2. "Combination of Modes and Spatial Components in Seismic Response Analysis," *Regulatory Guide 1.92*, United States Atomic Energy Commission (presently United States Nuclear Regulatory Commission), Dec., 1974.
3. "Damping Values for Seismic Design of Nuclear Power Plants," *Regulatory Guide 1.61*, United States Atomic Energy Commission (presently United States Nuclear Regulatory Commission), Oct., 1973.
4. International Conference of Building Officials, *Report No. 2350*, ICBO, Whittier, Calif., June, 1970.
5. International Conference of Building Officials, *Report No. 1372*, ICBO, Whittier, Calif., Dec., 1971.
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JOURNAL OF
THE POWER DIVISION

STATE-OF-THE-ART OF GEOTHERMAL RESERVOIR ENGINEERING

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INTRODUCTION

The history of geothermal reservoir engineering goes back to the beginnings of petroleum and gas reservoir engineering. Although reservoir evaluation undoubtedly first began with Drake's oil well in 1859, it is only during the last quarter of the century—since December, 1949, to be exact, when the *Journal of Petroleum Technology* was born with van Everdingen and Hurst's classic paper entitled, "The Application of the Laplace Transformation to Flow Problems in Reservoirs"—that the science of reservoir engineering has developed. Twenty-five years ago, a conformance of 50%-70% was the best that could be accomplished in matching actual reservoir behavior and calculated prediction. Today, a conformance exceeding 90% is commonplace in the petroleum industry.

The art of geothermal reservoir engineering can thus equivalently be placed somewhere before 1949. There are definite reasons why this state-of-the-art is relatively undeveloped:

1. Geothermal energy exploitation is in its infancy. Remember that almost a century elapsed before the science of petroleum reservoir engineering began to show progress. Although the first geothermal well began producing 70 yr ago, it is only during the past 15 yr that active evaluative efforts have been attempted.
2. There has been minimal interchange of ideas and methods, a carryover from the general secrecy practiced by the petroleum industry.
3. Geothermal reservoirs are complicated by the parameter temperature. Although petroleum can have at least three different substances to contend

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Note.—Discussion open until December 1, 1975. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Power Division, Proceedings of the American Society of Civil Engineers, Vol. 101, No. PO1, July, 1975. Manuscript was submitted for review for possible publication on January 21, 1975.

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with—gas, petroleum, and water—the dominant factor in geothermal wells, temperature, alters the situation significantly enough so as to change the rules of the game. Hardware problems are encountered at high temperatures, and software packages must incorporate temperature and its effects.

The "state-of-the-art" in geothermal reservoir engineering is for the most part still in the formative stages. Four groups in particular, though, have contributed much: (1) New Zealand, (2) the Bureau of Reclamation, (3) the U.S. Geological Survey, and (4) Stanford University. Also available are some individual investigations, as for example, Whiting's reservoir engineering study of Wairakei (personal communication).

The primary reason the literature is relatively sparse is that private companies treat geothermal well testing, the data, and methods of analysis as proprietary. Certain legal restrictions tend to preserve this form of classification. Fortunately, there appears to be an increasing international spirit of cooperation. The United Nations has done a remarkable job in attempting to unite the world.

The following report is based on a comprehensive survey involving some preliminary analysis, a thorough literature search, personal discussions with leaders in the field, and the results of responses to an international questionnaire. The report will be in six parts: (1) The nature of a geothermal reservoir; (2) geothermal reservoir engineering—hardware; (3) geothermal reservoir engineering—measurement and methods of analysis, (4) the international questionnaire; (5) what is a geothermal reservoir engineer? and (6) geothermal reservoir engineering: research plan for the Hawaii Geothermal Project.

NATURE OF GEOTHERMAL RESERVOIR

Speculations on the nature of geothermal reservoirs can be found in the literature. In the United States, the U.S. Geological Survey legally defines a geothermal reservoir as contained in either a Known Geothermal Resource Area (KGRA) or a Potential Geothermal Resource Area (PGRA). Geothermal reservoirs can be characterized in several other ways: (1) Depletable (self-sealed) or regenerative (recharged); (2) physical state—vapor-steam, liquid-hot-water (normally two-phased at wellhead), solid-hot rock, liquid magma; (3) physical condition—temperature/pressure, size/depth, production rate; and (4) degree of dissolved solid content.

In California, vapor dominated wells are considered to be depletable. A tax allowance is permitted under this classification, but a decision has not yet been made on other types of wells. There is reason to believe that all wells are at least partially regenerative because of the meteoric (rainwater) origin of geothermal fluids (19). Furthermore, reports of measurable pressure drops in steam-dominated geothermal fields seen after rainfall indicate that perhaps fluid recharge could be significant.

