A METHOD TO RECOVER USEFUL GEOTHERMAL-RESERVOIR PARAMETERS FROM PRODUCTION CHARACTERISTIC CURVES. (2) HOT WATER RESERVOIRS.

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ABSTRACT

In this paper we develop and demonstrate a method to estimate the reservoir pressure, a mass productivity index, and a thermal power productivity index for vertical water-fed geothermal wells, from its production characteristic (also called output) curves. In addition, the method allows to estimate the radius of influence of the well, provided that a value of the reservoir transmisivity is available. The basic structure of the present method is: first, the measured wellhead mass flowrates and pressures are transformed to downhole conditions by means of a numerical simulator; then, the computed downhole variables are fitted to a simple radial model that predicts the sandface flowrate in terms of the flowing pressure. For demonstration, the method was applied to several wells from the Cerro Prieto geothermal field. We found very good agreement of the model with this ample set of field data. The main advantages of our method are that it provides a way to retrieve important reservoir information from usually available production characteristic curves, that it works from easily and accurately taken wellhead measurements, and that its results address the two main aspects of geothermal resource utilization, namely, mass and heat production.

INTRODUCTION

Production characteristic curves, also called output curves, are routinely determinated for most geothermal wells. These curves relate mass flowrate at the wellhead with the corresponding wellhead pressure. Their normal uses include gathering qualitative information about reservoir properties (e.g. relative values of reservoir pressure, temperature or gas content, reservoir permeability) and about effects of scaling in the wellbore (eg. Grant et. al., 1982); estimating discharge enthalpy from the maximum discharging pressure (James, 1970, 1980 a,b); and, of course, predicting mass flow rates for given wellhead pressures and vice-versa.

Output curves contain mixed information about both the reservoir and the intervening wellbore. As pointed out, only qualitative information about the reservoir is ussually recovered from these curves. The sole exception to this, James' maximum discharging pressure method to estimate discharge enthalpy, is based on the fact that at low flowrates resistive wellbore effects are unimportant; that is, in this case the wellbore and reservoir information are already separated.

In this paper we develop and demonstrate, via field examples, a method to recover important quantitative information about the reservoir from output characteristic curves of water-fed wells. In a companion paper (Iglesias et. al., these Proceedings), we describe and demonstrate a similar method for steam wells. The method is based on unscrambling the wellbore and reservoir contributions to the output curves, by means of a wellbore flow numerical simulator, and then fitting these results to a simple radial model of the reservoir flow. The reservoir information retrievable with our method can alternatively be obtained by traditional methods, which require bottomhole measurements. These measurements are difficult to take in high temperature wells which, more often than not, contain corrosive fluids. Moreover, the method presented in this paper uses as input data characteristic curves that have to be determined, anyway, for other uses. Our method is, therefore, an efficient way for retrieving important reservoir information from usually available wellhead data, without resorting to more difficult bottomhole measurements. No previous similar work is known to the authors.

METHOD

The method presented here requires production characteristic curves as input data. These data are converted to the corresponding bottomhole quantities by means of a wellbore flow numerical simulator. Then, the computed bottomhole quantities are fitted with a simple model that predicts the sandface mass flowrate as a function of the bottomhole flowing pressure. The fit provides estimates of the reservoir pressure p_e, and the productivity index J_m of the well. If estimates of the reservoir transmissivity (kh/μ) are available, the radius of influence of the well can also be estimated.

Output characteristic curves are recorded during production tests. During these tests, the wells are typically flown through several orifices of varying diameters. For each orifice the flow is mantained until stable or quasistable conditions are reached. At this point, the mass flowrate and the corresponding wellhead pressure are recorded. Liquid-fed wells in high enthalpy fields usually produce mixtures of water and steam at the surface. In this type of well the data recorded are the steam and water flowrates, and the wellhead pressure. After recording the data, the flow is diverted through another orifice of different diameter, and the process restarts. Thus, for high-enthalpy water-fed wells production tests provide two related curves: water and steam flowrates versus wellhead pressures. These constitute the raw data of the method presented here.

The wellbore numerical model (WELFLO) used in this work is described by Goyal et. al (1980) and references therein. WELFLO is a finite difference, one dimenssional, multiphase, steady-state geothermal wellbore flow simulator appropriate for vertical multidiameter wells. It has been extensively validated against field data (Goyal et. al., 1980; Arellano, 1983). Two features of this code make it adequate for the problem at hand. First, the cappability to compute bottomhole conditions from wellhead input variables, as needed. Second, the assumption of steady-state flow in the wellbore. This assumption is required because the stable or quasi-stable conditions attained during the production test allow wellbore transients to die out. The input variables of WELFLO are the geometry of the well (lenghts, diameters, extent of open or ranurated interval), total mass flow rate, wellhead pressure, and wellhead total specific flowing enthalpy. Conductive heat losses to the wellbore walls are unimportant in steady-state flow (Goyal et. al., 1980; Gould, 1974) and were neglected in our calculations.

Our method requires to transform each and every measured data point of the characteristic curve to the corresponding bottomhole conditions. Of the complete set of bottomhole variables computed by means of WELFLO, we require only the flowing pressure and the total mass flowrate (which equals the wellhead flowrate, due to the steady state conditions of the flow in the bore). Errors of the wellhead input quantities affect the bottomhole flowing pressures (BHP's) computed by means of WELFLO in different fashions, as follows (Goyal et. al., 1980). Computed BHP's are relatively insensitive to errors of the wellhead total mass flowrate. Errors of wellhead pressures have effects of the same order of magnitude on computed BHP's. Input enthalpies greater than the true value decrease calculated BHP's in approximate proportion to the error. Finally, computed BHP's are very sensitive to negative errors of the input enthalpy.

Once the output characteristic curves are recorded, little can be done with respect to the errors of the mass flowrates and of the corresponding wellhead pressures. Fortunately, this is not the case for the flowing total specific enthalpy, the most sensitive quantity with regard to BHP's errors. The individual specific enthalpies corresponding to each data point of the characteristic curve are computed from the related water and steam flowrates and known separation pressure. These individual enthalpies are affected by the random errors of the measured water and steam flowrates. Now, for liquid-fed geothermal wells the flowing total specific enthalpy is constant and independent of wellhead pressure or mass flowrate (e.g. Grant et. al., 1982). Therefore, we take the arithmetic mean h_T, which is the best statistical estimate of the true value in a set of random measures, as the value of the constant flowing specific enthalpy h_T. This approach minimizes the errors of the computed BHP's. As a further precaution, we check the set of individual enthalpies for possible correlations with wellhead pressures or mass flowrates. The existence of such correlations may indicate two -phase flow in the reservoir, which in turn would invalidate the present analysis.

For the flow in the reservoir we chose a simple model suggested by experience: radial, horizontal, isothermal flow of a liquid through a porous, homogeneous, confined, cylindrical reservoir of constant thickness. If the outer boundary condition is constant pressure, then steady state can be achieved. In that case the mass flowrate is given by

$$W = \alpha \frac{kh}{\nu} \frac{(p_e - p_{wf})}{\ln (r_e/r_w)} , \qquad (1)$$

the well-known expression of Darcy's Law for steady-state radial flow, in massic form. Here α is a constant to accomodate different systems of units (nomenclature at the end of the paper). This steady-state model can approximately describe three situations of interest, with the restrictions commented below. (a) Infinite acting period, i.e. no boundary effects are felt during the time period Δt over which the output production data were collected; in this case Δt must be smaller than the time scale associated with the outward movement of the pressure perturbation in the reservoir, for equation (1) to a valid approximation. (b) Constant pressure outer boundary condition, which may arise from the existence of a strong radial recharge some distance away from the well; equation (1) is valid with no restrictions on Δt. (c) Finite reservoir, no-flow condition at $r=r_e$; approximation (1) is valid when Δt is smaller than the time scale associated with the decrease of p_e.

If the reservoir flow model summarized by (1) is valid for a given set of output data (production characteristic curve), a plot of the computed sandface flowrates versus the corresponding flowing pressures should give a straight line. From (1) the intercept of this line is

$$a = \alpha \frac{kh}{\nu} \frac{p_e}{\ln (r_e/r_w)}, \qquad (2)$$

and its slope is

$$b = -\alpha \frac{kh}{\nu} \frac{1}{\ln (r_e/r_w)}, \qquad (3)$$

The reservoir pressure is then easily computed from

$$p_e = -(a/b) \qquad (4)$$

A massic productivity index is naturally defined as

$$J_m = W/(p_e - p_{wf}) \qquad (5)$$

Then, from (1), (3) and (5)

$$J_m = -b. \qquad (6)$$

In geothermal applications a quantity of great interest is the thermal power of a given well. In analogy to (5), a useful power productivity index may be defined as

$$J_p = h_T J_m \qquad (7)$$

for water-fed wells. In definition (6) we have used h_T, the total specific flowing enthalpy, which is constant and independent of wellhead pressure and total mass flowrate, as mentioned. In practice, we estimate h_T by $\bar{h}_T$, the total specific flowing enthalpy averaged over the characteristic curve, to minimize errors.

Finally, if the reservoir transmissivity (kh/μ) is known, the radius of influence of the well can be estimated from (6) as

$$r_e = r_w \exp\{(\alpha kh)/(\mu v J)\}, \qquad (8)$$

where we have replaced $\nu = \mu v$, with v the specific volume of the liquid at reservoir conditions. In practice we estimate v by the specific volume of saturated water at the computed bottomhole temperature.

Estimates of r_e by this method are affected by the existence of a non-zero skin. This is because the permeability k in equation (8) represents the permeability "seen" by the well, which is not the reservoir permeability if there is a non-zero skin. In this case k should be replaced by the composite permeability

$$\bar{k} = \ln(r_e/r_w)/\left\{\frac{\ln(r_s/r_w)}{k_s} + \frac{\ln(r_e/r_s)}{k}\right\} \qquad (9)$$

Taking $(r_s/r_w) \simeq 1 + \varepsilon$, with $\varepsilon \ll 1$ as usually assumed, it is easy to show from (9) that

$$\bar{k} < k \qquad (10)$$

wether the skin is positive or negative. Expression (10) implies that (8) overestimates r_e if the reservoir permeability (e.g. as obtained from pressure tests) is used, when a non-zero skin exists. Given the exponential form of (8), these errors may be important.

FIELD VALIDATION

For validation purpouses we have applied our method to 5 wells from the Cerro Prieto geothermal field. Figure 1 shows their location.

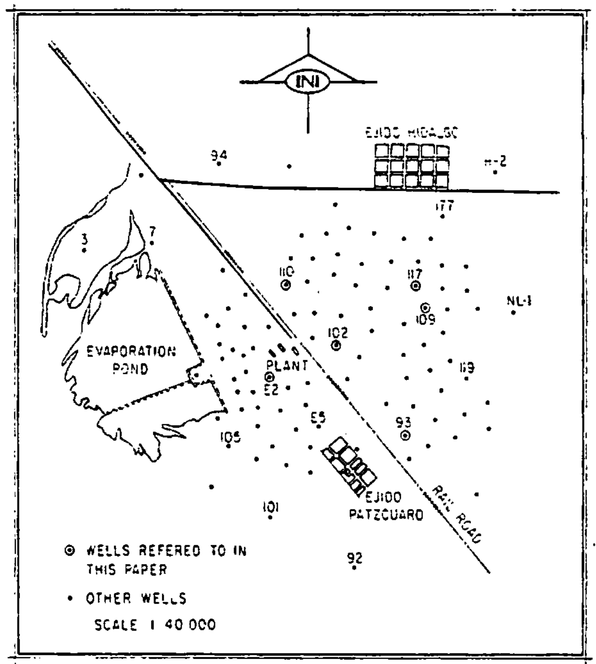

Fig. 1 Location of the processed wells from the Cerro Prieto geothermal field.

These wells were selected to satisfy the model assumption that the reservoir flow is exclusively single (liquid) phase. At the wellhead however, all these wells produce water and steam. This is because the liquid water entering the wellbore enventually flashes in its way up, due to the concomitant pressure decrease. During the production tests, from which the production characteristic curves were recorded, the wells were flown over wide ranges of wellhead pressures and flowrates. Our computations showed that, with one exception (M-93), two-phase flow developed in the reservoir around these wells at the higher flowrates. The points on the production characteristic curves corresponding to two-phase flow in the reservoir were discarded. All the results and figures in this section correspond to one-phase liquid flow in the reservoir.

The original production output curves and their transformation to bottomhole conditions are shown in Figs. 2 to 6. The corresponding results are summarized in Table 1. The excellent fits, evidenced by the high correlation coefficients, are strong evidence of the validity of the method presented here.

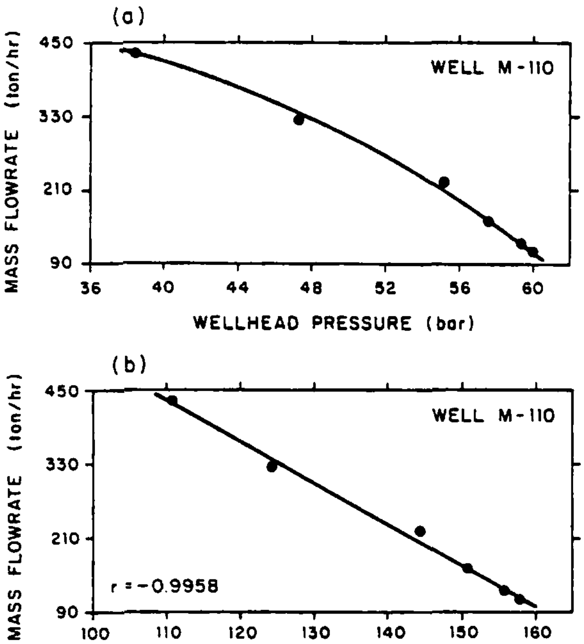

Fig. 2 (a) Characteristic curve of well M-110; (b) corresponding computed bottomhole variables, and fit to the steady-state radial liquid water flow model.

As another check on our method, we have compared the inferred reservoir pressures with measured shutin (or nearly shutin) downhole pressures. These results are shown in Table 2. The measured downhole pressures p_{meas} were corrected to the corresponding bottomhole depths by addition of the hydrostatic heads due to the differences of depth. Saturated liquid densities at the computed downhole temperatures were used in these calculations.

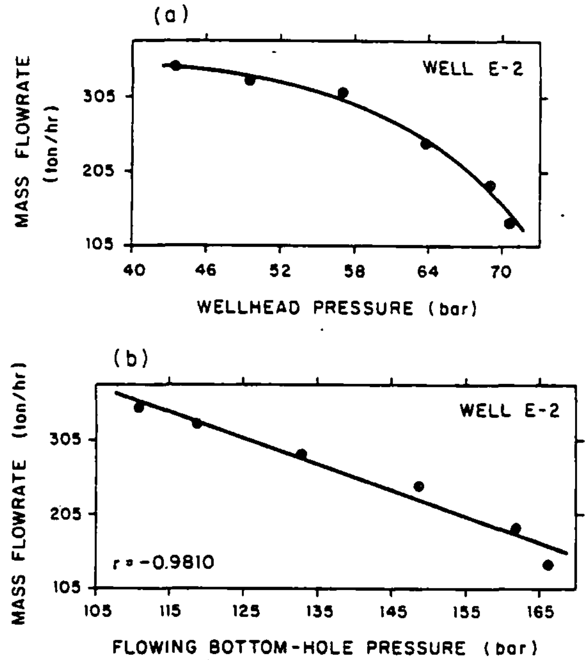

Fig. 3 (a) Characteristic curve of well E-2; (b) corresponding computed bottomhole variables, and fit to the steady-state radial liquid water flow model.

The inferred reservoir pressures agree with the measured shutin, or nearly shutin, downhole pressures to better than 17% in average. The agreement is good, considering the uncertainties involved, and the usual errors associated with alternative methods to estimate reservoir pressures. The uncertainties include errors in the measured or assumed input quantities of the

Table 1. Results of the method applied to hot water wells from the Cerro Prieto geothermal field.

Well	Correlation Coefficient	p_e (bar)	J_m (ton hr^{-1} bar^{-1})	$\bar{h}_T$ (MJ ton^{-1})	J_p* (MW bar^{-1})
M-110	-0.9958	175.1	6.64	1411.1	2.60
E-2	-0.9810	212.1	3.53	1484.3	1.46
M-93	-0.9683	266.5	2.79	1332.5	1.03
M-109	-0.8737	316.0	2.53	1323.0	0.93
M-102	-0.9718	235.9	1.50	1488.1	0.62

*Expressed in thermal MW per bar.

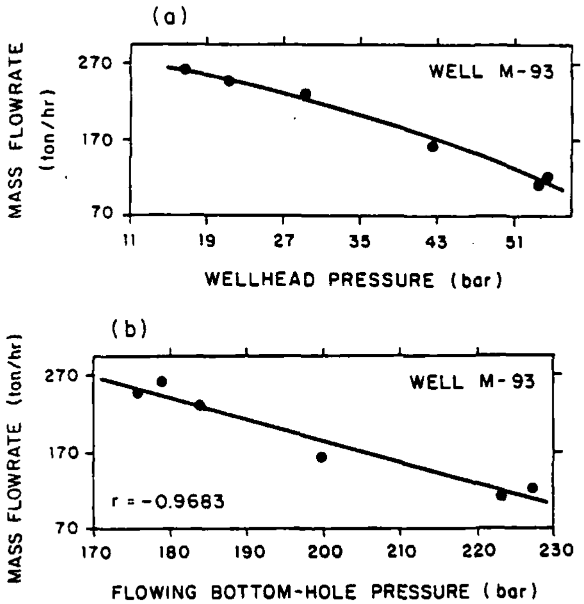

Fig. 4 (a) Characteristic curve of well M-93; (b) corresponding computed bottomhole variables, and fit to the steady-state radial liquid water flow model.

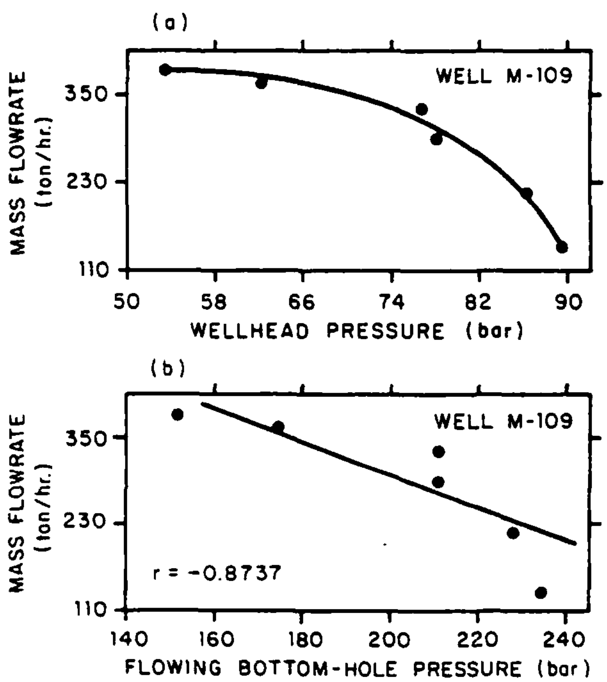

Fig. 5 (a) Characteristic curve of well M-109; (b) corresponding computed bottomhole variables, and fit to the steady-state radial liquid water flow model.

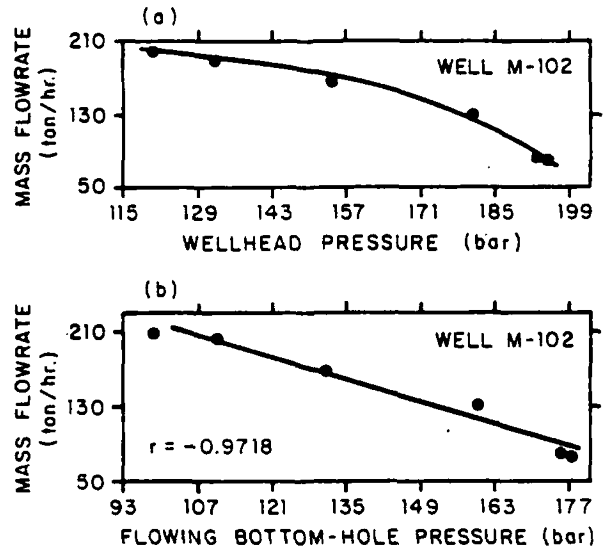

Fig. 6 (a) Characteristic curve of well M-102; (b) corresponding computed bottomhole variables, and fit to the steady-state radial liquid water flow model.

method, errors in the measured downhole pressures, and wether the measured downhole pressures represent reservoir pressures. As discussed in the previous section, errors in input variables of the method such as wellhead pressures, flowrates and enthalpies, or in the assumed inside diameters of the wells (possibly arising from scale deposits), might originate percentual errors of the order of magnitude shown in Table 2. On the other side, the measured shutin pressures, just like any other kind of measurement, are affected by instrumental and human errors. Finally, downhole pressure measurements may not represent true reservoir pressures, on two counts. First, it is often difficult to asses whether the shutin time has been long enough for equilibration. And second, geothermal shutin downhole profiles do not necessarily reflect reservoir pressure, except at the precise depth corresponding to feed points, even if shutin times are long enough (Grant, 1979; Grant et. al., 1981).

The inferred reservoir pressures shown in Table 2 appear to be systematically greater than the (corrected) measured pressures. This may be a random effect, masked by the relatively small size of the sample (5 cases), with the errors caused by the reasons discussed in the last paragraph. Alternatively, it may be a truly systematic effect introduced by the method presented here. More field data will be processed to solve this question.

Table 2. Inferred reservoir pressures vs. measured shutin (or nearly shutin) downhole pressures.

Well	MEASURED				INFERRED		DIFFERENCE
	p_{meas} (bar)	Depth (m)	Conditions	p_{corr}* (bar)	p_e (bar)	Depth (m)	$(p_e - p_{corr})/p_e$ (%)
M-110	163	1843	shutin	163.7	175.1	1854	+ 6.5
E-2	166.5	1762	flowing by ϕ=1" orifice	178.1	212.1	1946	+16.0
M-93	235	2553	flowing by ϕ=1" orifice	235.3	266.5	2558	+11.7
M-109	223	2385	flowing by ϕ=1/4" orifice	223.6	316.0	2395	+29.2
M-102	184	1900	shutin	189.6	235.9	1990	+19.6

*p_{corr} = p_{meas} corrected to bottomhole depth (see text).

SUMMARY AND CONCLUSIONS

We have developed and demonstrated a method to retrieve the reservoir pressure p_e, a mass productivity index J_m, and a thermal power productivit index J_p corresponding to vertical water-fed wells from its production characteristic curves. If an estimate of the reservoir transmisivity (kh/μ) is available, our method provides a way to estimate the radius of influence of the well.

We have successfully validated the method against an ample set of field data. The quality of the agreement is very good.

The main advantages of the method are as follows: It provides a way for retrieving important reservoir information from ussually available production characteristic curves; no extra measurements are needed. Unlike traditional methods that require significantly more difficult bottomhole measurements to evaluate the reservoir pressure and the productivity index, the present method works from more easily taken wellhead measurements. Finally, the method provides important information concerning the two main aspects of geothermal resource utilization: mass and heat production.

A distinctive feature of the method described in this paper is that it combines two of the most important aspects of the geothermal resource, namely, mass and heat production. This useful feature is illustrated by the results presented in Table 1: reservoir pressures and mass productivity indexes on the one hand, and enthalpies on the other, are combined in a single parameter, the power productivity index.

The results of Table 1 show that the mass productivity indexes are mostly independent of both the reservoir pressure and the specific enthalpies. These results also show that the specific enthalpies of the wells are rather independent of the corresponding reservoir pressure. Finally, there is a strong correlation (linear correlation coefficient= +0.9969) between J_p and J_m. If representative of the whole field, these results indicate that in Cerro Prieto the controlling factor for mass and heat production is reservoir transmissivity.

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NOMENCLATURE

a: Intercept of straight line (ton hr^{-1})

b: Slope of straight line (ton hr^{-1}/bar^2)

h: Reservoir thicknes (m)

h_T: Flowing total sprcific enthalpy (MJ ton^{-1})

$\bar{h}_T$: Flowing total specific enthalpy averaged over characteristic curve (MJ ton^{-1})

J_m: Mass productivity index (ton hr^{-1} bar^{-1})

J_p: Thermal power productivity index (MW bar^{-1})

k_s: Permeability of skin zone (md)

$\bar{k}$: Composite permeability seen by the well when there is a non-zero skin (md)

k: Permeability (md)

p_e: Reservoir pressure (bar)

p_{wf}: Sandface flowing pressure (bar)

p_{meas}: Measured shutin pressure (bar)

p_{corr}: p_{meas} corrected to bottomhole depth (bar)

r_e: Radius of influence of the well (m)

r_w: Wellbore radius (m)

r_s: Radius of the skin zone (m)

v: Specific volume of liquid water ($m^3\ kg^{-1}$)

W: Mass flowrate (ton hr^{-1})

α: Constant to accomodate different systems of units

μ: Viscosity (cp)

ν: Kinematic viscosity ($m^2\ s^{-1}$)

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MONTANA BUREAU OF MINES AND GEOLOGY

A REVIEW OF THE THERMAL INFRARED IMAGERY FOR THE JEFFERSON RIVER SURVEY, SOUTHWESTERN MONTANA

by

Daniel H. Vice

Preface

The use of thermal infrared imagery has interested many people as a potential geothermal exploration tool because it is one way to directly measure the land surface temperature over a geothermal system. However, as with many new exploration techniques, the actual results have been mixed because the limits and capabilities of this tool were not completely understood. This has led to disappointment and an unwillingness to use this method. The effective use of thermal infrared imagery for geothermal exploration requires the recognition that this tool is very limited by season and weather. But even the failures can provide information. To quote Clarke's Second Law, "The only way to discover the limits of the possible is to go beyond them into the impossible."

