest, depreciation, and rate of return on capital) of 17.3%.

Fuel costs are shown by Barr (p. 2269) in terms of British thermal units (assuming **10** *OOO* Btu are required to generate 1 kWh), and Table 2 shows the same relationship in mills / kWh.

Appendix **I1** presents the actual operating financial data for the 13 major western United States public utilities for operations conducted over a 12-month period, as reported to the United States Securities and Exchange Commission (SEC). The actual scheduled additions to new capacity and their projected costs as shown cumulatively in line 17 of Appendix 2 are shown in the reports filed with the SEC.

The highlights of the operating data are shown in Table 3 for the 13 major investor-owned utilities and also for **1 I** utilities, excluding the 2 largest. The accounting procedure "AFDC" (Allowance for Funds used During Construction) in this table permits utilities to capitalize all but a small percentage of all interest expenses incurred from funds used to build new generating facilities. Because interest expenses require cash outlays, the real cash earnings (income for common stock) of the utilities are lower than those actually reported. The accounting procedure "Total Capitalization" includes the long-term debt as shown, the equity of preferred-stock shareholders, and the shareholder equity or "book value" of the common-stock shareholders. The total capitalization represents the savings of the investing American public through their direct ownership of the various utilities' bonds or stocks, or their indirect ownership through the pension and retirement funds of their employers.

The capital costs of nuclear power plants presently operating in the United States historically have ranged between $250 and $400 per kW. Nuclear plants due for completion in 1980 and after, however, are projected to cost $800 to $I 100 per kW. When nuclear power generation costs are described as inexpensive or cheaper than oil, the reference is to those already in operation. Those scheduled for future completion, however, will be extremely expensive. A similar situation exists for coal-fired plants. Costs historically have run $150 to $200 per kW of installed capacity, but those plants scheduled for completion in 1980 are projected to cost from $600 to $800 per kW. Using historical and projected capital costs for oil-fired facilities of $15O/kW and $35O/kW, respectively, these observations may be highlighted in Tables 4a and b by converting capital costs into mills/kWh using Tables 1 and 2.

The transitional phase of the electrical generating industry is illustrated with the observation that the projected costs for new plant construction as estimated by the 13 Western utilities is $593/kW of installed capacity compared to an estimated cost for existing facilities of $203/kW (Table 3). By the time the new plants are constructed they will represent 40.5% of the utilities' total generating facilities. The estimat-

Table 3. Selected cumulative financial data for western utilities.

Category	13 utilities 6)	11 utilities* ($9	Reference line:
Revenue	4 466 900 000	1 892 900 000	1
Income for common stock-AFDC	476 300 000	172 300 000	8
Dividend cash required for total shares	436 900 000	207 200 000	35
Cash earnings after dividend	39 400 000	(34 900 000)	13
Existing generating capacity	8 318 000 000	3 428 000 000	18
Cost of projected additions to generating capacity	16 500 000 000	10 800 000 000	9
Long-term debt	9 068 000 000	4 022 000 000	12
Total caDitalization	17424000000	7 698 000 000	-
Existing cost of capacity ($/kW	203	223	-
Estimated cost of planned additions ($/kW	593	63 1	-
Existing capacity (MW	40 827	15 344	14
Scheduled additions to capacity (MW	27 812	17 113	17

Source: Earth Power Group, October 1975.
*Pacific Gas & Electric and Southern California Edison omitted.
tThe line in the table of Appendix II from which the data are taken.

SUMMARY OF SECTION XI

Table 4(a). Historical electrical generation costs.

Plant cost Plant cost Fuel cost Total cost

Type of plant	($ / kW	Fuel cost:	(mills/kWh)	(mills/ kWh)	(mills/kWh)
Oil	150	3	3.70	5.0	8.70
Coal	150	12	3.70	5.0	8.70
Nuclear	250	8	7.61	2.5'	10.11

Table 4(bL Proiected electrical generation costs (1 980-1 982).

Type of plant	Plant cost 6 / k W	Fuel cost:	Plant cost (mills/ kWh)	Fuel cost (mills/ kWh)	Total cost (mills/kWh)
Oil	350	12	9.88	20.0	29.88
Coa l	*600*	25	14.82	20.0	34.82
Nuclear	loo0	40	24.70	8.5*	33.20

*Source. Atomic Industrial Forum and NRC Docket No. 751206 (Spangled.
toil ($/bblJ, coal ($/ton), nuclear ($/lb U,O,J.

ed costs for new facilities represent a **292%** increase to costs estimated for existing generating facilities. **A 292%** increase in the rate base expanded 40.5% will require rate increases of **118.26%** by **1982** or **1983,** exclusive of increased fuel or operating expenses. The conclusion to be drawn from the financial data is that the utilities cannot afford to build the plants which are currently planned and that instead they are going ***to*** have ***to*** build smaller and less capital-intensive facilities.

There clearly exists a market for electricity and just as clearly there exists a market for new generating facilities. The economies of scale for geothermal power plant construction are achieved at the 50-MW to 100-MW level. The balance of this report will focus on the economics of producing electricity by using vapor- and liquid-dominated geothermal energy systems and the attendant importance of reservoir temperatures on the economics.

Greider (p. **2305)** outlines a budget for anticipated exploration and development costs required to delineate a field with a capacity of **200** MW in this country. The costs range from **$2.0** million to **$13.5** million. He outlines the parameters affecting development as follows: **(1)** exploration and evaluation costs, **(2)** volume and temperature of the carrier of the energy, **(3)** development schedule, **(4)** power plant design, ***(5)*** government regulation and taxes, and **(6)** market price of electricity.

Goldsmith (p. **2301)** outlines the costs for wells, pipeline, and power plant for a vapor-dominated (dry steam) plant such as exists at The Geysers. The actual costs at The Geysers are described by Greider (p. **2305)** but do not include the cost to the utility, Pacific Gas and Electric Company (PG&E), associated with the purchase of fuel (geothermal steam). PG&E's costs are described in detail in the paper by Finn (p. **2295).**

Greider points out the importance of distinguishing costs incurred by the steam supplier versus those incurred by the purchaser or other utility. The costs for dry steam production described by Greider may be combined with the compensation arrangements described by Finn to illustrate %&E's cost experience with vapor-dominated production at The Geysers.

The economics for the steam suppliers are not accounted for, using the experience of PG&E, but would not be representative of geothermal economics at any rate. First, no exploration costs (relatively speaking) were incurred in the discovery, and second, a significant portion of the development costs were incurred prior *to* recent drilling expense increases. It would also be difficult to factor in an estimated **$20.0** to **$30.0** million in productive wells which in some instances have been shut in for 5 to **10** years awaiting regulatory approval by the State of California to connect them to a turbine.

Finn **(p. 2295)** sets forth the formula by which the steam suppliers are compensated for the delivery of steam to Pacific Gas and Electric Company. The title of the paper is perhaps misleading. however, because it is not really the steam that is sold for which the steam supplier is compensated at The Geysers, but rather the amount of electricity that is generated by the steam delivered to the utility. The steam suppliers are required *to* supply, or have available at all times, certain minimum quantities of steam at specified temperatures and pressures; but PG&E is not required ***to*** accept delivery. Thus, the steam does not actually have a price, but rather the steam supplier is compensated by the amount of electricity that is actually produced. This may seem like a curious situation in light of present energy markets, but is explainable in its historic context.

A short history on development at The Geysers is a prerequisite ***to*** understanding both the nature of the contract between steam supplier and utility, and also the compensation formula for the steam suppliers. ***At*** The Geysers, PG&E and Magma-Thermal entered into the original contract in **1959.** In that year, the project was one-half owned by Magma Power Company and one-half owned by the Thermal Power Company. Understanding the nature of the contract is not difficult, but the realization that there was no government support of any kind involved in the project, and that both Magma and Thermal had committed substantially all of their corporate resources to The Geysers development, is worthy of note. **PG&E** had ample generating facilities at the time and did not have to expose themselves financially. They did have a substantial investment in the generating facilities and obviously intended to produce all of the kilowatt-hours they could.

There was no precedent for pricing natural steam at the time, and the formula that exists today, which is presented in Finn's paper, was the inspiration of Earl English, at that time an engineer with The Thermal Power Company. He was experienced in other sources of power generation; and knowing that PG&E operated fossil-fuel steam generat**ing** facilities and had plans to operate nuclear power plants, he weighed these considerations to come up with the formula described by Finn.

The critical element for determining the economic viability

Table 5. **Well** productivity-binary cycle **(flow** rate 550 **000** Ib/hr).

Temperature	Hot water required (1 b / kWh)	MW/ well	Wells/ I I O M W
250"F/ 120°C	400	1.375	82.3
300"F/148"C	210	2.620	42.0
35OoF/1 76°C	110	5.000	22.0
400°F/21 0°C	80	6.875	16.0
45OoF/23 1 "C	75	7.333	15.0
500"F/259"C	60	9.166	12.0

Source: Holt, E., and Erugman, J., 1974, Investment and operating costs of binary cycle geothermal power plants: US. National Science Foundation Conference on Research for the Development of Geothermal Energy Resources (September).

of geothermal hot-water systems for electrical power generation is temperature. The importance of temperature is twofold: first, fewer wells are needed by the energy supplier, and second, plant costs are significantly lower for the utility. Lower plant costs result from the fact that lower-pressure (temperature) turbines are larger (more expensive) than higher-pressure turbines.