Although vapor-dominated geothermal wells are generally contaminated with CO_2 (primarily) and H_2S, there is little dissolved solid content. However, some of the hot-water well samples in the Imperial Valley have shown as much as 30% dissolved solids by weight.

There seems to be no universal definition of a geothermal reservoir. A geothermal reservoir generally requires: (1) A heat source (magma or geopressure); (2) confinement in an aquifer, although nonpermeable hot rocks can be transformed into an aquifer through hydrofacturing/thermal cracking and the addition of water; and (3) caprock to hold the hot fluid in place, although this last requirement is controversial. Speculations on geothermal reservoirs have been advanced by White and Muffler (19) in the United States, Facca (6) in Italy, Elder (5) in New Zealand, and Hayashida (10) in Japan.

For the Island of Hawaii, it is generally believed that the system is self-sealed and liquid-dominated. Figs. 1 and 2 are conceptualizations of the expected system for Hawaii. Fig. 1 (not drawn to scale) is a macroview of the total underground system and Fig. 2 is a possible self-sealed system. Note that magma is generated at the crust-mantle interface. There is belief that for the Hawaiian Islands magma production could be as close as 20 miles from the earth's surface (15,21).

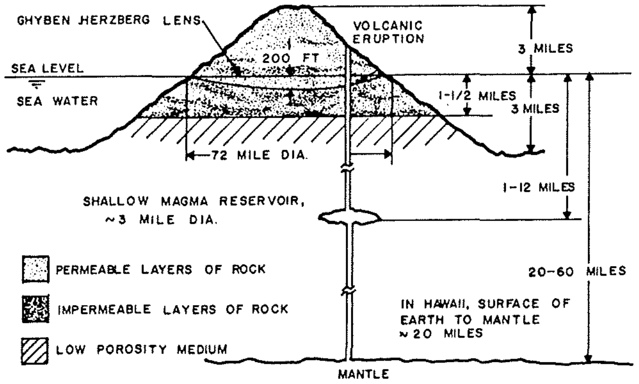

FIG. 1.—Speculative Cross-Sectional View of Island of Hawaii (1 mile = 1.61 km)

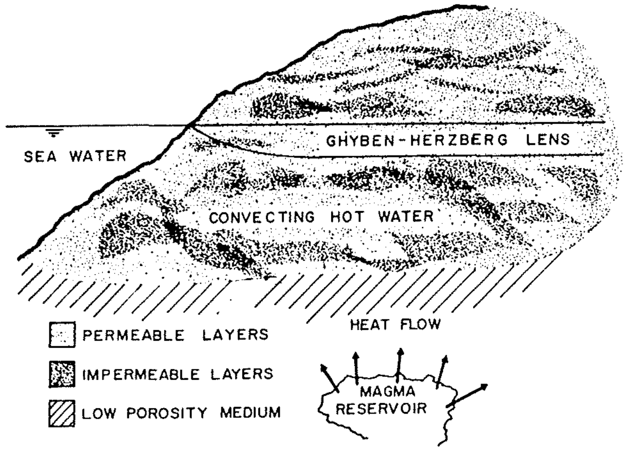

FIG. 2.—Self-sealed/Depletable Geothermal Reservoir

Keller, analyzing results of his drilling program at Kilauea Volcano (12), concluded that evidence favored the existence of hydrothermal convection cells and, most importantly, suggested the action of self-sealing within the porous island medium. The supposition is that Hawaiian geothermal reservoirs resemble Fig. 2, with the heat source being magma at depth which, with time, either: (1) Induced abnormally high circulation rates resulting in flashing or thermal deposition, effectively capping the reservoir, perhaps even above sea level; or (2) intruded above the magma chamber and released energy to the surrounding aquifer, in effect forming a system composed of a cooling vertical dike surrounded by hot fluid, which through the physical phenomenon as described in characteristic 1 has been capped into a self-sealed reservoir. In the latter case, Fig. 2 needs to be modified to show a vertical low permeability formation within the convecting geothermal fluid.

Although it has been reported that hot-water reservoirs are 20 times more prevalent than vapor-dominated ones (22), technical difficulties in the former have resulted in considerably more production from the latter. Table 1 shows five vapor, 11 hot water, and two binary cycle plants in operation or close to completion. This table is a synthesis of information collected from various geothermal energy publications, partially from the files of Don X. Finn, and correspondences with researchers. In the majority of cases, these developments tend to be heavily government subsidized. The hot rock concept is undergoing investigation by researchers from the Los Alamos Scientific Laboratory in New Mexico. A recent drill probe in Marysville, Mont. was largely unsuccessful.

