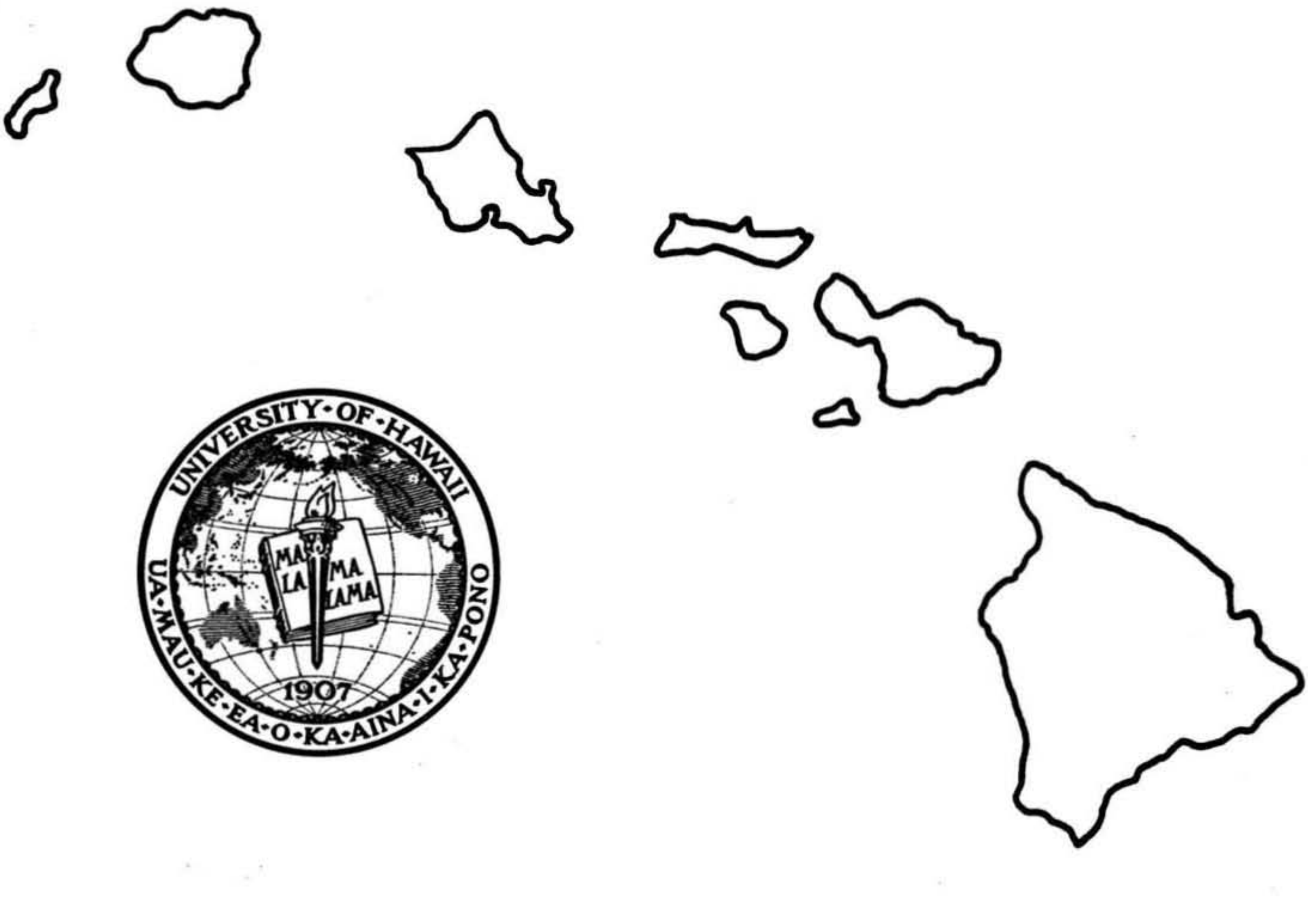
THE HAWAII GEOTHERMAL PROJECT

GEOTHERMAL RESERVOIR ENGINEERING:

STATE-OF-THE-ART

TECHNICAL REPORT NO. 3

May 1, 1974



HAWAII GEOTHERMAL PROJECT

ENGINEERING PROGRAM

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GEOTHERMAL RESERVOIR ENGINEERING: STATE-OF-THE-ART

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INTRODUCTION

The history of geothermal reservoir engineering really 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 century---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 to 70 percent 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

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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 years ago, it is only during the past 15 years 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--gas, petroleum, and water to contend with--the dominant factor, temperature, in geothermal wells, 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 in the most part formative. Three groups in particular, though, have contributed well: New Zealand (A1 - A28), the Bureau of Reclamation (A29), the U. S. Geological Survey (A30 - A40), and Stanford University (A41 - A48). Also available are some individual investigations, as for example, Robert Whiting's reservoir engineering study of Wairakei (A49). Appendix A lists these references. Appendix B is a complementary list of references useful for associated information.

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

The following report is based on a comprehensive survey involving a thorough literature search, personal discussions with leaders in this field, the results of responses to an international questionnaire, and some preliminary analysis. The report will be in six parts:

1. The nature of a geothermal reservoir.
2. Geothermal reservoir engineering--measurement and methods of analysis.
3. Geothermal reservoir engineering--hardware.
4. What is a geothermal reservoir engineer?
5. Geothermal reservoir engineering: research plan for the Hawaii Geothermal Project.
6. The international questionnaire (Appendix II, TABLE 2).

THE NATURE OF A GEOTHERMAL RESERVOIR

Speculations on the nature of geothermal reservoirs can be found in the literature. Legally, in the United States, the U.S. Geological Survey defines a geothermal reservoir to be contained in:

1. A known geothermal resource area (KGRA); that is, an area in which the geology, nearby discoveries, competitive interests, or other indicia would in the opinion of the Director of the Geological Survey engender belief in men who are experienced in the subject matter that the prospects for extraction of geothermal steam or associated geothermal resources are good enough to warrant expenditures of money for that purpose, or
2. A potential geothermal resource area (PGRA); that is, an area within a geothermal resource province that contains an inferred geothermal reservoir but which has not been determined by the Director of the

Geological Survey to be a KGRA.

Geothermal reservoirs can be characterized in several other ways:

1. Depletable (self-sealed) or regenerative (recharged),
2. Physical state,
   a. vapor - steam,
   b. liquid - hot-water, normally two-phased at wellhead,
   c. solid - hot rock,
   d. liquid magma.
3. Physical condition,
   a. temperature/pressure,
   b. size/depth,
   c. production rate,
4. Degree of dissolved solid content.

