TABLE I

SPECIFIC RESEARCH RECOMMENDATIONS FOR THE DEVELOPMENT OF GEOTHERMAL ENERGY

	BASIC RESEARCH						MY/YR	APPLIED RESEARCH						MY/YR	TECHNOLOGY DEVELOPMENT						MY/YR
	HYDROTHERMAL		GEOPRESSURED		HDR			HYDROTHERMAL		GEOPRESSURED		HDR			HYDROTHERMAL		GEOPRESSURED		HDR		
	S	P	S	P	S	P		S	P	S	P	S	P		S	P	S	P	S	P	
Hydrothermal Evolution of Geothermal Systems																					
a) Depth of circulation of water in hydrothermal systems	2	2	2	2	2	2	1	2	2	2	1	2	1	1	2	1	2	1	2	1	1
b) Formation of geopressured reservoirs	NA	NA	3	3	NA	NA	1	NA	NA	3	3	NA	NA	1	NA	NA	2	2	NA	NA	1
c) Effect of tectonic stresses and activity on permeability including statistics and distribution of connected cracks near faults	3	2	3	2	3	2	3+	3	2	3	2	3	2	3	3	3	3	3	3	3	3
d) Convection and recharge in geothermal reservoirs - favorable sites and depths for reinjection of cooled geothermal fluids	3	3	3	3	3	3	3+	3	3	3	3	3	3	3	3	2	3	2	3	1	2
Development of New and Improved Geophysical Probes																					
a) Deep seismic soundings (improve resolution at great depths)	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2
b) Deep magnetic, electric and electromagnetic soundings (relation of earth stress to asymmetries in resistivity at depth)	2	2	2	2	2	2	2	2	1	2	1	2	2	2	2	2	2	2	2	2	1
c) Study of short and long period variations in altitude of continental surface (satellite techniques for measuring surface inflation or deflation)	2	2	2	1	2	2	4	2	2	NA	NA	2	2	3	2	2	NA	NA	2	2	2
d) Study of short and long period variations in horizontal position or differential position (earth strain) on continental surface	2	1	2	1	2	1	4	2	1	NA	NA	2	1	3	2	2	NA	NA	2	2	2
d) Application of seismic techniques to 3-d fracture maping	3	2	3	2	3	2	4	3	2	3	2	3	2-	3							0
e) Three-dimensional stress measurements as a function of depth in deep boreholes	3	1	3	1	3	3	3	3	1	3	1	3	1	2	3	1	3	1	3	3	2

TABLE I (continued)

	BASIC RESEARCH						MY/YR	APPLIED RESEARCH						MY/YR	TECHNOLOGY DEVELOPMENT						MY/YR
	HYDROTHERMAL		GEOPRESSURED		HDR			HYDROTHERMAL		GEOPRESSURED		HDR			HYDROTHERMAL		GEOPRESSURED		HDR		
	S	P	S	P	S	P		S	P	S	P	S	P		S	P	S	P	S	P	
Physical Properties and Behavior of Rock-Fluid Samples at Elevated Temperatures and Pressures																					
a) Metamorphism (dissolution, recrystallization, diffusion)	3	3	NA	NA	3	3	3	2	2	NA	NA	2	2	2	2	2	NA	NA	2	2	2
) Sealing of cracks conditions, mechanism, time cale)	3	3	2	1	3	3	3	3	3	2	2	3	3	2	2	2	2	2	2	2	2
) Study of magma-water system vapor pressure, diffusion ates, phase changes vs. H20 ontent, pressure and emperature)	2	2	NA	NA	2	2	2	2	1	NA	NA	2	1	1	2	1	NA	NA	2	1	1
) Mechanisms involved in oling of magmatic intrusions ncluding development of ydrothermal circulation ystems	2	3	NA	NA	2	3	3	2	3	NA	NA	2	3	3	2	1	NA	NA	2	1	2
Geochemical thermometers	3	2	2	2	3	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	1
Physical and chemical teractions of gases in stems	1	2	1	2	1	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	1
Phenomenology and kinetics precipitation of CO_3 heavy metal sulfides and O_2 from geothermal brines	2	3	NA	NA	2	2	2	2	3	NA	NA	2	1	2	2	1	NA	NA	2	1	1
Elimination of plugging nomena in reinjection, luding mechanisms of bridging formation of filter cakes by ll particles, and ectiveness of chemical itives	3	3	3	3	3	1	2	3	3	3	2	3	1	2	3	3	3	1	3	1	2