Tables ***5*** and 6 show the number of wells required for the binary-stage and single-flash methods of converting hot water to electricity. Both tables assume aflow rateof ***550*** *OOO* pounds of hot water per hour.

Sapre and Schoeppel (p. **2343)** have designed a model for assessing the cost ***of*** electrical power based on the binary-cycle plant design. In his model, Sapre has defined a liquid-dominated reservoir as a "bed of hot porous rocks saturated with pressurized water at some equilibrium temperature. Such a reservoir may be characterized by its geothermal gradient, pressure gradient, and flow capacity." We have emphasized temperature (geothermal gradient) because of its importance and the effect of temperature causing pressures greater than hydrostatic. In fact, Sapre states, "If an area could be found where the natural hydrostatic gradient was **0.1** psi per foot more than normal, then the cost of power could be reduced by as much as one-half." This statement refers to his observation that electricity from geothermal energy will be economic where the temperature gradient is greater than 5"F/100 ft. That "such reservoirs can be identified easily" and that "with present technology, these reservoirs are available for almost immediate exploitation" still holds. Electricity can be generated profitably from geothermal energy where the temper-

Table ***6.*** Flash steam **well** productivity **(flow** rate, 550 **000** Ib/ hr).

Temwra t ure	Percent flash	Steam (Ib/hr)	MW/ well	Wells/ 110 MW
302"F/ 150°C	-	-	-	-
350"F/ 176°C	5.8	31 900	1.59	69.1
392OF/ 200°C	11.0	60 500	3.02	36.4
400"F/ 2 1 0°C	12.0	66 000	3.30	33.3
45OOF/23 1 "C	18.0	99 *OOO*	4.95	22.2
500°F / 259°C	24.2	133 100	6.65	16.5
5 72°F / 308°C	33.0	181 500	9.07	12.1

The flash percentages at 302°F (1SO"C), 392°F (200°C). and 572°F *(3WC)* are taken directly from US. Geological Survey, #726, p. 7; the other percentages are extrapolations. The percentage of flash is based on pressures of 50 psi and does not reflect multistage flashing, and, therefore, a potentially greater MW-capability per well. The MW/well data are based on converting 20 pounds of steam per hour to 1 kWh.

ature gradient is **5"F/100** ft according to the model.

A conclusion of Sapre and Schoeppel may also be used to describe Table ***5.*** "Initially as the temperature increases from **325°F** to about **350"F,** the cost of power decreases drastically. First, as the temperature of water at the plant inlet increases, the flow rate required to produce the same amount of power decreases. **As** shown in Figure **2,** for a particular plant design this decrease is very rapid until a temperature of around **360°F** is reached. Beyond this temperature (the decrease is still logarithmic) the rate of decrease is much smaller and hence it does not affect the flow rate in the same proportion. **Also,** with reduced water flow rate requirements, the number of production and injection wells is reduced proportionately."

The importance of temperature is illustrated by Bloomster (p. **2273)** somewhat differently. Where Sapre and Schoeppel have taken turbine inlet requirements and hypothesized temperature and flow rates to satisfy inlet conditions, Btoomster takes different temperatures and then shows what flow rates are required, assuming the same cost criteria, in his Figures **7** and **10.** Note that the flow rates are three to four times greater for temperatures of **149°C** than they are for **200°C.** If these data were shown for the same flow rate, the production cost for the lower-temperature resource would be three to four times greater (and most likely uneconomic).

Juul-Dam and Dunlap (p. **2315)** employ a computer modeling device based on a Monte Carlo simulation to estimate overall rate of return on a geothermal exploration budget large enough to assure a commercial discovery. The costs of all phases of development are included from reconnaissance and land acquisition through development drilling and plant construction. Probabilities have been assigned for the successful results for all stages of exploration, depth of production, temperature, and other factors affecting the economics of commercial geothermal power production. Because of computer programming complexities, the model assumes that only one target is explored at a time by one group of technicians. When the results are negative, another target is selected for exploration and the computer simulation is run again. There is a deficiency, therefore, in applying the simulation to real-world exploration activities because, in fact, a group exploring for geothermal energy can work on any number of targets simultaneously and therefore are not faced with the extremely long time lag that occurs in the method employed in the paper. Included in the Juul-Dam and Dunlap paper is a chart which shows a range of projected flow rates as a function of production depth. **As** pointed out by Sapre and Schoeppel, pressure will also influence the production rate.

Peterson (p. **2333)** discusses the rate of depletion of geothermal reservoirs as a factor which may be optimized when setting well production rates. At such time as the factors influencing production, such as temperature, pressure, and reservoir depth (see Juul-Dam and Dunlap; p. **2315,** Figures **4** and **5)** are better understood, the production optimization models described by Peterson will become extremely useful. Even without these data, his description of the discounted value of an income stream should be required reading for everyone associated with the regulation of geothermal energy, in order to impress upon them the costs incurred when production and the resulting generation of income is delayed.

Table **7** shows estimated capital costs for the construction

Table 7. Geothermal power plant costs ($/kW).*

Tvw	**Barr**	**Greider**
Vapordominated: dry	**127**	**210**
Liquiddominated: binary	**31 2**	**439**
Liquid-dominated: flash	**212**	**392**

‘Source: Barr, p. 2269; Creider, p. 2305

of geothermal power plants. From Table **1** it may be seen that capital costs are 2.74 mills/kWh at $l00/kW and **9.88** mills/kWh at $400/kW, assuming an **80%** operating rate. Banwell (p. 2257) shows historical costs ranging from 6.7 mills/kWh to 16.0 mills/kWh which are inclusive of both energy supply and plant construction costs. The costs are based on **19771** data and generally assume subsidized interest expense.

Sapre and Schoeppel (p. 2343) and Bloomster (p. 2273) also show estimated costs based on total costs. The Sapre and Schoeppel cost estimates are based on 1972 data and show a range of costs of 12.0 mills/kWh to 40.0 mills/kWh expressed as direct functions of temperature gradient and pressure. The Bloomster cost estimates are shown ranging from 14 mills/kWh to **38** mills/kWh. Both papers include an allowance for a fixed rate of return, but neither includes exploration costs.

The problem with combining energy supply and plant costs is twofold. First, total geothermal power generation costs are often compared with plant construction costs for conventional forms of power generation. Second, geothermal energy will be developed along the lines of conventional fuels, and the costs should be shown separately for exploration and field development and for plant construction. This will permit a comparative analysis of the economics of geothermal energy compared with oil, gas, coal, or nuclear power generation and serves to emphasize the risk element associated with exploration activities.

The separation of costs into field exploration and development and plant construction raises the question of establishing a value or price for geothermal energy. Some would say that geothermal energy is “free” because it flows from the earth, but on this basis oil is also “free.”

In a market economy the value of geothermal energy will be based on the price at which it can be sold. Price will be a matter of negotiation, and will take into consideration the amount of electricity which can be produced from a reservoir and the cost to the power producer to convert the geothermal energy to electricity. When considering what price should be paid for the geothermal energy. the utility will also consider alternative fuels such as oil, gas, coal, or nuclear energy.

Three approaches may be used to enter price negotiations which would establish the value for geothermal energy: (1) comparative Btu output at market prices to Btu's. (2) market cost for electricity, and (3) cost plus rate of return.

The comparative Btu output value may be established by estimating the quantity of an alternative energy source such as oil required to generate an equal amount of electricity. Table 8 illustrates this approach. The total revenues of $17 520 OOO assume a 100% operating rate. The per-mill value will remain the same at lower operating rates, but the total cost (income to geothermal supplier) will obviously be lower.

Having calculated the value of an alternative energy

Table 8.

Power plant size: 100 OOO kW 1.0 x lo5 kW
Time duration: one year = 8760
Maximum output: one year 8.76 x lo8 kWh
Btu oil for 1 kWh = 10 OOO Btu x 1.0 x lo4 Btu

Example of comparative Btu output value approach.

hours x 8.76 x l O 3 hours
Maximum Btu/year 8.76 x 10l2 Btu
Btu per bbl oil: 6.0 xIOb
Maximum bbl/year 1.46 x lO6 bbl
Price $12.00/bbl x 1.2 x 10/bbl
Maximum comparative cost per year 17.52 x lo6 $
kWh produced one year
Cost / kWh 2.0 x or
+ 6_.0 _x _lo6_ B_tu/~bbl _ _
- _8_.7_6 x_ ~10-' _k_W_h
20.0 mills/kWh

source. the quantity of either geothermal steam OJ hot water required to produce 1 kWh may be established and priced for delivery accordingly. For example, if 20 pounds of steam produces 1 kWh and the alternative cost is 20 mills, then the steam would be priced at 1.0 mill per pound, or perhaps more conveniently, $1.00 per thousand pounds (IO00 Ib). Similarly, if 200 pounds of hot water were required to produce 1 kWh, the value of the hot water would be $0.10 per thousand pounds. If only 100 pounds were required to produce I kWh, the value would be $0.20 per thousand pounds or twice the value of the hot water, assuming 200 pounds were required for 1 kWh. These conversion factors indicate hot water temperatures of 150°C compared to 180°C (Table 4b) and illustrate the importance of temperature on the economics of geothermal energy.