Two earlier, published thermal infrared surveys were made within the Northern Rocky Mountains. One survey, McLerran and Morgan (1966), covered portions of Yellowstone National Park in May of 1961. Although most of the hot features noticed within the imagery were hot springs or related steaming ground, one large ground anomaly was observed at Gibbon Hill (Ibid, p. 123). The second survey (Foote and Eliason, 1974) covers the Marysville area northwest of Helena. This survey was flown on October 3, 1978. Although one drillhole flowing warm water 24.7°C (76.5°F) was observed in the imagery, the principal feature was a large anomaly within the trees on the hillsides. The writer refers to this anomaly as vegetation but they were not certain about the cause. One possible explanation is that the anomaly is due to transpiration by the conifers.

An example of the successful use of thermal infrared in the exploration of remote areas for geothermal resources is given by DeDonato (1974). This article briefly describes the use of thermal infrared in Ethiopia and Kenya to locate a large number of hot spots rapidly. Land-based crews then went in to check these hot spots and obtained field data. In this way, a large area could be covered within a short time period. Several examples of the detailed information which can be obtained from thermal infrared surveys over geothermal areas are given by Hochstein and Dickinson (1970), Dawson and Dickinson (1970), and Dickinson (1975).

Sabins (1978) and Lillesand and Kiefer (1979) provide good general background information on the theoretical basis, the mechanical operation of the infrared scanner and interpretation of the imagery. They also show samples of the imagery which illustrate distortions or problems caused by common mechanical or climatic factors. Holmes and Thompson (1973) demonstrate the use of thermal infrared imagery to study surficial deposits, ground water discharge areas and soil moisture anomalies. They also very effectively demonstrate the use of mosaics of thermal infrared imagery.

The writer wishes to thank Robert Leonard, U.S. Geological Survey, and John Sonderegger, Montana Bureau of Mines and Geology, for providing the thermal infrared imagery. Thanks should be extended to John Sonderegger and Mari Vice for reviewing and commenting on the paper. The writer expresses his appreciation to Mari Vice for the drafting.

Introduction

The U.S. Geological Survey-Water Resources Division and the Montana Bureau of Mines and Geology cooperately sponsored a thermal infrared survey of hot springs on the Jefferson River, and at Boulder, Clancy, and Helena (See Figure 1). The hot springs covered by this survey include: Broadwater, Alhambra, Boulder, Pipestone, Renova, Silver Star, and New Biltmore. The U.S. Forest Service flew this survey on October 3, 1978. A Texas Instruments infrared scanner was used in a King Air Turbo Prop Twin platform. Although the survey was flown at about 1,500 feet above ground level, the imagery was processed to a variable scale between 1:25,000 and 1:50,000. The survey started at 7:50 A.M. at the Broadwater Hot Springs and ended at 9:20 A.M. over New Biltmore Hot Springs. Single passes were made over each of the hot springs.

John Sonderegger of the Montana Bureau of Mines and Geology asked the writer to review the imagery from the Jefferson River survey because of the writer's previous experience with the use of thermal infrared in geothermal exploration. Robert Leonard of the U.S. Geological Survey-Water Resources Division provided the writer with copies of the imagery. The imagery was examined during the winter of 1980-81 and the findings for each hot spring were compared to available geophysical and geological data.

Broadwater Hot Springs

Although considerable information can be gained from the thermal infrared imagery for Broadwater Hot Springs, the small scale (approximately 1:30,000) and the solar effects obscure much detail (Figure 2). Four ground anomalies are present within the thermal infrared imagery.

Site A appears to be associated with Broadwater Hot Springs. This site is irregular in shape and extending up on the lower slope of the south-facing hillside from the canyon floor. This site is considerably brighter than adjacent areas which argues against solar effect. The pressence of the anomaly on the canyon floor in an otherwise cool (dark) area also argues against a solar effect. The anomaly may be structurally controlled as a lineament extends to the north (see arrow). A telluric survey (Christopherson, et al, 1979) on the hillside immediately north of the hot springs showed a narrow, pronounced low adjacent to the lineament and the hot springs (Figure 3) which suggests that the lineament controls the hot springs.

Site B is not associated with any known hot springs but is believed to be a geothermal ground anomaly because it occurs on the canyon floor, has an irregular shape that does not appear to be related to any cultural feature or change in lithology, and occurs within a cool (dark) area.

Site C is a large anomaly near the mouth on Tenmile Canyon. It occurs on the hillside. Although a solar effect is present on the south-facing hillside, the anomaly is brighter than adjacent areas. As part of an effort to locate a heat source for the State Nursery and to extend the known area of geothermal activity, The Montana Bureau of Mines and Geology drilled a 280 foot temperature gradient well on this anomaly. A gradient of $9^{o}C/km$ was obtained (Donovan and Sonderegger, 1981). The low gradient and occurrence of cold water in several different zones in the well indicates that IR anomaly was due to solar effect on an outcrop of Precambrian Belt sediments (see Knopf, 1963).

Site D is an irregularly shaped anomaly which occurs on the canyon floor and extends up onto the north-facing hillside south of the canyon. The occurrence of the anomaly on a north-facing slope and the association with a lineament strongly indicates geothermal heat rather than solar effect.

Although the survey started after sunrise, the narrow, east-trending valley with high hills on the south subdued and kept the full force of the sun's rays away from the Broadwater Hot Springs area. Because of this fortuitous circumstance, more information is obtainable from the infrared imagery at this site than at most of the other sites.

Alhambra Hot Springs

The thermal infrared imagery for the Alhambra Hot Springs has too much solar effect (A) and is at too small a scale to provide much detailed resolution. Four sub-parallel lineaments (B) appear immediately east of the Alhambra fault (C) (Figure 4). These lineaments may represent faults that are associated with the Alhambra fault which controls the hot springs (See Leonard and Janzer, 1977). The solar effects largely obscure the hot springs (D). One spot anomaly or hot spot (E) was observed on a northward extension of the Alhambra fault into an unnamed draw north of Warm Springs Creek. Because of the scale, it is not possible to determine whether the spot anomaly represents a warm spring or an occupied house.

Boulder Hot Springs

The Boulder Hot Springs (Figure 5) can be located by the occupied buildings (A) which show up as rectangular, white or light gray features

The dark area with the white spot adjacent to the resort buildings (B) represents the hot springs. However, the solar effect and small detail of the imagery obscure most details fo the area so that any extensions of the hot springs are hidden. A very subtle, northwest-trending lineament (C) may represent the structural control for the hot springs.

Pipestone Hot Springs

Although scale (approximately 1:36,000) and solar effect cause problems in this area, a large, strong ground anomaly is present which stands out from the adjacent areas even though they show solar heating (A in Figure 6). This warm area or ground anomaly occurs within the stream bottom of Big Pipestone Creek. Both above and below the anomaly the stream bottom is the normal dark gray (cool) tone which occurs in areas of surface and near-surface waters such as stream bottoms and marshes. Several small white spots or "spot anomalies" (B) are present within the ground anomaly. These spots are believed to represent individual hot springs. Several sharp spikes or spots (C) occur within the stream channel where a hot spring has suddenly warmed the water. A second area (D) of spot anomalies within the stream channel occurs east of the main spring area.

Pipestone Hot Springs occurs at the intersection of two sets of lineaments. Two sub-parallel lineaments have an east-west trend which is followed by Big Pipestone Creek. Two other sub-parallel lineaments have a northeasterly trend. This second set of lineaments are highlighted by a changed in direction of an unnamed, ephermeral creek (D) north of Big Pipestone Creek. These northeasterly lineaments are probably the faults described by Chadwick and Leonard (1979, p. 15 and 16) as the controlling structure for Pipestone Hot Springs.

Renova Hot Springs

Solar effects and the small detail (approximately 1:28,000) obscure most of the detail of these hot springs. Two spot anomalies are present on the east side of the Jefferson River (See A and B in Figure 7). These anomalies are associated with folded and fractured Cambrian strata (C) (O'Haire, 1977, p. 66-80). Although the thermal IR imagery does not show all the faults present, it does outline the anticlinal nose very well.

Some spot anomalies (D) occur on the west side of the Jefferson River immediately across from the hot springs. These anomalies may be other hot springs but also may be solar effects on bare river gravel bars. The scale and the presence of similar anomalies that are probably solar effects prevent any greater discrimination of detail.

Silver Star Hot Springs

The thermal infrared survey was flown immediately east of Silver Star Hot Springs. Solar effects and the small scale of the imagery obscured the area adjacent to the hot springs and prevented locating any extensions. The wide, open, north-trending valley allowed the morning sun's rays to heat the area rapidly and thus mask any geothermal anomalies.

New Biltmore Hot Springs

Solar effects completely obscure and mask the warm springs at site. As with the Silver Star area, the topography aids in obscur warm springs from the thermal infrared sensor by allowing the sur rays to reach the site with full force as soon as it rises.

Summary and Recommendations

Some information can be gained from this thermal infrared survey for the Broadwater, Alhambra, Pipestone, and Renova Hot Springs. However, solar effects or heating are a problem for all of the sites and completely mask the Boulder, Silver Star and New Biltmore sites. The topography strongly influenced the amount of solar heating at each site, helping to mask the hot springs at Boulder, New Biltmore and Silver Star, but also restricting the solar effects at Broadwater.

The thermal infrared imagery for the Broadwater Hot Springs area suggests that the geothermal system extends discontinuously eastward from the known hot springs almost to the mouth of Tenmile Canyon. The larger size for this geothermal system could be very significant for potential space heating projects.

Although the information obtained for the Alhambra, Pipestone, and Renova Hot Springs is more limited than that for the Broadwater Hot Springs, useful information is present within the imagery for these areas. Possible structural controls are intrepreted on the infrared imagery for these areas while a possible extension is suggested for Alhambra. The thermal infrared imagery for the Pipestone Hot Springs not only suggests the structural controls, but indicates the size of the surface area affected by the thermal waters. The infrared imagery for Renova Hot Springs indicates the association with favorable rock strata and some possible springs on the west side of the Jefferson River.

Much more detailed information could have been obtained for all of the thermal springs within the study area if this thermal infrared survey had followed certain operational procedures. Although the survey was flown at a sufficiently low altitude above ground level to provide detailed spatial resolution, the imagery was processed to give too small a scale (between 1:25,000 and 1:50,000) so that much needed resolution was lost. A larger scale, for example, a scale of approximately 1:15,000, would have allowed the discrimination between true spot anomalies and false anomalies created by occupied homes or other cultural features.

To avoid the problem of solar effects, the survey should have been flown before sunrise. The late flying time for this survey has resulted in a loss of approximately 75 percent of the effectiveness of the data. Accurate navigation and/or location of the study area can be obtained by the use of an Omega VLF, Inertial Navigational System, or Doppler guidance system. These systems can be used to fly the survey at any time after midnight and before sunrise which will eliminate almost all of the solar effect. If the only navigational technique available is visual, then the altitude of the survey can be increased and the survey can be flown using the early light before dawn and using stream drainages for laying out the flight lines. This will still eliminate most of the solar effect.

The solar effects can also be minimized by flying the thermal infrared survey later in the fall. The optimum time is from mid-October to late November. The days are shorter and the air temperatures are cooler. Both factors will help reduce the solar heating of bare rock and soil and keep this solar heating from carrying over to the next day.

One technique to provide more detailed information on any geothermal area is to fly complete IR coverage of one or two townships around each hot spring or group of hot springs or other surface manifestation. The six to twelve individual flight strips of such a survey can then be pieced together as a mosaic which is used for the interpretation. The extent of the thermal spring activity can be more accurately located, particularly for systems such as at Broadwater and Silver Star, where the activity may extend over a distance of two or three miles and may be partially masked by alluvium or near surface waters. Structural control of the thermal springs can be determined at the same time the extent of the thermal spring activity is located.

Thermal infrared surveys are a tool which can be very useful in the reconnaissance stage of geothermal exploration if it is properly used. Because it measures a characteristic feature of geothermal systems, heat, the infrared survey can move quickly and accurately outline the extent of the system and detect those areas which are masked by vegetation or alluvium than standard air photos, color infrared, field mapping, and other reconnaissance techniques.

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Figure 2

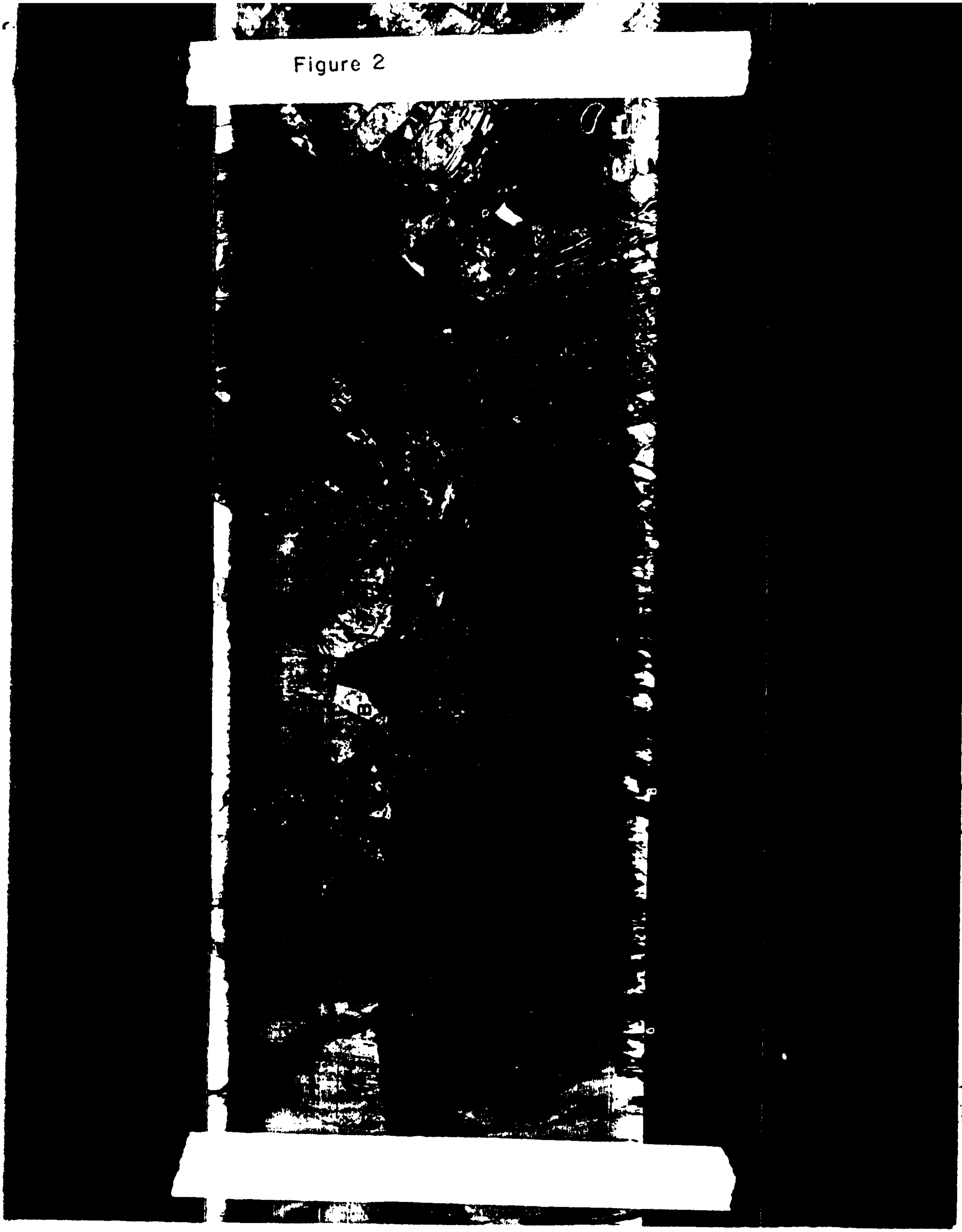

Figure 4

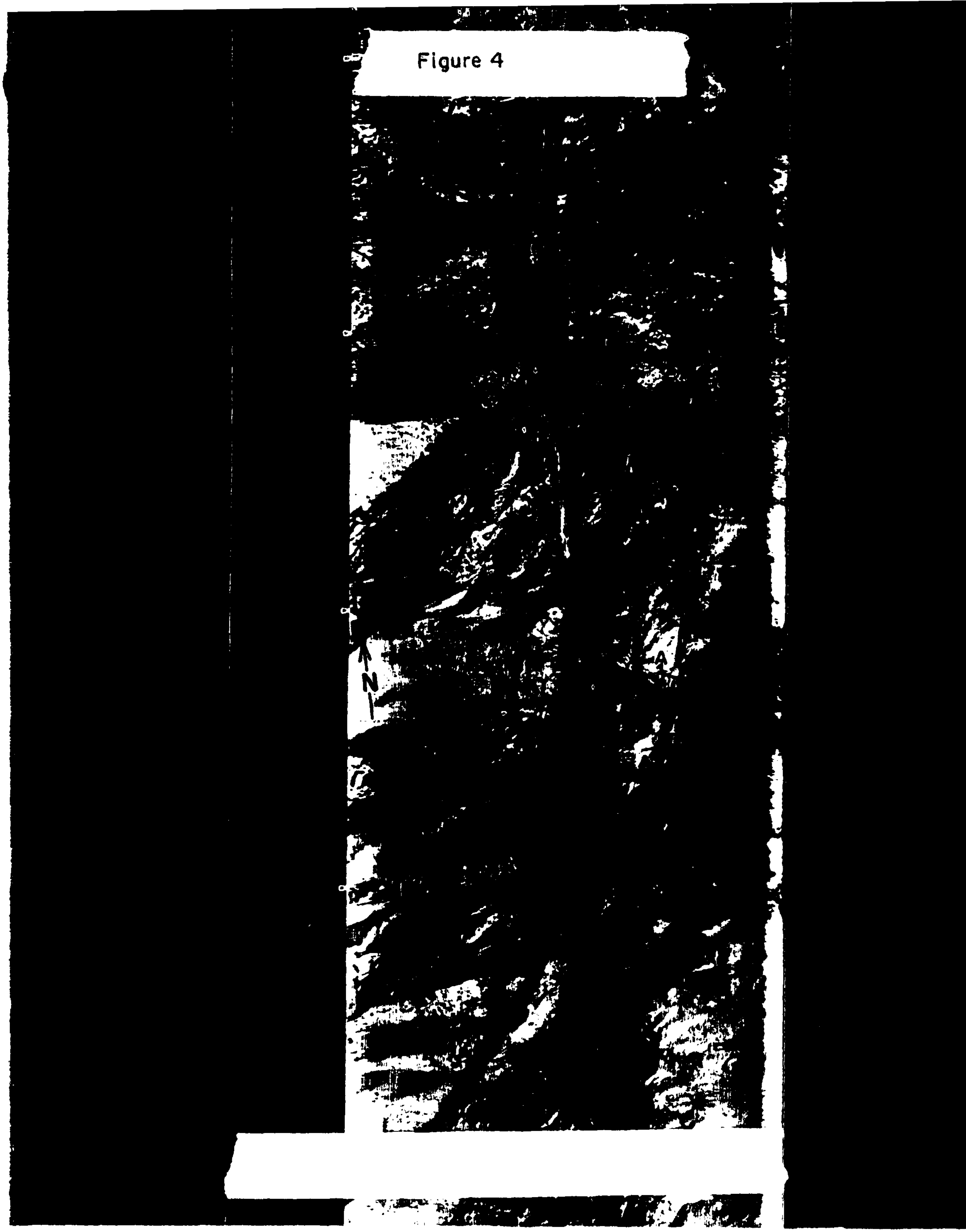

Figure 5

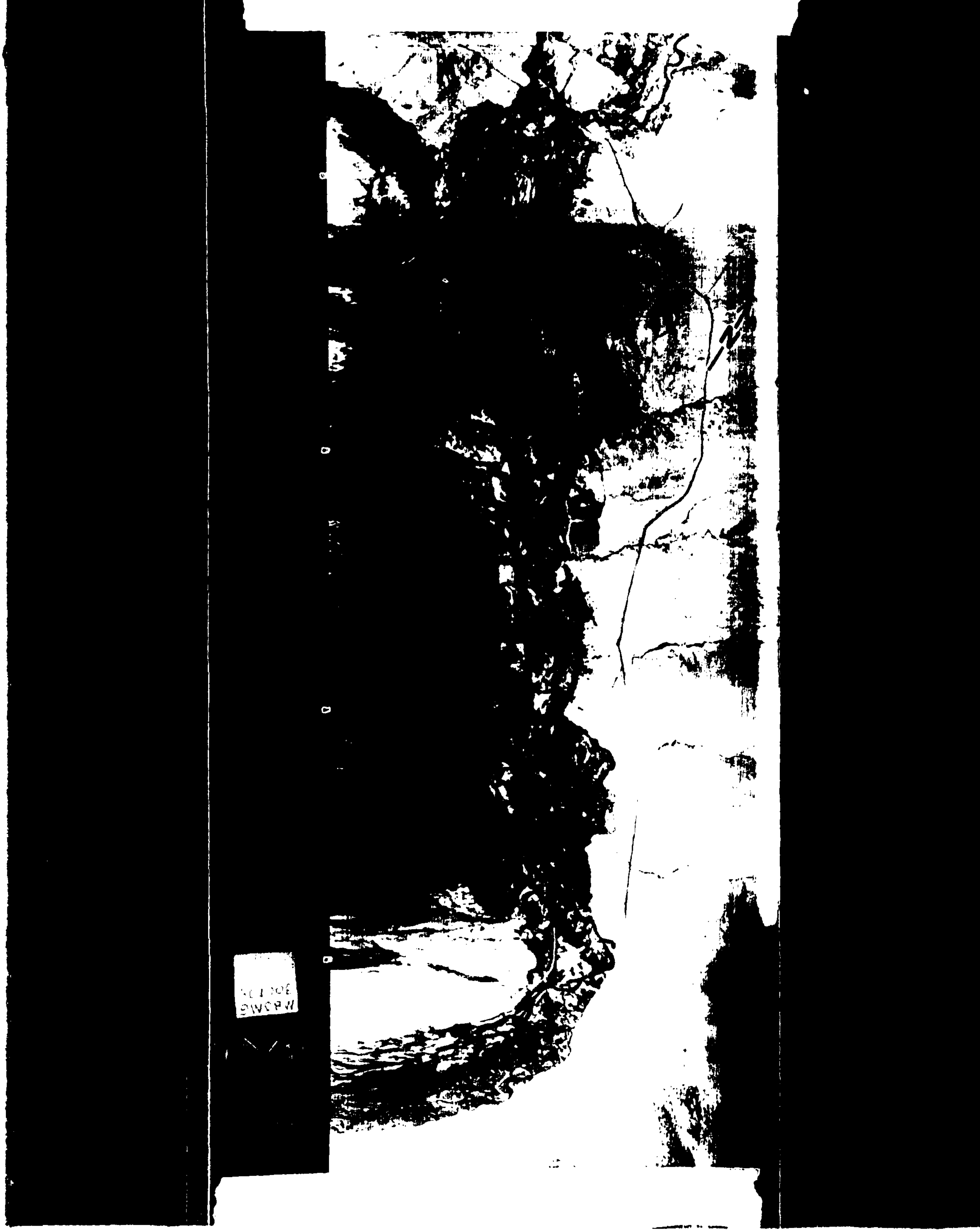

Figure 6

Figure 7

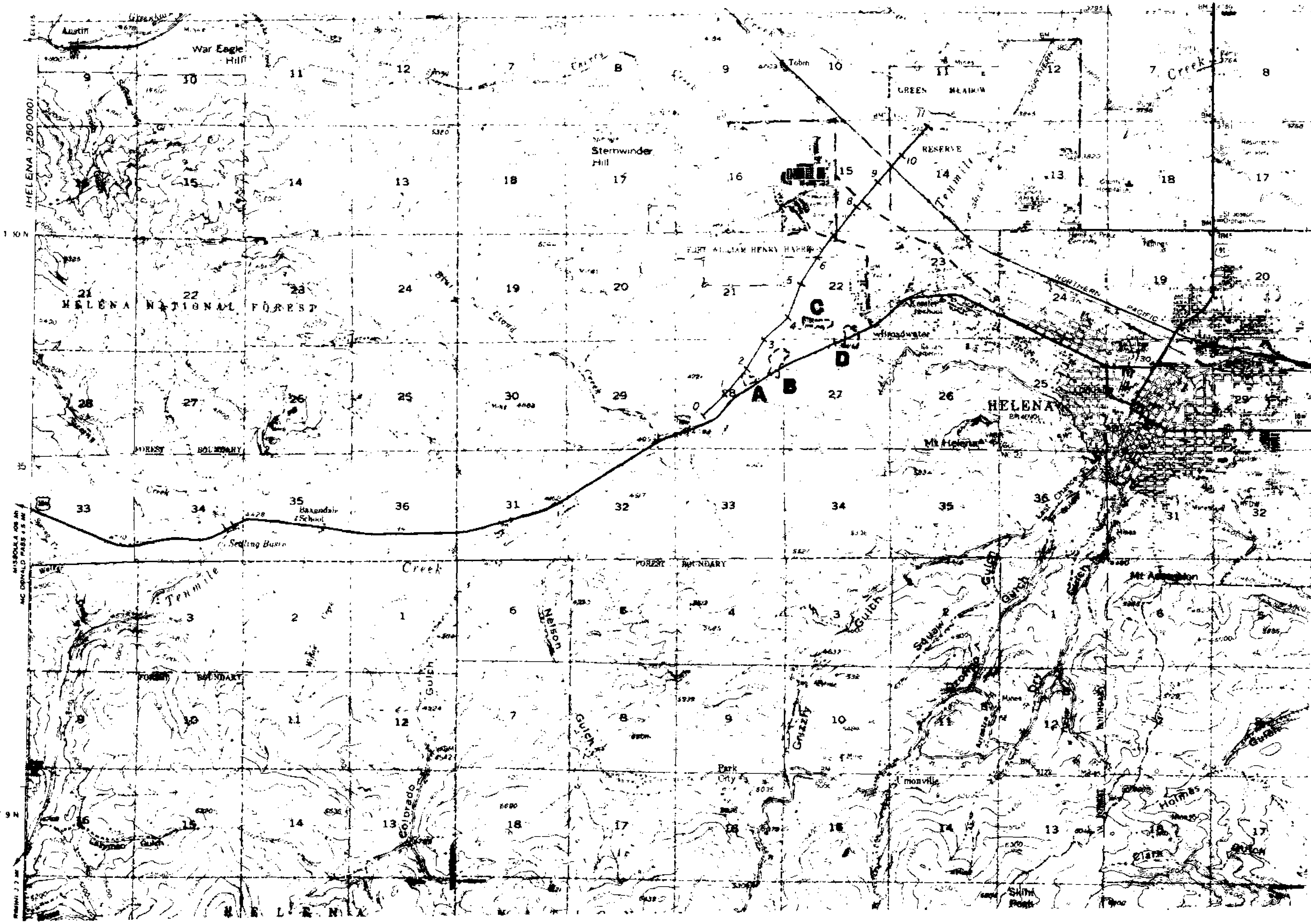

Figure 3.— Correlation of Thermal IR and Independent Geophysical Data

IR Ground Anomalies

1 2 3

Approximate Location of Telluric Survey

BASE U S Geological Survey Helena 15' Quadrangle

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UNITED STATES GOVERNMENT

Memorandum

SUBJ
GTHM
MF

Mike wright.