TABLE I (continued)

	BASIC RESEARCH							APPLIED RESEARCH							TECHNOLOGY DEVELOPMENT						
	HYDROTHERMAL		GEOPRESSURED		HDR		MY/YR	HYDROTHERMAL		GEOPRESSURED		HDR		MY/YR	HYDROTHERMAL		GEOPRESSURED		HDR		MY/YR
	S	P	S	P	S	P		S	P	S	P	S	P		S	P	S	P	S	P	
chanics																					
icture toughness vs. rock structure, temperature	3	2	2	1	3	3	4	2	1	2	1	2	3	3	2	1	2	1	2	1	2
fects of pore pressure on re behavior	2	1	2	1	2	3	2	2	1	2	1	2	3	2					2	2	1
fects of rock structure and condition on drilling ions	3	3	3	3	3	3	2	3	3	3	3	3	3	2	3	3	3	3	3	3	2
eep and stress relaxation ictions of T, P, and rock	3	1	3	1	3	2	4	3	1	3	1	1	2	3	3	3	3	3	3	3	3
irge volume experimentation imens = 1m)	3	3	3	1	3	3	4	3	3	3	1	3	3	3	3	3	3	1	3	3	3
ffects of rock structure and s condition on fracture tation and shape	2	3	1	2	2	2	2	2	3	1	2	2	2	2	2	3	1	2	2	2	2
ing and Completion iology																					
Improved drilling methods	NA	NA	NA	NA	NA	NA	0	3	2	3	3	3	3	4	3	2	3	3	3	3	4
Improved high temperature ctional drilling	2	2	1	1	3	3	2	2	1	1	1	3	3	2	2	1	1	1	3	3	2
Improved reliability of hole pumps (t > 200°c)	NA	NA	NA	NA	NA	NA	0	3	2	NA	NA	3	3	2	3	2	NA	NA	3	3	2
rvoir Confidence																					
Improved reservoir engineer- and assessment technology	2	2	3	3	3	3	4	2	2	3	3	3	3	4	NA	NA	NA	NA	NA	NA	0

Examples of unique phenomena applicable to geothermal energy systems are presence or movement of magma within a few kilometers of the surface, weak seismic signals from thermal-stress cracking, thinning of the crust in regions of extension, and temperatures above the Curie point at shallow depths. Geophysical effects from all these phenomena have been detected, but have not yet been widely employed for geothermal exploration. Corresponding geochemical phenomena are isotope ratios in rocks and water as well as new information deduced from the concentrations of chemical species. Recent developments in both geophysics and geochemistry are given by White and Guffanti.[26]

VI. SPECIFIC RESEARCH RECOMMENDATIONS

A. Introduction

Table I lists specific research suggestions grouped in seven areas: 1) Fundamental Geological Studies, 2) Hydrothermal Evolution of Geothermal Systems, 3) Physical Properties, 4) Development of New Geophysical Tools, 5) Rock Mechanics, 6) Drilling and Completion Technology, and 7) Reservoir Confidence. Each general research area includes specific research needs. Each specific need is evaluated according to basic research, applied research, and technology development needs. We estimate for each, current status of research (S) and priority of need for new research (P). In these estimates "1" indicates best understanding and least need; "3" indicates poorest understanding and greatest need. We emphasize that every research need in the table is important, but some are more important than others. Finally, we estimate the requirement to fulfill the needs in each category in man years per year. In an attempt to constrain the size of a potential research program, we give conservative manpower requirements. Note however that for basic research alone in one year, needs exceed 80 man years. This evaluation exhibits both the magnitude of the problems attendant with development of geothermal energy and the extent of the need for research and development. We estimate manpower needs for five years. For example, the needs for regional isotherm analysis of available aeromagnetic and magnetotelluric data for hydrothermal, geopressured, and hot dry rock geothermal totals