The market cost for electricity approach is based on the total cost for electricity for the next conventional plant in a particular service area. This is the approach used by Juul-Dam and Dunlap (p. 2315), based on a market price of 20.0 mills/kWh to calculate discounted cash flow after allowing for exploration costs and the cost of a plant. The approach may be termed the "ARCO" approach after their employer, The Atlantic Richfield Company. After converting the geothermal plant cost into mills/kWh, this amount is subtracted from the total cost of the conventional plant in mills/kWh to determine the mills/kWh rate used to evaluate the geothermal energy. Table 9 is an example of this approach. If 110 pounds of hot water per hour are required to produce 1 kWh, then the value of 110 pounds produced for 1 hour will be 14.94 mills/kWh. One thousand pounds produced for an hour will therefore have a value of W. l358/ IO00 Ib.

Should the resource in Table 9 be a vapor-dominated system rather than a hot-water system, the capital cost of the plant would be $200/kW or 4.94 mills/kWh (Table 1). Using the "ARCO" market cost approach, this amount gives

Table 9. Example of market cost for electricity approach.

Energy cost
Unit cost (rnills/kWh)
Capital cost for new coal-fired
Fuel cost for delivered coal $ **25/ton** + 10.00
Total cost conventional - **24.82**
Binary cycle geothermal plant $400/kW - **9.88**
Value geothermal hot water - **14.94**
unit **$600/kW 14.82**
Note: Conversion from unit **cost** to **mills/kWh from Tables** 1 **and 2**

a value of 19.88 mills/kWh (24.82 mills/kWh total cost-4.94 mills/kWh capital cost geothermal plant = 19.88 mills/kWh value of geothermal steam fuel). The per-mill valuation would then convert to $0.994/1000 Ib based on 20 pounds/hour for 1 kWh.

The rate-of-return approach would involve all costs incurred leading to a discovery of geothermal energy, the separation of development drilling and plant construction costs, and the addition of a profit for the geothermal energy supplier. Maslan, Gordon, and Deitch (p. 2325) state that geothermal energy can be economically developed and project that 190 000 MW to 250 000 MW of electrical capacity can be established by the year 2000 out of an estimated capacity at that time of 2 000 000 MW. By 1985, 7000 MW to 20 000 MW may be produced by using geothermal energy. Maslan, Gordon, and Deitch list and discuss eight major areas on which geothermal energy may have an impact: (I) electric utility fuel mix; (2) growth of supply businesses for geothermal expenditures ($95 billion by the year 2000); (3) meeting of overall electricity demand and marginal effects on other energy sources; (4) stimulation of a national electricity grid; (5) coordination of research, regulation, and other institutional considerations; (6) relocation of industrial activities to new regions and cities; (7) international energy markets; and (8) environmental issues and land use.

De Marchi (p. 2291) outlines the basis on which an understanding of the economics of geothermal energy can be used to help formulate national energy policies. This outline is then applied to a country with a pattern of high per-capita energy consumption and a negative balance of trade. There are three observations which immediately become apparent. First, any steps taken in the direction of independence will aim to reduce rather than to annul energy importation. Second, determining the form of energy imports to be reduced will take into account, or provide some means of maintaining, an energy base not subject to interruption by extra-national influences. Third, he points out that energy investments are capital intensive and that financial considerations which would be a drain on a country's near-term resources must be weighed against energy development over the **long** term. Energy conservation can be helpful in temporarily reducing energy imports, but in the **long** term increased energy must be made available in order to maintain the economic growth necessary to overcome trade imbalances while maintaining or improving existing standards of living.

De Marchi proceeds to describe a mathematical framework for extracting useful energy from geothermal waters. He concludes that actual utilization versus that hypothesized is dependent upon output rate of a single well, and that for purposes of utilization the potential number of wells become the base for an economic evaluation.

In order to determine the merits of a geothermal system a simple comparison can be made with the costs **of** other alternatives. The comparison would include an evaluation of the costs for the extraction of geothermal energy, the effects **on** the balance of payments, and a comparison with the capital requirement needs. **A** mathematical formula further demonstrates how these considerations would be evaluated. **A** financial consideration will require the analysis of raw material or “know-how” which must be imported.

COMMENTS

Geothermal energy is not an inexpensive alternative fuel for making electricity. The economics of geothermal energy are complex and dependent upon the geologic setting of the reservoir and the reservoir’s temperature. Vapor-dominated systems capable of supplying over 200 MW can be developed at relatively low costs and will therefore yield a higher-than-normal rate of return to the geothermal energy supplier. High-temperature liquid-dominated reservoirs may also be commercially developed **on** a basis profitable to the energy supplier. Even where a government is the geothermal energy supplier, it will need these higher temperature reservoirs to offset research and development expenditures.

The expanded utilization of geothermal energy requires a significantly higher rate of exploratory drilling. **As** the more desirable reservoirs are discovered, they will be put into production expeditiously by those charged with the responsibility of producing electricity. Only 5 out of the 13 utilities in the western United States have had geothermal wells drilled within their service areas. **In** each case they are progressing as rapidly as permitted under existing institutional constraints, such as obtaining permits to conduct exploration and evaluating hypothesized environmental impacts. Except in The Geysers’ area, where Pacific Gas and Electric Company is aggressively endeavoring to develop geothermal energy, the production history of the wells drilled to date is almost negligible. Not only do more wells need to be drilled, they must be allowed to flow. The evidence contained in the papers presented at the Second United Nations Geothermal Symposium point conclusively to the commercial feasibility of high-temperature geothermal reservoirs; and as operating histories are developed, commercialization of the resource at a more moderate temperature will occur.

The expertise and application of existing technology for the conversion of geothermal energy to electricity, developed in the United States and synthesized through international forums such as those sponsored by the United Nations, appear certain to assure development of geothermal energy **on** a scale equivalent to millions of barrels of oil per day.

Appendix I. Geothermal potential and daily world oil production.
Region Geothermal Daily Oil Region Geothermal Daily Oil
and Country Setting' Productiont and Country Setting' Productiont
Africa (North)
A l ger i a
Morocco
United Arab Republic
Sudan
Africa (Central)
Cameroon
Chad
Nigeria
Virunga volcances
Africa **(Easf)**
Ethiopia
Somali Republic
Kenya
Uganda
Rwanda
Congo (East)
Zambia
Mozambique
Rhodesia
Malagasy Republic
America (North)
Canada
Mexico
United States
Poland C
Romania C
Spain (S. coast Canary Islands) A, B
NL
NL
33 850
915 300
628
214 185
NL
NL
NL
1 711 253
NL
Far East
Australia
Burma
China (E. provinces)
China Sea (South)
Bengal (East)
India
Indonesia
Japan
New Guinea
Timor
413 510
23 000
?
?
NL
165 000
1 231 271
12 943
NL
NL
B
B
B, C

A
B, C
B
B
B
B
B
B
B
B
B, C
NL
NL
NL
NL
NL
37 523
NL
NL
NL
NL
Middle East
Afghanistan
Baluchistan
Pakistan
Persian Gulf
Iran
Israel
Jordan
Lebanon
Saudi Arabia
Syria
Tibetan Highlands
Turkey
Island Arcs.
(1) Pacific
Aleutians
Fuji-Bonin Zone
Halmahera
Japan (N. and W.)
Indonesia Sumatra-Java
Marianas
Kamchat ka
New Britain
New Hebrides
New Zealand
N. Celebes
Philippines
Ryuku Is.
Solomon Is.
Tonga Kermadec Is.
(2) Caribbean
Lesser Antilles
Puerto Rico
(3) E. Mediterranean
Aegean Islands
Greece
Northern Crete
150
NL
5 839
5 445 193
71 8
NL
NL
6 574 655
174 296
NL
59 933
II
1 209 170
680 766

8 201 000
America (Central)
Guatemala
El Salvador
Honduras
Nicaragua
Costa Rica
Panama
British Honduras
America (South)
Colombia
Venezuela
Trinidad, Tobago
Ecuador
Peru
Chile
Brazil (Andean)
Bolivia
Paraguay
Argentina
Galapagos Islands
Antarctica
South Shetlands
Graham Land
NL
NL
NL
NL
NL
NL
NL
A
A
A
A
A
A
A
A
A
A
A
A
A
A
A
NL
NL
NL
12 943
1 231 271
NL
NL
NL
NL
3 601
NL
NL
NL
NL
NL
166 398
2 529 659
210 526
137 704
76 590
25 014
173 865
38 414
NL
401 388
NL A
A

NL
NL
A
A
NL
NL
A
A
A
NL
NL#
NL
Europe
Austria
France
Germany (West)
Great Britain
Holland
Hungary
Italy
Mid-Atlantic Ridge
Iceland A
Jan Mayen A
Spitzbergen A
Russia ***(USSR)*** C
C
C
41 400
20 883
125 624
15 644$
26 388
NL
20 2175
NL
NL
NL
C
C
C
C
A, 8, C
8 500 000 est.
Note: **A,** acid volcanic association; B, high-temperature zones; C, high-pressure reservoirs; NL, none listed.
'Source: Banwell (p. 2257).
?Source: *Oil* and Gas journal, December 29, 1975.
$Excludes North Sea.
5Excludes offshore discovery.
llCountries not listed by Banwell; oil production significant.
#Excludes significant offshore discovery.