TO : Robert Christiansen,
Coordinator, USGS Geothermal Research Program

DATE: December 29, 1977

FROM : Patrick Muffler

SUBJECT: "Geothermal Resources of the United States -- 1978"

This memorandum is intended as a status report to acquaint you and other interested persons with the plans for the 1978 USGS geothermal resource assessment of the United States. Please see the attached paper (presented on December 14, 1977 at the 3rd Stanford Reservoir Engineering Workshop) for background and objectives.

I am responsible for coordinating and drawing together this new geothermal resource assessment, and shall be assisted in all aspects of the task by Marianne Guffanti. Publication in circular format is planned for January 2, 1979. Accordingly, we must have final manuscript and illustrations through technical review and revision by October 1, 1978. SI units will be used throughout, with conversion to English units only in summary tables.

I propose that "Geothermal Resources of the United States -- 1978" follow the successful format pioneered by Circular 726, "Geothermal Resources of the United States -- 1975", and suggest the following organization:

I. Introduction
  A. Terminology (in response to the April 21, 1976 memorandum from the Chief Geologist)
II. Hydrothermal convection systems >90°C
  A. Accessible resource base
    1. >150°C
    2. 90°C-150°C
  B. Recoverability and resources
III. Geothermal resources at <90°C.
  A. Regional heat flow
  B. Regional hydrology
IV. Geopressured resources
  A. Accessible resource base
    1. Onshore Tertiary rocks of Gulf Coast (revision)
    2. Offshore Tertiary rocks of Gulf Coast (new)
    3. Onshore Cretaceous rocks of Gulf Coast (new)
    4. Other geopressured basins
  B. Recoverability and resources.
V. Young igneous systems as geothermal targets
VI. Summary

The accessible resource base in hydrothermal convection systems will be put together by a group consisting primarily of Charlie Brook (geologist, Conservation Division), Bob Mariner (geochemist, Water Resources Division), Don Mabey (geophysicist, Geologic Division), and Jim Swanson (GEOTHERM data, Geologic Division). I am asking Brook to coordinate this group and to take responsibility for pulling together the product. In addition to the above persons, I anticipate important contributions from Bill Isherwood (interpretation of KGRA lease evaluation data) and Al Truesdell (reservoir temperatures from ^{18}O analyses of water and dissolved sulfate).

Recoverability of thermal energy in hydrothermal convection systems is being evaluated by an ad hoc group composed of Rob Potter, Manny Nathenson and me, working from p. 4-6 of the attached manuscript and from comments on Circular 726 received from various persons. I have requested assistance from the Centers for the Analysis of Thermo-Mechanical Energy Conversion Concepts (CATMECS) and from the reservoir engineering community represented at the 3rd Stanford Reservoir Engineering Workshop (see attached paper), and plan to pursue these sources during the coming months.

Geothermal resources <90°C will be evaluated by Ed Sammel. Methodology and approach have not yet been fixed, but await Sammel's transfer to Menlo Park in early January as well as receipt of a memorandum from DOE Division of Geothermal Energy outlining its needs in this area. Assessment of geothermal resources <90°C will be based primarily on data collated by the DOE State Cooperative Program, and evaluation will by necessity be limited to data available in usable format by July, 1978.

The accessible resource base in geopressured reservoirs will be compiled by Ray Wallace and his associates, building on the work outlined by Wallace, me and Frank Trainer at our Bay St. Louis meeting of Sept. 22, 1976. The recoverability aspect probably needs only minor revision and restatement, primarily with respect to subsidence and to the experimental data on methane solubility being measured by Ken McGee (Experimental Geochemistry and Mineralogy Branch, Geologic Division).

Tables 7 and 8 of the chapter on igneous-related geothermal systems in Circular 726 will be updated using the compilations of young volcanic rocks generated over the past few years by Bob Luedke and Bob Smith. In addition, the fundamental assumption that convective cooling is balanced by magmatic preheating and gains of magma needs to be re-evaluated in light of the recent modelling work of Larry Cathles, Denis Norton and others. I need your attention to defining a person to do this evaluation.

I hope that graphics can be significantly improved over Circular 726, hopefully making use of our new computer plotting capabilities. In addition, I hope to include two color, fold-out maps, one of hydrothermal convection systems and young volcanic areas in the western United States, and one of geopressured resources of the Gulf Coast. On January 9, I shall be meeting with Paul Grim (NOAA, Boulder, Colorado) concerning this matter.

I plan to pay particular attention to the summary chapter of the 1978 geothermal resource assessment, with careful consideration of the needs of potential users. In addition to a summary table similar to the attached table prepared from 1975 data for our IASPEI/IAVECEI paper, I plan tables, maps, and resource for 5-10 regions of the United States.

If you or anyone else has comments, questions, suggestions, or criticisms please contact me as soon as possible, but no later than February 1, 1978.

Distribution

Bob Christiansen
Bob Coleman
Bob Tilling
Don Klick
Frank Olmsted
Bob Mallis
Charlie Brook
Marianne Guffanti
Bill Isherwood
Bob Luedke
Don Mabey
Bob Mariner
Ken McGee
Manny Nathenson
Rob Potter
Bob Smith
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Al Truesdell
Ray Wallace
Bob Fournier
Art Lachenbruch
Steve Papadopulos
Reed Stone
Frank Trainer
Don White
Jack Salisbury, DOE/DGE
Clayton Nichols "
Cliff McFarland "
Marshall Reed "
Paul Grim, NOAA
Mike Wright, UURI
Ed Sammel, MP/WRD

1978 USGS GEOTHERMAL RESOURCE ASSESSMENT

L. J. Patrick Muffler
MS 18, U. S. Geological Survey
Menlo Park CA 94025

Geothermal resource assessment can be defined as the broadly based estimation of supplies of geothermal energy that might become available for use, given reasonable assumptions about technology, economics, governmental policy, and environmental constraints (Muffler and Christiansen, 1978). This assessment implies not merely the determination of how geothermal energy is distributed in the upper part of the earth's crust but also the evaluation of how much of this energy could be extracted for man's use. Thermal energy in place in the earth's crust (relative to a reference temperature) is the geothermal resource base. The accessible resource base is the thermal energy at depths shallow enough to be tapped by drilling in the foreseeable future (Muffler and Cataldi, 1978). That fraction of the accessible resource base that could be extracted economically and legally at some reasonable future time is the geothermal resource (Muffler, 1973; White and Williams, 1975; Muffler and Cataldi, 1978). This geothermal resource contains both identified and undiscovered components. Finally, the geothermal reserve is identified geothermal energy that can be extracted legally today at a cost competitive with other energy sources. The relationships between these terms can be illustrated on a McKelvey diagram for geothermal resources (figure 1).

In the United States, the U. S. Geological Survey (USGS) is the government agency responsible for assessing mineral and energy resources, including geothermal energy. The goal of the Survey's geothermal assessment is to provide a knowledge of the Nation's geothermal resource in sufficient breadth and detail to allow optimum energy planning, to encourage systematic exploration, and to support appropriate development of geothermal resources by private industry.

The first systematic effort to estimate the geothermal resources of the entire United States was carried out by the USGS in 1975 and published as USGS Circular 726 (White and Williams, 1975). This study evaluated the geothermal resource base to specified depths in several categories: (a) regional conductive environments, (b) igneous-related geothermal systems, (c) hydrothermal convection systems, and (d) geopressured systems. For each category, the USGS study then evaluated the part of the resource base that might be recovered under reasonable technological and economic assumptions.

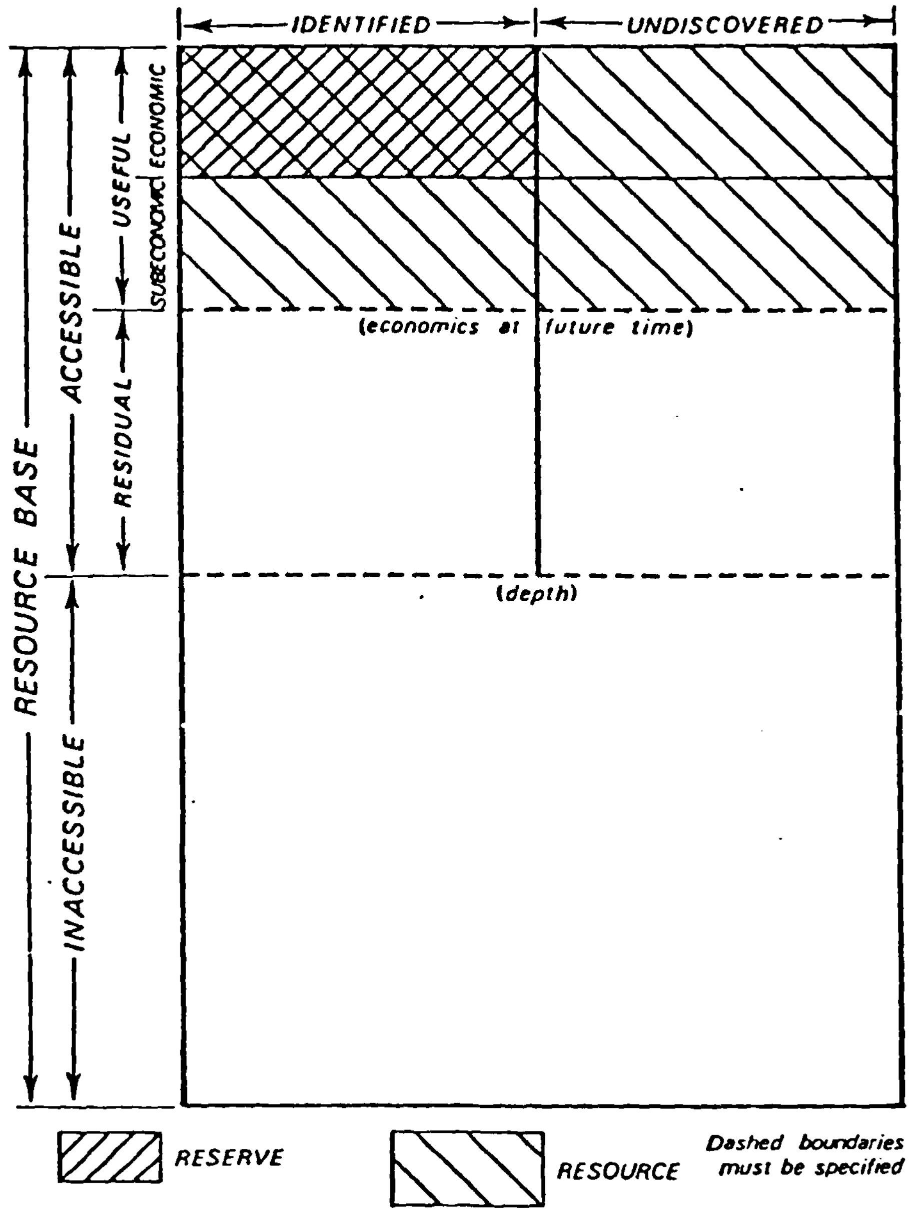

Figure 1.—McKelvey diagram for geothermal energy showing derivation of the terms resource and reserve (from Muffler and Cataldi, 1978, fig. 3). Scales are arbitrary, and thus the relative sizes of the rectangles have no necessary relation to the relative magnitudes of the categories.

Any resource assessment should be periodically updated in response to changing conditions. For geothermal energy, among these conditions are (a) increased data, resulting from expanded exploration and drilling activity, (b) development of improved and new technologies for exploration, evaluation, extraction, and utilization, (c) rapid evolution of geothermal knowledge, and (d) the increased role of geothermal energy in response to changing economic, social, political, and environmental conditions (in particular, an increasing awareness of the limits to petroleum and natural gas resources, both domestic and international).

Accordingly, the USGS plans to carry out an updated and expanded geothermal resource assessment of the United States by the end of 1978. Aspects to be given increased emphasis include the following:

a. Refinement of areas, thicknesses, and temperatures of high-temperature (>150°C) and intermediate-temperature (90-150°C) hydrothermal convection systems, in part using data acquired and compiled in the course of systematic evaluation of Known Geothermal Resource Areas (Mabey and Isherwood, 1978).

b. Improvement of methodology for estimating the fraction of energy in hydrothermal convection systems or geopressured systems that might be recoverable at the surface.

c. Interpretation of available data on low-temperature (<90°C) geothermal systems, in cooperation with the State Cooperative Direct-Heat Geothermal Program of the Division of Geothermal Energy of the Department of Energy.

d. Utilization of GEOTHERM, the new USGS system of computer-based storage and retrieval of geothermal data (Swanson, 1977).

e. Assessment of geopressured resources not inventoried in 1975 (offshore Tertiary deposits and onshore Mesozoic deposits of the Gulf Coast, and geopressured resources of other sedimentary basins).

f. Refinement of the size and age of young igneous systems and more thorough evaluation of the effects of hydrothermal convection on the cooling of plutons.

g. Evaluation and possible use of the techniques of subjective probability and Monte Carlo aggregation used in recent oil and gas resource assessments of the United States (Miller, et al., 1975).

h. Presentation of data and conclusions on a regional as well as a national basis.

This past year, the USGS has cooperated with the National Electric Agency of Italy (ENEL) in evaluating techniques for geothermal resource assessment, under the sponsorship of the U. S. Energy Research and Development Administration (ERDA), recently absorbed into the new Department of Energy. Recommendations for uniform terminology and methodology were presented at the ENEL-ERDA Larderello Workshop on Geothermal Resource Assessment and Reservoir Engineering (Muffler and Cataldi, 1978) along with a test application to central and southern Tuscany (Cataldi et al., 1978).

These joint studies identified a number of problems in geothermal resource assessment, one of which bears directly on the reservoir engineering community. This is the question of recoverability. In the petroleum and mining industries, one makes a careful distinction between the total amount of a given deposit underground prior to extraction, and that part of the deposit that might be extracted under foreseeable economics and technology. Commonly, the recoverable part is expressed as the total deposit multiplied by a recovery factor.

Extension of the term "recovery factor" to geothermal resources leads one to define geothermal recovery factor as the ratio of extracted thermal energy (measured at the wellhead) to the total thermal energy contained in a given subsurface volume of rock and water (Muffler and Cataldi, 1978). Implicit in this definition is the necessity that recovery take place in an industrial time frame (10 to 100 years) rather than in a geologic time frame ($>10^3$ years).

Recovery factors for hydrothermal convection systems were discussed in detail by Muffler and Cataldi (1978), and the test of geothermal assessment methodology in central and southern Tuscany (Cataldi et al., 1978) used the following formulations: (1) for systems producing by intergranular vaporization, the formulations of Bodvarsson (1974) and of Nathenson (1975) were modified for a 2.5 bar final pressure limitation (figure 2), and (2) for systems producing by intergranular flow, the analysis of Nathenson (1975) was extended to give a geothermal recovery factor scaled linearly from 50% at an effective porosity of 20% to 0% at an effective porosity of 0 (figure 3).

The first formulation is fairly rigorous, with the major assumption being whether the reservoir initially is filled with water or is vapor-dominated (White et al., 1971). The second formulation, however, is little more than a guess. A better basis for estimating the geothermal recovery factor is needed for geothermal resource assessment,

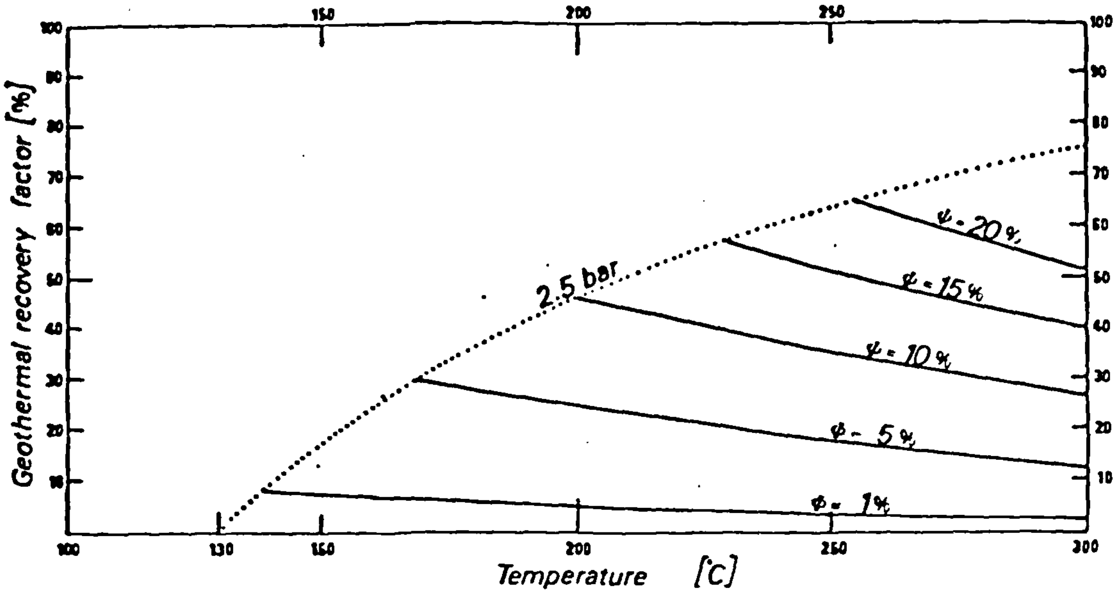

Figure 2.--Graph showing geothermal resource recovery factor (Rg) as a function of reservoir temperature and effective porosity (ϕ_e) for reservoirs produced by intergranular vaporization. From Muffler and Cataldi (1978, fig. 7), adapted from Nathenson (1975, fig. 4).

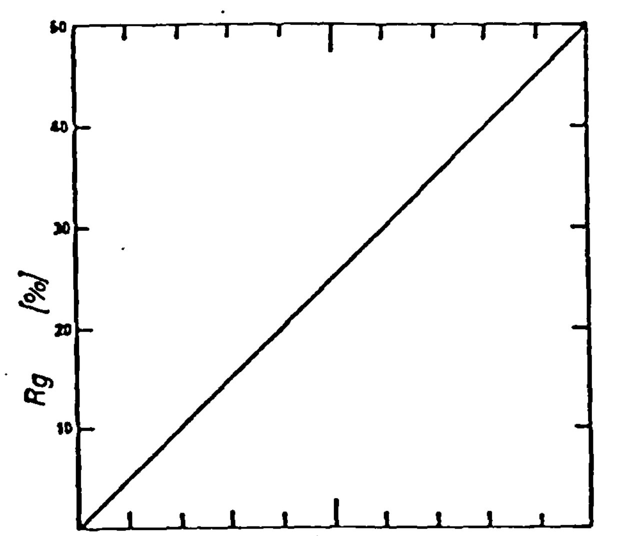

Figure 3.--Graph showing possible variation of geothermal resource recovery factor (Rg) as a function of effective porosity (ϕ_e) for reservoirs produced by intergranular flow. Rg is taken to be 50% for an ideally permeable reservoir in which total porosity = effective porosity = 20%. From Cataldi et al. (1978, fig. 9).

and I solicit the help of the reservoir engineering community in developing improved ways of estimating geothermal resources from hydrothermal convection systems produced by means of intergranular flow.

Acknowledgments

This contribution draws heavily on manuscripts prepared for the Geothermal Symposium at the IASPEI/IAVCEI Assembly of August 1977 (Muffler and Christiansen, 1978) and the Larderello Workshop on Geothermal Resource Assessment and Reservoir Engineering of September 1977 (Muffler and Cataldi, 1978; Cataldi et al., 1978).

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	Resource base (10^{18} cal)	Recovery factor for heat	Resource (Heat recoverable, 10^{18} cal)	Electricity Conversion Factor [m]	Electricity (MW·c)	Utilization Efficiency	Beneficial heat (10^{18} cal)
Conduction-dominated environments	8,000,000 [a]	0	0	-	-	-	-
Hot igneous systems							
Evaluated	25,000	0	0	-	-	-	-
Unevaluated	75,000	0	0	-	-	-	-
Hydrothermal convection systems							
Vapor-dominated							
Identified	26 [b]	.1	1.9 [c]	.2	494	-	-
Undiscovered	24	.1	2.4	.2	625	-	-
Hot-water (>150°C)							
Identified	370 [a,d]	.25	59.5 [c]	.08-.12	7,506	-	-
Undiscovered	~1,230	.25	~308	.08-.12	~38,000	-	-
Hot-water (90-150°C)							
Identified	345 [e]	.25	86	-	-	.24	20.7
Undiscovered	1,055	.25	~260	-	-	.24	~62
Geopressured systems							
Evaluated -- Plan 1	10,920 [f]	.021	229 [g,h]	.08	24,380 [i,j]	-	-
Plan 2		.033	359 [g]	.08	38,140 [i]	-	-
Plan 3		.005	53 [g,h]	.08	5,690 [i,k]	-	-
Unevaluated	33,000 [l]	>.023	>750 [g,h]	.08	~75,000 [i]	-	-

[a] To 10 km.
[b] Includes 7.1 X 10^{18} cal in National Parks.
[c] Excludes National Parks.
[d] Includes 133 X 10^{18} cal in Yellowstone National Park.
[e] Bruneau-Grandview area of Idaho, 263 X 10^{18} cal.
[f] "Fluid resource base" to 7 km in Louisiana and 6 km in Texas.
[g] Plus thermal energy from combustion of dissolved methane.
[h] Plus thermal equivalent of mechanial energy.
[i] Plus any electricity generated from methane.
[j] Plus 9,970 MW·c from mechanical energy.
[k] Plus 3,560 MW·c from mechanical energy.
[l] Offshore Gulf Coast, deeper parts of Gulf Coastal Plain, and other geopressured basins.
[m] Ratio of electricity generated to the enthalphy of the fluid at the indicated temperature (relative to a reference enthalpy of 15°C water).

important but there's also a large unfulfilled need for 150-250°C components. Although pieceparts of this technology exist, industry is not moving very fast into this temperature regime.

The Committee asked how far away is commercial manufacturing of high temperature CMOS logic circuits. Sandia replied that experimental circuits have been successfully built and tested in the laboratory but no funds are available to support commercial manufacture. This effort would require an estimated $200K per year for about two years.

One of the semiconductor industry representatives indicated that dielectrically isolated high temperature amplifiers could be improved to operate up to 300°C. Improvements need to be made in the circuit's metallization, processing, and packaging. Sandia has made a proposal to DOE Fossil Energy and the Navy to accomplish this task.

Quartz Pressure Transducer - Sandia asked what would be the recommended way to transfer this rapidly developing technology to industry. The consensus was that Sandia should publicly document its progress, distribute the information to all interested parties, and include this subject in the December seminar.

Cables - In addition to the ongoing cable testing effort, Sandia has just issued an RFP for investigation of new directions in geothermal cable design. The best conventional cables use PFA or TFE Teflon® and these are only good to about 275°C. Besides being about 4 times more expensive than conventional logging cables, these Teflon insulated cables have a limited life because the insulation is in direct contact with hot brine.

The goals of cable development are to achieve better reliability, less aging, and lower cost. The temperature performance specification was 100 hours at 350°C and 10,000 hours at 275°C. The Steering Committee questioned the need for the 350°C specification, especially in view of the recently published USGS Circular 790 which emphasizes the importance of the lower temperature geothermal regime and deemphasize temperatures above 275°C with regard to the estimated geothermal reserves. In reply to this question, Sandia responded that there is a definite need for very high temperature cables and that at lower temperatures such a cable will have a greatly extended life. In any case, if the new cable achieves greater performance at lower cost, the geothermal industry will greatly benefit.

The question of fiber optics for well logging was raised. In response, Sandia's position is that this is a rapidly developing area of technology where many things need to be proven at low temperatures before spending any effort to upgrade for geothermal. No specific activities are planned for fiber optics in geothermal at this time. However, progress at the lower temperatures is being monitored to identify any advantages for geothermal applications.