IV. ROCK-WATER INTERACTIONS

Basic research in chemical interactions between hot water and rock provides valuable tools for understanding natural hydrothermal systems. Several geothermometers exist.[19-20] The silica geothermometer is based on measurement of the concentration of silica in water from hot springs, the assumption that these concentrations arise from solution equilibrium between the water and quartz in the rock at the reservoir temperature, and that it is unchanged as the water rises to the surface. Geothermometer data have been used to locate fourteen producing geothermal wells in the Central Philippines.[21]

Scaling and corrosion are the principal obstacles in development of liquid-dominated geothermal reservoirs. Scale is principally composed of silica, carbonates, metal sulfides or sulfates, or mixtures of these. It is usually formed by loss of CO_2 (which changes the pH), concentration of dissolved materials by flashing, or by changes in temperature of the fluid. Methods of scale control such as injection of acids or organic scale inhibitors, use of binary cycles to prevent flashing, and development of fluidized bed heat exchangers[22] are currently under study. Corrosion is due to high-temperature fluids with high-chloride or hydrogen-sulfide content combined with low pH and high oxidation potential. Methods for the control of corrosion in geothermal systems exist,[23-24] but much research remains to be done to achieve understanding of corrosion mechanisms.

V. GEOPHYSICAL AND GEOCHEMICAL EXPLORATION

Various geophysical measurements are applied in exploration for hydrothermal systems. New Italian geothermal fields at Cesano, Torre Alfina, Bagnore, Piancastagnio and Poggio Nibbio, all without surface manifestations, were discovered by exploration techniques including reflection seismic surveys, gravity contouring, resistivity surveys, and measurement of geothermal gradient in shallow boreholes. Wells were successfully drilled in the region of highest heat flow.[25] Geophysical exploration techniques were developed originally for petroleum and mining exploration and well logging. In geothermal exploration some anomalies of interest, such as low resistivity at depth, may or may not arise from hot water or brines.

TABLE I (continued)

	BASIC RESEARCH							APPLIED RESEARCH							TECHNOLOGY DEVELOPMENT						
	HT		GP		HDR		MY/YR	HT		GP		HDR		MY/YR	HT		GP		HDR		MY/YR
	S	P	S	P	S	P		S	P	S	P	S	P		S	P	S	P	S	P	
<u>Fundamental Geological Studies on the Cause and Distribution of Elevated Isotherms within the North American Plate</u>																					
a) Regional Curie isotherm analysis of available aeromagnetic and magneto-telluric data	3	2	2	1	2	3	3	2	3	1	1	3	3	3	3	1	3	1	3	1	2
b) Conduct deep crustal seismic reflection surveys using shear wave or combined compressional and shear wave vibrators	1	2	1	1	1	2	COCORP	1	2	1	1	1	2	COCORP	1	1	1	1	1	1	COCORP
c) Using distant and regional earthquakes, map seismic velocity and attenuation variations, with attention to depth to Moho	3	3	3	3	2	3	2	1	2	1	2	1	2	1	2	1					
d) Study of relationship between gravity surveys and regions of anomalous heat flow	2	3	3	1	2	3	1	2	3	3	1	2	3	1	2	1	3	1	2	1	1
e) Map contours of saturation temperature using geochemical thermo metric data	1	3	3	1	3	1	2	1	3	3	1	3	1	2	3	1	3	1	3	1	2
f) Age-date youthful volcanic events	1	1	NA	NA	1	1	1	1	1	NA	NA	1	1	1	1	1	NA	NA	1	1	1
g) *Study distribution of* radioactivity in plutons. and sediments	1	1	NA	NA	1	3	1	1	1	NA	NA	1	3	1	1	1	NA	NA	1	1	1
h) Emplacement mechanisms of igneous intrusions.	3	3	NA	NA	3	3	3	2	2	NA	NA	2	2	2	2	2	NA	NA	2	2	2

EXPLANATION:

S = Status = where we are
P = Priority = what we need
3 = poorest understanding (status), greatest need
2 = moderate understanding, moderate need
1 = best understanding, least need
NA = not applicable

point concerning the research and development outlined in the table is that much of it has high potential for technology transfer. Many of the problems associated with development of geothermal energy are those related to other energy technologies; for example, waste management or the development of fossil fuels. Furthermore, most of the proposed research constitutes high-quality basic research.