In California, vapor dominated wells are considered to be depletable. A tax allowance is allowed under this classification. A decision has not yet been made on other types of wells. There is some reason to believe that all wells are at least partially regenerative because of the meteoric (rainwater) origin of geothermal fluids (18). Furthermore, reports of measurable pressure drops in steam-dominated geothermal fields seen after rainfall lead one to suspect 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. On the other hand, 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 clear cut answer to a universal definition of a geothermal reservoir. A geothermal reservoir needs:

1. A heat source, magma or geopressure,

2. To be confined in an aquifer, although non-permeable hot rocks can be transformed into an aquifer through hydrofracturing/thermal cracking and the addition of water,
3. Caprock--to hold the hot fluid in place.

Speculations of how a geothermal reservoir might look have been advanced by White and Muffler (18), U.S.; Facca (6), Italy; Elder (5), New Zealand; and Hayashida (10), Japan.

For the island of Hawaii, it is generally believed that the system is liquid dominated with or without recharge. Figures 1, 2, and 3 are conceptualizations of the expected systems for Hawaii. Figure 1 is a macro-view of the total underground system; Figure 2 is a possible self-sealed system, and Figure 3 is the most probable recharged system. It should be noted that magma is generated at the crust-mantle interface. For the Hawaiian Islands, there is reason to believe that the production of magma could be as close as 20 miles from the surface of the earth (14, 22).

Although it has been reported that hot water reservoirs are twenty times more prevalent than vapor-dominated ones (23), technical difficulties in the former have resulted in considerably more production from the latter. Table I shows that five vapor, eleven hot water, and two binary cycle plants are either operating or close to completion (7). Hot rock concepts are undergoing investigation by researchers from Battelle (for Montana) and the Los Alamos Scientific Laboratory (for New Mexico) (1). Finally, a fourth concept, direct utilization of magma, was originally advanced by George Kennedy and David Griggs in 1960 (12). A recent conference on volcano energy (Hilo, Hawaii) supported the reasonability of this latter scheme. Some preliminary work, mostly in the proposal stage, is being advanced by researchers from Sandia (New Mexico), Lawrence Livermore Laboratory, and the University of Hawaii.