Amendix II. Western utilities financial analysis, latest 12-month r>eriod ($ **millions except** *).

STATE
PROSPECTUS MTE
UTILITY t
1. REVENUE
2. I N C W FOR C@HHON
3. DEPRECIATION
4. REFURTED CASH FLOW
5. AFDC (NON-CASH)
6. DIVIDENDS PAID COM.
7. NET CASH(4)-(5)+(6)
8. INC Po8 COH(Z)-AFDC(5)
ARIZ CAL CAL CAL COL IMHO MONT NEV N. HBX ORE ORE ORE UTAH
TG&E PG&E SDG&E SealEd PS Colo Id P Co MontPCo Sierra PS Nn Pac P&L Puget Port GE Utah E L
144.0 1103.0 289.0 1471.0 363.0 90.3 125.0 70.5 74.1 269.0 149.0 159.0 160.0
16.5 195.0 28.6 182.0 29.6 23.8 24.1 8.4 9.3 55.0 19.0 27.0 23.0
13.6
30.1
8.6
10.2
11.3
7.9
8/26/75 4/29/75 4/16/75 3/6/75 2/30/75 10124174 7/8/75 3/4/75 8/26/75 9/4/75 8/21/75 8/21/75 4/23/75

- 166.0 25.1 116.0 36.4 -8.5 -8.3 -6.4 -8.3 33.0 14.0 13.0 17.0
361.0 53.7 298.0 66.0 32.3 32.4 14.8 17.6 88.0 33.0 40.0 40.0

57.0 4.2 16.0 8.1 10.1 4.7 2.6 1.7 23.0 5.0 19.0 5.0
124.0 16.8 74.0 21.2 13.6 14.6 6.3 5.3 40.0 13.0 20.0 17.0
180.0 32.7 208.0 36.7 8.6 13.1 5.9 10.6 25.0 15.0 1.0 18.0
138.0 24.4 166.0 21.5 13.7 19.4 5.8 7.6 32.0 14.0 8.0 18.0

- -- -

- -- -

9. lONG TERM DEBT 169.0 2952.0 438.0 2094.0 574.0 336.0 254.0 130.0 144.0 828.0 351.0 402.0 396.0
10. PREFERRED EQUITY
11. CBlyRl EQUITY
12. "l!AL CAPIULIZATION

82.0 689.0 133.0 562.0 169.0 36.0 21.0 39.0 40.0 117.0 66.0 110.0 125.0 -175.0 2-002.0 - 281.0 -1424.0 353.0 194.0 236.0 77.0
102.0 558.0 186.0 283.0 290.0
428.0 5645.0 853.0 4081.0 1097.0 567.0 512.0 247.0 286.0 1496.0 604.0 796.0 812.0
13. ELEC GEN CAP (6 OLD MJ) 248 2846 417 2044 548 328 190 119 159 744 100 88 487
14. ELEC GEN CAP ElW OLD * 1116 13292 2141 12191 2538 1636 766 566 882 2659 592 661 1787
15. EG CAP ($COST/KW) (13) 5 (14) * 222 214 194 168 215 200 248 210 180 279 168 133 272
16- EG CAP (SNEWJKW) (18) + (17) * 518 360 809 726 355 689 428 600 708 782 491 668 654
17. ELEC GEN CAP ElW NEW * 685 5656 1727 5043 1680 1166 750 250 905 2595 2154 3126 2075
18. ELEC GEN CAP ($NEW HU) 355 2037 1398 3663 598 800 321 150 641 2031 1059 2089 1358
19. NEW EGP $(1a) AS % TO TOT CAP 82 X 36 % 163 % 89 2 54 2 141 % 62 9. 60 2 224 1; 135 % 175 Z 762 Z 167 %
20. YR-YRS FOR NEW ElW COMPLETION * '81-6 '81-6 '83-8 '82-7 '80-5 '81-6 '80-5 '80-5 '86-11 '85-10 '85-10 86-11 'W-9
21. COH STOCK PRICE 9/15/75 $ * 10.75 19.75 10.82 18.25 14.00 28.62 22.37 9.62 17.00 18.37 25.37 16.25 25.62
22. AVE COH SHR REPORTED (OOO)* !0,635 66,145 13,697 44,580 17,657 7,350 7,937 5,288 4,408 24,920 4,624 13,125 7,279
23. TOT COH SHR OUT (ooO)* 13,000 80,030 17,000 47,484 21,256 7,350 10,247 5,791 5,101 26,725 5,751 15,500 9,109
24.EPSAVESHRSREPORTED $ * 1.56 3.27 2.09 4.10 1.68 3.25 2.75 1.60 2.13 2.22 4.24 2.13 3.24
25. EPS TOT COH OUT $ * 1.26 2.43 1.68 3.83 1.39 3.25 2.35 1.45 1.82 2.05 3.30 1.74 2.52
26. DIV AVE SHR REPORTED $ * .90 1.88 1.20 1.68 1.20 1.86 1.80 .89 1.22 1.62 2.02 1.55 2.35
27. DIV RATE 9/15/75 $ * .96 1.88 1.20 1.68 1.20 2.06 1.80 .92 1.28 1.70 2.16 1.58 2.36
28. YIELD 9/15/75 ; $ * 8.9% 9.5% 11.09. 9.2% 8.5% 7.1% 8.0% 9.5% 7.52 9.24. 8.52 9.7% 9.2%
29. INCW-AFDClTUT SHR(8I 25) $ * .60 1.72 1.43 3.49 1.01 1.86 1.89 1.00 1.48 1.19 2.43 .51 1.97
30. BOOK VALUE: AVE SHRS 16.45 30.26 20.51 31.90 20.00 26.39 29.73 14.56 23.13 22.39 40.22 21.56 39.84
31. BOOK VALUE: TOTAL OUT !: 13.46 25.01 16.52 29.80 16.60 26.39 23.03 13.29 20.00 20.87 32.34 18.25 31.83
32. P-E AYE SHRS '21!5(22) * 6.8~ 6.0~ 5.1% 4.4~ 8.3~ 8.h 8.1~ 6.h 7.9~ 8.2~ 5.9~ 7.6~ 7.9~
33. P-E TOT COH OUT (21)?(23) * 8.5~ 8.1~ 6.4~ 4.7~ 10.7% 8.h 9.5~ 6.6~ 9.3~ 8.9~ 7.6% 9.3~ 10.1~
34. P-E/TOT SHR-AFDC(21)*(29) * 17.9~ 11.4% 7.5~ 5.2~ 13.8~ 15.3~ 11.8~ 19.6~ 11.4~ 12.4~ 10.4~ 31.8~ 13.0~
35. DIV CASH REQ'D 9/15 TOT SHR 12.4 150.0 20.4 79.7 25.5 15.1 18.4 5.3 6.5 45.4 12.4 24.4 21.4

Note: Utilities included are the following: TG&E, Tucson Gas & Electric Co.; PG&E, Pacific Gas and Electric Co; SDG&€, San Diego Gas and Eleclric Co.; SoCalEd, Southern California Edison Co.; PS Colo, Public Service Co. of Colorado; Id P Co, Idaho Power Co.; MontPCo, The Montana Power Co.; Sierra, Sierra Pacific Power Co.; PS NM, Public Service Company of New Mexico; Pac P&L, Pacific Power & Light Co.; Pugel, Pugel Sound Power & Light Co.; Port GE, Portland General Electric Co.; Utah P&L, Utah Power & Light Co.

Summary of Section XI I
Legal and Institutional Aspects

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INTRODUCTION

In general the papers in this section dealing with legal and institutional matters covered the more important aspects of the subjects. These papers will provide a reader with an excellent background. The history of geothermal law in New Zealand, Iceland, Japan, and the United States is presented and compared. Without doubt geothermal legal and institutional problems are universal in nature; however. some countries are more advanced than others in their solutions to the problems.

In addition. numerous peripheral problems are included, such as: water law, definition of the resource, geothermal rights, and preservation of unique geothermal hot springs areas. Some of the papers deal with economic and forecasting

models.
In summary, they are well worth reading and a few contain exciting concepts, which I have identified in this report.