A fourth concept, direct utilization of magma, was originally advanced by Kennedy and Griggs in 1960 (13). A recent conference on volcano energy supported the reasonability of this latter scheme (5). Some preliminary work, mostly in the proposal stage, is being advanced by researchers from Sandia (New Mexico), the Lawrence Livermore Laboratory, and the University of Hawaii.

When calculating the usable energy in a geothermal reservoir, note that only 1% of the total available energy can be converted to electrical energy from a hot-water reservoir using present proven technology. The equivalent figure from a vapor-dominated reservoir is 2%-5% (19). Nevertheless, it should be realized that on an absolute energy scale, a self-sealed liquid-dominated reservoir, per cubic foot of reservoir, will produce more energy than a vapor-dominated one. A quick comparison of water and steam densities bears this out. Secondly, the thermal conductivity of rock precludes conduction as a mechanism for regenerating a geothermal well. For example, Ramey has reported that the net heat recharge rate in the Big Geysers is less than 0.6% (personal communication). However, the possibility of extraordinary fluid convection through porous media as driven by circulating magma should not be discounted; thermal cracking of the receding, cooled magma can result in high permeability. Unfortunately, unless the magma chamber is extremely large or self-sealing occurs, this energy will quickly dissipate with recharging meteoric water.

Under present economic and technical conditions, a viable geothermal reservoir is generally one that (1) Has a minimum temperature of 356° F (180° C) to conform to current steam turbine design; (2) is located within 10,000 ft (3,000 m) from the surface; and (3) can produce steam at a minimum rate of 40,000 lb/hr (18,000 kg/hr) with a 9-5/8-in. (240 mm) diam hole. Geothermal wells not quite satisfying the aforementioned criteria can be used for special applications, e.g., the 158° F (70° C) binary system in the Union of the Soviet Socialist Republic. Furthermore, there is every reason to believe that wells exceeding

10,000 ft (3,000 m) will, with improved drilling technology and increasing energy fuel prices, become economically feasible.

The general nature of a geothermal reservoir is contentious. The question of its being self-sealed or regenerative has not been completely answered. The qualitative "state-of-the-art" is relatively well developed compared to the quantitative. The remainder of the paper will be largely devoted to the quantitative aspects of geothermal reservoir engineering.

TABLE 1.—Geothermal Plants

Type of plants (1)	Capacity, in megawatts (2)	Initial operations (3)
(a) Dry Steam		
Italy		
Lardarello	380	1904
Monte Amiata	26	1967
United States		
Geysers, California	502	1960
Japan		
Matsukawa	20	1966
Hachimantai	10	1975
(b) Flashed Steam		
New Zealand		
Wairakei	192	1958
Kawerau	10	1969
Japan		
Otake	13	1967
Hatchobaru	50	late 1970's
Mexico		
Pathe	3.5	1958
Cerro Prieto	75	1973
Iceland		
Namafjall	3	1969
Hengrill	13-32	late 1970's
Philippines		
Tiwi	10	1969
Union of Soviet Socialist Republic		
Pauzhetsk	6	1967
El Salvador		
Ahuachapan Field	30	1975
(c) Binary Cycle		
Union of Soviet Socialist Republic		
Paratunka	1	1967
United States		
Imperial Valley, California	10-50	1975-1980

GEOTHERMAL RESERVOIR ENGINEERING: HARDWARE

Well tests are performed in two phases. In the first phase, tests are performed during open hole drilling operations. The tests consist of fluid temperature measurement, fluid sampling, core analysis, and formation logging. After completion, the producing well must undergo a second phase of tests to determine the thermodynamic condition of the fluid and the adequacy of the reservoir producing cone. Measurements are taken both at the wellhead and downhole.

The following list outlines the hardware necessary to adequately measure a geothermal reservoir (8,9,13,14,16,20):

1. Subsurface formation condition: Permeability—resistivity logs and core sampling; porosity—resistivity logs, core sampling, density logs, neutron logs, and sonic logs; and water saturation—resistivity logs and porosity measurements.
2. Evaluation of well casing: Inclination for deviation survey, wellbore calipering, and casing condition.
3. Downhole fluid condition: Pressure—Amerada-Kuster RPG-3 gage, pressure transducer, and gas purge tube with pressure element; temperature—expansion thermometer, resistance thermometer, thermocouple, geothermograph, maximum registering thermometer, temperature sensitive paint, metal, and ceramic pellets; flow rate—mechanical spinner and electronic flowmeter; and fluid sampling—Kuster sampler, Schlumberger sampler, and gas purge tube with fluid sampler.
4. Surface fluid condition: Pressure—aneroid barometer, mercury column, glass manometer, and pressure recorder; temperature—filled thermal measuring systems, resistance bulbs, and thermocouples; and flow rate (and enthalpy)—separator, orifices, and weirs for separate vapor and liquid flow, beta ray, gas method, magnesium sulfate injection, critical lip pressure, conductivity, and calorimetry.