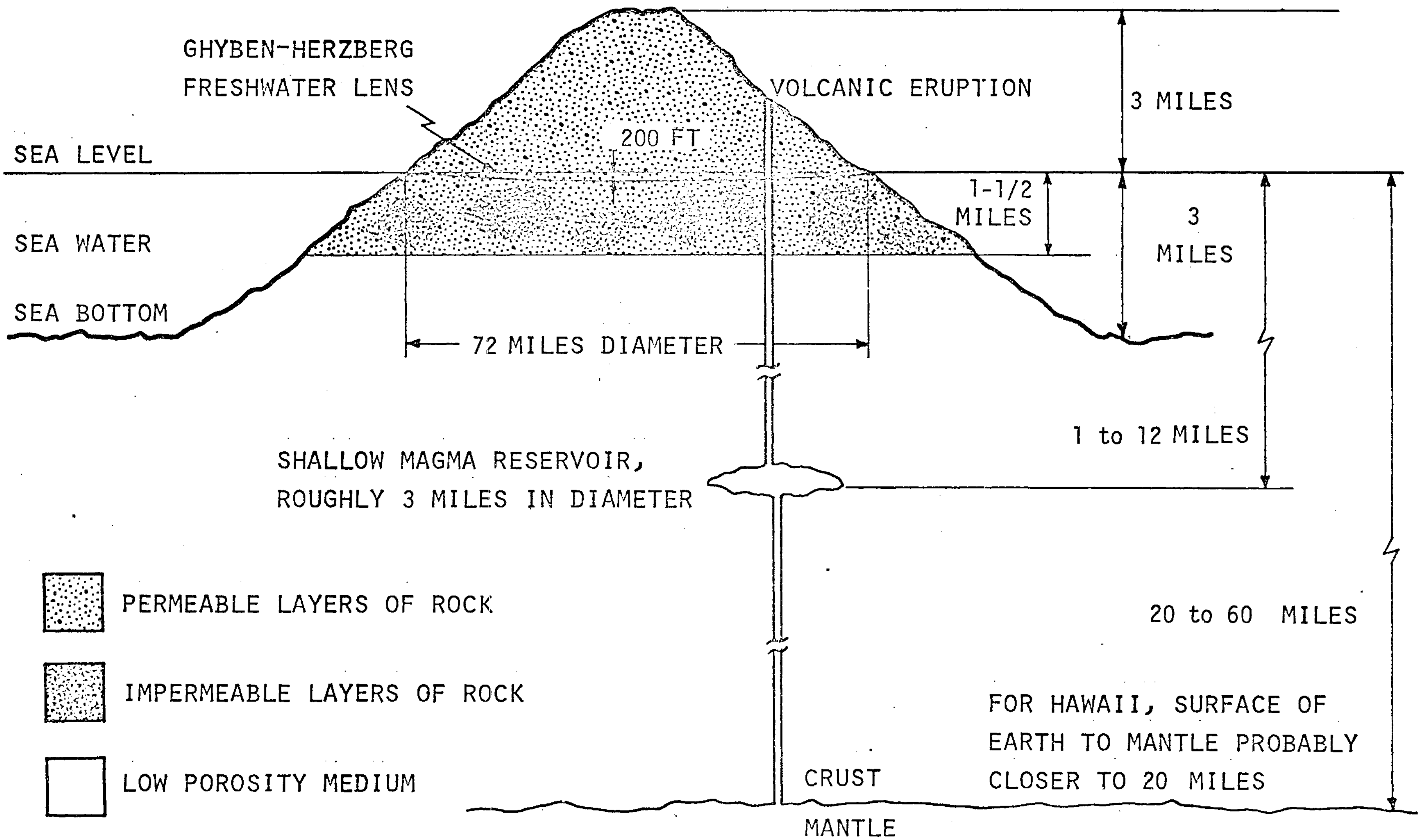

FIGURE 1. SPECULATIVE CROSS-SECTIONAL VIEW OF THE ISLAND OF HAWAII

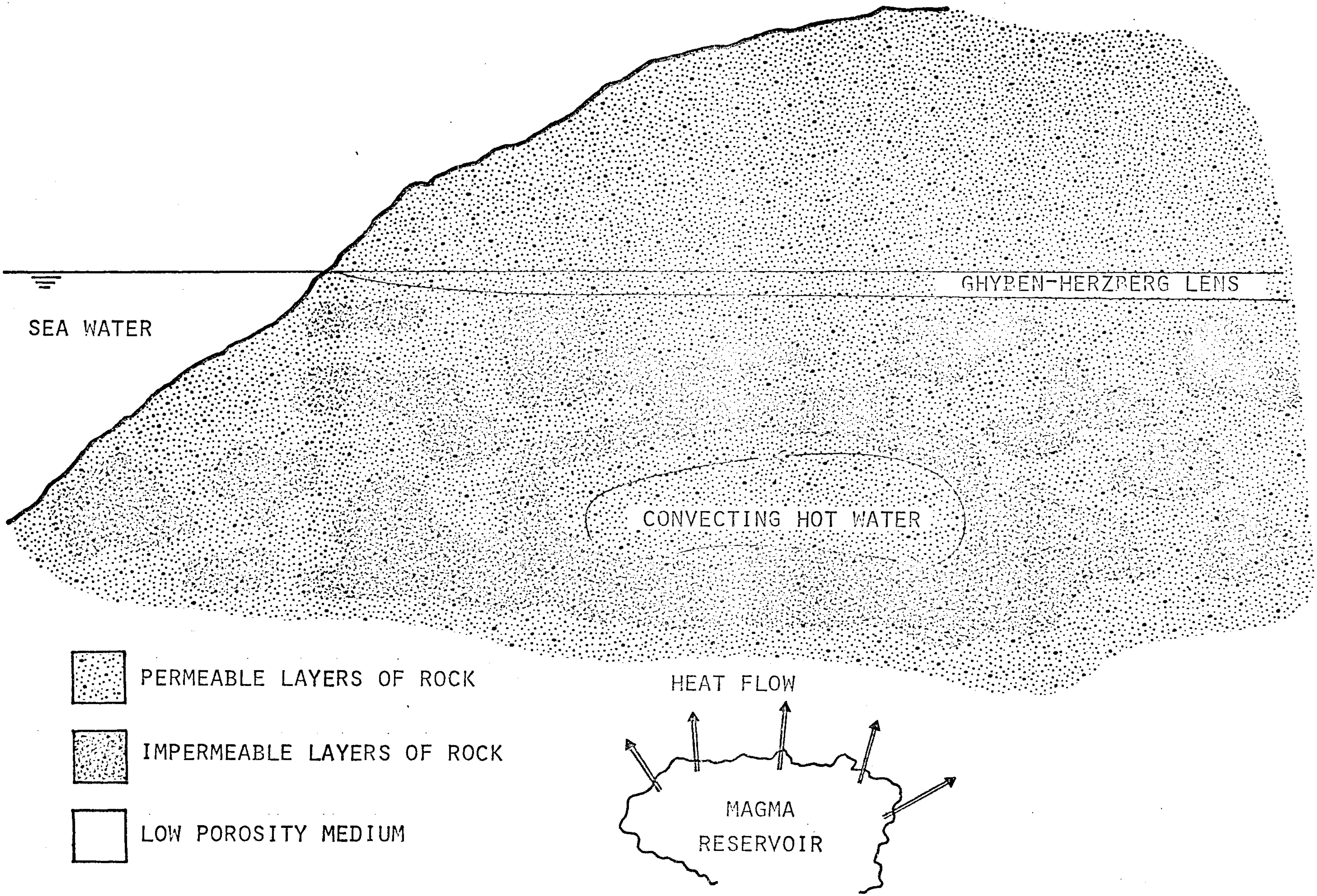

FIGURE 2. SELF-SEALED / DEPLETABLE GEOTHERMAL RESERVOIR

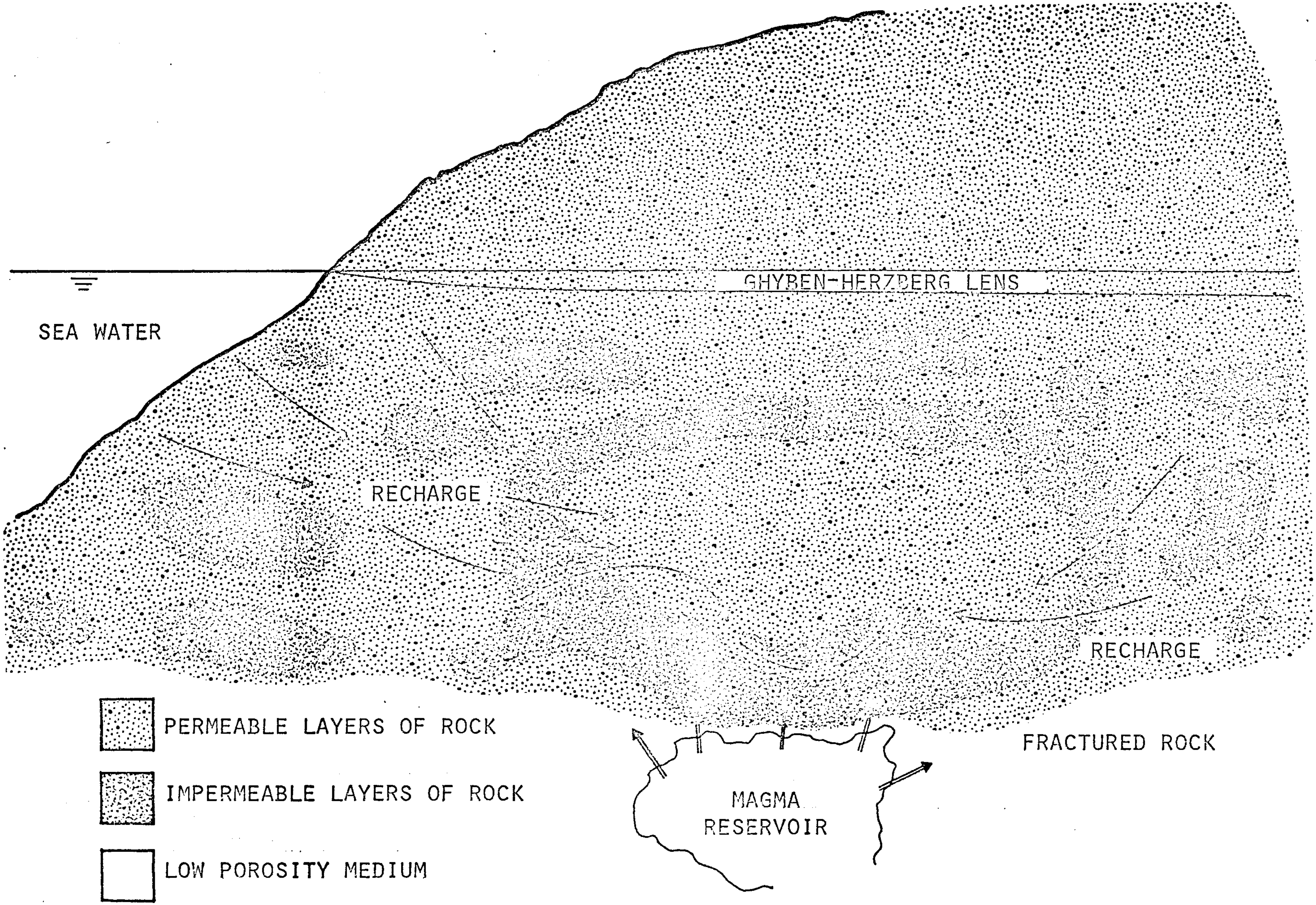

FIGURE 3. RECHARGED / REGENERATIVE GEOTHERMAL RESERVOIR

TABLE 1. GEOTHERMAL PLANTS

DRY STEAM PLANTS	MW CAPACITY	INITIAL OPERATIONS
Italy		
Lardarello	365	1904
Monte Amiata	25	1967
U.S.A.		
Geysers, California	411	1960
Japan		
Matsukawa	20	1966
Hachimantai	10	1975