Cable-Head and Seals - The Committee recommended that Sandia continue to investigate elastomer "o"-ring seals rather than the exclusive use of metal seals in the prototype tools; the reason for this is industry's high investment in tools that use "o"ring seals and the unfamiliarity of field personnel in the use of metal seals. DOE/DGE has a substantial effort underway in elastomeric development. Sandia will try to incorporate the results of this research into tool seal designs.

Up-Hole Equipment - Sandia has a general purpose experimental capability that uses a microprocessor based data collection system and conventional cable hoise and mast truck units. This equipment supports DGE field test experiments and is not meant to advance the state-of-the-art, so no extensive developments are planned in this area. The Steering Committee supported this position.

Field Testing with Geothermal Producers and Service Companies - The Committee concensus was that the Sandia experimental equipment appears to be adequate for field testing; they recommend Sandia accelerate cooperative testing with service companies and geothermal producers.

Discussion of Prototype Tools

In reviewing the proposed list of prototypes, the Committee recommended adding the following tools:

1. Two Phase Flow Meter
2. Density Instrument
3. Fluid Sampler
4. Rock Sampler

Sandia reviewed the rationale for tool development and grouped the tools into the following three categories:

I. Prerequisite Tools (Needed for Log Instrumentation and Reservoir Engineering)

   1. Temperature
   2. Pressure

3. Flow
4. Caliper
5. Casing Collar Locator

II. <u>Essential Tools for Drilling, Production, and Formation Evaluation</u>

1. Fracture Mapping
2. Casing and Cementing Inspection
3. Free Point (Stuck Drill Pipe) Detector
4. Two Phase Flow Meter
5. Density
6. Fluid Sampler
7. Rock Sampler
8. Resistivity
9. Spontaneous Potential
10. Borehole Chemistry
11. Subsidence

III. <u>Advanced Formation Evaluation Tools</u> (Some of these are currently available but only as conventional oil and gas instruments that are packaged in dewar flasks)

1. Gamma Ray
2. Neutron
3. Gravimeter
4. Dipmeter

The Group I tools and their components are presently under field test evaluation and commercialization. Some work has started on Group II components and there are plans to develop the technology to ensure that all these tools can be built by industry. There are no current plans to upgrade the Group III tools.

The Committee agreed with this approach but inquired about the status of a combined production tool (i.e., simultaneous measurement of temperature, pressure, and flow). Sandia replied that the key part of this tool is a multiplexer circuit and that a multiplexer has been designed and breadboarded in the laboratory. Next fiscal year the multiplexer will be fabricated as a hybrid circuit by a commercial supplier. Also, the combined prototype tool will be designed in FY80 and fabricated in FY81 using the commercial multiplexer circuit.

Executive Session

IRT Neutron Based Formation Temperature Tool - The Committee concensus was that a strong case was not made for further efforts in this project. First, the radial temperature gradient may extend some distance (perhaps 2 feet or more) into the formation away from the borehole. This distance is not known precisely nor is the temperature profile being measured known exactly. Second, it's still not known how precisely the IRT instrument will be able to measure the temperature at a given depth into the formation. Because neither the need for this tool nor its performance are established and because of the extensive effort that needs to be done to develop the technique and build a high temperature instrument, the Committee recommended that no further development be pursued in this area.

Borehole Televiewer Development - The Committee expressed many reservations about this instrument: 1) the BHTV's usefulness for geothermal has not been proven - no one has established the relation between production and fractures; 2) the BHTV has had poor acceptance in the oil and gas industry; 3) there are many problems with the BHTV even at low temperature, especially in the area of read out and interpretation.

Sandia's response to these reservations was to propose that Sandia continue a low key effort in cooperation with the USGS in areas of Sandia/DOE expertise such as materials and seals. The Committee agreed with this position and requested that Sandia and the USGS present a progress report on this BHTV effort at the next Steering Committee Meeting.

General Remarks - The Committee's concensus was that the Sandia program was proceeding rapidly and successfully in the area of component development and commercialization but they cautioned that prototype tool development could be very costly and yield only one-of-a-kind instruments that can only be run by laboratory personnel.

Sandia responded that a limited number of prototype tools must be built as test beds for the component technology so that the entire instrumentation system can be field tested to verify the technology and stimulate commercial application with geothermal producers, logging service companies, and component suppliers.

The Committee recommended that the prototype tool development be approached on a case-by-case basis and they requested that at our next meeting Sandia again review prototype tool development status and plans.

Planning for the December Seminar - Several Steering Committee Members participated in a planning exercise for the proposed December Workshop. They recommended that it be structured as a seminar rather than a workshop because there are reservations about the possibility of disclosing proprietary information in a workshop setting. They also recommended that the seminar be structured with an overview presentation during the first half-day and that each major theme or subject be a selfcontained session with a prepared list of questions and papers distributed beforehand and presentations, questions and answers, and a wrap-up all in one block of time. Following all the individual sessions there should be a brief wrapup report by each session chairman to the entire seminar audience.

Meeting with Dr. Markley DOE/FE - Following the above discussion, Dr. Richard Markley of DOE's Division of Fossil Fuel Extraction was introduced to the Committee. Dr. Markley asked the Committee: "Is there a federal role in the development of instrumentation oil and gas?"

The Committee's response to the above question was as follows:

1. Deep drilling is increasing at the rate of 20% per year and the number of steam injection wells is also increasing at about the same rate. Last year, there were about 600 wells deeper than 15,000 feet and there were about 4,000 steam injection wells.

2. The temperature regime of interest for oil and gas is less than 250°C.

3. Private enterprise has a keen interest in fulfilling the instrumentation needs in this area and substantial efforts are underway in tool development and service logistics to fulfill these needs.

4. There is no need for specialized tools at this time.

5. There is no need for government R&D into instruments development for less than 250°C operation.

6. There is an unfilled need for component development in the area of high temperature integrated circuits. Individually, the service companies are too small a market for any of the semiconductor houses to justify the R&D costs to develop the circuits. No one is spearheading the component development effort to identify a large enough market for the semiconductor manufacturers to entice them into providing the necessary hardware. The service companies don't want to get into the semiconductor business--they can't afford it.

7. If DOE can accelerate commercial component developments for this temperature range, then the industry will begin applying those components and these applications; and therefore, the markets will multiply to the point were private industry is doing it all.

Following the above discussion, Dr. Markley asked about the philosophy of a steering committee in this area. The Committee replied that they would be pleased to communicate with DOE in this fashion; in fact, their main interest in the geothermal area is not so much geothermal itself but the hot oil and gas market because it's much larger. The work DOE is doing in geothermal is pioneering technology that will improve the reliability, performance, and temperature range of hostile environment logging tools.

Next Steering Committee Meeting

The Committee recommended that the next meeting be held immediately following the seminar during the first week in December.

GEOTHERMAL LOGGING INSTRUMENTATION DEVELOPMENT PROGRAM
STEERING COMMITTEE MEETING - AGENDA

May 30 & 31, 1979

Congressional Room, Quality Inn-Capitol Hill, Washington, DC

Wednesday, May 30, 1979

Time	Subject	Speaker
8:30	Welcome & Introductions	J. Salisbury/DOE/DGE
8:45	Geothermal Logging Instrumentation Development Strategy	A. Veneruso/Sandia
9:20	275°C Geothermal Well Field Test Results	F. Heard/Sandia
9:40	Industrial Utilization of DOE/DGE Developed Technology - 275°C Hybrid Circuits	J. Slomski/Teledyne Philbrick
10:00	Questions & Answers Concerning the Above	
10:15	Break	
10:30	Experience With Commercial Geothermal Logging & Log Interpretation Problems	M. Mathews/LASL
10:50	Questions & Answers	
11:00	Geothermal Cable Testing & Development	A. Veneruso/Sandia
11:30	Discussion	
12:00	Luncheon	
1:30	Quartz Resonator Pressure Transducer	T. McConnell/Sandia
2:00	Commercial Needs for Generic, High Temperature Silicon Integrated Circuits	P. Sinclair/ Schlumberger
2:20	Questions & Answers	
2:30	Component Technology Developments	R. Heckman/Sandia
3:00	Break	
3:15	Discussion - Technology Development Priorities	Committee
4:00	Summary of First Day	
4:30	Adjourn	

Thursday, May 31, 1979

Time	Subject	Speaker
8:30	Discussion of Technology Transfer to Industry - Strategy & Status:	Committee with A. Veneruso/Sandia Discussion Leader
	a) High Temperature Electronics	
	b) Quartz Pressure Transducer	
	c) Cables	
	d) Cable-Head & Seals	
	e) Up-Hole Equipment	
	f) Field Testing with Geothermal Producers & Service Companies	
10:00	Break	
10:15	Neutron Based Formation Temperature Tool	N. Vagelatos/IRT
10:35	Questions & Answers	
10:45	Reservoir Engineering Requirements for Downhole Instruments	R. Schroeder/LBL
11:15	Discussion of Prototype Tools as Test Beds for Component Development	Committee with A. Veneruso/Sandia Discussion Leader
	a) Geothermal Requirements	
	b) Tool Status	
	c) Developments Priorities	
12:00	Luncheon	
1:30	Executive Session - Direction from Committee	
2:45	Summary	
3:00	Break	
3:15	Planning For A Fall Workshop on High Temperature Instrumentation	A. Veneruso/Sandia
4:00	Adjourn	

Welcome and Introductions

J. Salisbury - DOE/DGE

Mr. Jack Salisbury, Deputy Director of DOE's Division of Geothermal Energy (DGE), welcomed the Steering Committee and then he reviewed DGE's overall strategy, structure, and plans. The goals are to reduce the cost of geothermal power and to accelerate industry efforts to bring geothermal power on line. He remarked that the Logging Instrumentation Program is working well and that the Steering Committee appears to be a key ingredient in the success of the program.

Hydrothermal Functional Organizations

Assistant Secretary For Resource Applications

- **Geothermal Resource Manager**
  - **Hydrothermal Marketing Program**
    - Regional Planning
    - Market Penetration Analysis
    - Federal Incentives
    - Legal, Institutional, & Environmental Barriers
    - Intergovernmental Relations
    - Industrial Relations
    - Geothermal Loan Guaranty Program

RA/ET Coordination (links Geothermal Resource Manager and ETS Program Director)

Assistant Secretary For Energy Technology

- **ETS Program Director**
  - **Division Of Geothermal Energy**
    - Regional Assessment
    - Resource Definition
    - Engineering Applications
    - Environmental Control
    - Geothermal Technology Development
    - Facilities

GS7901371-2/3

Division of Geothermal Energy

Office of the Director

Director (Acting)	Bennie G. DiBona
Deputy Director	John W. Salisbury (1)
Technical Asst.	Ronald S. H. Toms

Program Coordination Branch

Chief	David B. Lombard

Hydrothermal Support Branch

Chief	John W. Salisbury (1)

Hydrothermal Technology Section

Chief	Clifton McFarland
Program Manager	Robert R. Reeber
Program Manager	Lawrence Ball
Program Manager	Raymond LaSala

Reservoir Assessment Section

Chief	Robert Gray
Program Manager	Gerald Brophy (2)
Program Manager	Marshall Reed (1, 3)
Program Manager	(Vacant)

Direct Heat Applications Section

Chief	Morris Skalka
Program Manager	Donald B. Elmer

Advanced Technology Branch

Chief (Acting)	Clifton Carwile (1)

Advanced Energy Systems Section

Chief	Clifton Carwile (1)
Program Manager	Allan J. Jelacic

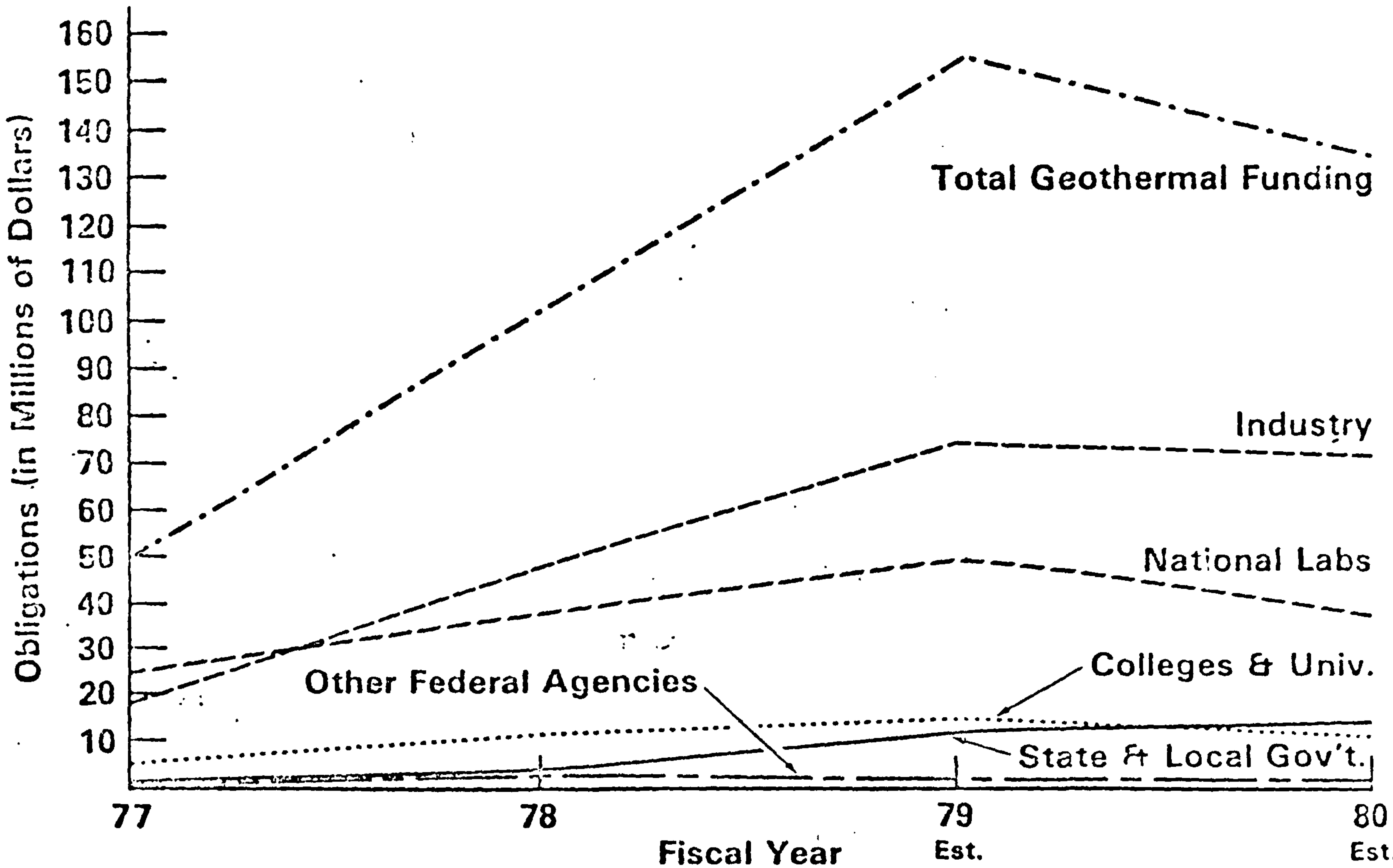
Drilling and Stimulation Section

Chief (Acting)	Arthur B. Follett
Program Manager	(Vacant)

(1) Dual Capacity
(2) IGPA-in
(3) Detailed from US Geological Survey

GS 7902626 3 6

Geothermal Funding by Contractor Type



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Hydrothermal Technology Section

Activities	Program Manager	FY79 Budget ($ Million)	FY80 Budget Request ($ Million)
Conversion Technology	Cliff McFarland/ Ray LaSala	10.9	7.0
Stimulation	Cliff McFarland	3.3	2.7
Geochemical Engineering and Materials	Robert Reeber	6.7	3.5
Geoscience Technology Development * Logging Instrumentation * Log Interpretation * Rock Properties	Larry Ball	3.5	2.0

GS7902626 5 6

National Laboratory Geothermal Funding Subcontracted in FY 1979

	Total Lab Budget	Amount Subcontracted	% Subcontracted
ANL	$ 10K	$ 0K	0%
BNL	1,630	571	35%
INEL	14,700	7,056	48%
LBL	6,402	2,433	38%
LLL	1,899	342	18%
ORNL	715	164	23%
PNL	1,494	239	16%
LASL	16,411	7,713	47%
Sandia	7,676	4,759	62%
	$50,937K	$23,277K	46%

TONY VENERUSO

DIVISION 4736

SANDIA LABORATORIES

GEOTHERMAL LOGGING INSTRUMENTATION
PROGRAM OBJECTIVES

PHASE I. DEVELOP PREREQUISITE COMPONENTS AND CAPABILITIES

- DEMONSTRATE THE FEASIBILITY OF 275°C ELECTRONIC COMPONENTS
- TRANSFER TECHNOLOGY TO INDUSTRY
- DEMONSTRATE BASIC 275°C LOGGING TOOLS
- STIMULATE INDUSTRY APPLICATION AND R&D

PHASE II. DEVELOP FULL COMPLEMENT OF ESSENTIAL CAPABILITIES

- PROVIDE THE FULL COMPLEMENT OF ESSENTIAL 275°C ELECTRONICS
- EXTEND LIFETIMES OF 275°C ELECTRONICS AND CABLES BEYOND 100 HOURS
- DEMONSTRATE THE TECHNOLOGY REQUIRED TO PRODUCE THE FULL SUITE OF GEOTHERMAL LOGGING TOOLS
- INVESTIGATE FEASIBILITY OF 350°C TECHNOLOGY
- STIMULATE INDUSTRIAL APPLICATION AND R&D

Sandia Laboratories

STATUS

- DEVELOPED PREREQUISITE HYBRID THICK FILM MICRO-ELECTRONIC COMPONENTS
- SUCCESSFULLY TESTED A TEMPERATURE TOOL UP TO 275°C
- PREPARING TO TEST FLOW AND PRESSURE TOOLS TO 275°C
- INDUSTRY IS FABRICATING SEVERAL 275°C GENERIC CIRCUITS DEVELOPED BY SANDIA.
- DEVELOPING THE FULL COMPLEMENT OF ESSENTIAL 275°C ELECTRONICS - DIODES, CAPACITORS, TRANSISTORS, ETC.
- DEVELOPING A HIGH RESOLUTION, QUARTZ CRYSTAL PRESSURE TRANSDUCER - FIRST MODEL TESTED TO 1000 PSI AND 275°C
- CONTINUING JOINT DEVELOPMENTS AND FIELD TESTING WITH INDUSTRY.

FY 1979 FUNDED ACTIVITIES AND WHY

Activities In Support of Interim 275°C Goals	Contract Amount	Why
• Commercial Fabrication of 275°C Hybrid Circuits with Teledyne Philbrick	$39K	Transfer Technology to Industry
• Develop 275°C Electronics With:		Satisfy Essential Component Needs for 275°C Logging
Purdue U. - Thick Film Materials	$40K	
Texas A&M - Magnetics	$60K	
MacDonnel Douglas - GaAs Diodes	$57K	
Clemson U. - Integrated Circuits (IC's)	$48K	
In-House-Discrete Semiconductors, IC's & Specific Passive Components		
• Develop Quartz Pressure Transducers With Paroscientific - Ultrahigh Resolution	(No Cost)	Required for Reservoir Assessment
• Develop & Test Cables	($200K From Materials Program)	Qualify Geothermal Cables
• Develop and Field Test 275°C Prototypes with:		Verify New Technology & Demonstrate Tools with Producers & Service Companies
Gearhart Owen Industries - Prototypes	$17K	
Simplec Mfg. Co. - Fracture Mapping	$16K	
IRT Corp. - Neutron Temp. Tool	$28K	
Union Geothermal & Phillips - Test Wells	(No Cost)	
• Develop 275°C Circuits - In-House - Amplifiers, Logic Circuits, Multiplexers		Develop Basic Circuits for Logging Instruments
• Develop 350°C Electronics with:		Development Prerequisite for 350°C
U of Arizona - Thin Film Circuits & Components	$80K	
In-House - GaAs Semiconductors, Thick Film Resistors & Capacitors		
Total	$402K	

FUTURE PROGRAM PLANS

- STIMULATE COMMERCIAL AVAILABILITY OF 275°C COMPONENTS
- CONTINUE DEVELOPMENT OF ESSENTIAL 275°C COMPONENTS - DIODES, CAPACITORS, TRANSISTORS, AND TRANSDUCERS
- DEVELOP LONG LIFE 275°C CABLE
- DEVELOP AND FIELD TEST A HIGH RESOLUTION, QUARTZ CRYSTAL PRESSURE SONDE (GOAL: ± 0.01 PSI IN 7000 PSI UP TO 275°C)
- DEVELOP AND FIELD TEST OTHER CRITICALLY NEEDED PROTOTYPES - CALIPER, FRACTURE MAPPING, CASING AND CEMENTING INSPECTION, ETC.
- INVESTIGATE 350°C COMPONENTS

PRELIMINARY RECOMMENDATIONS FOR FY1980

	Contract Amounts	
Activities to Support 275°C Goals	**Budgeted FY79**	**Estimated FY80**
• COMMERCIAL FABRICATION OF ELECTRONIC CIRCUITS & COMPONENTS PREVIOUSLY DEVELOPED	$104K	$200K
• COMMERCIAL FABRICATION OF TRANSDUCERS-QUARTZ PRESSURE, ETC.	$0K	$75K
• CABLE DEVELOPMENT AND TESTING (FROM MATERIALS PROGRAM)	($200K)	($300K)
• DEVELOPMENT OF ELECTRONIC DEVICES & CIRCUITS	$315K	$276K
• DEVELOP & FIELD TEST PROTOTYPES WITH SERVICE COMPANIES & GEOTHERMAL PRODUCERS	$78K	$75K
Activities to Support 350°C Goals		
• INVESTIGATE 350°C ELECTRONICS	$80K	$0K
TOTALS	$577K	$626K

275°C GEOTHERMAL FIELD TEST RESULTS

STEERING COMMITTEE PRESENTATION

MAY 30, 1979

JOE A. COQUAT

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ALBUQUERQUE, N.M. - A prototype geothermal borehole temperature logging instrument developed by Sandia Laboratories has been successfully operated in a geothermal well for 1-1/2 hours at 275°C - the highest operational temperature ever achieved for an uncooled, non-thermally insulated instrument equipped with active electronics. This test also involved operating the instrument for 18 hours at the 2286m (7500 ft) level of the geothermal well where temperatures reached 241°C. A separate electronic tool which measures geothermal well flow rates was also operated to a peak temperature of 221°C.

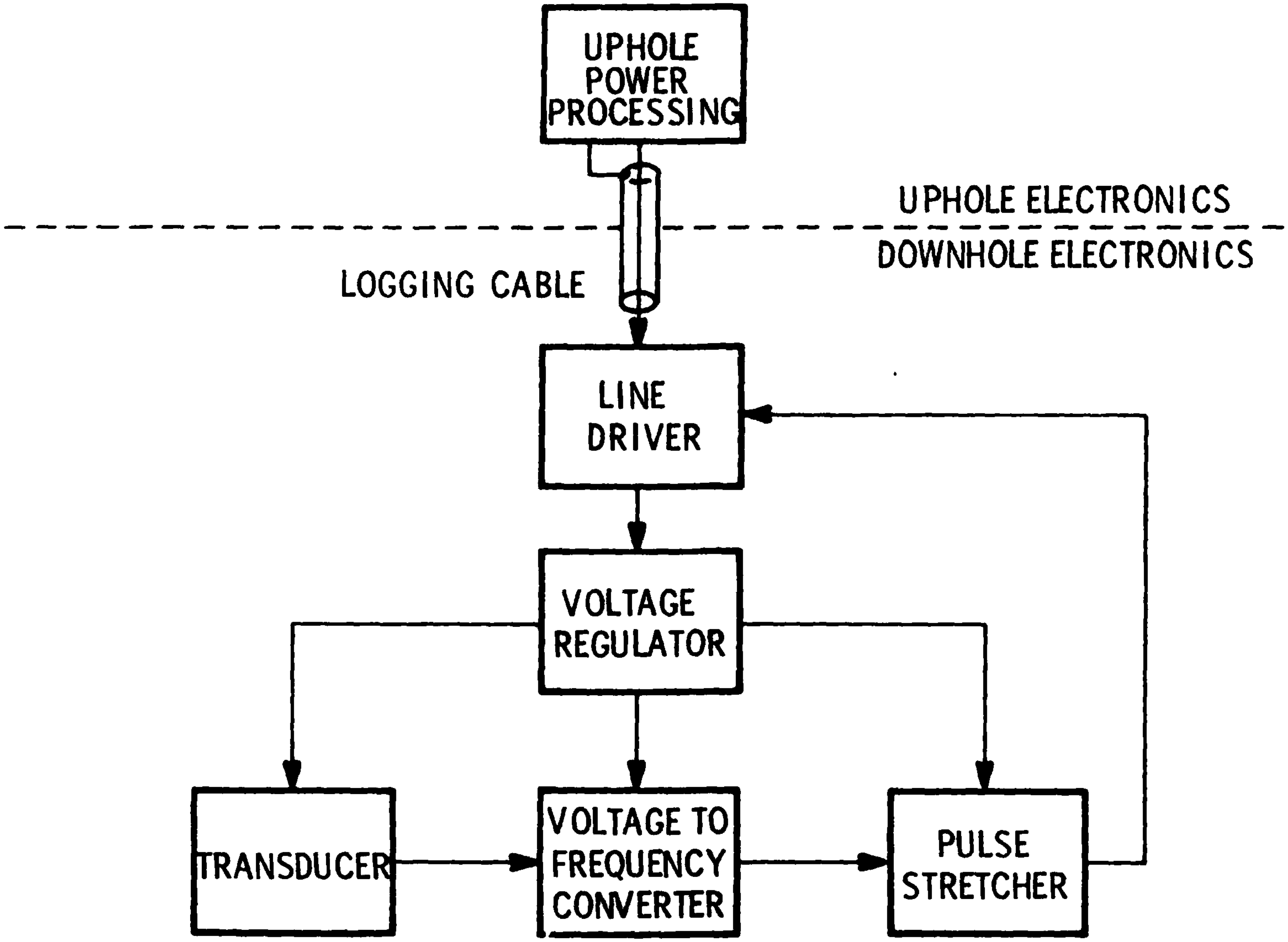
This field test, conducted in a Union Oil Co. geothermal well to pressures of 3500 psi at a depth of 2452m (8045 ft), is part of a Department of Energy (DOE) program to develop, demonstrate, and commercialize instrumentation technology to reduce geothermal well development costs and risks. Sandia manages this $1.4 million program for DOE's Division of Geothermal Energy.