DISCUSSION

Aidlin (p. 2351). a longtime advocate of geothermal development, has included in one paper the most pressing problems delaying the development of geothermal resources in the United States. In providing a background. he correctly observes that the challenges presented in the development of geothermal energy are universal in nature and that the regulation of their exploration and exploitation must be balanced. He continues by stating that although the federal government and most state governments consider geothermal resources as the natural heat of the earth, they fail to consider them as being unique; and as such, they should not be placed under existing law, as are oil, gas. water, and minerals.
Governmental agencies have been very slow in establishing criteria and accepting concepts applicable to geothermal resources. Possibly because of the recent emphasis placed on the protection of the environment, governmental agencies have been fearful of imaginary and exaggerated dangers that have caused the emplacement of restraints and conditions on development before the real nature of the resource had been ascertained. In addition, legislators and regulators have developed a mistrust of business and industry and have saddled them with laws and regulations that, instead of allowing development to take place, have imposed barriers and delays that are unnecessary and unreasonable.
Without doubt the most important point made-and to my recollection the first time it has appeared in such a well-thought-out and reasonable manner-is that environmental reports, statements, assessments, and ***so*** on are not intended to protect the environment but to guide governmental agencies in making decisions on the desirability of projects. An impact document is not required to identify environmental problems. but strong regulations are required to prevent the environment from being adversely impacted. [It is just possible that we have been moving in the wrong direction in the development of our environmental laws and regulations.]
There are some good signs: Imperial County in California (counties in California are very strong) has realistically approached the development of geothermal resources, and the benefits of this approach are now starting to bear fruit. In addition, some states have avoided until now the imposition of onerous regulations on developers, and hopefully when they do develop regulations they will be more realistic than those of their predecessors.
There is a lack of an integrated geothermal policy within the federal government. and the new Energy Research and Development Administration has yet to press the stated policy of encouraging the acceleration of geothermal exploration, development. and use. In concert with the lack of a policy is the lack of understanding by Congress and others of the numerous problems delaying development. The list of problems includes establishment of a tax policy to encourage development. the provision of a suitable loan

program, the amendment of the Geothermal Steam Act to correct the flaws which are related to leasing, the revision of legislation relating to proprietary rights, and a legislative provision for joint private and public projects.

His final pertinent comment is that we must find a way for developers and legislators to openly discuss new legislation prior to the hearings in committee; without this ability we have little hope for future relief.

The major geothermal legislation in the United States, with one exception, came after 1970. New Zealand's Geothermal Energy Act was passed in 1953. This 17-year difference has provided the New Zealand government with the regulatory background which enables them to speak from a position of authority.

Dench (p. 2359) starts with the New Zealand Geothermal Steam Act and its definition of geothermal resources, which separates high- and low-temperature reservoirs at 70°C. Sections are included on the ownership of the resource (the sole right to exploit the energy is vested in the Crown,

effectively the nation) and on well spacing. Persons desiring to drill below **61** m **(200** ft) deep need a license to do so. Rental rates (royalty rates) are discussed at length. An amendment to the Steam Act of **1953** effectively changed the bases for rental rates from the savings achieved by using geothermal energy rather than another source to the quantity of net heat used.

Geothermal safety (exploration and development regulations) became a reality with the acceptance of the Geothermal Energy Regulations in 1%1. The regulations are comprehensive and rightly point out that it is not feasible to promulgate detailed rules that will apply to all circumstances. Testing (the requirement for the driller to take rock samples at various depths and make temperature profiles) is also included.

New Zealand geothermal legislation has a unique feature: a single city, Rotorua, is empowered through the Rotorua City Geothermal Energy Empowering Act of **1%7** to act as the legal authority to control geothermal prospecting and utilization. The act was *so* extensive that the city, in most matters, acts in place of the central government.

This paper also contains a section on general legislation, which includes environmental control, water and air pollution, planning, and industrial safety.

Einarsson (p. **2363)** has succeeded in his paper in putting into perspective the geothermal development in Central America. He begins with an outline of the geography, geology, and indigenous energy potential of the various countries and continues with an energy growth rate chart that shows a steady growth in demand for energy.

A section is given over to an outline of the existing electrical energy supply of the entire six countries, including the generation mix, hydropower potential, breakdown of users, and the present costs of fossil fuels. This section is followed by specific outlines for each of the countries which bring out details such as the number of potential geothermal areas, the number of areas that are being developed, the number of power plants under construction and planned, the hydrogeneration potential, and the plans for hydrogeneration development. This section is followed by a section on economics which contains a comparison of the capital costs for geothermal, hydropower, and fossil-fuel power development.

The author concludes the paper with short sections on nonpower uses of geothermal energy and possible obstacles to the development of geothermal energy. In reference to the latter, he cites the shortage of experienced personnel for geothermal exploration and development as one of the most significant.

Eisenstat (p. **2369),** a tax attorney with a long-time interest in geothermal development, has in his paper treated what most observers believe to be the greatest problem delaying the development of geothermal energy in the United States. Without tax shelters, investment capital for both large and small operators (developers) will be difficult to raise, in particular in the case of the small operator.

As so many others have in the past, he makes the case that without tax incentives the geothermal industry will not be able to tap the private capital it needs for development. In order to gain an equal position, the tax incentives which are available to developers of all other sources of energy should be made available to geothermal developers.

In support of this position a discussion of the subject and itemized examples of intangible drilling and percentage depletion deductions are presented. The author continues with a legal history of the development of geothermal tax law, what there is of it, including the courts' definition of geothermal resources. Also included is a discussion of "tax planning" with examples of what could be provided to the potential investor to gain the maximum tax benefit.

Franzen (p. **2373)** deals with the complex problem of property rights applied to geothermal resources. The author provides the reader with an overview of some of the more important aspects, for example, certainty of rights o ~ n e r - ship, freedom to transfer that ownership, and external and internal development costs.

With this background the reader is led through **a** history of water rights from the English common law through to the correlative rights doctrine that was developed, and is presently in use, in California. Also included is a short discussion on the economic evaluation of underground-water law, its applicability to geothermal resources, and how it is affected by federal law.

The above is a prelude to the main discussion in this paper, the "common pool problem." To put this problem into perspective, a survey of oil and gas law is provided just prior to a section covering reservoir production characteristics for two geothermal fields.

A section on the solution to common pool problems follows, which includes discussions of single ownership, compulsory unitization, production quotas, and property rights restructuring,

The author concludes with some recommendations which include two significant ideas:

I. A geothermal system is more closely related to an organism than an oil or gas pool, and the owners or lessees should be viewed as trustees or guardians.

2. The heavy expenditures in time and money needed to build a geothermal plant, coupled with the fact that the plant must be built close to the wells, seems to require that a permanent type of title to the rights, as opposed to the title to oil and gas rights, be available to the developer.

Kamins (p. **2383)** reports that the Hawaiian Islands are almost totally dependent on imported energy. What local energy is produced comes from the burning of sugar-cane waste and small hydropower projects. As the world energy prices have risen, industry has been forced to curtail operations or has decided not to develop. Yet some of the islands have geothermal potential due to their volcanic origin and continued volcanic activity.

In the early **1970s** the Hawaiians embarked on a project to explore their geothermal resources. Concurrent with lab and field operations, a team was designated to develop a policy and a law that would allow the state to lease lands and regulate exploration and development operations.

The policy, subsequently backed up by law, placed geothermal resources under reservation on behalf of the Hawaiian government and includes consideration of dependence on imported fuel, decongestion of high-population centers, employment, environment, and state revenues. In addition several policy models were developed, ranging from minimal state intervention to government monopoly.

Kleeman, Haynes, and Freeland (p. **2389)** have developed a model to assess the economic impact of the development of geopressured resources in the Corpus Christi area of Texas. They also provide the reader with a brief but factual

background in the physical aspects of geopressured resources, including possible environmental problems that could arise during production, possible methane gas recovery, and power plant economics.

Lindsay (p. **2403)** in his paper has condensed California geothermal law dealing with the leasing of land and the regulation of exploration and development operations. He includes and clearly explains legal points and omissions in the different acts concerning state jurisdiction on wells drilled on federal lands, general leasing regulations, rental and royalty rates, prospecting permits, competitive bidding (as yet never held in California), and preferential rights of surface owners.

The author rightly concludes that the State government has provided a comprehensive legal framework for the development of geothermal resources within the state.

In **1%0** the first geothermal power plant went on line in the United States. The subsequent energy rise in the cost of foreign petroleum caused numerous estimates to be made of the total geothermal potential in this country.

The Futures Group-whom Maslan, Gordon, and Stover (p. **2409)** represent-specializes in predicting future trends and occurrences.

Their paper outlines the basic parameter that must be considered in making a suite of estimates for specific milestones in the future. The development of the scenarios, methodology, and the physical, social, and economic factors are included. The estimates include energy from vapor and liquid geothermal reservoirs, hot dry rock, geopressured zones, and magma.

Having spent the last five years working with the development of geothermal laws and regulations and not having much to show for it, I can sympathize with the problems facing the Japanese in their attempts to develop a legal foundation for the development **of** geothermal energy in Japan.

As described by Nakamura, Nakahara, and Iga (p. **2421),** existing Japanese law does not provide for the development of geothermal energy; that is. there are no specific geothermal rights, only a vague right to prospect. The term "geothermal" itself does not exist in Japanese law.