FLASHED STEAM PLANTS	MW CAPACITY	INITIAL OPERATIONS
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
USSR		
Pauzhetsk	6	1967
El Salvador		
Ahuachapan Field	30	1975

BINARY CYCLE PLANTS	MW CAPACITY	INITIAL OPERATIONS
USSR		
Paratunka	1	1967
U.S.A.		
Imperial Valley, California	10-50	1975-1980

When calculating the usable energy in a geothermal reservoir, one should be aware that only 1% of the total available energy is converted to electrical energy from a hot-water reservoir using present proven technology, and from 2% to 5% of a vapor-dominated reservoir can be converted to electricity (18). It should nevertheless be realized that on an absolute energy scale, a liquid dominated reservoir, per cubic foot of reservoir, contains more energy than a vapor dominated one. Secondly, the thermal conductivity of rock precludes conduction as a mechanism for regenerating a geothermal well. For example, H. Ramey has reported that the net heat recharge rate in the Big Geysers is only 0.6% (19). However, the possibility of extraordinary fluid convection through porous media as driven by circulating magma should not be discounted--thermal cracking of the cooled magma can result in high permeability.

Under present economic and technical conditions a viable geothermal reservoir is generally one which:

1. has a minimum temperature of 180°C--to conform to current steam turbine design,
2. is located within 10,000 feet from the surface,
3. can produce steam at a minimum rate of 40,000 lb/hr (9 5/8" D hole).

Geothermal wells not quite satisfying the above criteria can nevertheless be used for special applications, as for example, the 70°C binary system in the U.S.S.R. Furthermore, there is every reason to believe that wells exceeding 10,000 feet will with time and increasing energy fuel prices become economically feasible.

The general nature of a geothermal reservoir seems to be fairly well understood. There is some contention on the self-sealed/regenerative issue. However, the "state-of-the-art" in a qualitative sense is sufficiently developed--quantitatively, though, the challenges are only now beginning to surface.

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 which control the behavior of fluids in the reservoir. Some of the questions that needs to be asked are:

1. What are the temperature and pressure ranges of the fluid in question?
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 are the expected production rate and expected life of the reservoir?

After the geologists have decided on the drill site, a reservoir analysis and formation evaluation program should be outlined as follows:

1. Bore Hole Tests
   a. Geographical Logging:
      1) electric logging - to determine formation resistivity and self potential,
      2) radioactivity logging - to determine rock density and porosity,
      3) acoustic logging - to determine rock velocities and in turn the porosity.
   b. Driller's Log: to help interpret the results from various geographical loggings
   c. Drilling Fluid and Cutting Analysis
      1) to prepare a lithologic log,
      2) to measure change of rock temperature if flow line temperature both in and out are monitored.
   d. Coring and Core Analysis: when situation warrants, cores are retrieved for petrographic study and for laboratory study of rock

porosity, permeability, fluid saturation and thermal conductivity.

e. Drill-stem Tests: to obtain values of the formation pressure and temperature; these data are used to assess a formation or stratigraphic interval as to its fluid production potential.

f. Geochemistry Analysis: to be analyzed for their chemical composition.

2. Well Completion Methods: if most of the data obtained above support the possibility of a potential formation, the well should be completed, probably by perforated casing.

3. Well Tests

a. Temperature Survey: quasi-steady temperature vs. depth after completion of well,

b. Pressure Survey: quasi-steady state pressure vs. depth after completion of well,

c. Pressure Drawdown Test: a series of bottomhole pressure measurements made during a period of flow at constant production rate. An extended drawdown should possibly be run to estimate reservoir volume. Also, transmissivity (the product of the average permeability and the thickness of the reservoir) and skin effects can be estimated.

d. Pressure Buildup Test: a series of bottomhole pressure measurements made just before and after the well is shut down. Information such as the transmissivity, skin effects and flow efficiency can be estimated to aid the prediction of future production rate and production life of the reservoir.

e. Flowrate and Enthalpy Measurements: continuous wellhead monitoring during production to determine flowrate, energy extracted and the quality of the fluids flowing out.

f. Geochemistry Analysis: further analysis of the chemical composition of the fluids produced.

g. Well Interference Test: if more than one hole is drilled, a well interference test should be run to determine the reservoir connectivity, directional reservoir flow pattern, and the nature and magnitude of an anisotropic directional reservoir permeability.

4. Reservoir Analysis and Formation Evaluation Interpretation: the petroleum industry has developed most of the above testing instruments and procedures. However, one cannot blindly use their methods to interpret the results of the tests to geothermal fields. A geothermal reservoir in general has a higher temperature than a petroleum reservoir. Furthermore, most of the petroleum reservoir analysis is based on isothermal conditions which is not true in a geothermal field. Whiting (25) and Ramey (19) have successfully demonstrated that the regular volumetric balance method in petroleum engineering does not apply to geothermal reservoir but rather a material and energy balance method is needed.

In the general sense, software encompasses both computer programs and the standard type curve analysis. It appears that the methods of analysis used in the petroleum and gas industries cannot be naively applied to geothermal systems. In most cases, 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-phase. Two-phase well prediction is an extremely challenging and fruitful area for research.

Well test analysis, though, can perhaps best be summarized by quoting Alex

Muraszew, writing on "Geothermal Resources and the Environment," in the 1972 GEOTHERMAL WORLD DIRECTORY (16),

> "....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 shown. The Stanford group has made admirable progress. A parallel laboratory study extending the work of Miller (17) and Cady (4) is being pursued at Stanford. The U.S.G.S. is devoting effort towards computer model studies with M. Nathanson, of the Menlo Park unit, beginning to publish. The University of Hawaii group is adding to this body of knowledge. The geo/hydrology group at California-Berkeley, has produced excellent computer models in this area.

In summary, the types of ongoing software analytical work include:

1. Prediction of performance and resource available from temperature and pressure data.
2. Reservoir simulation.
3. Well log analysis.

GEOTHERMAL RESERVOIR ENGINEERING: HARDWARE

Well tests are performed in two phases. In the first phase tests are performed during open hole drilling operations. They 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 zone. Measurements are taken both at the wellhead and downhole.