In fluid measurement the data obtained from one particular downhole instrument are not always reliable due to its operational characteristics. Combined readings from two or more instruments for a certain parameter are desirable in order to predict a specific subsurface condition. Data generated from these measuring devices are cross-verified to determine the probable downhole condition.

In formation evaluation the logs include, to varying degrees, the effects of the borehole and tool response characteristics. Therefore, they must be interpreted to obtain the derived formation parameter log. In early logging, most interpretation was done manually through detailed statistical correlation of logs and core analysis data. However, with significant advances in log interpretation by well service companies, the process is now performed by applying computer programs for specific types of geothermal formations. The programs interpret the data from the logs, cross-verify the input data and results, and conveniently determine the various parameters that are desired.

GEOTHERMAL RESERVOIR ENGINEERING—MEASUREMENT AND METHODS OF ANALYSIS

The purpose of a reservoir engineering study is to collect enough information to reveal the nature of the reservoir and to determine the pertinent physical parameters that control the behavior of fluids in the reservoir. The pertinent questions requiring answers include:

1. What are the temperature and pressure ranges of the fluid?
2. What is the nature of the fluid, i.e., vapor, liquid, or a mixture of both?
3. What is the chemical composition of the fluid?
4. What is the expected production rate and expected life of the reservoir?

After the geologists and geophysicists have decided on the drill site and drilling has commenced, a reservoir testing program of measurement and analysis should be outlined. The measurements begin at the borehole; various geophysical loggings, e.g. electric, are recorded to determine formation resistivity and self-potential, radioactivity for rock density and porosity, and acoustic for porosity. At the same time, drilling fluid and cores are analyzed for rock temperature, porosity, permeability, fluid saturation, and thermal conductivity. Up to and including well completion, drill-stem tests are run to obtain values of the formation pressure and temperature.

The producing well receives both wellhead and downhole tests, initial quasi-steady state temperature and pressure surveys versus depth, followed by pressure drawdown and build-up tests. The drawdown test is a series of bottomhole pressure measurements made during a period of flow at a constant production rate. Reservoir volume, transmissivity (product of average permeability and reservoir thickness), and skin (resistance to flow at casing area) effects can be estimated. The build-up test is another series of bottomhole pressure measurements made just before and after a stepwise reduction in flowrate, or a complete shutting down of the well. Some information, e.g., the transmissivity, skin effects, and flow efficiency, can be estimated to aid in predicting optimal production rate and life of the reservoir.

The wellhead is continuously monitored during production to determine flowrate, energy extracted, and quality and geochemistry of the fluid. If flow is two-phased, present technology requires separation of liquid from steam. Developments incorporating magnetic and nuclear techniques have not been perfected. Finally, if more than one hole is drilled in the same area, well interference tests are run to determine the reservoir connectivity, directional reservoir flow pattern, and the nature and magnitude of anisotropic permeability.

Fluid flow through porous media is generally considered to be laminar with the exception of flow near the well. The basic equations used are the law of conservation of mass, Darcy's Law, and equation(s) of state.

By taking the following assumptions: (1) Small pressure gradient; (2) small and constant fluid compressibility; and (3) isometric rock properties, the following simplification results:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) = \frac{\phi\mu}{k} c_t \frac{\partial p}{\partial t} \quad \ldots\ldots\ldots\ldots \quad (1)$$

in which ϕ = formation fraction porosity; μ = fluid viscosity; k = formation permeability; $c_t = c + c_r$ = total system effective isothermal compressibility; p = pressure; t = time; and r = radial distance. Solving Eq. 1 with the appropriate boundary conditions in terms of dimensionless parameters:

$$p_D(r_D, t_D) \approx \frac{1}{2}\left(\ln\frac{t_D}{r_D^2} + 0.80907\right) \qquad (2)$$

in which $t_D/r_D^2 > 70$. Using a graph of p_D versus t_D/r_D^2 on a log-log plot, a relationship can be found determining $p_{r,t}$, the pressure at any location and time:

$$p_{r,t} = p_i - \frac{q\mu}{2\pi kh} p_D \qquad (3)$$

in which h = aquifer thickness; and q = production rate. Mass and volumetric and heat balances are now used to determine the desired properties. For mass balance:

$$W_c = W - W_p - W_L + W_E \qquad (4)$$

in which W_c = current mass in reservoir, in pounds; W = initial mass in reservoir at the start of production, in pounds; W_p = mass produced, in pounds; W_L = mass loss via springs, wild wells, etc., in pounds; and W_E = mass influx from aquifer, in pounds. For volumetric balance:

$$V\phi = W_c[X(V_g - V_f) + V_f] \qquad (5)$$

in which V = reservoir bulk volume, in cubic feet; ϕ = porosity; X = steam quality in reservoir, mass fraction of fluid which is in steam; V_g = specific volume of steam, in cubic feet per pound; and V_f = specific volume of liquid water, in cubic feet per pound. For heat balance:

$$W_c h_c = (1 - \phi) V \rho_r C_r (\mathrm{T} - \mathrm{T}_o) = W h_i + (1 - \phi) V \rho_r C_r (\mathrm{T}_i - \mathrm{T}_o)$$
$$- W_p h_p - W_L h_L + W_E h_E + Q_s \qquad (6)$$

in which h_c = average enthalpy of total fluids in reservoir, in British thermal units per pound; h_i = average enthalpy of initial fluids in reservoir, in British thermal units per pound; h_p = average enthalpy of produced fluids, in British thermal units per pound; h_L = average enthalpy of lost fluids, in British thermal units per pound; h_E = average enthalpy of liquid water influx, in British thermal units per pound; ρ_r = formation density, in pounds per cubic foot; C_r = specific heat of formation, British thermal units per pound-degrees Fahrenheit; T = current reservoir temperature, in degrees Fahrenheit; T_i = initial reservoir temperature; in degrees Fahrenheit; T_o = some reference temperature, in degrees Fahrenheit; and Q_s = net heat conducted into reservoir, in British thermal units. Average enthalpy of any liquid-steam combination can be expressed as

$$h = X(h_g - h_f) + h_f \qquad (7)$$

in which h = enthalpy of steam quality, in British thermal units per pound; h_g = enthalpy of saturated steam, in British thermal units per pound; and h_f = enthalpy of saturated liquid, in British thermal units per pound.

The mass, volumetric, and heat balance equations are good for any system, liquid, liquid-steam, or steam. The initial condition of the reservoir can be compressed liquid, saturated liquid, and steam or superheated steam.

With previous records of average pressure versus cumulative production several parameters can be optimized, e.g., initial volume, temperature, and pressure. It is also possible to conjecture about the initial fluid condition and then to make performance predictions.

In general, software encompasses both computer programs and the standard curve analysis. The methods of analysis used in the petroleum and gas industries cannot be applied to geothermal systems. A geothermal reservoir has temperature as the dominant parameter. Most petroleum reservoir analyses are based on isothermal conditions. Whiting and Ramey (private communication) have successfully demonstrated that the regular volumetric balance method in petroleum engineering does not apply to geothermal reservoirs where a material and energy balance method is needed. In most cases, however, the principles of petroleum reservoir engineering for single-phase liquid flow can be applied with certain modifications to hot water reservoirs (2). In the same manner, there is a kind of one-to-one analogy for the gas industry and vapor-dominated wells. Alas, nature is unprovidential, as the majority of reservoirs are steam-flashed or two-phased. Two-phased well prediction is an extremely challenging and fruitful area for research.

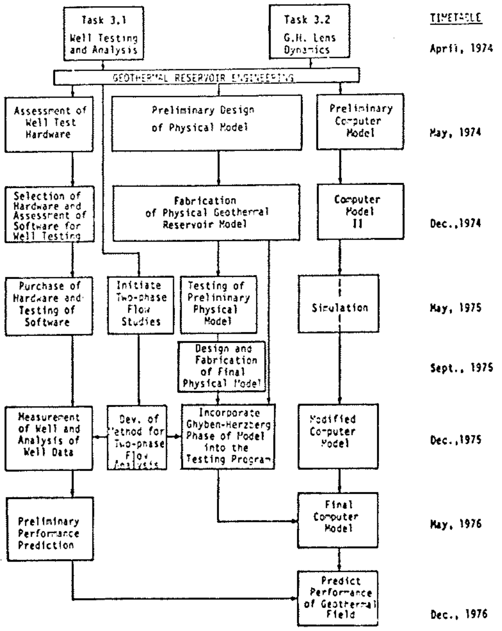

FIG. 3.—Organizational Plan for Task on Geothermal Reservoir Engineering

Well test analysis can perhaps best be summarized by quoting Muraszew (17): ". . . with the present state-of-the-art, neither the capacity of the reservoir nor its longevity can be accurately predicted. . . ."

Fortunately, as undeveloped as this field is, definite progress is being made. The Stanford group has made admirable progress; the United States Geological Survey is devoting effort towards computer model studies; the geo/hydrology group at California-Berkeley has produced computer models in this area; and

Systems, Science and Software of San Diego is beginning a study. Finally, as Fig. 3 reveals, the research team at the University of Hawaii is adding to the body of knowledge.