Present development **is** loosely based on a Hot Springs Law, and, where applicable, the Natural Park Law must be considered. These laws, while dealing with natural phenomena, do not address geothermal energy in the context of power generation.

To complicate the problem, most of the potential geothermal areas are found in national parks or on national lands and are subject to the restrictions of the National Property Law, the Forest and Field Law, the Pollution Control Law, and the Forestry Law, all of which deal with environmental protection. In addition, the Environmental Agency and the Ministry of International Trade and Industry have restricted the development of geothermal energy to six areas in the entire country.

Needless to say, geothermal legislation is needed and was in preparation at the time the Symposium was held. This proposed legislation is outlined and briefly discussed and includes sections on definitions, prospecting, geothermal rights, tax incentives (it is the policy of Japan to promote development), and applicable amendments to other laws.

Sakakura (p. **2431)** explains that Japan, being dependent on imported energy for over **70%** of its needs, was hard hit by the energy crisis. As a result the government has launched a long-term project to develop indigenous forms of energy. This project, hailed as "Project Sunshine," includes geothermal development supported by an everexpanding multimillion dollar budget.

The project as outlined for geothermal development has two major components: **(1)** Technological Development, which includes exploration, drilling, power generation, multipurpose use, and environmental protection; and **(2)** Research and Development, which includes extraction, hotwater utilization, development of methods to use actual volcanic heat, and multipurpose use.

According to Torfason (p. **2435)** the country of Iceland is no stranger to geothermal development. Their first law that dealt with geothermal energy was enacted in **1923,** but was overshadowed by the Right of Ownership and Use of Geothermal Resources Act of **1940.** The Act **of 1940** has since been incorporated into the Energy Act of **1968,** which is the basic legal authority for geothermal development in Iceland.

The Energy Act left the ownership of waters of the country under the domain of private ownership, but subjected their use for power development and other purposes to the interests of the state and neighboring landowners. However, it is still unclear at what depths or temperatures of the resource or exploitational capabilities of the landowner (geothermal rights owner) the Icelandic government becomes the owner of the resource. This arrangement has not resulted in any material hindrance of geothermal development.

Warren (p. **2439)** presents an overview of the geothermal laws in California, how they affect the development of this energy source and what the major problems are. He also gives a brief overview of a recently passed bill (the Warren-Alquist Act), its effects, pending legislation, the potential of geothermal resources in California, and the obstacles to development.

Wehlage (p. **2443)** presents a philosophical discussion of the development of geothermal resources and how society, caught in the wave of environmental protection, has imposed restrictions through its governmental representatives on its development. He also includes several other topics, including social problems, the nature **of** geothermal energy, and the impact of its development.

Weinstein, Gordon, and Maslan (p. **2447)** have provided a brief but informative discussion of geothermal law in the United States. They have outlined the history of federal law that has either dealt directly with or used to deal with geothermal energy, starting with the General Mining Act of **1872** and ending with the Energy Research Development and Demonstration Act of **1974.** The outline includes discussions **on** important factors of the law and how it affects water law, land leasing, competitive bidding, conversion rights, rents, royalties and lease terms, size of leases, land-use aspects, drilling agreements, and exploration rights. The paper also includes a section on state leasing laws, overlapping regulatory jurisdictions, and tax treatment.

Wilson (p. 2457) discusses a subject that most geothermal developers would rather let lie: the effects of geothermal development on surface phenomena, that is, geysers, hot springs, hot pools, and so on. However, his basic concern is not to stop geothermal development but to protect those unique areas in the world, and in particular the one in New Zealand, that he considers as “World Hot-Spring Regions.” Included within the paper is a definition of a hot-springs

region, and descriptions of five areas in the world that fit the definition.

The five areas are located in the following countries: United States (Yellowstone Park), Iceland, Russia (Kamchatka), northern Chile, and New Zealand; the last of these is the most vulnerable to geothermal development. The tourism. development of power generation facilities at Wairakei has already eliminated a splendid geyser.

The author has proposed that a national park be created in the hot-springs region and supports this stance by providing an economic analysis of the income from the power generation plant at Wairakei versus an adjusted income from

SECTION I

Present Status of World Geothermal Development

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ABSTRACT

Recent changes in the world energy situation are reviewed together with their effect on the course of development in the field of geothermal energy. An overview is given of the geothermal installations existing in various parts of the world categorized under the characteristics of the geothermal heat sources.

The paper surveys the status of new projects which are in the planning, exploration, or exploitation phases in different countries. In all, upwards of **50** countries have either commenced or are displaying interest in geothermal development in their territories. In many of these countries which lack significant deposits of fossil fuels, the use of geothermal energy as an alternative energy source is particularly attractive because of the opportunity it offers for making considerable savings in the foreign exchange required for the importation of fuel.

The present rapid rate of development of geothermal energy resources has been accompanied by difficulties associated with shortages of both equipment and suitable expertise.

INTRODUCTION

Although the use of geothermal hot water for balneological purposes has been known for hundreds of years, the utilization of geothermal energy for the production of electricity and the supply of domestic and industrial heat dates only from the early years of the twentieth century. For 50 years the generation of electricity from geothermal energy was confined to Italy and interest in this new and specialized technology was slow to spread elsewhere. In **1943** the use of geothermal hot water for space heating was pioneered in Iceland although it was not until **1%9** that electricity was first produced from geothermal steam in that country. During the decade following 1950, intensive exploration work was undertaken in New Zealand, Japan, and the United States, which led to the commissioning of geothermal power stations in **1958, 1961,** and **1960,** respectively. Thus, prior to 1950 there was comparatively little global activity in geothermal energy and despite the excellent prospects existing in many developing countries they were for the most part unaware of their potential in this field.

The decade to **1970** was marked by a greater realization of the benefits of geothermal energy, particularly following the United Nations Conference on New Sources of Energy which was held in **1961.** This meeting, attended by representatives of many developing countries helped to publicize the possibilities of utilizing geothermal energy as an indigenous means of producing electricity. From **1964,** rising interest in geothermal development was characterized by the starting of many preliminary investigation projects, particularly in developing countries. These formed the basis of many reports and scientific papers submitted to the United Nations First Symposium on the Development and Utilization of Geothermal Resources held in Pisa in **1970.** The exchange of information and experience at this meeting provided a further impetus to the development of geothermal energy on a global basis.

A growing interest in the development of geothermal energy was the result of its demonstrated economic advantages over the utilization of fossil fuel alternatives. Geothermal power stations were seen to be more economical in small sizes and less capital-intensive than conventional plants and this was of particular interest to many developing countries having small electricity systems and many competing demands for their limited capital resources.

RECENT CHANGES IN ENERGY SITUATION

At the end of **1973** events took place which had a dramatic impact on the global energy scene. The restriction of oil supplies and quintupling of world oil prices abruptly changed the economic base which had hitherto governed the international energy economy. These conditions caused consequences of such magnitude that energy problems have since become a major concern both of governments and the international community.

It has been estimated by the International Bank for Reconstruction and Development that in **1973** developing countries spent **$5.3** billion in foreign exchange for imported fuel oil, or 8% of the value of all imports. For the year **1974** these figures had risen to **$14.9** billion and *20%*. Over the same period, the cost of oil imports to developed economies rose from approximately **$37** billion to $99 billion.

In the light of this situation, strenuous efforts are being made throughout the world to develop those indigenous energy resources which will substitute for imported oil supplies. Geothermal energy is one such resource which in suitable locations now offers even more attractive economic possibilities for replacing oil in the generation of electricity and the supply of heat.

In many developing countries, electricity systems are still too small to support nuclear power stations large enough to be economical and this alternative cannot, therefore, be pursued. However, the exploitation of geothermal energy in those small developing countries situated in volcanic

regions may assume greater relative importance than in larger and more developed nations. In addition, the comparatively small size of geothermal power stations is better suited to the present scale of electricity supply systems in most developing countries. For the foregoing reasons, the exploitation of geothermal energy in suitable developing regions of the world is likely to assume increasing importance. At the present time, as will be seen from the following survey, the utilization of geothermal resources is taking place mainly in developed countries. However, it can be anticipated that, under the stimulus of current conditions in the international energy field, the transfer of appropriate technology and experience to developing countries will proceed on an urgent basis and will result in rapid progress.

The exploitation of geothermal energy can be reviewed by subdividing it in accordance with the basic characteristics of the heat source. Thus, the following status review of geothermal energy resources can be conveniently considered by placing them into the categories of: **(1)** dry steam fields;

(2) wet steam fields; and (3) hot water fields.

DRY STEAM FIELDS

Although dry steam fields appear to be much less common than wet steam fields, they account for the greater part of the electricity now being produced geothermally.