The following list outlines the hardware necessary to adequately measure a geothermal reservoir (8,9,13,15,20,21):

1. Subsurface formation condition

   a. Permeability

      1) Resistivity logs

      2) Core sampling

   b. Porosity

      1) Resistivity logs

      2) Core sampling

      3) Density logs

      4) Neutron logs

      5) Sonic logs

   c. Water saturation

      1) Resistivity logs

      2) Porosity measurements

2. Evaluation of well casing

   a. Inclination: deviation survey

   b. Cementing program: wellbore calipering

   c. Casing condition

      1) Casing calipering

      2) Sonic readings

3. Downhole fluid condition

   a. Pressure

      1) Amerada - Kuster RPG-3 gage

      2) Pressure transducer

      3) Gas purge tube with pressure element

   b. Temperature

      1) Expansion thermometer

      2) Resistance thermometer

3) Thermocouple

4) Geothermograph

5) Maximum registering thermometer

6) Temperature sensitive paint, metal, and ceramic pellets

c. Flow rate

1) Mechanical spinner

2) Electronic flowmeter

d. Fluid sampling

1) Kuster sampler

2) Schlumberger sampler

3) Gas purge tube with fluid sampler

4. Surface fluid condition

a. Pressure

1) Aneroid barometer

2) Mercury column

3) Glass manometer

4) Pressure recorder

b. Temperature

1) Filled thermal measuring systems

2) Resistance bulbs

3) Thermocouples

c. Flow rate (and enthalpy)

1) Separator, orifices, and weirs for separate vapor and liquid flow

2) Beta ray

3) Gas method

4) Magnesium sulfate injection

5) Critical lip pressure

6) Conductivity

7) Calorimetry

A quick recap of the more important downhole devices follows:

1. Formation evaluation (21)

   a. Electrical logs: This log determines the resistivity values of different formation areas invaded by the mud filtrate from drilling operations. The resistivity values are obtained by passing currents through the formation and measuring the voltages between inserted electrodes. The measured voltages provide the resistivity values; empirical relations have been derived to correlate resistivity to formation parameters such as permeability, porosity, and water content.

   b. Sonic logs: This technique measures the interval transit time, Δt, for an acoustic wave to travel through a certain depth of formation along a path parallel to the borehole. An empirical relation for determining porosity from sonic log is,

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta tf - \Delta t_{ma}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

   where Δtf = transit time in pore fluid and Δt_{ma} = transit time in rock matrix. The log works well for clean, compacted formations, but tends to ignore secondary porosity.

   c. Radioactive logs: Radioactive particles are emitted and detected by an emitter and a counter, respectively. The detector counter response gives an indication of formation porosity.

2. Fluid condition

   a. Pressure gages

1) Amerada-Kuster RPG-3 gage (13): This instrument consists of a helical bourdon tube connected to a bellows unit as shown in Figure 4A. The fluid pressure acts on the bellows unit which, in turn, activates a bourdon tube to scribe a line on a cylindrical chart driven axially by a clock mechanism: The gage is suspended from a stainless steel (s.s) wire passed through a seal at the wellhead. To keep the bourdon tube flexible, measurements are taken from the bottom of the well first. The gage is left at each depth for a period of time to stabilize itself with respect to pressure. Readings are generally taken about every 100 meters (330 ft). Dimension: 1 1/4 inch diameter X 6 1/2 feet length.

2) Pressure transducer: This pressure measuring device is shown in Figure 4B. These pressure readings are obtained by measuring the difference in pressure between two pressure-sensing elements spaced a certain distance apart. Dimension: 1 3/4 inch diameter X 15 feet length.

b. Temperature gages

1) Expansion thermometer: Pressure of vapors are used to record temperature changes by the use of a bourdon tube instrument. The recording apparatus is identical to the RPG-3 gage, and the pressure element is replaced by a temperature sensing bourdon tube.

2) Resistance thermometers: These instruments sense the changes in electrical resistance as changes in temperature occur. In general, there are two types: platinum wire (positive increase in resistance with increase in temperature)