INTERNATIONAL QUESTIONNAIRE

Over 20 replies were received from companies, institutions, and government agencies from all of the prominent geothermal energy nations. While some of the responses were received through oral communication, the majority were in the form of written correspondence. Many of the individuals chose to answer the questions by citing published technical literature. All responses were evaluated and the most appropriate ones were tabulated in a matrix arrangement as shown in Table 2. This table should be a convenient guide for quick reference to geothermal reservoir engineering.

WHAT IS GEOTHERMAL RESERVOIR ENGINEER?

To obtain an appreciation of the field of geothermal reservoir engineering, an attempted quick definition of a Geothermal Reservoir Engineer (GRE) is appropriate. The diversity of functions the GRE is expected to perform makes it imperative that he has a multidisciplinary background. As the GRE will be working with geologists, geophysicists, geochemists, drilling engineers, hydrologists, thermodynamicists, fluid dynamicists, mathematicians, lawyers, computer scientists, and economists, it is important that the GRE become acquainted with each field so that he can better communicate with these specialists, better understand the interrelationships and complexities, and know when to consult them. As an example, the GRE must develop the geologist's cognizance of sediments and other underground conditions, the chemists knowledge of chemical properties and electrical conductivity, the mechanical engineer's grasp of the associated hardware, the chemical engineer's familiarity with reservoirs, the civil engineer's competence at analyzing porous media, the mathematician's flexibility with numerical analysis and computer programming, the lawyer's understanding of certain statutes, and the economist's overview of the financial implications.

A GRE must be trained. An engineer who has had exposure to petroleum well testing and analysis but has had no reservoir experience would need training involving several short courses on reservoir engineering and well test analysis combined with on-the-job experience at a geothermal well site. Hands-on training is essential.

In preparation for the aforementioned training, the prospective GRE should acquaint himself with the following publications:

1. Joseph Barnea, "Geothermal Power," *Scientific American*, Vol. 226, Jan., 1972.
2. H. Christopher Armstead, ed., *Geothermal Energy*, UNESCO, Paris, France, 1973.
3. Paul Kruger and Carel Otte, *Geothermal Energy*, Stanford Press, Stanford, Calif., 1973.
4. B. C. Craft and M. F. Hawkins, *Petroleum Reservoir Engineering*, Prentice-

TABLE 2.—Responses to International Questionnaire

Name and affiliation (1)	Nature of geothermal reservoir (2)	Well testing and hardware (3)	Analysis software (4)
B. C. McCabe Magma Power Company United States	In geothermal reservoir engineering, the theoretical information for determining the size or longevity of a geothermal field is a very inexact science. For steam and hot water reservoirs, no one knows what the percentage of replaceable heat coming into the reservoir is in proportion to the amount being withdrawn. Probably, the replacement heat is much greater than it is generally imagined.	No reply	No reply
W. K. Summers New Mexico Bureau of Mines United States	Geothermal fluids consist of two components: meteoric water and gases (H_2S and CO_2), rising from great depths. The mixture of the components occurs in fractures. If the fractures are sufficiently close together, a well will produce routinely. Otherwise, only occasional wells will produce.	Petroleum or groundwater hydrology equipment can be used, as modified to incorporate temperature.	Computer technology is generally adequate, but software is dependent on adequate sampling of the flow continuum and the proper incorporation of the parameter temperature.
Giancarlo E. Facca Registered geologist Italy and United States	Geothermal fields are composed of: a deep sequence of layers, heated by an underlying magmatic stock and which, in turn, heats the overlying porous strata; a very permeable layer with thickness, porosity, and permeability of such an order as to allow the formation and the permanence of a system of convection currents in the water filling the pores of the rock; and	Refer to United Nations and UNESCO publications in Appendix A (A10, A12, A17, A22, A23).	Refer to United Nations and UNESCO publications in Appendix A (A10, A12, A23, A26, A27, A28).