While Sandia developed the high temperature electronics in this recently tested tool, the mechanical parts were designed and fabricated by Gearhart-Owen Industries, a logging service company. The entire instrumentation package, which weights about five pounds, slips into a four-foot-long, two inch-diameter steel housing. Included in this package is a temperature or pressure sensitive device along with the necessary electronics to measure and communicate the downhole information. These electronics are built using special hybrid transistor circuits.

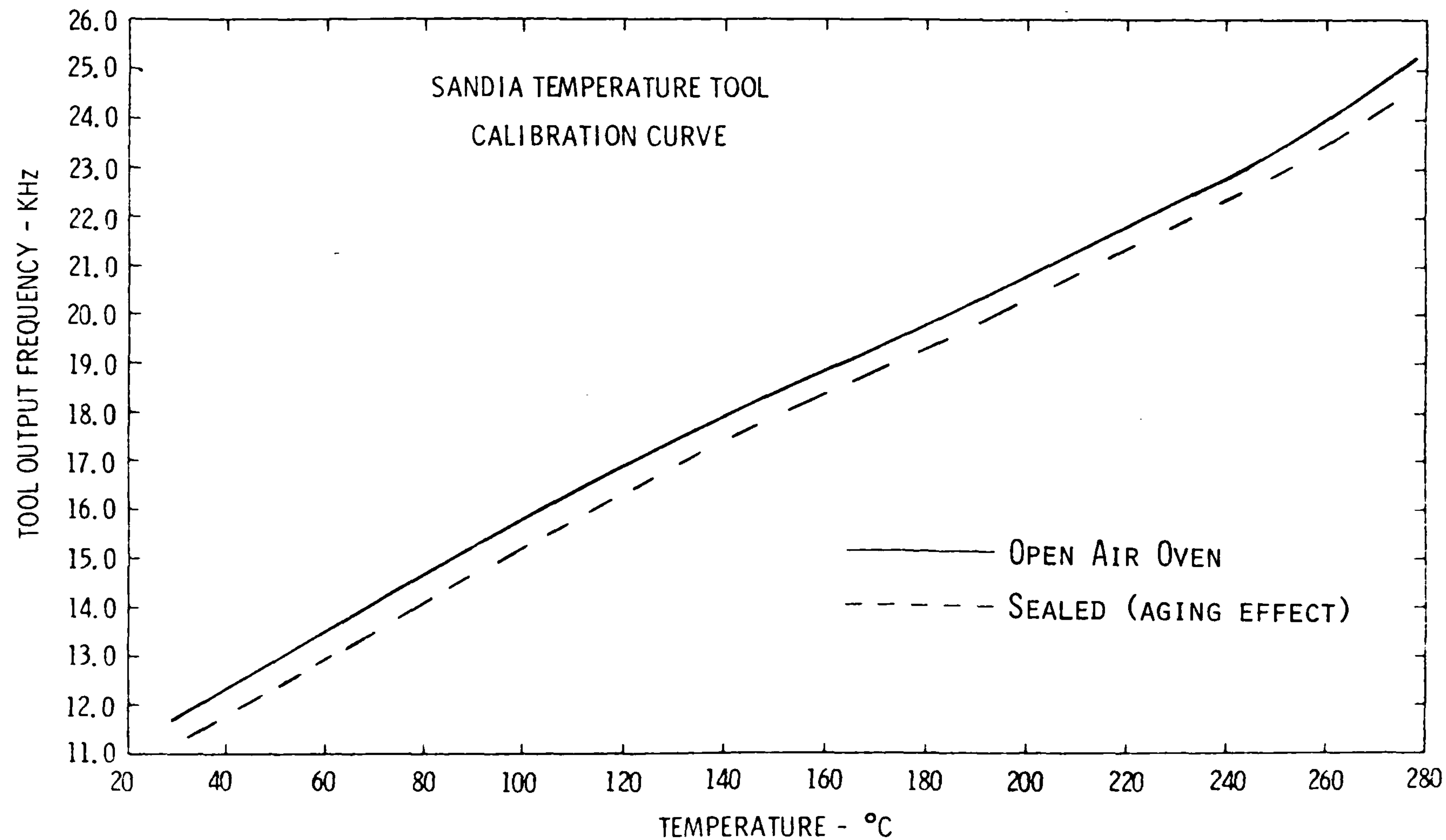
While many other essential geothermal instrumentation developments are continuing at the labs, the technology demonstrated in this first instrument is being transferred to industry. For this purpose, a contract was initiated with Teledyne Philbrick. They are working closely with Sandia to fabricate some of the high temperature electronics. This technology is needed in industry for many other high temperature logging applications.

Geothermal well logging tools are needed because conventional oil and gas logging tools are not reliable much above 150°C while geothermal resources of economic interest are typically above 200°C and range as high as 350°C.

A. F. Veneruso, supervisor of Sandia's Geothermal Technology Division says: "Logging is indispensable in determining reservoir rock and fluid properties and thus the ultimate production potential of geothermal reservoirs. In addition, logging provides information essential for modeling the reservoir, planning well completions and production, and determining environmental impact to avoid inadvertent thermal and chemical pollution of groundwater."



SANDIA
GEOTHERMAL TEMPERATURE TOOL
BLOCK DIAGRAM


SANDIA TEMPERATURE TOOL
CALIBRATION CURVE
TOOL OUTPUT FREQUENCY - KHz
TEMPERATURE - °C
OPEN AIR OVEN
SEALED (AGING EFFECT)
26.0
25.0
24.0
23.0
22.0
21.0
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
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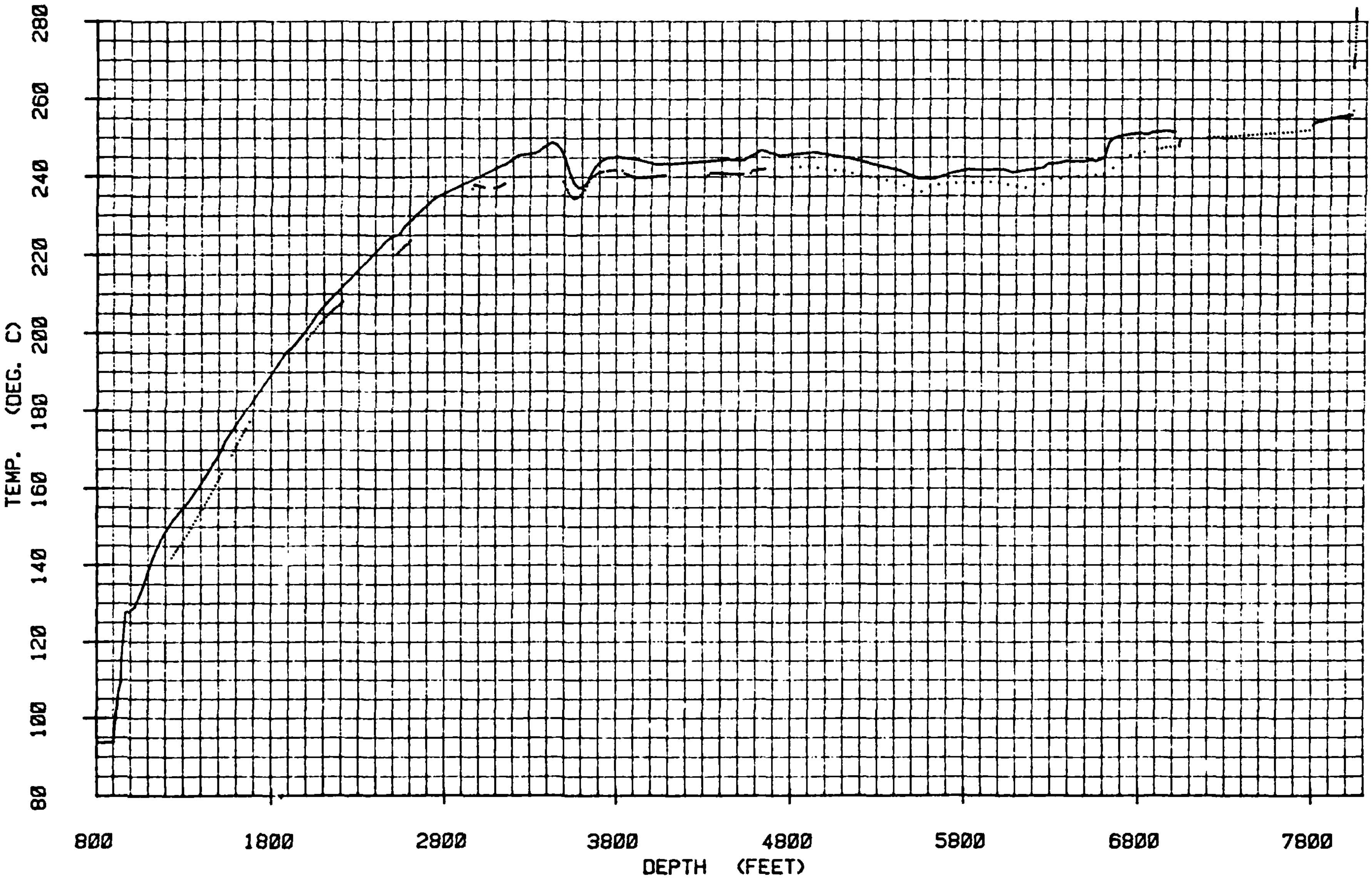
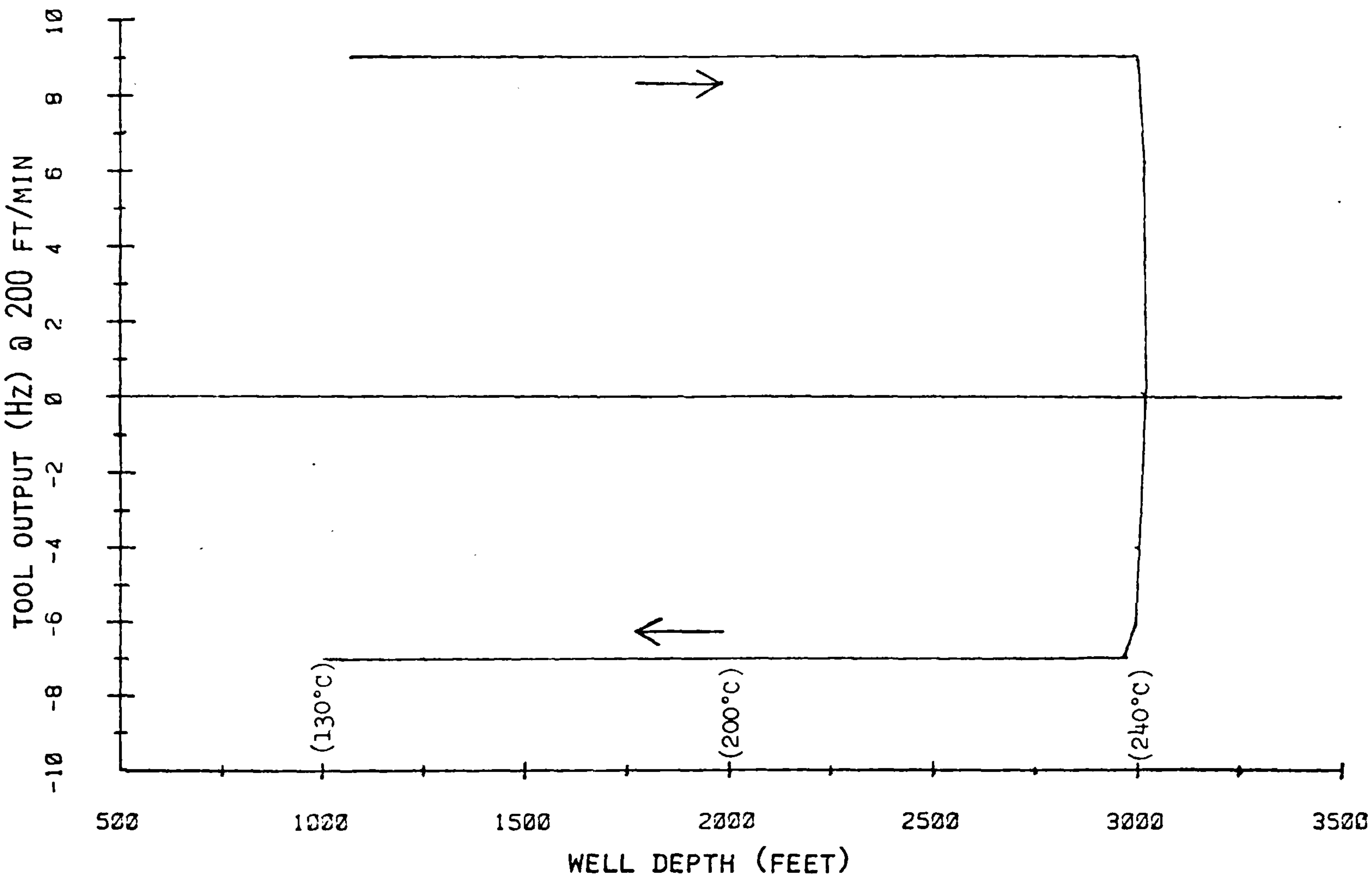
260
280

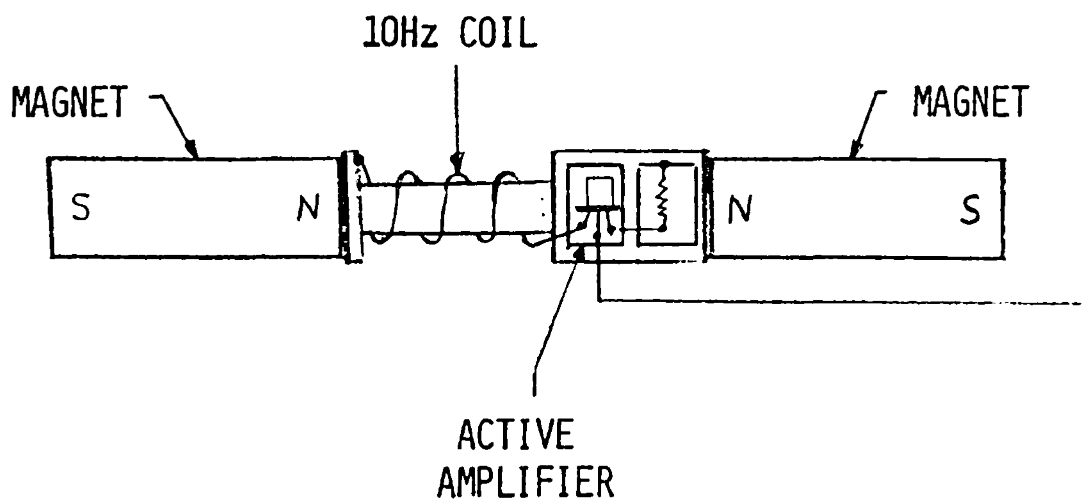
UNION TEMPERATURE LOGS NOV. 1978



FLOW TOOL OUTPUT AT CONSTANT LOGGING SPEED VS. DEPTH (TEMPERATURE)



CASING COLLAR LOCATOR (CCL)
FOR 275°C TOOLS



275°C FIELD TEST SUMMARY

- CABLE SUCCESSFUL
- CABLEHEAD, TOOL SEALS, & MECHANICAL DESIGN
- CASING COLLAR LOCATER
- FLOW TOOL TRANSDUCER THEORY
- TEMPERATURE ELECTRONICS NECESSITY FOR HERMETIC SEALS IDENTIFIED

J. Slomski - Teledyne Philbrick

Industrial Utilization of DOE/DGE Developed Technology
275°C Hybrid Circuits

Mr. Joe Slomski, of Teledyne Philbrick, discussed his company's utilization of DOE/DGE developed high temperature electronics technology. He described how the contract with Sandia functions on a day-to-day basis; that is, engineers and technicians from Teledyne and Sandia are working closely together and visit each others facilities to review the progress in the commercial hybrid circuits fabrication. He showed an example of the orginal hybrid layout for a voltage regulator that required 4 separate substrates. Teledyne reconfigured and simplified these packages down to 1 substrate. This engineering R&D is expensive so he recommended that the emphasis should be placed on developing standardized circuit blocks rather than specialized instrument circuits.

A question was asked concerning delivery and price. The answer was that it's too early to estimate those without better knowledge about product fabrication costs, performance, and market volume. The present effort with Sandia will help to answer these questions. In addition, successful development of these 275°C circuits has many spinoffs to other circuits for other customers as well as giving confidence in circuit performance at lower temperature (i.e., 200°C) applications. No viewgraphs were presented during this talk.

Mark Mathews

Los Alamos Scientific Laboratory

The following are abstracts of two presentations that were given at the SPWLA Twentieth Annual Logging Symposium, June 3-6, 1979. These papers review recent logging field tests in geothermal wells in terms of the tool responses and comparison of results.

Log Responses From The Geothermal Calibration/Test Well C/T-2

The Geothermal Log Interpretation Program (GLIP) has made available well C/T2 (Phillips 9-1) in the Roosevelt Hot Springs Geothermal Field for control, testing, and calibrating wireline logging tools. The Roosevelt Hot Springs Field is located in the southwestern part of Utah, approximately 15 km north of Milford, Utah, and is situated along the west-central flank of the Mineral Mountains, the easternmost fault-block mountains at this latitude in the Basin-Range province. This area is dominantly underlain by granitic rocks of the Mineral Mountain pluton along with biotite and hornblende gneisses. The well C/T-2 has a total depth of 2098 m (6885 ft), is cased (5-1/2 inches OD) to 1280 m (4200 ft), and is open hole (8-1/2 inches) for 818 m (2685 ft) at the bottom of the well. It has a bottom hole temperature of approximately 225°C (440°F) and penetrates igneous lithology of diorite, granodiorite, and granite. Suites of logs have been run in this well and include: temperature, caliper, induction, gamma-ray, neutron, density, and cement bond log. A qualitative comparison has been made between these logs. These data provide a background with which future logging systems can be tested and calibrated.

Log Comparison From Geothermal Calibration Test Well C/T-1

The Geothermal Log Interpretation Program (GLIP) has made the C/T-1 (Mesa 31-1) well in the East Mesa Geothermal Field available for use in quality control, testing, and calibrating wireline logging tools. The East Mesa Geothermal Field is located in the Imperial Valley of California approximately 30 km east of El Centro, Calif., and 60 km north of the Cerro Prieto Geothermal Field in Mexico. C/T-1 well is 1880 m (6175 ft) deep, is fully cased (7-5/8 inches O.D.), has a bottom hole temperature of approximately 165°C (330°F), and penetrates Plio-Pleistocene deltaic sandstones, siltstones, clays, and shales. Several suites of logs have been run in this well by different logging companies. These logs include: temperature, pressure, caliper, density, neutron, gamma-ray, and cement bond logs. A qualitative comparison will be made between these logs, the detailed lithologic log, and the open hole logs run in this well. These data provide a background upon which future logging systems can be tested, quality controlled, and calibrated.

GEOTHERMAL CABLE & CABLEHEAD TESTING & DEVELOPMENT

STEERING COMMITTEE PRESENTATION

MAY 30, 1979

JOE A. COQUAT

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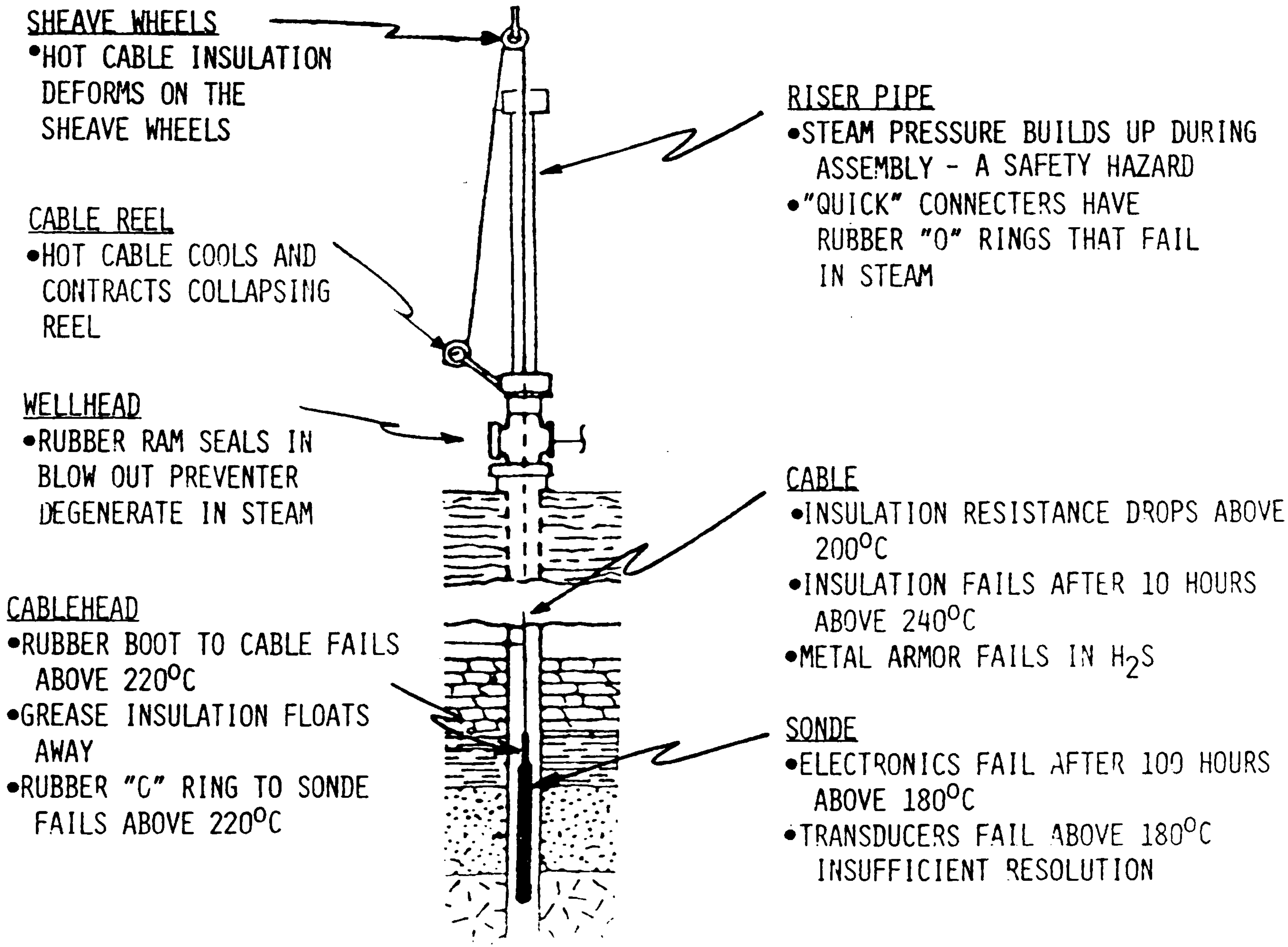
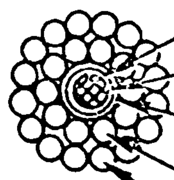
GEOTHERMAL LOGGING DEFICIENCIES



AN ARMORED LOGGING CABLE INTENDED FOR HIGH TEMPERATURE USE, CONSISTING OF ONE # 20 AWG CONDUCTOR INSULATED WITH TFE AND PROTECTED WITH A 10 X 16 ARMOR OF CORROSION-RESISTANT ALLOY.