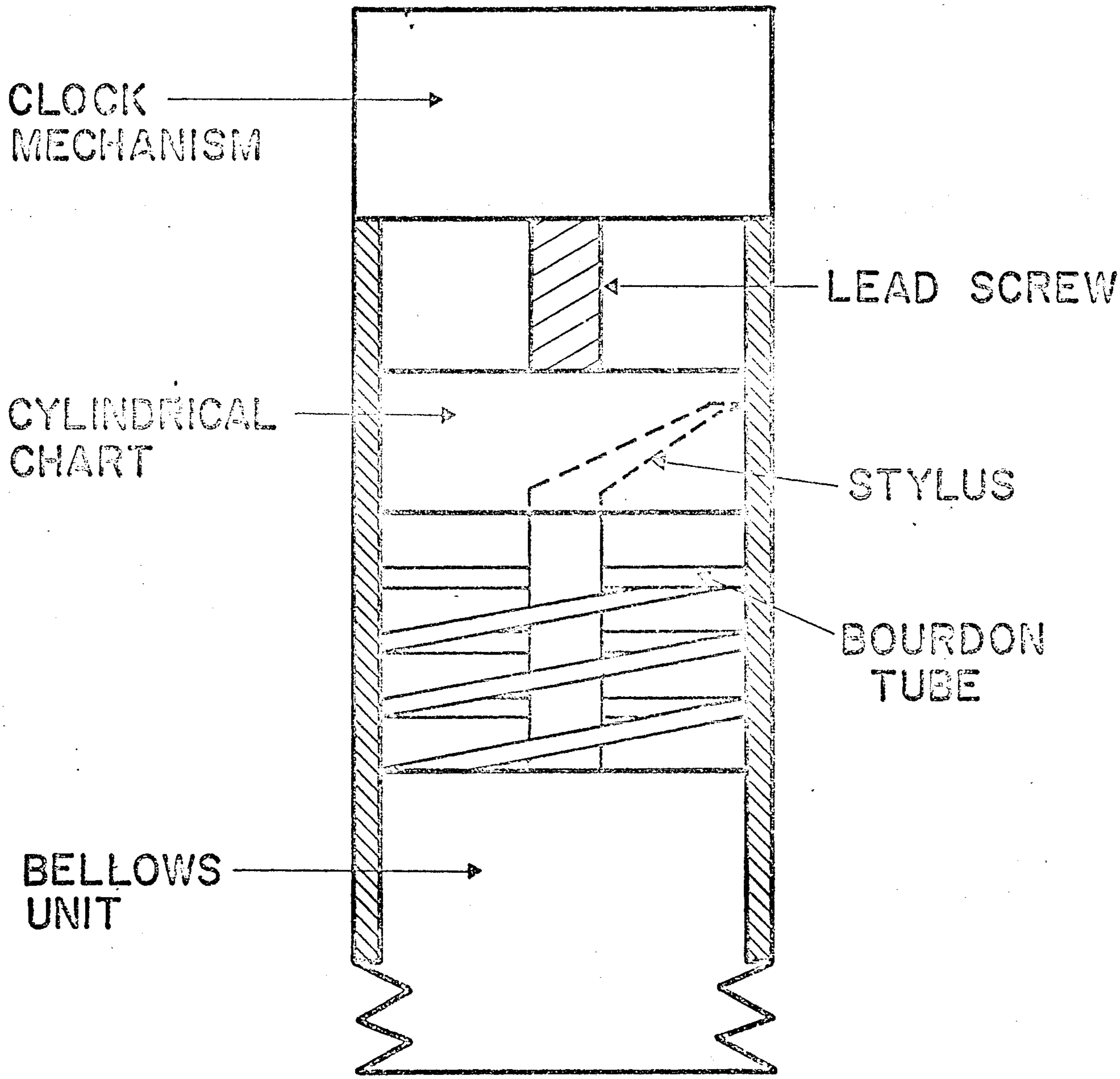

FIGURE 4A. RPG-3 PRESSURE GAGE

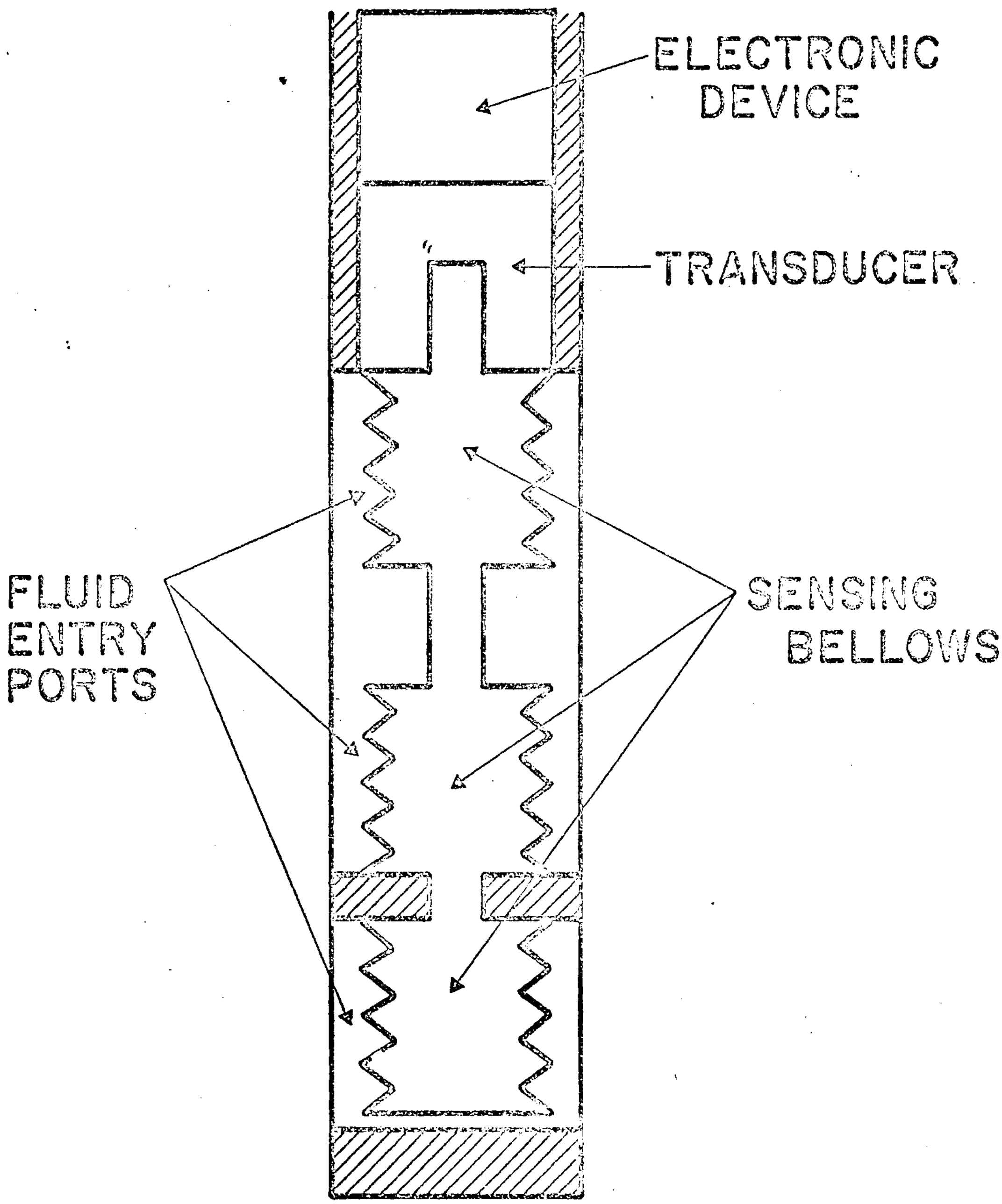

FIGURE 4B. PRESSURE TRANSDUCER

and thermistors. Measurements are taken by a direct deflection on a voltmeter or by an electrical balance adjusted by a potentiometer. Continuous recordings can thus be provided, but an elaborate winch assembly is required. Correspondingly, the cost is higher than for the bourdon type instruments.

d. Flow rate gages

1) Mechanical spinner: An outer housing encloses a rotor or spinner which is rotated by the fluid velocity. A magnet attached to the rotor causes a similar movement of a corresponding gear reducer magnet. This motion is transmitted through a rotary translator to a stylus shaft. The translator converts rotary motion to small deflections in the shape of an arc. A stylus assembly then, transmits the arc movement to a recording chart. The recording mechanism is identical to the RPG-3 gage, with the spinner replacing either the pressure or temperature element. Dimension: 1 3/4 inch diameter X 2 feet length.

2) Electronic Flow meter: The spinner device is similar to the mechanical type except for the translator. It is replaced by a small magnet attached to the spinner shaft which causes an alternating current to be generated in an adjacent pickup coil, as shown in Figure 4C. The frequency of this current is measured and recorded by a surface recorder which gives the flow rate of the fluid. Dimension: 1 3/4 inch diameter X 5 feet length.