B. Fundamental Geological Studies

Emphasis here is on basic research. We stress the need for use of new geophysical techniques to map thermal anomalies, especially in the crust. Geophysical exploration is especially vital to geopressured technology. Of greatest importance to hydrothermal and hot dry rock geothermal is an understanding of emplacement mechanisms of igneous intrusions. We need more research and development on regional Curie isotherm analysis of available aeromagnetic and magnetotelluric data. We expect the Consortium for Reflecting Profiling (COCORP) to continue to conduct important deep crustal seismic reflection surveys, some of them in prospective geothermal terrain.

C. Hydrothermal Evolution of Geothermal Systems

Here R and D needs consist of three topics common to all geothermal technologies: 1) ground-water circulation, 2) effect of tectonic stresses on permeability, 3) convection and recharge. We see the latter two as the most important and requiring the most manpower, especially in basic and applied research. Understanding the formation of geopressured reservoirs is vital to that technology, but we believe it requires less manpower inasmuch as geopressured zones are becoming more interesting for the gas they contain and less so for their potential thermal development.

D. Physical Properties and Behavior of Rock-Fluid Samples at Elevated Temperature and Pressure

Four research needs are common to all geothermal technologies: 1) sealing of cracks, 2) development of geothermal thermometers, 3) physical and chemical interaction of gases in systems, and 4) elimination of plugging phenomena. Clearly the last problem is the most important of the four.

Estimates of the recoverable geothermal and methane energy are 2800×10^{18} J and 1640×10^{18} J, respectively.[16] These estimates are uncertain because of lack of production experience in geopressured wells, and lack of knowledge of the in situ permeabilities of undercompacted sandstone and shale, especially as fluid pressure drops during production.

C. Conductive Systems

Hydrothermal convective systems, discovered and undiscovered, may contain only one percent of the 10^{24} J of igneous-related geothermal energy present to a depth of 10 km[17]; much of the remainder must be locked up in relatively dry rock. About 3×10^{25} J may reside in rock showing no recent igneous activity, at depths above 10 km.[17] A hot dry rock experiment has been carried out in which approximately 5 MWT was extracted for 75 days, with negligible water losses, from impermeable crystalline rock at the Fenton Hill site near Los Alamos, New Mexico.[18] The prospect for several times this much power for 20 years or more from a single pair of wells is promising and is being actively investigated. Artificial geothermal systems will be of many kinds, depending on permeability of the rock and fluid pressure in its pores. These reservoirs will range from high-pressure circulation systems in very impermeable rock to hot water convective systems with reinjection of all the extracted fluid, which may equally well be called stimulated hydrothermal systems. Since these reservoirs will be constructed (and, ideally, engineered), new methods of securing information about reservoir rock and growth of the reservoir are needed. Knowledge of directions and magnitudes of principal earth stresses, joint patterns, pore-fluid pressure, rock permeability and temperature gradient would be useful in the initial design of an artificial reservoir, and knowledge of fracture shape and fluid flow paths is needed during operation.

When rock cools it undergoes thermal stress cracking, which may enlarge artificial reservoirs and extend their life almost indefinitely. Study of this process and where it occurs in nature (i.e., in "lava lakes" near active volcanoes, in near-surface intrusions and at oceanic ridges) may be valuable in designing artificial geothermal reservoirs.

with present U.S. electric power consumption of 250 000 MW and total yearly energy use of 80 x 10^{18} J[14], hydrothermal systems may supplement U.S. energy needs, but are not a long-term answer.