ELECTRICAL:	D.C. RESISTANCE:		11.6 OHMS/KFT MAX
	INSULATION RESISTANCE:		1500 MEGOHMS/KFT MIN
	CAPACITANCE:		45 PF/FT
	VOLTAGE RATING:		600 VRMS
MECHANICAL:	TEMPERATURE RATING:		600°F
	WEIGHT IN AIR:		89 #/KFT
	WEIGHT IN WATER:		74 #/KFT
	BREAK STRENGTH:	ENDS FIXED:	4530 #
		ENDS FREE:	3180 #

VECTOR
Schlumberger

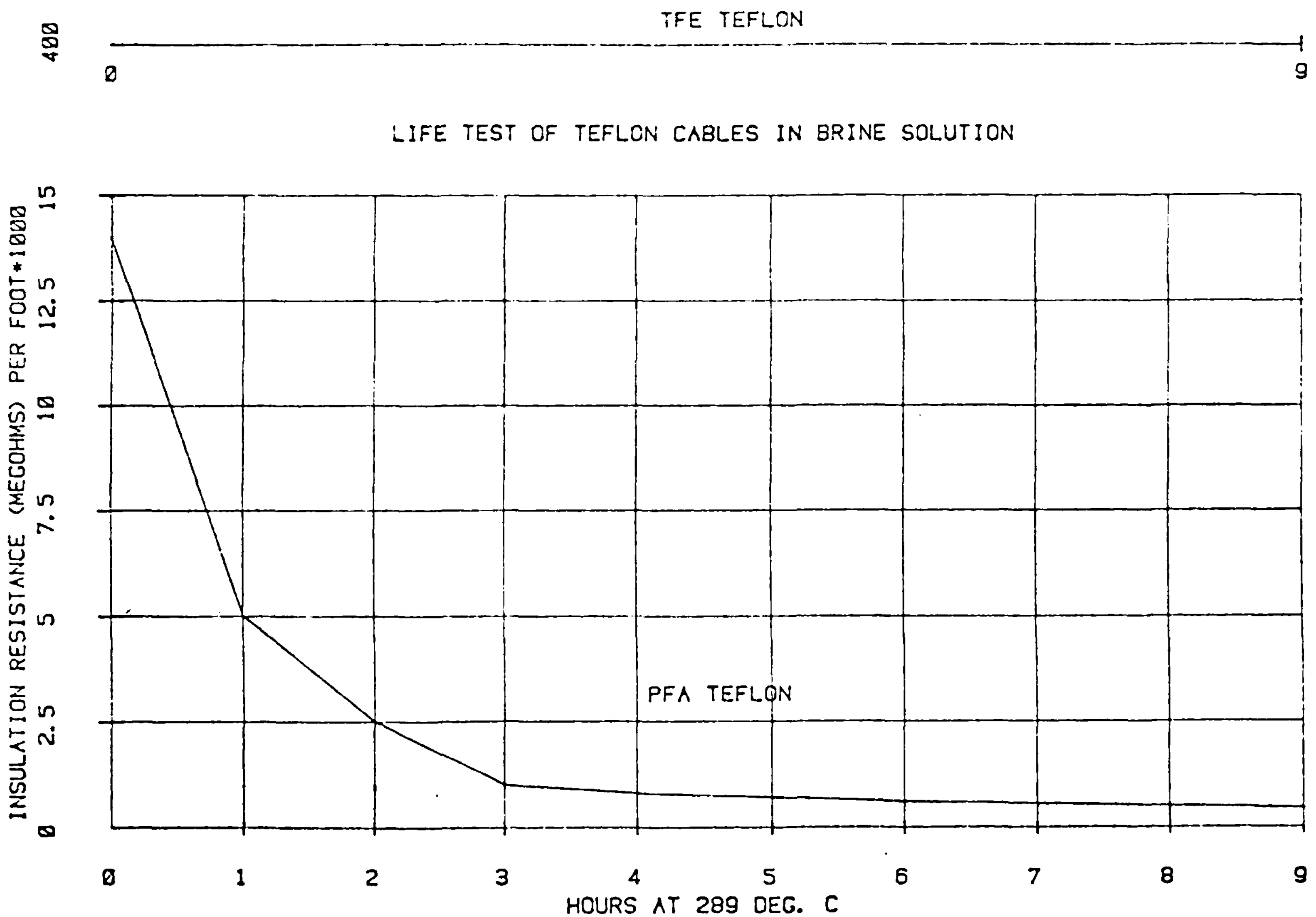

TFE TEFLON
400
Ø
9
LIFE TEST OF TEFLON CABLES IN BRINE SOLUTION
INSULATION RESISTANCE (MEGOHMS) PER FOOT*1000
15
12.5
10
7.5
5
2.5
Ø
PFA TEFLON
Ø
1
2
3
4
5
6
7
8
9
HOURS AT 289 DEG. C

Table 1

Cable Specifications

Construction:	Conductors:	1
	Armor:	Double Layer Counter Wound Torque Balanced
Electrical at 275°C:	D. C. Resistance:	12.0 ohms/KFt max.
	Insulation Resistance:	1500 Megohms/KFt min.
	Capacitance:	25 pf/Ft. max.
	Voltage Rating:	600 VRMS min.
Mechanical	Temperature Rating:	275°C 12 months minimum
		350°C 10 hours minimum
	Pressure:	
	Absolute	20,000 psi
	Gradient	500 psi in 5 feet
	Outside Diameter:	.205" max.
	Break Strength:	
	Ends Fixed	4500# min.
	Ends Free	3150# min.
	Repeated Use:	Retains all electrical and mechanical properties during 1,000 passes over a standard two sheave wheel logging set-up with 2,000 pounds of tension
Chemical:	Corrosiveness & Embrittlement: In response to the brine & H_2S composition given in Table I	Retains all electrical and mechanical properties during 12 months at 275°C and 10 continuous hours of operation at 350°C
Economic:	Cost:	Commercially available product with $5 per foot in 1979 considered an absolute ceiling price

KRYTOX® 143 AD FLUORINATED OIL

E. I. DUPONT DE NEMOURS & CO. (INC.)
PETROLEUM CHEMICALS DIVISION
WILMINGTON, DEL. 19898

APPROXIMATE BOILING RANGE, @ .001 PSI

282°C - (> 399°C)

DENSITY

75°F (24°C)	1.91 G/ML
400°F (204°C)	1.60 G/ML

VOLATILITY, WT LOSS IN 6.5 HRS @ 1 ATM

500°F (260°C)	2%

ELECTRICAL PROPERTIES @ 25°C

VOLUME RESISTIVITY, Ω CM	10^{12} TO 10^{15}
DIELECTRIC CONSTANT @ 100 Hz	2.1 TO 2.2
DIELECTRIC LOSS INDEX @ 100 Hz	0.0001

VISCOSITY

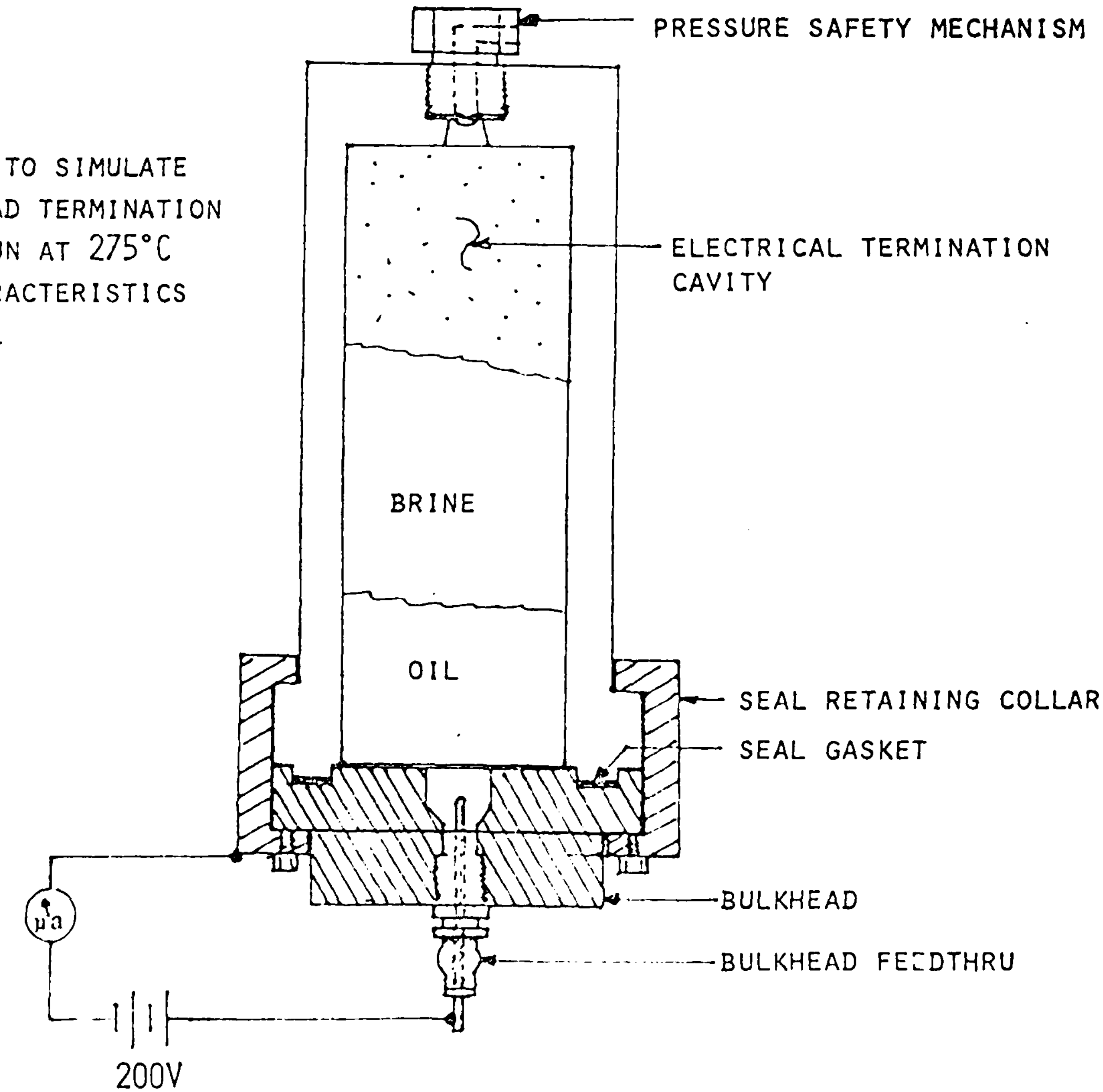
100°F (38°C) >320 cST 611 CP; H_2O = 1 CP @ 25°C

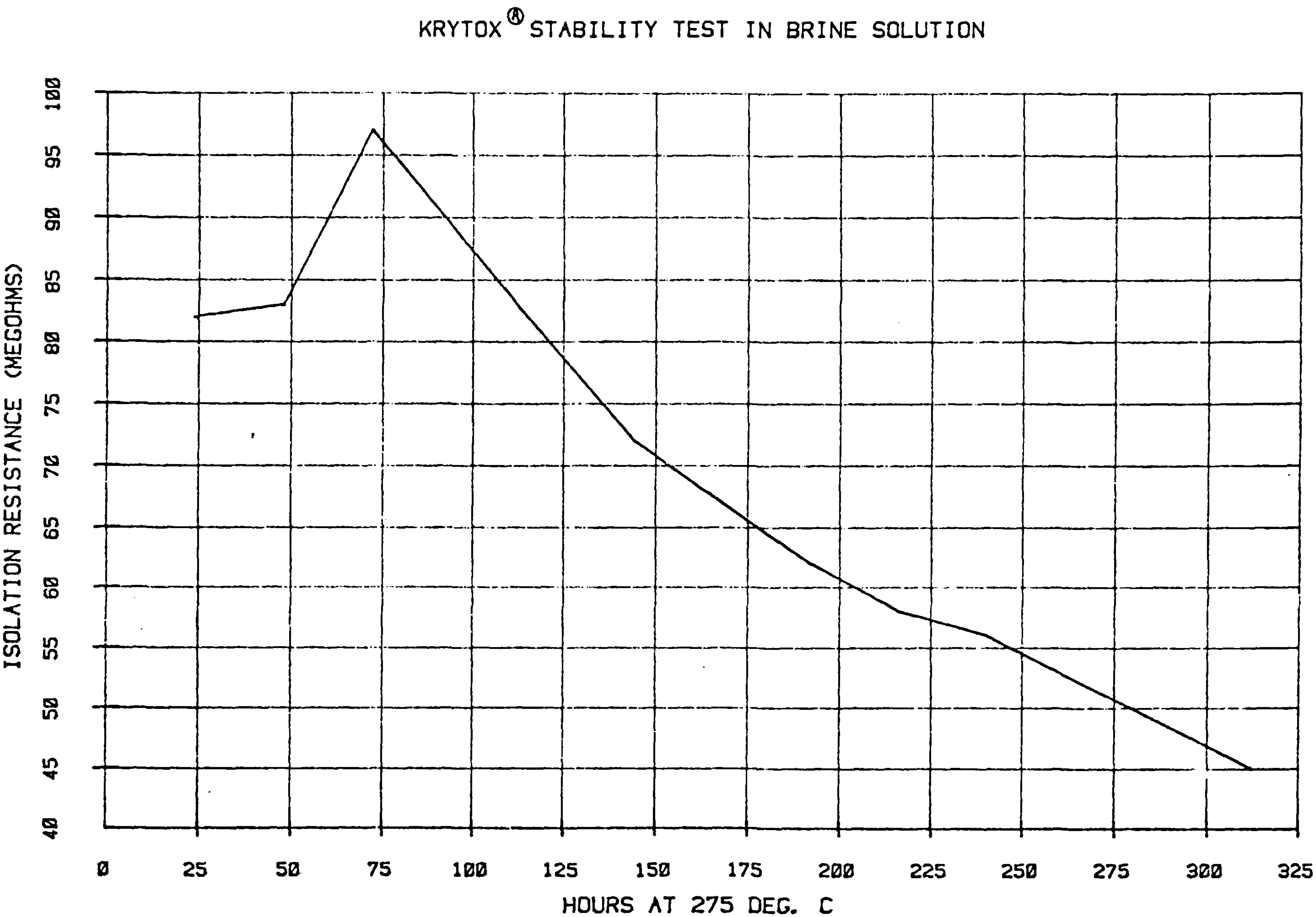
500°F (2.3) cST

VAPOR PRESSURE IN CLOSED SYSTEM

400°F (204°C)	.002 PSI
500°F (260°C)	.027 PSI
600°F (316°C)	.174 PSI

TEST VESSEL USED TO SIMULATE DOWNHOLE CABLEHEAD TERMINATION SECTION. TEST RUN AT 275°C TO DETERMINE CHARACTERISTICS OF INSULATING OIL




KRYTOX® STABILITY TEST IN BRINE SOLUTION
ISOLATION RESISTANCE (MEGOHMS)
100
95
90
85
80
75
70
65
60
55
50
45
40
0
25
50
75
100
125
150
175
200
225
250
275
300
325
HOURS AT 275 DEG. C

GEOTHERMAL PRESSURE TOOL DEVELOPMENT

STEERING COMMITTEE PRESENTATION

MAY 30, 1979

THOMAS D. McCONNELL

SANDIA LABORATORIES
DIVISION 4736
ALBUQUERQUE, NM 87185
PHONE (505) 264-7185
FTS 475-7185

GEOTHERMAL PRESSURE

TOOL GOALS

(FROM STEERING COMMITTEE)

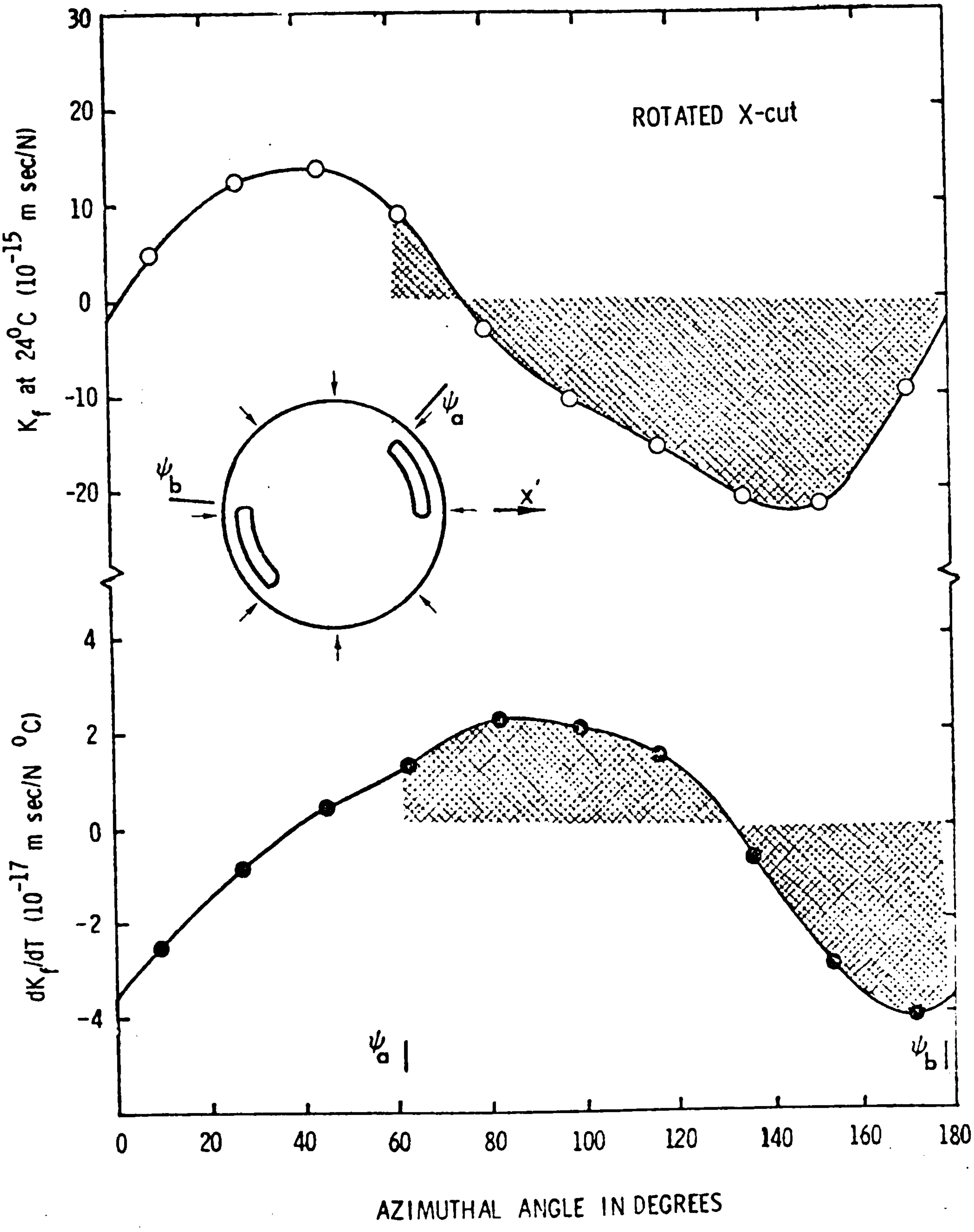
- PRESSURE UP TO 7000 PSI
- TEMPERATURE UP TO 275°C
- RESOLUTION ± 0.01 PSI

QUARTZ RESONATORS FOR PRESSURE MEASUREMENTS

- EXTREMELY STABLE ACOUSTIC RESONANT FREQUENCIES ($1/10^{10}$ PER MONTH)

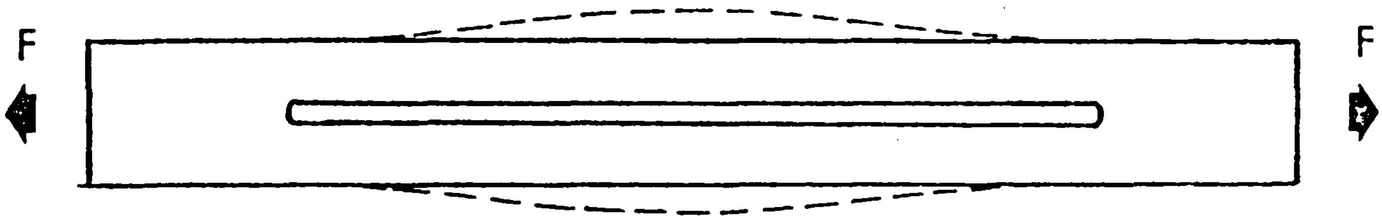
- RESONANT FREQUENCIES SENSITIVE TO MECHANICAL STRESS BIAS IN QUARTZ THROUGH ELASTIC NONLINEARITIES
  (1 PSI $\approx 1/10^7$ FREQUENCY SHIFT FOR HIGH PRESSURE DEVICE DESIGN)

POTENTIAL PRESSURE RESOLUTION OF 0.01 TO 0.001 PSI ON 10000 PSI FULL SCALE


ROTATED X-cut
K_f at 24°C (10^{-15} m sec/N)
dK_f/dT (10^{-17} m sec/N °C)
30
20
10
0
-10
-20
4
2
0
-2
-4
ψ_a
ψ_b
x'
0
20
40
60
80
100
120
140
160
180
AZIMUTHAL ANGLE IN DEGREES

MINIATURE QUARTZ RESONATOR FORCE TRANSDUCER

(Double-Ended Tuning Fork)



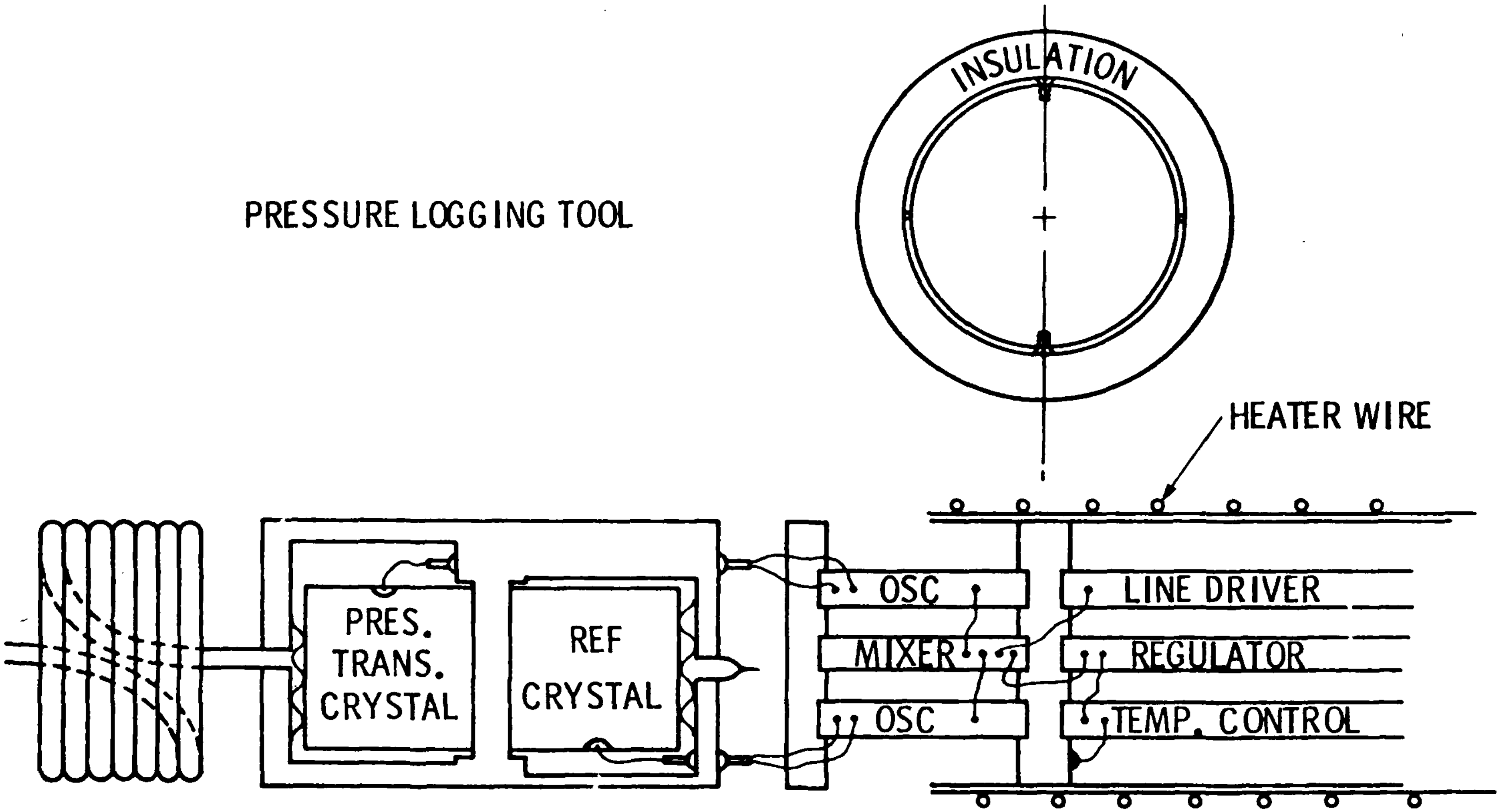
$$\frac{\Delta f}{f} = 5.43 \times 10^{-2} \text{ (ppm/dyne)} \times F\text{(dyne)}$$

Advantages:

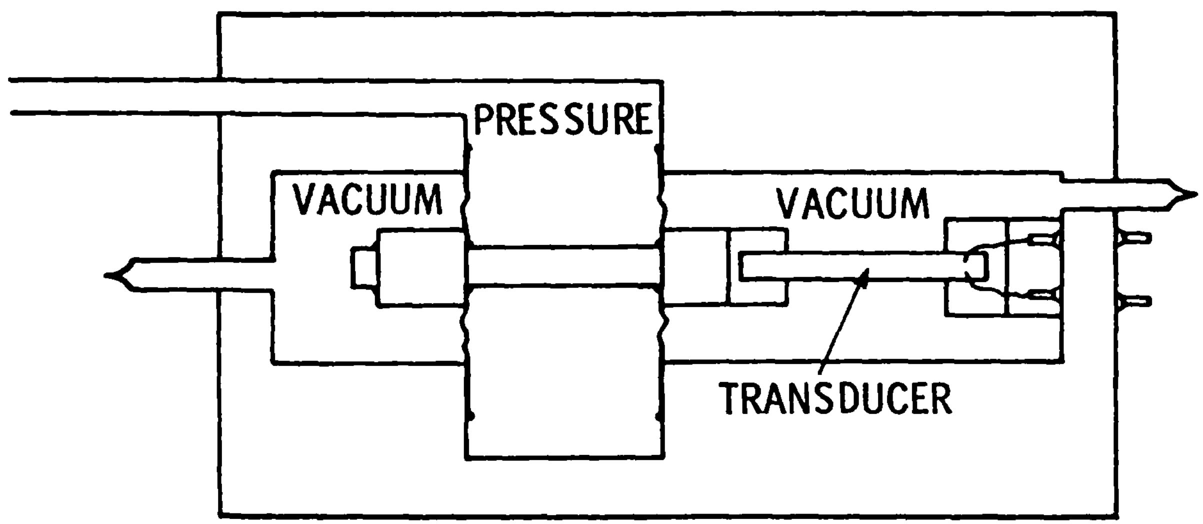
- Digital Output (Frequency)
- Low Power (10μW)
- Small Size (0.004 x 0.1 x 1.0 cm ^{3})
- High Sensitivity (1 Dyne)
- High Resolution (1 x 10^{-5} full scale)
- Low Cost (<$1)

Sandia Laboratories

PRESSURE LOGGING TOOL



TRANSVERSE RESONATOR PRESSURE TRANSDUCER



SUMMARY

- CHARACTERIZATION OF 275°C CRYSTAL COMPLETE AND RESOLUTION LIMITATIONS BEING ATTACKED.
- HYBRID CIRCUIT FOR 275°C READY FOR TESTING.
- DOUBLE-ENDED TUNING FORK BEING INVESTIGATED.
- MECHANISM FOR TUNING FORK BEING MODELED.
- COMMERCIAL GAUGE BEING UPGRADED.