Italy

The use of dry steam for electricity production was pioneered at the Larderello geothermal field and development in Italy had resulted in an installed generating capacity of 384 MW, as reported at the Pisa Symposium in 1970. The use of large quantities of geothermal steam over a period of many years, particularly in the boraciferous region near Larderello, has necessitated a continuous well drilling program to maintain the output from existing power stations. In view of the difficulties encountered in increasing steam supply from the Larderello and Monte Amiata areas, considerable attention is being given to enhancing electricity production by replacing atmospheric turbines with condensing units. These will have lower specific steam consumptions and allow more electricity to be generated from the available steam. As part of this program, a new 15 MW condensing turbogenerator was added to the Serrazzano power station at Larderello during March 1975. Any substantial rise in the use of geothermal energy in Italy must depend upon the discovery of new fields and, to this end, the State Electrical Power Board and National Research Council are participating in joint efforts to explore promising areas (Leardini, 1974).

During the course of such an exploratory program at Travale, 20 km southeast of Larderello, a well was drilled in 1972 having aproductioncapacity of 15 MW. In 18 months, this well was coupled to a 15 MW atmospheric turbine and has operated continuously as a remote-controlled base load power station.

In 1973 a new discovery of steam was made near Mt. Volsini, ***50*** km southeast of Monte Amiata, and deep drilling **is** proceeding with a view to the installation of a 15 MW turbogenerator similar to that installed at Travale.

The drilling of five wells at Alfina, **110** km north of Rome, has established the presence of a water-dominated field, and a water-steam separation plant is now under construction. Further exploration will begin shortly in the pre-Appenine belt lying between Larderello and Naples and it is expected that at least **10** wells will be drilled annually for the next five years (Tongiorgi, 1974, personal commun.).

The total installed capacity of geothermal generating plants in Italy now stands at 420.6 MW.

Japan

Japan has considerable geothermal resources which, while consisting mainly of wet steam, include an important dry steam field at Matsukawa. Japan's first geothermal power station was commissioned at this location in 1%6 with a capacity of 22 MW. After overcoming various problems it is now operating successfully as is evidenced by its 1973 generation load factor of 94%. Plans have been made to extend the capacity at Matsukawa to **90** MW.

During the course of a recent survey the Electric Power Development Company of Tohoku located a dry steam field at Onikobe on the island of Honshu. Production at this field is being obtained from 10 wells at a depth of only 300 m and work is under way on a power station installation of 25 MW capacity which should be in service during 1975.

USA

The only dry steam development in the United States at present is The Geysers field in California and this is being rapidly exploited. The speed of development can be gauged from the installed generating capacity which was reported to the Pisa Symposium in 1970 as 78 MW and now stands at 500 MW, making it the largest geothermal power plant in the world. The rapidity with which plant capacity has been increased is due to a considerable extent to the use of the largest sizes of geothermal turbogenerators to be found anywhere. Six have been installed with capacities of 53 MW while the latest unit commissioned in January 1975 has a capacity of 103 MW (Worthington, 1975, these Proceedings). Rapid progress has also been assisted by gearing development to the reservoir study results which have been accepted, thereby avoiding the empirical well testing previously carried out over long periods.

Present plans envisage the installation of a further 406 MW of generating plant by 1978, bringing the total to over 900 MW. Since The Geysers plant is linked to a large interconnected electricity network, there will be no difficulty in operating it at a high load factor. This will result in the maximum savings from displacing the output of power stations burning expensive fuel oil.

WET STEAM FIELDS

Wet steam fields occur more frequently than dry steam fields and although hitherto they have been less important for the production of electricity, it is anticipated that the current upsurge in geothermal development on aglobal scale will discover many such fields and thereby increase their relative importance.

Japan

Japanese experience with the production of electricity from wet geothermal steam dates from 1%7 with the com

missioning of the Otake power station in Kyushu. Geological conditions throughout the country are particularly favorable for the occurrence of geothermal energy resources, and the impact of the present world energy situation has provided a strong developmental stimulus to further exploration.

The 13 MW Otake power station was followed by a 10 MW installation in 1973 at Onuma which supplies electricity for the use of the Akita factories of the Mitsubishi Company. Kyushu Electric Power Company has begun an exploration project at Hatchobaru near the existing Otake power station. Wet steam has been found at a depth of lo00 m and seven wells are in production. A geothermal power station of 50 MW capacity is under construction and is expected to be in service during 1976. Present indications are that this field will be able to support a generating plant totaling 200 MW.

Further development has been indicated at Katsukonda which is situated between Matsukawa and Onikobe. Exploration has been successful and the 50 MW power station which is in the course of construction will be commissioned during 1977. It is expected that this field will eventually

be capable of supporting a 200 MW installation.
It must be added that considerable attention is being focused at present in Japan on environmental quality and the development of geothermal energy is consequently taking place against a background of environmental constraints.

New Zealand

Following the successful development of the geothermal resources at Wairakei and Kawerau, exploration was extended to other areas of New Zealand. Of these, the most promising was found to be situated at Broadlands where maximum temperatures of up to 295°C were found, together with high well yields. The development of this geothermal field for electricity production was delayed by the discovery of a large natural gas field which was utilized in preference to geothermal steam. Under the changed conditions which have prevailed in the overall energy field during the recent past, priority has now been given to the development of Broadlands up to a capacity of 120 MW (Bolton, 1975, these Proceedings).

Mexico

Geothermal exploration commenced during **1%0** in the Cerro Prieto region of northern Mexico. Production wells were subsequently drilled to an average depth of 1300 m and each produces the equivalent of 5 MW of power.
Following the successful testing of the field, two 37.5 MW steam turbogenerators were installed in March 1973. Although some degree of calcification has been experienced with the production wells, this has not been excessive and operating experience with this installation has been good.
Work is now proceeding on the drilling of further wells designed to double the size of the power station. During the course of this drilling program steam has been located at a depth of 2000 m at a temperature of 344°C. It has been estimated that the area at present being exploited by producing wells is capable of supplying up to an ultimate capacity of 400 MW.

Iceland

Present conditions in the international energy field have focused renewed attention on geothermal exploration and a new steam field has been located at Svartsenti in southwestern Iceland as a result of an exploration project which started in **1W2.**
In the northeastern part of Iceland at Krafla, a steam field has been evaluated from the results obtained by drilling exploration wells. As a result of these preliminary tests it has been decided to commence drilling production wells during the summer of 1975 with a view to the construction of a power station consisting of two 30 MW generators.
Although the detailed timing of this development must necessarily depend upon the results obtained with the production drilling, it is hoped that it will be possible to commission the new plant during 1977 (Palmason, 1975, these Proceedings).

Chile

Geothermal exploration in Chile began in 1967 under the aegis of a United Nations technical assistance project and reconnaissance surveys were carried out in the three areas of El Tatio, Puchuldiza, and Polloquere. As a result of this reconnaissance, detailed geological, geochemical, and geophysical exploration surveys were undertaken in Puchuldiza and El Tatio. Following this work the El Tatio area was selected for exploration drilling, and from 1970 to 1972 six 4411. diameter wells were completed to 600 m. The highest temperature encountered was 240°C and the maximum steam production was equivalent to approximately 1 MW per well.

This slim hole exploration program was followed in 1973 by the drilling of seven 8-in. production wells to a maximum depth of 1800 m. These wells encountered permeability problems and although two produced steam equivalent to 7 MW each, the performance of the others was disappointing.

At the end of 1974 exploration was resumed at Puchuldiza and geological, geochemical, and geophysical surveys are now in the course of completion. It is anticipated that following these surveys, drill sites will be selected and two exploration holes will be drilled during 1975.

During 1974 afeasibility study was commissioned, directed toward the construction of a 15 MW power station to utilize the steam which is at present available. It is hoped that further drilling will enable the plant capacity to be increased to 20 MW. In view of the need for potable water in Chile, arrangements were made with the government of the United Kingdom to finance a pilot desalination plant which was connected to one of the small exploration drill holes. This plant is being used to evaluate the possibility of corrosion and scaling problems arising in large-scale desalination plants based on geothermal hot water (Lahsen, 1975, these Proceedings).

The government of Chile has set up a National Geothermal Enterprise to be responsible for controlling the production and commercial aspects of geothermal energy development.

El Salvador

A geothermal survey was started in El Salvador in 1965 under a United Nations technical assistance project. In 1969, work was concentrated on the Ahuachapan geothermal field where the highest temperature located was 237°C. In this phase of the project five wells were drilled which proved to have sufficient steam for a 30 MW power station.

Water disposal posed a problem at this site since use

could not be made of the Paz River because of the quantity of effluent envisaged for a large-scale development of the field and the downstream use of the river for crop irrigation. Considerable attention was therefore given to the question of reinjecting well effluent into the reservoir and a suitable reinjection system was constructed and successfully tested in December 1970 to take the full output of one of the production wells. Continuous reinjection at a rate of 91 I/sec was carried out for almost six months during 1971 without noticeable silica deposition inside the well or interference with the temperature of producing wells located only 400 m away.

A reservoir study carried out in 1971 estimated the Ahuachapan reservoir at 40 km3 with a minimum energy reserve of 5000 MW years based on single stage flashing. As a result of this evaluation it was recommended that the field be initially developed in three stages of 30 MW each. It was also considered feasible, on the basis of the field tests, to reinject into the local reservoir at 150°C. In 1971 a power station feasibility study was prepared and recommended the initial installation of a 30 MW geothermal power plant. The first machine will be commissioned during June 1975, and the government of El Salvador is planning to install a second 30 MW unit during February 1976, followed by a third in 1979 (Valiente, 1975, these Proceedings).