Some hydrothermal systems have been extensively studied. A good example is the Taupo geothermal district in New Zealand. This region, in an area of 2500 km^2, contains two major hydrothermal areas, Waiotapu and Wairaki, plus a number of small ones, and has an average heat flow about 35 times the world average.[15] Geological evidence shows that this activity persisted for more than one million years. This reservoir is driven by a magmatic intrusion, which lies within a few kilometers of the surface.

B. Geopressured Systems

These systems are differentiated from hydrothermal systems in that no natural fluid convection system exists. However, sufficient fluid may be present in the rock, and the rock permeability may be high enough, so that heat may be extracted from the rock for extended periods simply by drilling into the reservoir. By definition, a geopressured rock contains fluid at pressure greater than would exist at the same depth in a column of water extending to the surface, i.e., hydrostatic pressure.

Geopressured reservoirs of interest for geothermal energy occur near the Gulf Coast in Texas and Louisiana. Reservoir rocks were deposited as sediments in river-bed, delta and marine environments, resulting in intermixtures of sandstone and shale rocks. When expulsion of pore fluids from the sandstones is restricted (the shales are almost impermeable), fluid pressures above hydrostatic arise from compaction and from alteration of the shale by heat and pressure. The water temperature may be in the range 100-200°C, depending on location and depth. The water is saturated with methane, so three kinds of energy are theoretically available from a well--kinetic, thermal, and chemical. Because there is essentially no convective heat loss from a geopressured reservoir, and reservoirs are overlain by sediments of low conductivity, it is not necessary to postulate intrusive volcanic rocks as heat sources for the geopressured reservoir--the heat may have been deposited by normal heat flow over tens of millions of years. However, the depth to a given isotherm varies by a factor of two over the geopressured region[16] and study of the origin of the heat may be fruitful.

low-temperature metamorphism, magma-water systems, mechanisms involved in magma cooling, and phenomenology and kinetics of precipitation of carbonates, sulfides, and silicates from brine. Many of these geochemical research needs have strong technology transfer potential, especially to the needs in waste isolation.

E. Development of New and Improved Geophysical Probes

"The greatest technological challenge, aside from high-temperature technology, is to obtain natural-state information by drilling, sampling, and testing with minimum effect on the formation and formation fluids."[27] This statement taken from the NAS "Continental Scientific Drilling Program" text also expresses the need in geothermal. Other recent reports come to the same conclusion regarding research and development required for new and better geophysical nondestructive tools and remote sensing devices.[28,29] Furthermore, many geophysical tools cannot operate for long periods at temperatures much above 200°C in an aqueous environment. There is special and immediate need for equipment designed to function in the temperature range 200°C to 350°C.

Two of the most important needs are improved application of geophysical techniques to map flaws in rock (fractures, faults, joints) remotely and three-dimensionally. This particular research and development requirement is common to waste isolation and fossil fuels as well. Another vital need is research to develop better methods for taking reliable three-dimensional stress measurements in the field, especially downhole in boreholes. Understanding the state of stress in the earth's crust is poor and must be upgraded.

We recommend research and development using satellite techniques and imagery to study short- and long-period variations in altitude and horizontal position of the continental surface. These studies should assist us to understand fundamental tectonic mechanics now affecting continental movements. Geodynamics in the 1980s[30] will focus on crustal dynamics with emphasis on origin and evolution of continental crust, the continent-ocean transition, relation of mantle dynamics to crustal dynamics, and a framework for understanding resource systems and natural hazards.[27,30,31] All of these research areas are vital to community, the Department of Energy possesses a unique opportunity to gain for its energy technology requirements great dividends through encouraging and supporting the proposed research in continental geodynamics.

F. Rock Mechanics

Several recent publications examine research and development needs in rock mechanics specific to energy technologies.[28,32,34] Again, many needs in waste isolation and fossil fuel development are exactly those in geothermal energy. We do not completely understand the physics of fracture, especially in hot rock. How does fracture toughness vary with rock type? How does pore pressure affect fracture behavior, creep and stress relaxation behavior of rocks at high temperatures for long periods of time? What are the effects of rock structure and stress condition on fracture orientation and shape? A particular problem associated with deep drilling in hard rock concerns effects of rock structure and stress on drilling deviation.