TABLE 2.—*Continued*

(1)	(2)	(3)	(4)
	an impermeable layer over the reservoir.		
W. E. Allen Oil and Gas Conservation Commission (Arizona) United States	Refer to articles in Appendices A and B.	Refer to articles in Appendices A and B.	For the purpose of predicting well performance, there are no marketing companies in Arizona.
Robin Kingston Kingston, Reynolds, Thom, and Allardice, Ltd., New Zealand	Refer to United Nations publications in Appendix A.	Refer to articles by D. K. Wainwright (A11) and A. M. Hunt (A12) in Appendix A.	Prediction of well performance is a composition of permeability, temperature, reservoir capacity, and rate of flow. Permeability in geothermal terms depends on fracture zones much more than on porosity. Oil reservoir assessment techniques can in some applications be modified for geothermal applications.
Enrico Barbier International Institute for Geothermal Research Italy	Refer to United Nations and UNESCO publications Appendix B (B16, B24).	Equipment and other hardware are generally not available.	The evaluation of the quality of a geothermal well is uncertain. Analogies are generally made with existing wells.
J. L. Guiza Geothermal Resources Cerro Prieto Mexico	Geothermal fields are classified into two major groups: sedimentary fields and volcanic fields. In a sedimentary field the productive strata is a permeable sandstone interbedded by impermeable clay layers. The sandstone is saturated with meteoric water, and the heat flow is due to the faults and fissures of the granitic basement. In volcanic fields the possible production mechanism is due to the water flow through fissures in the volcanic rocks being heated by a cooling magmatic body.	For the determination of reservoir parameters such as permeability index and porosity, the synergetic log named SARABAND is used. For temperature, pressure and flow measurements the conventional systems (Kuster RPG and KTG instruments) are employed.	The performance in a well can be predicted by means of a hydrologic model modified by the temperature effect and taking into account the physical characteristics of the productive sandstone as well as the physical-chemical properties of the geothermal fluids. For the purpose of optimizing well locations, computer programs are used to simulate field production.

Hall, Inc., Englewood Cliffs, N.J., 1959.

5. C. S. Matthews and D. B. Russell, *Pressure Buildup and Flow Tests in Wells*, Society of Petroleum Engineers, American Institute of Mining, Metallurgical, and Petroleum Engineers, 1967.
6. *New Sources of Energy, Proceedings of the Conference*, Vols. 2 and 3, Rome, Italy, August 21-31, 1961.
7. *Geothermics* (All proceedings and regular publications).
8. *Well Testing*, American Petroleum Institute.
9. *Wireline Operations and Procedures*, American Petroleum Institute.

If a more comprehensive formal course on geothermics is desired, Japan has a 3-month course and Italy has a 9-month one. Both courses are taught in English.

What is a geothermal reservoir engineer? He is many things at once and never everything he might want to be. The field is so multidisciplinary that the ideal GRE always knows less than the individual specialists on a given topic, but can bring the necessary perspective into the picture, as interfacer, integrator, and synthesizer.

GEOTHERMAL RESERVOIR ENGINEERING—RESEARCH PLAN

As the field of geothermal reservoir engineering is just beginning to develop, a firm research base must be established. The Hawaii Geothermal Project, a multidisciplinary research program of the University of Hawaii primarily funded by the National Science Foundation and the State of Hawaii, has, in the specific case of geothermal reservoir engineering, consolidated several diverse research investigations into a unified systems study. Fig. 3 depicts the organizational plan.

The geothermal reservoir engineering research team is composed of three subtask groups: (1) Computer modeling; (2) physical modeling; and (3) geothermal well testing/analysis. All three subtasks have the ultimate goal of predicting the performance of producing geothermal fields. The computer modeling group is using a mathematical model approach, the physical modeling group is scale modeling a geothermal system, and the testing/analysis group is evaluating existing geothermal and petroleum/gas hardware and software techniques with the aim of synthesizing optimal measurement and prediction alternatives. The previous sections essentially summarized the work of the third group. The next two sections report on the activities of the first two subtasks.

Computer Modeling.—The two objectives of the computer modeling group are to predict the performance of geothermal wells and to study the environmental impact of the geothermal system, especially with respect to the stability of the Ghyben-Herzberg lens. Specifically, the initial phase of the work has focused on free convection in a coastal aquifer with geothermal heating from below.

Cheng and Lau derived a set of finite difference equations and obtained a computerized numerical solution using a perturbation method (4). Fig. 1 is a speculative cross-sectional view of the Island of Hawaii. The computer study simplified the 1-1/2-mile (2.4-km) deep by 72-mile (120-km) diam aquifer region into a two-dimensional rectangular model. Preliminary studies have concluded that: (1) The pressure in an unconfined geothermal reservoir is almost hydrostatic;

(2) the flow rate of seawater depends only on the horizontal temperature gradient of the reservoir; (3) although there is some decrease in temperature distribution in the lower portion of the aquifer in a small region near the ocean as a result of inflow of cold water, the water also acts as a heat-carrier in the rest of the aquifer; (4) the convection of heat is more efficient vertically than horizontally; (5) the size of the geothermal source has an important effect on the temperature distribution in the reservoir; (6) the location of the heat source has some effect on the temperature distribution in the region near the ocean, but its effect on the temperature for the rest of the aquifer is small; (7) the discharge number has a strong effect on the temperature distribution of the aquifer; and (8) there is a noticeable upwelling of the water table at the location directly above the heat source, the amount of upwelling depending on the vertical temperature gradient of the porous medium and the prescribed temperature of the impermeable surface.