Turkey

In 1967 a geothermal exploration project was commenced in Turkey under the United Nations Technical Assistance program. Initial scientific surveys carried out under this project identified nine geothermal prospects in Western Anatolia. During the course of more detailed investigations a deep borehole drilled in 1968 revealed the existence of a wet steam field at Kizildere. Twelve other wells were subsequently drilled in this area between 1968 and 1971, directed toward the evaluation and development of the field. Of these wells, eight were suitable for production and the highest temperature encountered was 206°C. Unfortunately, the flashing of the hot water during its passage up the well bore released carbon dioxide causing calcium carbonate to deposit as scale in the well and in the surface equipment. The rate of scaling was so rapid as to restrict steam flow over a short period of time and prevent economical operation of the wells for power production. In view of the importance of this problem, special tests were carried out with a view to the establishment of some practical operating regime which would allow the field to be used for power production. The best suggestion was directed toward keeping the geothermal fluid in a liquid phase by pumping it out of the well at a pressure high enough to avoid flashing. However, this solution would have required the use of deep-well pumps operating at a depth of 400 m. Since this was beyond the scope of current experience, the idea has been abandoned until such time as future progress in this field improves its feasibility. Although it has not been possible to proceed with the development of the Kizildere field for the large-scale production of electricity, a pilot greenhouse scheme was started in October 1972. Under this project a lo00 m2 plastic greenhouse was erected close to one of the production wells and heated by air blown through a radiator through which borehole water was circulated under pressure to prevent scaling .

More recently, geothermal exploration work has been carried out in Turkey close to the city of Afyon. A short distance from the city, wells drilled into the Omerli hot springs have located water at 100°C. In view of the possibilities of using this hot water to supply heat to the city of Afyon, a deep drilling program was commenced during 1974. The first well drilled under this program resulted in the production of 20 I/sec of water at 100°C.

HOT WATER FIELDS

It has been established that some parts of the world contain considerable deposits of hot water which form large reservoirs of low-grade heat. Although in many cases this heat cannot be used economically for the direct production of electricity, it can be a cheap source of space heating where climatic conditions enable it to be used at sufficiently high load factors. It is becoming increasingly recognized that the use of geothermal water for space heating is to be preferred to the burning of a highly refined petroleum product at 1000°C in a power station boiler if the end-product is to be air at 21°C.

In view of the climatic conditions needed for the development of space heating, the exploitation of geothermal hot waters has so far been concentrated in Iceland, Japan, USSR, Europe, and the USA.

Iceland has a long history of utilizing geothermal hot water for space heating and this interest has been maintained during the course of the last five years. Space heating for the city of Reykjavik is now supplied completely from geothermal sources. In addition, the hot water supply system is at present being extended to three communities totaling 75 000 people in the vicinity at Raykjavik and it is anticipated that this work will be completed within the next two or three years.

In addition to a history of the balneological use of geothermal hot water extending over hundreds of years, Japan has used this heat source widely for hothouses, fish farming, and animal raising.

It has been estimated that hot water may be found in over 20% of the area of USSR territory. Considerable development of this resource has already taken place and geothermal hot water is being used to supply district heating, domestic hot water, greenhouses, and animal husbandry installations. In addition, the use of the binary cycle for the production of electricity from hot water was pioneered by the USSR with the commissioningof the Pauzhetka power station in 1%7.

The considerable deposits of hot water in the sedimentary Hungarian basin have been utilized for many years for district and industrial heating schemes as well as hothouses and animal rearing.

In some instances hot geothermal water has been located as a result of drilling oil exploration wells; examples are Romania, Czechoslovakia, and the Paris basin. In Romania, geothermal hot water is being used on a pilot basis for greenhouses and the methane obtained from the water is being utilized to supply peak heating demands. In Czechoslovakia, geothermal hot water is supplying a pilot greenhouse installation and the United Nations has given advice on proposals for using geothermal heat in district heating. This proposal is of particular interest in that it involves

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an examination of the feasibility of feeding geothermal hot water into the existing district heating scheme of Bratislava.

In the United States a small geothermal district heating scheme has been in operation for many years at Klamath Falls, Oregon. At Boise, Idaho, a detailed study is now in progress on the feasibility of supplying geothermal heat to the State Capital Building and several large office buildings.

OTHER EXPLORATION PROJECTS

Ethiopia

During **1970** a geothermal exploration project commenced in Ethiopia under the United Nations Technical Assistance program. The first phase of this project was directed toward identifying hydrothermal areas in the Ethiopian Rift system and assessing their relative technical prospects for detailed exploration and subsequent development. During the course of the survey many gas and water samples were collected and analyzed and the results were presented in the form of a technical report.

As a result of this survey, areas of special geothermal promise were identified in the Lakes District, the Awash Valley and the Northern Danakil Depression. The second phase of this project initiated in October **1974** has been formulated to contain proposals for geotechnical studies in the Lakes District leading to the selection of drilling sites and the drilling of production wells sufficient to supply a pilot power station with a capacity of up to **10** MW.

Since the Lakes District is comparatively close to Addis Ababa there will be no difficulty in absorbing the output from such a geothermal power station in the Addis electricity network. Concurrently, with the carrying out of detailed geophysical and geochemical investigations in the Lakes District, an economic feasibility study will be undertaken to assess the possible economic impact of developing geothermal energy in the other two regions. The cost benefit analysis obtained from this study will be of considerable assistance to the government in deciding on the priorities for subsequent geothermal development work.

India

Since **1973,** geothermal investigations have been carried out in India at Puga Valley, Ladakh. As a result of this work steam and hot water at temperatures up to 130°C were found in some shallow wells from **30** to **90** m deep.

To utilize this geothermal fluid and also obtain valuable operating experience, the government plans to install a **1** MW pilot geothermal power plant in the near future.

The United Nations will carry out a technical assistance project in geothermal resource exploration for the government of India, and an international staff is being recruited.

In this project, further investigative work will be undertaken in the trans-Himalayan region as well as in the area of west India to the south of Bombay.

Indonesia

Since the Pisa Symposium, the compilation of an inventory of geothermal areas has been continued by the Geological Survey of Indonesia with technical assistance from New Zealand. As part of this program, six exploratory holes were drilled during **1972** at Dieng in central Java. In March **1974** the Indonesian State Oil Company (Pertamina) accelerated surveys in Java and Bali and these have now been completed in West Java at Banten, Kamojang, and Derajat.

At the end of **1974,** deep drilling was commenced at Kamojang and two wells were successfully completed. On the basis of the results achieved at Kamojang plans have been made for the construction of a power station having a capacity of at least 30 MW. The deep drilling program is at present being extended to cover a more detailed investigation of the Derajat and Dieng areas (Akil, **1975,** these Proceedings).

Kenya

A program of geothermal exploration was commenced in Kenya during **1970** as a United Nations technical assistance project. After preliminary exploration tests, a production drilling program started at the end of **1973** and continued for over a year. Of the four wells drilled in this phase, the first did not produce but the second had an initial flow equivalent to approximately 6 MW. The output from the remaining two wells was low, in the range of I to 2 MW, and the general indications are that permeability may present a problem at this location.

The present position is that testing is being carried out on wells 2, **3,** and **4** with a view to obtaining detailed information on reservoir behavior. The government of Kenya has bought a drilling rig and intends to continue a reservoir assessment program.

The present high cost of generating electricity from oil-fired power stations in Kenya has improved the competitive position of geothermal energy and it is anticipated that a geothermal power station would be economical even with comparatively modest well outputs. However, a firm decision on the advisability of building a power station is now awaiting the results of the reservoir evaluation.

Philippines

Exploration projects have been carried out by the Union Oil Company of America in the Tiwi and Los Banos areas of Luzon. Both projects have been successful in locating steam, and production wells are being drilled. On the basis of results achieved to date the government has placed firm orders for the supply of four 50 MW turbogenerators which will be commissioned in two separate power stations during **1977.**

Concurrently with developments in Luzon the government of New Zealand is providing assistance with geothermal exploration at Leyte. Present indications are that it may be possible to generate up to **100** MW from this geothermal area.

INDUSTRIAL USE OF GEOTHERMAL STEAM

At present, geothermal steam is being used for industrial processes in two countries-Iceland, which possesses a diatomite drying plant, and New Zealand, where geothermal steam is used for a wood pulping mill, several small industries, and a hotel air conditioning system. Despite the present conditions in the energy field occasioned by fuel oil price rises, there does not seem to be any pronounced upsurge

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in interest for the industrial use of geothermal steam.

Although geothermal steam and hot water are obtainable in abundant quantities, they cannot be transmitted over long distances and must therefore be used relatively close to the well head. Since industrial processes also need raw materials, their development in geothermal areas must depend upon the geographical coincidence of raw material and heat sources. In addition, the proximity of a market for the final product is also of considerable importance.

These locational restrictions explain why geothermal steam has not been more widely used for industrial processes up to the present time.

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