PAUL SINCLAIR

SCHLUMBERGER

Commercial Needs for Generic, High Temperature Silicon Integrated Circuits

FUNCTIONS REQUIRED

Function	Technology	
MULTIPLE TRANSISTOR ARRAYS	DIELECTRIC ISOLATION BIPOLAR	
OPERATIONAL AMPLIFIERS	DIELECTRIC ISOLATION BIPOLAR	HYBRID I.C. IMPLEMENTATION
MEDIUM POWER BUFFERS	DIELECTRIC ISOLATION BIPOLAR	HYBRID I.C. IMPLEMENTATION
LOW NOISE AMPLIFIERS	DIELECTRIC ISOLATION BIPOLAR	HYBRID I.C. IMPLEMENTATION
COMPARATORS	DIELECTRIC ISOLATION BIPOLAR	HYBRID I.C. IMPLEMENTATION
VOLTAGE-FREQUENCY CONVERTERS	DIELECTRIC ISOLATION BIPOLAR	HYBRID I.C. IMPLEMENTATION
DIGITAL-ANALOG CONVERTERS	DIELECTRIC ISOLATION BIPOLAR	HYBRID I.C. IMPLEMENTATION
ANALOG MULTIPLEXERS	CMOS	HYBRID I.C. IMPLEMENTATION
MONOSTABLES	CMOS	HYBRID I.C. IMPLEMENTATION
LINE DRIVERS	CMOS	HYBRID I.C. IMPLEMENTATION
RANDOM-LOGIC GATES (SSI)	CMOS	HYBRID I.C. IMPLEMENTATION
COUNTER, REGISTERS, ARITHMETIC ELEMENTS (MSI)	CMOS	
RAMS, ROMS, EPROMS (LSI)	CMOS	
MICROPROCESSORS (LSI)	CMOS	

GENERIC IC REQUIREMENTS

SYSTEM DESIGNERS VIEWPOINT

SEEK	AVOID
BUILDING BLOCKS	"SYSTEMS ON SILICON" OVERSPECIALIZED CIRCUITS
HIGH ELECTRICAL PERFORMANCE	PERFORMANCE COMPROMISES TO MEET HI-TEMP REQUIREMENT
RELIABILITY	DESIGN SHORTCUTS TO MEET MARKETING REQUIREMENTS
AVAILABILITY	LOW-YIELD PROCESSES WITH UNRELIABLE DELIVERY OR THAT ARE NOT COMPATIBLE WITH HYBRID ASSEMBLY TECHNIQUES

HIGH TEMPERATURE INTEGRATED CIRCUITS

260° C SPECIFICATIONS

ANALOG CMOS MULTIPLEXERS (WITH FULL LEVEL-SHIFTING)

D.C.	LEAKAGE CURRENT	< 10 μA
	ON RESISTANCE	< 100 Ω
A.C.	NOISE VOLTAGE	< 2 $nV\sqrt{Hz}$
	SWITCHING SPEED	< 20 nS

DIGITAL CMOS COMPONENTS (5-15 V. RATING)

TYPICAL PROPAGATION DELAY/GATE	< 20 nS
QUIESCENT POWER DISSIPATION/GATE	< 1 mW

4000-SERIES IMPLEMENTED IN HI-TEMP TECHNOLOGY.
ALL SSI AND MSI DEVICES REQUIRED.
SOME LSI DEVICES SUCH AS EPROMS, TELEMETRY CONTROLLERS, 4-BIT MICROPROCESSORS, ALSO DESIRABLE.

260° C SPECIFICATIONS

LINEAR AMPLIFIERS (DUAL OR QUAD)

GAIN-BANDWIDTH	> 100 MHz
SLEW RATE	> 100 VOLTS/μS
OFFSET VOLTAGE	< 1 mV
OFFSET DRIFT	< 3 μV/°C
INPUT NOISE VOLTAGE	< 5 nV/$\sqrt{Hz}$

POWER BUFFER (UNITY VOLTAGE GAIN)

OUTPUT CURRENT	± 1 Amp
SLEW RATE	> 500 VOLTS/μS

COMPARATORS (CMOS OUTPUTS)

PROPAGATION DELAY	< 100 nS
OFFSET VOLTAGE	< 1 mV
OFFSET DRIFT	< 3 μV/°C

VOLTAGE-FREQUENCY CONVERTERS

FREQUENCY RANGE	> 5 MHz
DYNAMIC RANGE	> 60 dB
LINEARITY	< 1% Error

DIGITAL-ANALOG CONVERTERS

SPEED - 8 BITS	< 50 nS
12 BITS	< 200 nS
CMOS DIGITAL INPUT REGISTER	

DICK HECKMAN

DIVISION 2151

SANDIA LABORATORIES

HIGH TEMPERATURE ELECTRONICS

FY'79 CONTRACTS

1. HYBRID MANUFACTURE — TELEDYNE/PHILBRICK — $100.0

   PRODUCE 50 HYBRID VOLTAGE REGULATORS,
   A/D CONVERTORS, LINE DRIVERS.
   USE SANDIA TECHNOLOGY.

2. THICK FILM MATERIALS DEVELOPMENT — PURDUE UNIV/ ROBERT VEST — $55.0

   DEVELOP STABLE FRITS & CONDUCTOR, RESISTOR,
   DIELECTRIC ADDITIVES.
   *DEVELOP/SUPPLY 500°C MEDIUM DIELECTRIC CONSTANT INKS.
   *DEVELOP/SUPPLY 500°C CONDUCTOR INKS.
   *DEVELOP/SUPPLY 500°C 100 & 100K Ω/□ INKS, SMALL TCR.
   *DEVELOP/SUPPLY 300/500°C THERMISTOR INKS.
   *DEVELOP SEMICONDUCTOR INKS FOR H.T. DIODES.

3. MAGNETIC MATERIALS — TEXAS A&M/RK PANDEY — $85.0

   EVALUATE COMMERCIAL MAGNETIC MATERIALS.
   EVALUATE MAGNET WINDINGS/INSULATION.
   *DEVELOP ALTERNATE MATERIALS FOR HIGH TEMPERATURE.
   *DESIGN/FABRICATE POWER TRANSFORMERS, INDUCTORS,
   IMPEDANCE MATCHING TRANSFORMERS, CORE MEMORY
   DEVICE, BUBBLE MEMORY DEVICE.

*TO BE DONE PARTY OR ENTIRELY IN LATER YEARS.

4. IC SURVEY & DEVELOPMENT — CLEMSON/J. PRINCE — $48.0

EVALUATE COMMERCIAL ICs.
*DEVELOP HT IC DESIGN RULES.
*REDESIGN (W/COMMERCIAL FABRICATION) STD. LINEAR/DIGITAL CIRCUITS.

5. GAAS DEVICES — MCDONNELL DOUGLASS ASTRONAUTICS — $58.0

DETERMINE METALLIZATION, PASSIVATION, DOPING.
DESIGN DIODES/TRANSISTORS.
FABRICATE/SUPPLY 50 EA. OF 2 DIODE TYPES, 300°C.
ASSESS FEASIBILITY OF 400°C DIODES/TRANSISTORS.
*FABRICATE 400°C DIODES.
*DESIGN/FABRICATE 350°C JFETs.

6. THIN FILM CVD STUDIES — UNIV. OF ARIZ./L. RAYMOND, D. HAMILTON — $80.0

DEVELOP 500°C THIN FILM RESISTORS & CAPACITORS, USING CVD PROCESS.
DESIGN PASSIVE COMPONENTS FOR ICs.
DEVELOP METALLIZATION FOR HIGH TEMPERATURE ICs.
DEVELOP RESISTORS FOR INTEGRATED THERMIONIC DEVICES (1000°C).

*TO BE DONE PARTLY OR ENTIRELY IN LATER YEARS.

HIGH TEMPERATURE MAGNETICS
NEEDS (5/79)

APPLICATION	CHARACTERISTICS
Collar Locator	Square Loop
Rotational Sensors (Flow Tool)	Square Loop, Stable, Temp Insensitive
Insitu Markers	Square Loop, Stable
Motors	Narrow Loop, Stable, Low Loss
Mechanical Relays	Square Loop
Transformers - Power - Impedance Matching - Step-Up, Hi. Voltage	Narrow Loop, Low Loss, High Insulation Resist., Ferrites High Breakdown Voltage
RF Chokes & Inductors	Narrow Loop, Ferrites, HF
Core Memories	Ferrites
Bubble Memories	

HIGH TEMPERATURE MAGNETICS
1978 STATE OF THE ART

5/79

PERMANENT MAGNETS

- ALNICO II, V, VI CAN BE USED TO 500°C WITH LARGE MAGNETIZATION CHANGES.

TRANSFORMERS-INDUCTORS

- FE-SI FUNCTIONS TO 500°C. LOW FREQUENCY LOSSES REDUCED AT HIGH TEMPERATURE. SUBSTANTIAL CHANGE IN MAGNETIC PERMEABILITY.

- NI FERRITES USED TO 250°C. 20% PERMEABILITY CHANGE.

SQUARE LOOP MATERIALS

- LI-FERRITES USED TO 300°C. DIFFICULT TO MANUFACTURE.

HIGH TEMPERATURE MAGNETICS
PROGRESS TO DATE 5/79

TEXAS A&M UNIVERSITY

EVALUATION OF TRANSFORMER MATERIALS

- SUPERMENDUR (HIGH CO ALLOY)
- DELTAMAX (HIGH NI ALLOY)
- METGLASS (AMORPHOUS, $Fe_{82}B_{12}Si_6$)

WINDING EVALUATION

- Al-Al_2O_3

GENERAL MAGNETICS (211 GROVE ST., BLOOMFIELD, NJ 07003)

500°C MAGNETIC COMPONENTS

- 20V TO 200V STEPUP TRANSFORMER*
- 20V TO 2000V STEP TRANSFORMER (IN DEVELOPMENT)*
- POWER MULTIPLIER (SIGNAL CONDITIONING)*
- ISOLATION TRANSFORMER, 1 AMP (IN DEVELOPMENT)

*DEVELOPED AND SUPPLIED UNDER SANDIA PURCHASE ORDERS. SUPERMENDUR, MgO INSULATION COATING, Al/Al_2O_3 WINDINGS, REFRACTORY POTTING, HERMETICALLY SEALED.

HIGH TEMPERATURE CAPACITORS NEEDS

(5/79)

USE	APPROXIMATE SIZE
• CIRCUITS	
SIGNAL	< 1000 pF, 30 V
COUPLING-BYPASS	.001 to .1 μF, 30 V
• FILTER	1-10 μF, 100 V
• STORAGE	10 μF, 2000 V

FEATURES

SMALL PHYSICAL SIZE

LOW TEMPERATURE COEFFICIENT OF CAPACITANCE

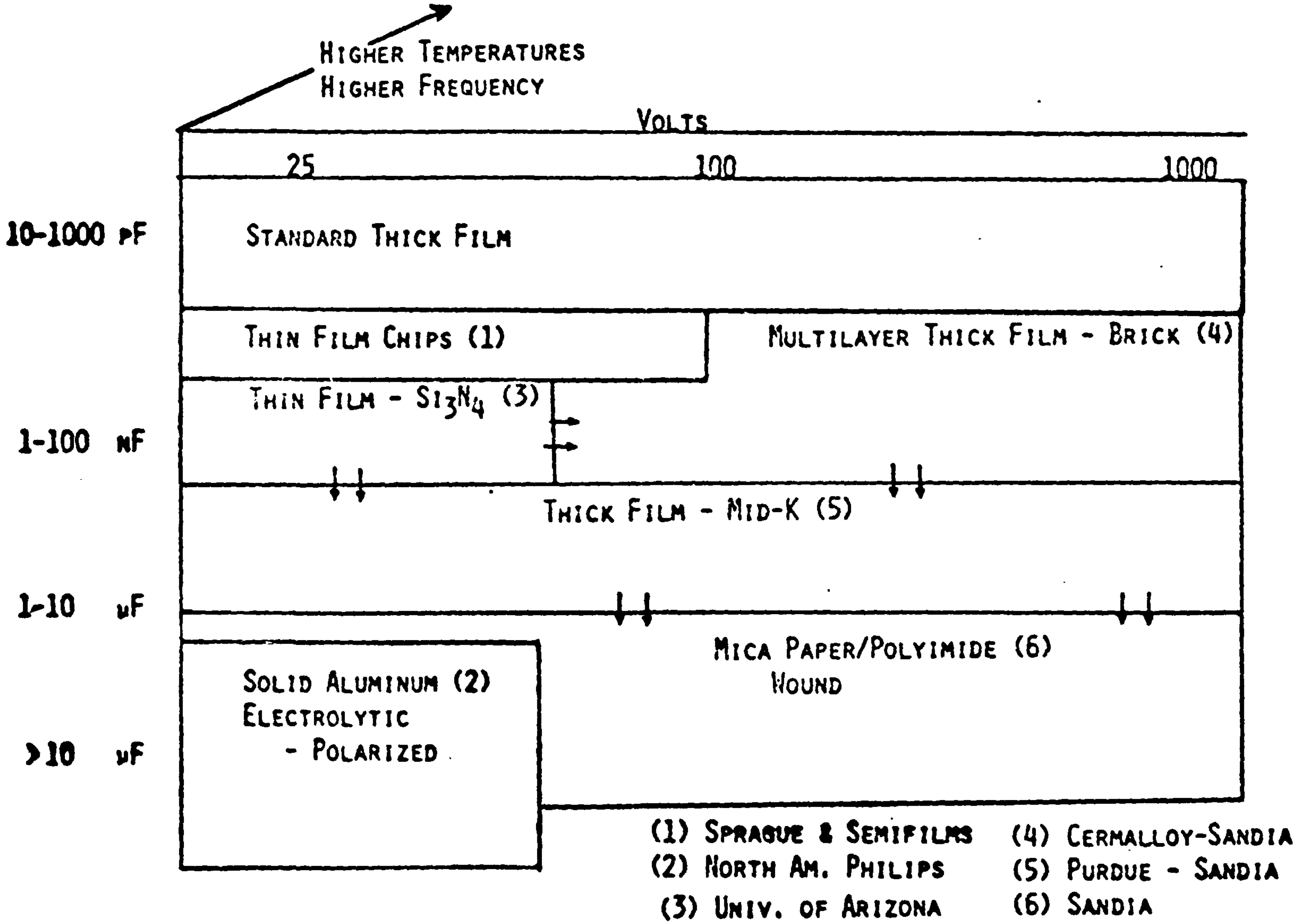
LONG TERM STABILITY

HIGH LEAKAGE RESISTANCE

HIGHER TEMPERATURE PERFORMANCE

HIGHER FREQUENCY OPERATION

HIGH TEMPERATURE CAPACITORS (5/79)



HIGH TEMPERATURE ELECTRONICS
SILICON-MOS DEVICES

SANDIA AND UNIVERSITY OF ARIZONA

BASED ON A SERIES OF WAFER RUNS IN SANDIA PROCESSING LAB. N- AND P-CHANNEL DEVICES, NO INPUT OR OUTPUT PROTECTION CIRCUITRY.

- LOW CONTAMINATION IMPROVES DEVICE STABILITY AT HT.

    CLASS 100 CLEAN ROOM.

    ALUMINUM METALLIZATION PERFORMED WITH ELECTRON BEAM EVAPORATION. LOW IONIC CONTAMINATION IN GATE OXIDE.

- AL METALLIZATION ACCEPTABLE FOR 1000 HR AT 300°C UNDER ELECTRICAL LOAD.

    THIS CONFLICTS WITH LITERATURE.

    INVESTIGATION OF TUNGSTEN METALLIZATION IN PROCESS (U. OF AZ).

- INCREASED SUBSTRATE AND P-WELL DOPING REDUCE DRAIN/SUBSTRATE JUNCTION LEAKAGE, ENABLE ENHANCEMENT MODE OPERATION OVER WIDER TEMPERATURE RANGE.

HIGH TEMPERATURE ELECTRONICS
GaAs/GaP Devices
Status 5/79

McDonnell-Douglas

GaAs

- Diodes have been processed - 1000-hr life test in progress. ~25 μA reverse bias (5V) leakage.
- Further iterations in diode design will probably be needed.

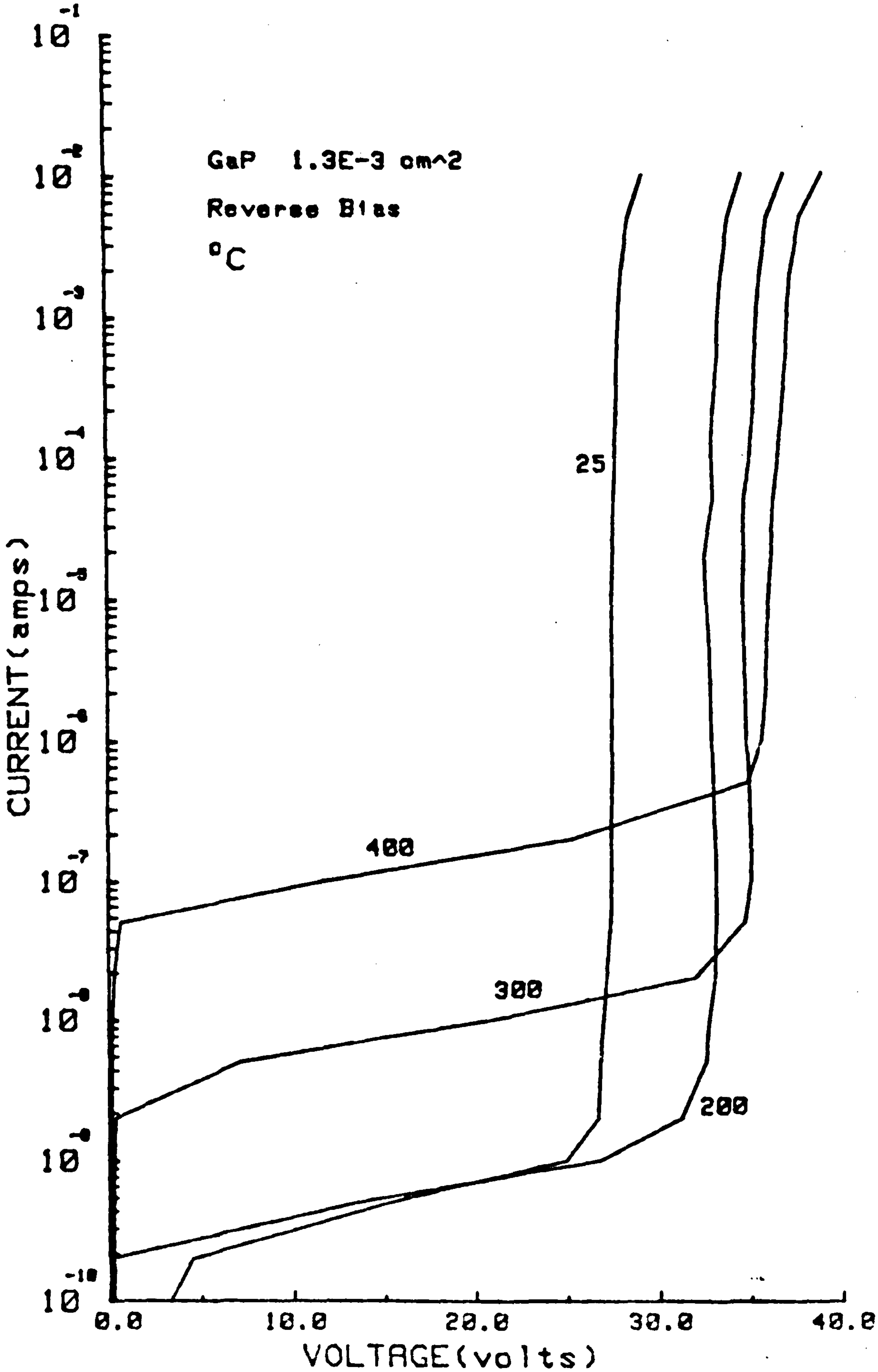
Sandia

GaP Diodes

- Satisfactory operation for several hundred hours at 400°C.
- Stable metallization (temporarily under patent protection).
- ~10 nA leakage current at 300°C, 10^{-3} cm^2.
- May not be suitable for JFETs because of low mobility.

GaAs

- Metallization studies continue, but no marked success as yet.



GaP 1.3E-3 cm^2
Reverse Bias
°C
25
400
300
200
CURRENT(amps)
VOLTAGE(volts)
0.0
10.0
20.0
30.0
40.0