Many energy technologies--including geothermal--require facilities for large volume experimentation on instrumented samples as large as 1 m in diameter. Advantages of large volume experimentation include: 1) substitution for <u>in situ</u> tests, 2) ability to examine scale-dependant effects, i.e., mechanisms which manifest only in large samples, 3) potential to study effects of flaws in blocks so large the flaw scale becomes small, 4) validation of small scale tests as a link to field observations, and 5) simultaneous measurements. Perhaps the most compelling reason for performing large volume tests is the control a researcher obtains in a laboratory experiment as compared with its field alternative.

Most energy-related rock properties such as thermomechanical, failure criteria, porosity, permeability, and chemically induced effects could be examined with simultaneous measurements in large volume apparatus and supporting facilities. Appropriate loading frames exist at several federal facilities. New apparatus is not required for this research; however, funding support for people, facilities and modifications is required.

G. Drilling and Completion Technology

B. Convective Transport

The depth to which water penetrates the crust is uncertain. In tectonically active regions water-filled cracks may extend to 10 km.[9] Although fractures probably seal rapidly from mineral transport and deposition at water temperatures above 300°C,[10] new fractures form by tectonic activity to maintain access to heating zones and to provide permeable reservoirs for storage of hot fluid.[11]

The lithosphere is a poorly defined region above the partial melt zone, in which the mantle and crust behave as a solid. Its thickness is 150-200 km under continents, and nonradiogenic heat must penetrate this region to supply a hydrothermal field. If conduction and water convections are limited to a few kilometers, some other mechanism must be invoked. Association of known hydrothermal fields with volcanism suggests that the mechanism is "penetrative convection" of magma,[12] in which a bubble (perhaps many kilometers wide) of magma rises from a region of the mantle in which the temperature has been temporarily raised by some undefined process (e.g., subductive friction). After some millions of years, during which complicated processes such as crustal melting, stoping, and recrystallization at the base of the bubble occur, the bubble rises high enough to begin to supply heat to a hydrothermal system above it, perhaps with an intervening region of conductive transport. This process may not be necessary to formation of warm water reservoirs with little surface manifestation, but must apply to large hydrothermal reservoirs like the Taupo district of New Zealand, described below.

III. GEOTHERMAL RESERVOIRS

A. Hydrothermal Systems

The term "geothermal energy" is almost synonymous with hydrothermal energy--other types of reservoirs are under development, but are unproven. In the U.S., geothermal energy produces about one one-thousandth of the total electric power production. A recent estimate of the energy recoverable from known and undiscovered hydrothermal reservoirs at temperatures above 90°C and depths above 3 km is 2400 x 10^{18} J, which could contribute 100-150 MW of electricity for 30 years, together with 230-350 x in the Atlantic Coastal Plain that derive their heat from buried granitic plutons, or of artificially creating reservoirs in granitic ranges such as the White Mountains of New Hampshire. Many questions remain as to the general applicability of this exponential distribution in rocks of various kinds with various emplacement histories; do some regions exist where the heat flow is not linear with surface radioactivity?

II. TRANSPORT OF GEOTHERMAL ENERGY

Volcanoes provide impressive evidence that the earth's internal heat may sometimes emerge at the surface at a very high rate. Large hydrothermal areas with surface manifestations of steam and hot water also require heat fluxes much greater than normal to support them. These two phenomena typify the two main aspects of a natural hydrothermal system: first, transfer of heat from the mantle into the upper part of the crust, and second, transport of heat within this upper region. Sensible heat may be transferred by conduction or by convection of water or molten rock, so we must examine these processes separately and relate them to various geothermal energy systems.