Physical Modeling.—The physical model is a necessary balance to the ongoing software investigations. The physical model will not only serve as a convenient check on the mathematical model, but will simulate conditions not easily attempted by software. The objectives of the initial physical model studies will be to bring together known information about related laboratory studies, analyze the state-of-the-art, design the hardware system required for simulation, and initiate fabrication and preliminary tests.

Very little physical modeling work has been reported in the literature. The significant studies related to geothermal reservoirs include those of Cady (3), Miller (18), Henry and Kahout (11), and the remotely related work of Bear (1). However, none of the reported investigations approached the problem on a total systems basis while considering the high [2,012° F (1,100° C) for magma and 527° F (275° C) at wellhead] temperatures expected.

In movement of fluid through a geothermal reservoir, the driving force is primarily the buoyant force. This force is created by heat within the geothermal system which decreases the fluid density.

The dimensionless number determined to be of prime interest to the study is the Rayleigh number, Ra. The Rayleigh number is the product of the Grashof, Gr, and Prandtl, Pr numbers, in which

$$\mathrm{Gr} = \frac{\text{buoyant force}}{\text{viscous force}} \qquad (8)$$

$$\mathrm{Pr} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} \qquad (9)$$

$$\mathrm{Ra} = \mathrm{Gr}\,\mathrm{Pr} = \frac{\rho_s g \beta K (T - T_s) h}{\mu \alpha} \qquad (10)$$

in which ρ_s = density of fluid; g = gravitational constant; β = coefficient of thermal expansion; K = permeability of porous medium; $(T - T_s)$ = temperature driving force; h = depth of permeable bed; μ = viscosity of fluid; and α = thermal diffusivity of fluid.

The literature is sparse on the range of Rayleigh numbers meaningful to actual geothermal systems. In general, the study is investigating the range of Ra between 30 and 1,000, by altering the permeability of the solid medium and the temperature of the system. The permeability can be altered by changing the mesh size of the sand or glass bead bed. The temperature change will, in turn, determine the values of the coefficient of thermal expansion β, thermal diffusivity α, viscosity μ, and density ρ of the fluid.

The preliminary physical model has been constructed and tests are being conducted on the various parameters in question. Temperature profiles are being investigated and the matter of self-sealing is being observed.

CONCLUSIONS

A comprehensive survey of the "state-of-the-art" of geothermal reservoir engineering has resulted in a report that laments the lack of quantitative information available. The presentation has taken the form of a survey paper, examining the nature of a geothermal reservoir, the parameters requiring measurement in a geothermal well, the hardware and software required for well test and analysis, and orientation to the field of geothermal reservoir engineering. The report also presented the research plan and accomplishments of the geothermal reservoir engineering group within the Hawaii Geothermal Project. Their approach will be a total systems study of the subject. Developmental work is progressing in computer simulation, physical models, and well test analysis.

The international nature of this topic generally compounds the difficulties experienced in a survey paper. The field of geothermal reservoir engineering will show significant progress during the next few years, accelerated because of improved international communications, the availability of computers, and the threat of another energy crisis, which has resulted in the release of funds for research and development in this area.

ACKNOWLEDGMENTS

Grateful appreciation is extended to the many geothermal energy specialists throughout the world who were contacted and responded with invaluable information. The following list, although incomplete, focuses on those who were especially generous with their expertise: H. J. Ramey (Stanford University, California), L. J. P. Muffler (United States Geological Survey, California), G. Facca (consulting geologist, now located in California), David Anderson (Geothermal Regulations, California), Jim Vohs (Schlumberger, California), Jim Kuwada (Rogers Engineering, California), Anthony Chasteen (Union Geothermal Division, California), W. K. Summers (New Mexico Bureau of Mines), W. E. Allen (Oil and Gas Conservation Commission, Arizona), J. L. Guiza (Mexico), E. Barbier (Italy), R. Kingston (New Zealand), T. Iwamizu (Japan), and G. R. Robson (United Nations). Additional thanks go to the National Science Foundation for Research Grant No. GI-38319 and the Lawrence Livermore Laboratory for providing the initial impetus. The survey could not have been accomplished had it not been for their financial and resource assistance.

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JOURNAL OF THE POWER DIVISION

DISCUSSION

Note.—This paper is part of the copyrighted Journal of the Power Division, Proceedings of the American Society of Civil Engineers, Vol. 101, No. PO1, July, 1975.