In fluid measurement the data obtained from one particular downhole

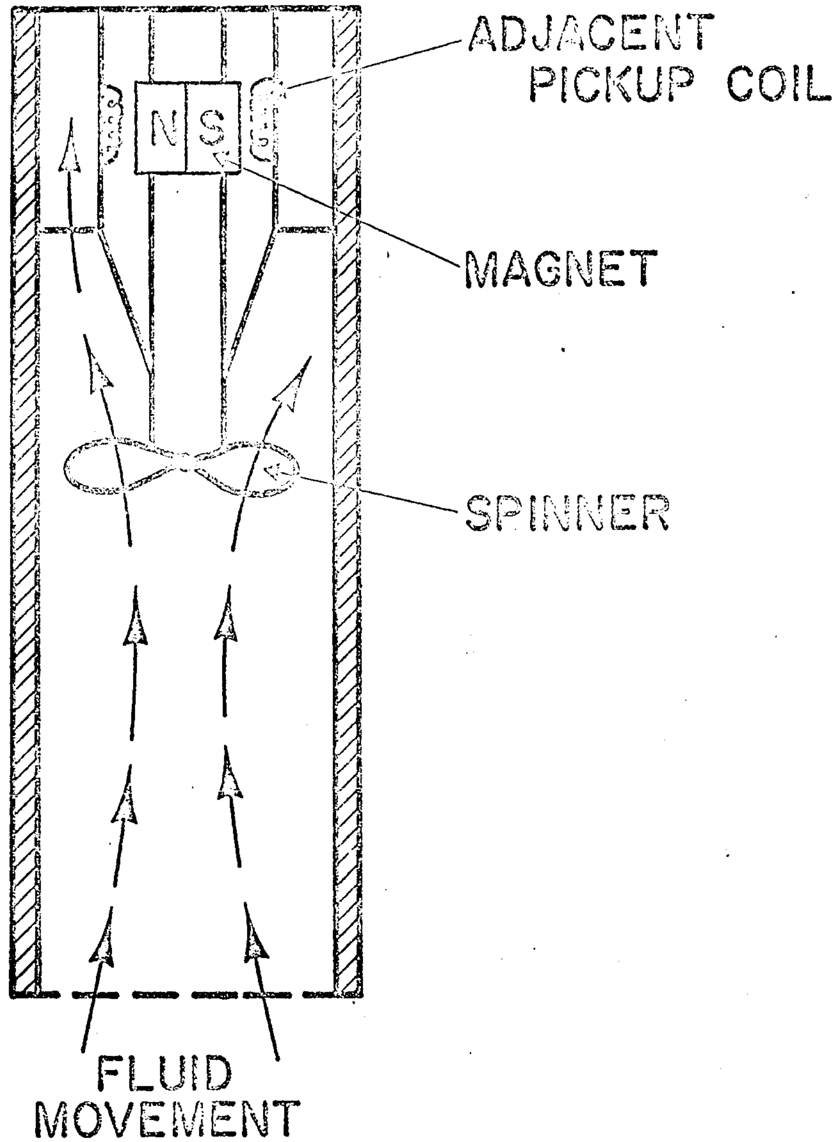

FIGURE 4C. ELECTRONIC FLOWMETER

instrument is not always reliable due to its operational characteristics. Combined readings from two or more instruments for a certain parameter are desirable 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-verifies the input data and results, and determines automatically the various parameters that are required.

WHAT IS A GEOTHERMAL RESERVOIR ENGINEER?

To obtain an appreciation of the field of geothermal reservoir engineering, a quick attempt at defining what is a geothermal reservoir engineer (GRE) is appropriate. The diversity of functions the GRE is expected to perform makes it imperative that he has a multi-disciplinaried 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 knows a little bit about 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 chemist's knowledge of chemical properties and electrical conductivity - the mechanical engineer's grasp of the associated hardware - the chemical engineer's acquaintance of reservoirs - the civil engineer's familiarity of flow through porous media - the mathematician's flexibility with numerical analysis and computer programming - the lawyer's understanding of the legalities - and the economist's overview of the fiscal matters.

A GRE must be trained. The ideal starting point is an engineer who has had exposure to petroleum well testing and analysis. If reservoir experience has been nil, a reasonable training program would involve 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 above training, the prospective GRE should acquaint himself with the following publications:

1. Joseph Barnea, "Geothermal Power," *SCIENTIFIC AMERICAN*, Vol. 226, January, 1972.
2. H. Christopher Armstead, Editor, *GEOTHERMAL ENERGY*, UNESCO, Paris, 1973.
3. Paul Kruger and Carel Otte, *GEOTHERMAL ENERGY*, Stanford Press, 1973.
4. B. C. Craft and M. F. Hawkins, *PETROLEUM RESERVOIR ENGINEERING*, Prentice-Hall, 1959.
5. C. S. Matthews and D. B. Russell, *PRESSURE BUILDUP AND FLOW TESTS IN WELLS*, Society of Petroleum Engineers of AIME, 1967.
6. *NEW SOURCES OF ENERGY, PROCEEDINGS OF THE CONFERENCE*, Rome, 21-31 August, 1961, Vol. 2 and 3.
7. *GEOTHERMICS* (All proceedings and regular publications)
8. American Petroleum Institute, *WELL TESTING*.
9. American Petroleum Institute, *WIRELINE OPERATIONS AND PROCEDURES*.

If a more comprehensive formal course on geothermics is desired, Japan has a three month course and Italy has one that lasts for nine months. Both courses are taught in English.

So 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 is one who always knows less than the individual specialists on a given topic, but because he can bring perspective into the picture, he is a necessary interfacer, integrator, and synthesizer.

GEOTHERMAL RESERVOIR ENGINEERING - A RESEARCH PLAN

As the field of geothermal reservoir engineering is just beginning to develop, it is important that a firm research base be established. The Hawaii Geothermal Project, a multidisciplinary research program of the University of Hawaii, has in the specific case of geothermal reservoir engineering, consolidated several diverse research investigations into a unified systems study. Figure 5 depicts the organizational plan.

The geothermal reservoir engineering research team is composed of three sub-task groups: computer modelling, physical modelling and geothermal well testing/analysis. All three sub-tasks have the ultimate goal of predicting the performance of producing geothermal fields. The computer modelling group will use a mathematical model approach, the physical modelling group will scale model a geothermal system and the testing/analysis group will evaluate existing geothermal and petroleum/gas hardware and software techniques with the aim of synthesizing optimal measurement and prediction alternatives.

1. Computer modelling

The two objectives of the computer modelling 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