A. Conductive Transport

Rocks are good thermal insulators with high heat capacity, so it is difficult to extract heat from a large body of rock. Thermal conductivity, k, of a typical crystalline rock is 3 W/(mk). Thermal diffusivity, n, is k/(p c), where p is the density and c the specific heat per unit mass. Typical values of p and c for crystalline rock might be 2700 kg/m^3 and 1000 J/(kg K) making n- 1.1 x 10^{-6} m^2/s. The distance, L, from which heat can be extracted by conduction in time, t, is $L - \sqrt{nt}$. Values of L for t = 1 year, 100 years, 10^4 years and 10^6 years are 6 m, 60 m, 600 m and 6 km, respectively.

The mean geothermal flux over the whole earth is 0.06 W/m^2. The temperature gradient corresponding to the flux is 20 K/km in crystalline rock. A heat flux much greater than the mean, if sustained by conduction alone, requires correspondingly higher temperature gradients, with very high temperatures at the base of the crust. Mechanisms other than simple conduction must operate in regions of abnormal heat flow.[8]

include improved drilling methods, improved high temperature directional drilling, and increased reliability of downhole high-temperature pumps. Emphasis here is not, however, on basic research, but rather on applied research and technology development.

H. Reservoir Confidence

Improvements are needed in reservoir engineering and assessment technology. These improvements may arise from development of better and more sophisticated computational models to more accurately characterize reservoir potential and behavior with time upon resource extraction. Research of this type would immediately benefit many other energy and mineral extraction technologies.

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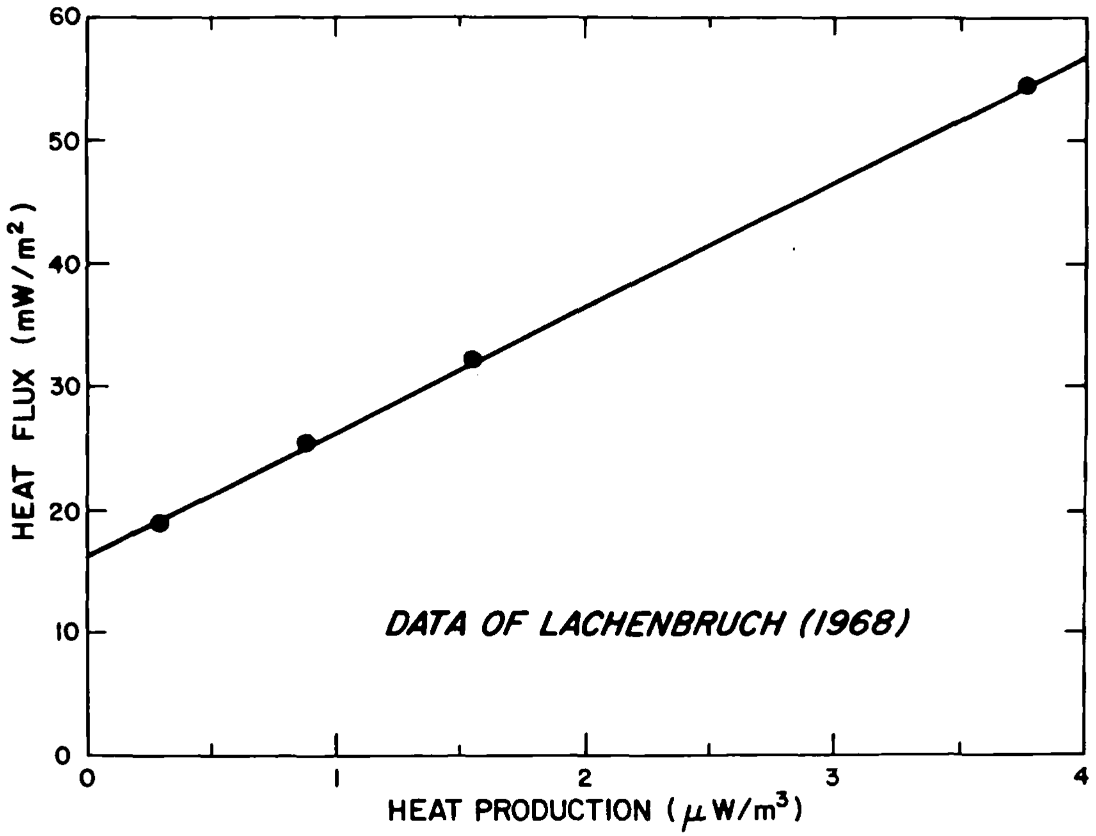

Fig. 1. Plot of heat flow vs heat production in surface rocks. Figure shows linear relation with a finite value of heat flow at zero heat production (after Lachenbruch, 1968).

distance in which the heat generation falls by a factor of e. From Fig. 1, D = 10 km in the central Sierra Nevada region where the data were taken. The left hand intercept of the curve represents the contribution from the mantle, about 17 mW/m^2 in this region.

This study of the heat flux from within the earth is a good example of the kind of basic research that has important consequences in geothermal energy extraction. It also shows that the question, "What basic research is needed to facilitate the extraction of geothermal energy?" involves a contradiction because it cannot be answered precisely, i.e, if the research is truly basic, the results of the research will be unexpected. Conversely, if research results can be predicted, then very little new (or basic) information can be expected from the research.

Distribution of radioactivity in rock is of special interest to the geothermal energy program because of the possibility of finding reservoirs

120 000 000 years, the heat flow from the ocean bottom arises from cooling of the crust.[1-2] After this time some conduction through the crust from the mantle is needed to sustain the flux.

There are indications of extensive hydrothermal activity near ocean ridges, where this crustal heat first arises. Studies of these regions will yield important information for possible advanced geothermal energy systems.

B. Subduction Zones

Most of the heat flux through the ocean floor was carried into the crust by convection at the oceanic ridge; the downward sinking crust at a subduction zone gives rise to another region of increased heat flow, and such regions, near the boundary of continents and island arcs, are the location of most of the world's geothermal energy systems. A major cause of this volcanic activity over subduction zones may be the hydrated (and consequently lower melting point) sediments that cover the descending plate.[3]

C. Continental Heat Flow

Anomalous heat flows described above are restricted to regions near subduction zones. An interesting question for geothermal research is whether or not ancient subduction zones exist in the continental interior. If so, they may be potential geothermal resources.[3]

Radioactivity originally present throughout the earth now concentrates in the continental crust. The radioactivity generates heat, and the heat flow through the continental crust can be separated into two parts--a flux from the mantle and a flux generated by radioactivity in the crust. Birch et al., Roy et al., and Lachenbruch[4-7] discovered that over wide regions (heat-flow provinces), a plot of heat flow vs heat production in surface rocks is linear, with a finite value of heat flow at zero heat production, as in Fig. 1. As Lachenbruch showed, if different amounts of rock have been removed by erosion at the various locations where measurements were made and the relation remained true during all this time, then radioactivity must be distributed exponentially in the rock, decreasing with depth. Such a distribution has the property that if the rock is sufficiently thick the integral of all the heat generated below a depth, z, where the local heat generation is A(z), is equal to DA(z),

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BASIC RESEARCH NEEDED FOR THE DEVELOPMENT OF GEOTHERMAL ENERGY

by

R. Lee Aamodt and Robert E. Riecker

ABSTRACT

This report was prepared for the Office of Basic Energy Sciences of the U. S. Department of Energy. The purpose of the report is to identify basic research needed to facilitate development of geothermal energy. An attempt has been made to make the report representative of the ideas of productive workers in the field. The plan of the report is to discuss the present state of knowledge of geothermal energy and then to list specific recommendations for further research, with status and priorities. Discussion is limited to a small number of applicable concepts, namely:

1) Origin of geothermal flux,
2) Transport of geothermal energy,
3) Geothermal reservoirs,
4) Rock-water interactions, and
5) Geophysical and geochemical exploration.

I. ORIGIN OF GEOTHERMAL FLUX

A. Oceanic Crust

Flux of heat from oceanic crust was thought for many years to arise from the mantle by conduction. According to the theory of plate tectonics, new oceanic crust spreads out from oceanic ridges for thousands of kilometers at the rate of a few centimeters per year, and finally descends in

This gave a new picture of oceanic heat flow. For about

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Basic Research Needed for the Development of Geothermal Energy

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