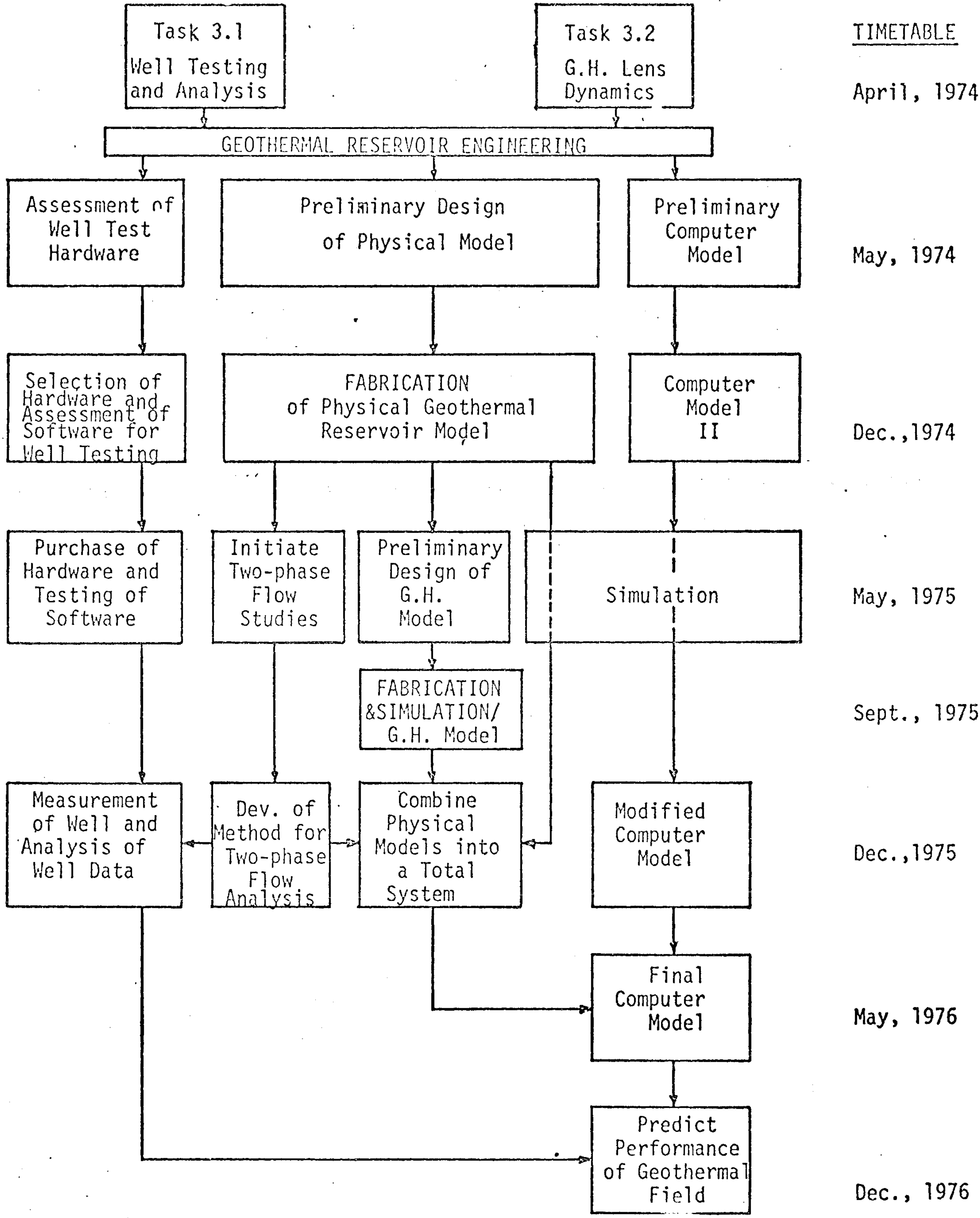

FIGURE 5. ORGANIZATIONAL PLAN FOR THE TASK ON GEOTHERMAL RESERVOIR ENGINEERING

lens. Specifically, the initial phase of the work has focused on free convection in a coastal aquifer with geothermal heating from below.

A technical discussion of this work, conducted by Ping Cheng and Kah Hie Lau, is being prepared for publication. In summary, a set of finite difference equations were derived and a computerized numerical solution was obtained using a perturbation method.

Figure 1 is a speculative cross-sectional view of the island of Hawaii. The computer study simplified the 1 1/2 inch mile deep by 72 mile diameter 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 sea water 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; 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.

2. Physical modelling

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 math 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 parametric tests.

Very little physical modelling work has been reported in the literature. The significant studies related to geothermal reservoirs include those of G. Cady (4), H. Henry and F. Kahout (11), and the remotely related work of J. Bear (2). However, none of the reported investigations approached the problem on a total systems basis while considering the high (1100°C for magma, 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 (N_{Ra}). The Rayleigh Number is the product of the Grashof (N_{Gr}) and Prandtl (N_{Pr}) Numbers, where

$$N_{Gr} = \frac{\text{buoyant force}}{\text{viscous force}} \qquad (2)$$

$$N_{Pr} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} \qquad (3)$$

$$N_{Ra} = N_{Gr} \cdot N_{Pr} = \frac{\rho_s g \beta K (T - T_s) h}{\mu \alpha} \qquad (4)$$

where 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,

α = thermal diffusivity of fluid.

The literature is sparse on the range of Rayleigh Numbers meaningful to actual geothermal systems. In general the study will investigate the range of N_{Ra} between 30 and 1000. This will be accomplished 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 diffusity (α), viscosity (μ), and density (ρ) of the fluid.

CONCLUSIONS

A comprehensive survey into the "state-of-the-art" of geothermal reservoir engineering has resulted in a report which laments the general lack of hard quantitative information available. The presentation has taken the form of a survey paper. Discussed were topics treating the nature of a geothermal reservoir, parameters requiring measurement in a geothermal well, hardware and software required for well test and analysis, and a section which makes quick orientation to the field of geothermal reservoir engineering possible.

The report also presented the research plan and accomplishments of a recently established geothermal reservoir engineering group within the Hawaii Geothermal Project. The approach will be a total system study of the subject. Developmental work is progressing in computer simulation, physical models, and well test analysis.

The international flavor of this topic generally compounds the difficulties experienced in a literature survey. A comprehensive list of references is attached. Particular note can be made of the large number of articles originating from New Zealand.

The field of geothermal reservoir engineering will show significant progress during the next few years. The progress will be an accelerated one because of improved international communications, the availability of computers, and the possible threat of another energy crisis, which has resulted in the release of funds for research and development in this area.

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APPENDIX II. INTERNATIONAL QUESTIONNAIRE

Over twenty replies were received from companies, institutions, and government agencies from most of the prominent geothermal energy countries. While some of the responses were received through oral communication, the majority of them were in the form of personal 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.

TABLE 2. RESPONSES TO INTERNATIONAL QUESTIONNAIRE

NAME AND AFFILIATION	WHAT IS THE NATURE OF A GEOTHERMAL RESERVOIR	WELL TESTING AND ANALYSIS: HARDWARE	SOFTWARE
B. C. McCabe Magma Power Company USA	In geothermal reservoir engineering, the theoretical information to determine the size or longevity of a geothermal field is a very inexact science. For steam and hot water reservoirs, no one knows what the % of replaceable heat is coming into the reservoir 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 USA	Geothermal fluids consist of two components: 1) meteoric water and 2) gases (H_2S and CO_2), rising from great depths. The mixture of the components occur 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 USA	Geothermal fields are composed of: 1) a deep sequence of layers, heated by an underlying magmatic stock and which, in turn, heats the overlying porous strata, and 2) 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 3) an impermeable layer over the reservoir.	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)

W. E. Allen Oil and Gas Conservation Commission (Arizona) USA	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 avaialble.	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: 1) sedimentary fields and 2) 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.