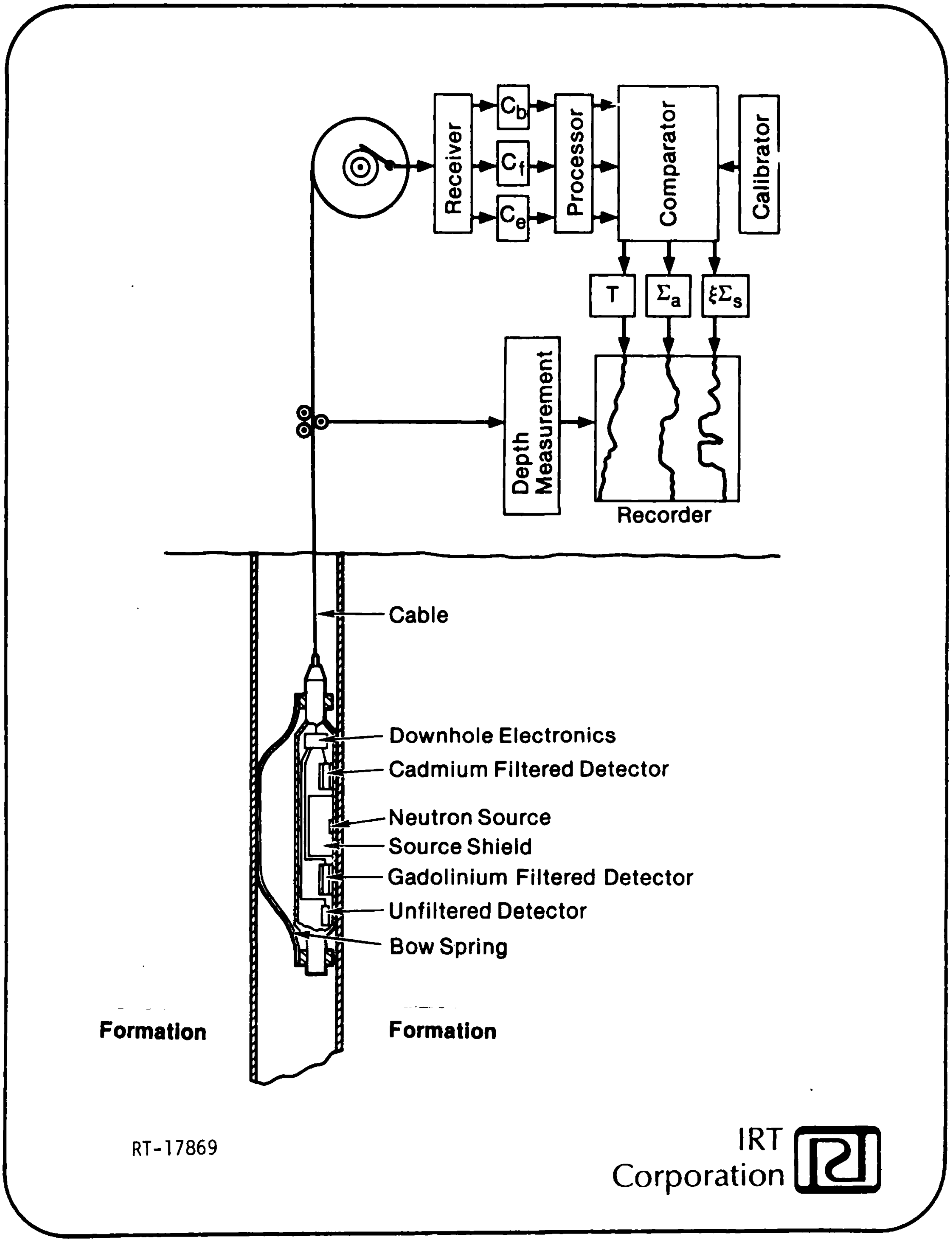
NICHOLAS VAGELATOS

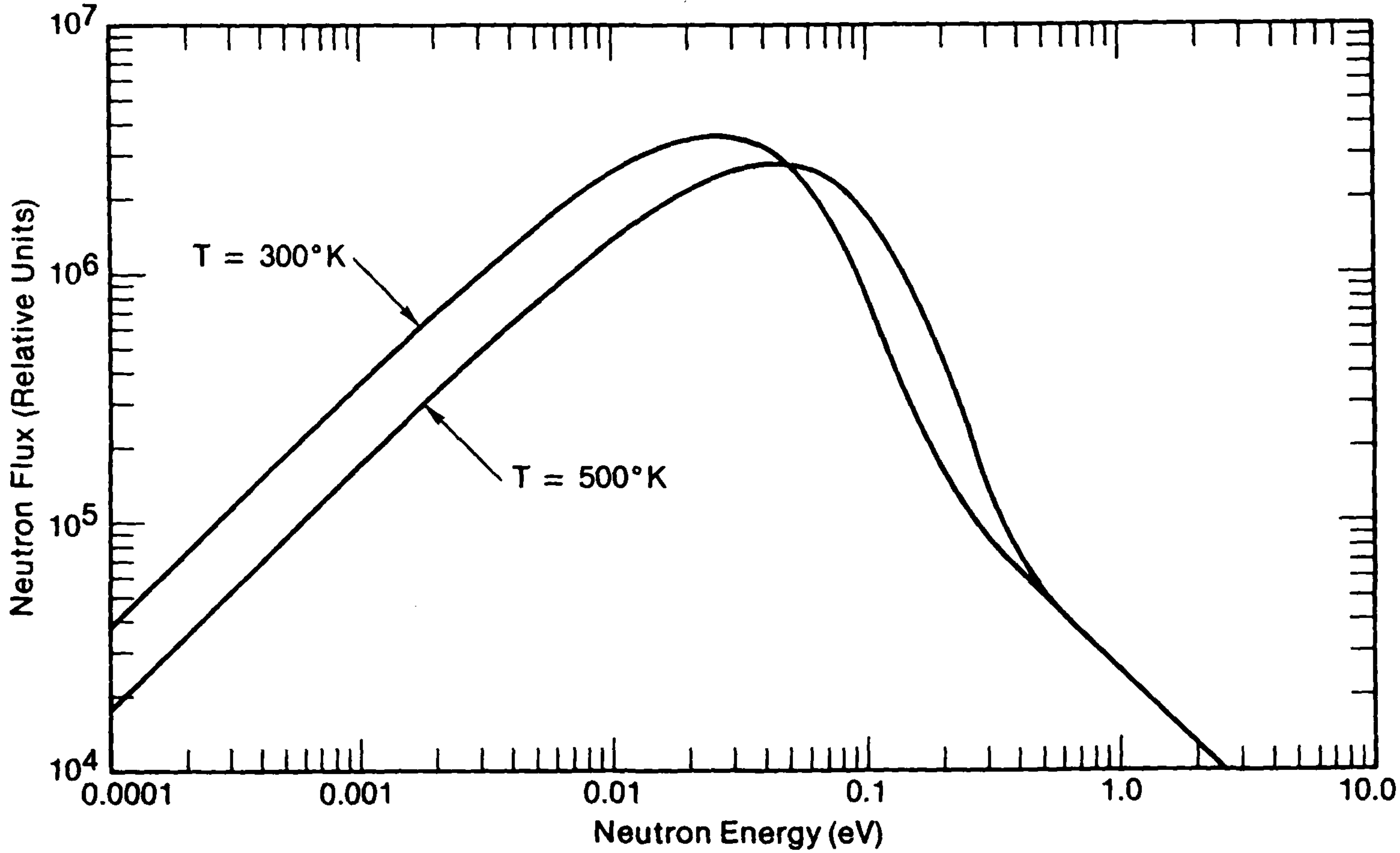
IRT CORPORATION

GEOTHERMAL FORMATION TEMPERATURE WELL LOGGING

- Current Temperature Logging Methods
  - Indirect
  - Generally Adequate For Shallow and Intermediate Depth Boreholes
  - Inadequate For Deep Boreholes
  - Time Consuming and Expensive
- Need For Direct, Reliable Formation Temperature Logging Instrumentation

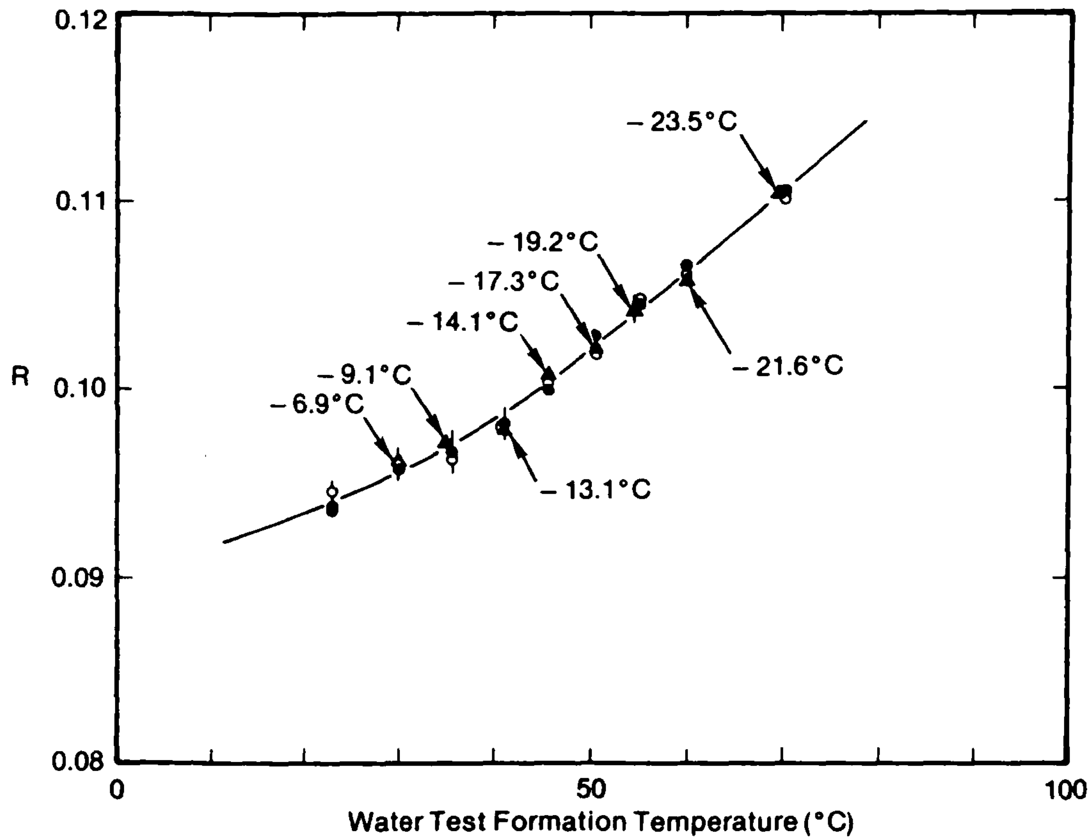
IRT
Corporation


Receiver
C_b
C_f
C_e
Processor
Comparator
Calibrator
T
Σ_a
$\xi\Sigma_s$
Depth Measurement
Recorder
Cable
Downhole Electronics
Cadmium Filtered Detector
Neutron Source
Source Shield
Gadolinium Filtered Detector
Unfiltered Detector
Bow Spring
Formation
Formation
RT-17869
IRT Corporation



RT-17868

IRT Corporation



IRT
Corporation

TFTS PERFORMANCE SPECIFICATIONS ESTIMATES

• Logging Mode	Continuous or Stationary
• Logging Speed (Max)	25-50 ft/min Continuous 20-70 ft/min Stationary
• Neutron Source Strength	50-150 μg Cf-252
• Formation Properties Determined	Temperature, Neutron Absorption Cross Section, Saturated Porosity
• Accuracy of Temperature Determination	±2°C at T $\gtrsim$ 100°C ±3.5°C Near Room Temperature
• Depth of Penetration	6-12 Inches
• Borehole Effects	Small Corrections Necessary For: Parallel Tool Standoff $\lesssim$ 0.5 Inches Borehole Fluid Salinity Borehole Fluid Density $T_F \gg T_{BH}$

IRT Corporation

TFTS PERFORMANCE SPECIFICATIONS ESTIMATES

• Formation Neutron Absorber Concentration Limit	Technique Applicable In All Known Geothermal Resource Areas
• Temperature Limitations	No Inherent Technique Limitations. He-3 Detectors Operable at T $\lesssim$ 260° C. Some Electronic Components Are Presently Limiting.
	High Temperature Multiconductor Cable Tested to 260° C.

IRT Corporation

TFTS POTENTIAL UTILITY

- Bottomhole Temperature Measurement
- Measurement of Temperature 6-12 Inches Away From Wellbore
  - Couple With Well Bore Temperature to Facilitate Extrapolation to Equilibrium Value
  - Indicate Rate of Formation Temperature Rebound After Drilling Disturbance and/or Chilling.
- Neutron Absorption Cross Section Measurement
- Saturated Porosity Determination
- Fracture Zone Detection (Location)

IRT Corporation

TRUE FORMATION TEMPERATURE SONDE (TFTS) DEVELOPMENT

- Concept Development
- Scientific Feasibility Demonstration
- Technical Feasibility Demonstration
- Low Temperature ($\lesssim$125°C) Engineering Prototype Development
  - Design and Fabrication
  - Calibration
  - Field Testing
  - Modification
- High Temperature ($\lesssim$325°C) Engineering Prototype Development
  - "Design" and Fabrication
  - Calibration
  - Field Testing
  - Modification
- Production Prototype Development
  - Fabrication
  - Calibration
  - Field Testing and Demonstration
- Commercial Use

IRT
Corporation

RON SCHROEDER

LAWRENCE BERKELEY LABORATORY

THREE TYPES OF WELL MEASUREMENTS
FOR RESERVOIR ENGINEERING

1. Static Well Logs (profiles)

2. Flowing Well Logs (profiles)

3. Transient Measurements

Ron Schroeder - LBL

Downhole Instrumentation Requirements for Reservoir Engineering

Reservoir Engineering = Science of Fluid Flow in a Reservoir

Review of Existing Equipment

Amerada p, T, q, C (>300°C)
no surface readout (clock driven)
low sensitivity

Sperry Sun p, C (no temperature limit)
H_2S embrittlement
temperature transients (even ambients)

RTD's (>350°C)
multiconductor

Strain Gages p (>300°C)
multiconductor (accurate constant i or V)
adequate for production tests

Quartz Gages

Hewlett-Packard (<180°C)
single conductor (cablehead)

Paroscientific ($\lesssim$180°C)
best of all (but latter requires multiconductor

Turbine Meters ($\approx$300°C)
low rates of flow can't be determined
two phase not easily analyzable

Samplers
flash into chamber
gas in contact with fluid

Quality
1. Separation of phases q_ℓ, q_s (wellhead)
2. Critical flow p, q_ℓ (well head)

We need instruments now.

Multiconductor cable would give use improved capability.

Downhole circuitry is not the only important answer to providing tools to industry.

PRIMARY MEASUREMENTS

USED BY RESERVOIR ENGINEERS

1. Temperatures
2. Pressures
3. Fluid Flow
4. Fluid Samples (concentrations)
5. Quality (enthalpy)

Desirable Features

Surface Readout (display)

Real-time

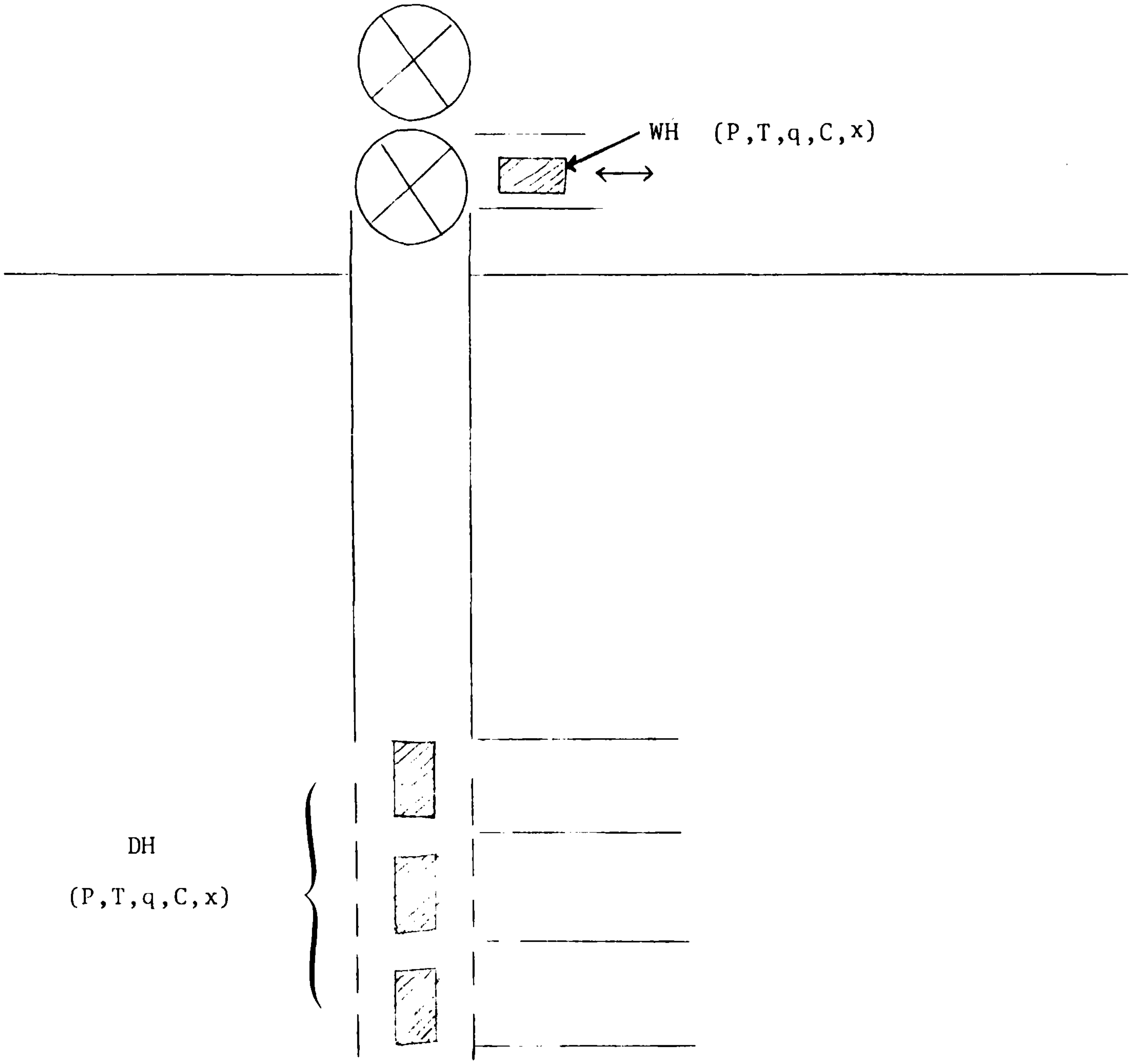
Two Regimes of Sensitivity for Transient Pressure Measurements

1. Near the wellbore during production, the drawdowns range from ~10 to ~500 psi.

2. Away from the producing wellbore, the drawdown ranges from ~0.05 to ~50 psi (depends on distance from the producer).

Note: Earth tides have amplitudes ranging from 0.02 to 0.1 psi.

Ideal Measurement System (Transient)



Production Tests for up to 2-3 weeks

Interference Tests for up to 2-3 months

GEOTHERMAL LOGGING INSTRUMENTATION STEERING COMMITTEE MEETING

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Man-Made Geothermal Reservoirs

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ABSTRACT

Many drilled holes encounter rock at usefully high temperatures but produce little or no natural steam or hot water. The energy content of these "dry" geothermal reservoirs is enormous; and if means can be found to extract and use it economically, it can contribute significantly to satisfying the world's energy needs.

One way to accomplish this is to inject water into the hot rock through one hole, permit it to circulate through natural or man-made flow passages, and recover it as steam or hot water through another hole. The major problems are those of avoiding excessive water loss if natural permeability is high or, if it is low, of creating openings for fluid circulation and enough surface to permit extraction of heat at a useful rate for a usefully long time.

The possibilities, problems, and engineering requirements of such man-made geothermal systems are now being investigated in the hot granites underlying the Jemez Plateau of northern New Mexico. These contain many natural fractures which, however, are well sealed at most horizons, so that *in situ* permeabilities are generally low. Hydraulic fracturing—a promising method of creating flow channels and new surface—has been accomplished at pumping pressures of less than 175 bars at 760 m (rock temperature 100°C), at 2040 m (rock temperature 146°C), and at 2920 m (rock temperature 197°C). The fractures produced have been essentially vertical and the rate of water loss from them has been low.

Additional experiments are now in progress at 2920 m and drilling has begun on the first of two holes expected to reach depths of about 3810 m and rock temperatures of about 250°C. These will be connected at depth through a large hydraulic fracture to produce a circulation loop for geothermal energy extraction.

INTRODUCTION

It has been demonstrated in many places in the world that geothermal temperatures as low as 80°C are economically useful for space heating and many other purposes, and in a much smaller number of places that 180°C is a sufficient temperature for economical generation of electricity. If the mean temperature at the earth's surface is 10°C and a "normal" geothermal gradient of 25°C/km exists, a "useful" temperature of 80°C should normally be encountered at a depth of about 2.8 km, and the relatively high geothermal temperature of 180°C at about 6.8 km. These are depths that are now reached more or less routinely in the petroleum and natural gas industries using conventional drilling equipment and procedures. Evidently, geothermal heat at usefully high temperatures is now accessible to man from most points on the earth's surface, and the energy supply which it represents is enormous. The problems of extracting and using it are simply those of engineering and economics.

Where a natural hydrothermal system can be found which contains steam or hot water at a usefully high temperature, the engineering problem of extracting energy from the earth is relatively simple. Wells are drilled into the reservoir and heat is brought to the surface in the natural or pumped flow of steam or hot water. Unfortunately the combination of high rock temperature, adequate permeability, low reservoir pressure, and a sufficient water supply, all of which are required to maintain a "vapor-dominated" geothermal system, is rare in nature; and productive natural steam fields are correspondingly uncommon. "Liquid-dominated" systems, in which the fluid pressure in the reservoir is sufficient to prevent boiling, are much more common, although the frequency of their occurrence diminishes with increasing temperature. In general, the higher the temperature of a geothermal water, the more mineral it will have dissolved during its residence in the geothermal reservoir. Particularly if the reservoir rock contains highly soluble minerals (as, for example, do the evaporites of California's Imperial Valley), the hotter geothermal waters are usually so saline that they are extremely corrosive to drilling tools, production piping, and surface plumbing. They are also generally troublesome with regard to plugging and scaling by minerals deposited as their temperatures and pressures are reduced, whether in the reservoir, in the production string, or at the surface. Commercial utilization of heat from liquid-dominated reservoirs has been handicapped in many places by the geochemical problems associated with both the production and the use of the highly mineralized waters which they normally contain.

Many "dry" holes—not productive of useful amounts of any reservoir fluid—have been drilled in exploring for petroleum, natural gas, and geothermal energy, and for other purposes. Often these have penetrated rock at commercially useful temperatures. Obviously, and as would be expected, geothermal heat is present and accessible even when geothermal fluids are almost or entirely absent. If means can be found to extract and use such heat economically, it is sufficiently abundant and broadly distributed so that it can contribute significantly to the world's energy supply. Further, since it already exists as heat, it should in general be possible to produce and use it in environmentally acceptable ways.

EXTRACTION FROM DRY RESERVOIRS

A variety of methods can be suggested for penetrating "dry" geothermal reservoirs and recovering heat from them. Certainly the simplest and probably the most economical of these is to imitate nature by introducing water into the hot rock where nature has failed to provide it, permitting it to circulate until it has been heated to a usefully high temperature, and then recovering it as either steam or hot water. Where the permeability of the hot rock is high, the problems of circulating and heating the water are minimal but those of containing and recovering it are difficult. Efficient heat-extraction systems are probably possible using water-flooding and reservoir-management techniques similar to those developed for secondary recovery of petroleum. Unless the geologic structure is very unusual, however, this requires drilling an array of holes in which injection wells are surrounded by recovery wells and vice versa, and developing effective hydraulic control at the perimeter of the field to minimize fluid loss to the permeable formations around it. Very large man-made systems of this type should be possible, producing very large amounts of energy by sweeping the natural heat efficiently from large masses of permeable rock. Small water-flooding systems, however, are likely to be inefficient with regard to recovery both of the water injected into the reservoir and of the heat which it extracts from the rock. They are likely to be used only where water is plentiful and the accessible geothermal reservoir is so large that efficiency in the recovery of heat is unimportant.

Where permeability of the dry hot rock is low, the problems of containing and recovering the injected water are replaced by those of creating flow passages through which it can circulate freely and sufficient heat-transfer surface so that usefully large rates of heat extraction can be maintained for economically long periods of time.

LASL GEOTHERMAL ENERGY PROJECT

Under sponsorship of the Division of Geothermal Research of the U.S. Energy Research and Development Administration (ERDA), the Los Alamos Scientific Laboratory (LASL) of the University of California is investigating the possibilities and problems of extracting energy from "dry" hot rock in the earth's crust. To minimize both the fluid-containment and recovery problems and also those associated with dissolution and reprecipitation of minerals, LASL is investigating first the development of man-made geothermal systems in the hot, relatively impermeable granitic rocks which, at moderate depth, underlie the southern Rocky Mountains in northern New Mexico. It is hoped that the technology developed there will be useful wherever low-permeability rock at usefully high temperatures can be reached economically from the earth's surface. And it is intended that, when systems that are economically useful in this environment have been developed and demonstrated, modifications of them will be investigated that may be useful in other geologic situations elsewhere—at higher and lower temperatures, greater and shallower depths, in other types of rock, where permeabilities are greater, and in more complex geologic settings.

To create a fluid circulation system for successful energy extraction from hot rock having initially low permeability, it is necessary to produce continuous flow passages between the injection and recovery holes with reasonably low impedance to fluid flow and large surface area for heat transfer from the rock to the fluid. There are several obvious ways in which this might be accomplished, including chemical leaching, fragmentation by explosives, and hydraulic fracturing, and probably all of these should eventually be tried. It has been decided, however, that the first major LASL experiments should be with hydraulic fracturing, on the basis of its apparent environmental acceptability, probable economy, and familiarity as a common method of well stimulation in petroleum and natural gas fields. Because there was little experience in the hydraulic fracturing of crystalline rocks and apparently none at all in hot granitic rocks, many advisers to the LASL project expressed grave doubts that this was a feasible approach to creating the proposed energy extraction system. Accordingly, much of the project emphasis has so far been on investigations of the production and behavior of hydraulic fractures in hot granitic rocks.

To avoid the problems associated with two-phase fluid flow and with mineral precipitation where boiling occurs, and to maximize the rate of energy transport up the recovery well, it is desirable to operate the proposed circulation system with a condensed phase throughout—that is, with liquid water instead of steam or a mixture of the two. This requires pressurization throughout the system sufficient to prevent boiling. Computer modeling of fluid flow and heat transfer within the hydraulic fracture (McFarland, 1975) has demonstrated the desirability of holding the fracture open with fluid pressure alone—without the use of particulate proppants—if this can be done without excessive fluid loss or uncontrolled extension of the fracture. Again many advisers to the LASL project have been convinced that this will prove impractical because of high rates of fluid loss into natural joints and fractures in the rock or because of inherent instability of a large inflated crack. Accordingly, much project attention has also been given to initial permeability of the hot granite at depth, to its stress and pore-pressure environment, and to its behavior with regard to inflation, deflation, extension, and return of the contained fluid when it is permitted to collapse.

To this point, no attempt has been made to produce the pressurized-water circulation loop with which continuous energy extraction will eventually be accomplished. Project activity has been directed entirely toward acquiring the background information required to understand and design such a system and toward developing the technology required to create it.

Site Selection

The Valles Caldera in north-central New Mexico formed several million years ago on the western edge of the Rio Grande rift. Caldera collapse was followed by deposition of sediments, resurgence, extrusion of a series of rhyolite domes along the ring fault bounding the caldera, and most recently—about 50 000 to 100 000 years ago—by a pumice and a vitrophyre flow at the southwestern edge of the caldera

Purtymun, 1974). Because of this geologically recent volcanism, the generally high terrestrial heat flow along the western edge of the rift valley is enhanced locally, and relatively high geothermal temperatures are encountered at moderate depths.

As might be expected from its history of collapse, caving, sedimentation, resurgence, periodic volcanism, and repeated faulting, the geologic structure within the caldera is exceedingly complex and, at least locally, is highly permeable to ground-water circulation. The commercial possibilities of a liquid-dominated geothermal reservoir discovered in the southwestern part of the caldera are now being investigated by a major energy company.

Outside the caldera the geology is much less disturbed than within it, the depth to the basement granite is moderate, and heat flow is still relatively high. In 1971 seven shallow temperature-measurement holes were drilled by LASL in the National Forest east, south, and west of the caldera rim (Fig. 1). Geothermal gradients in the surface volcanics were found to increase along the counterclockwise path from east to west around the outer caldera rim. Accordingly, in 1972, four deeper heat-flow holes were drilled west of the caldera to depths of 150 to 230 m. These penetrated the Cenozoic volcanics and entered the Permian sediments. Measured heat flows about 3 km west of the ring-fault structure were 5 to 6 hfu (μcal/cm^2-sec), increasing slightly from south to north, and decreasing rapidly with increasing radial distance to 2.2 hfu at a point 7 km west of the ring fault (Albright, 1974). Two deep exploratory holes have since been drilled in the area: GT-1, completed in 1972

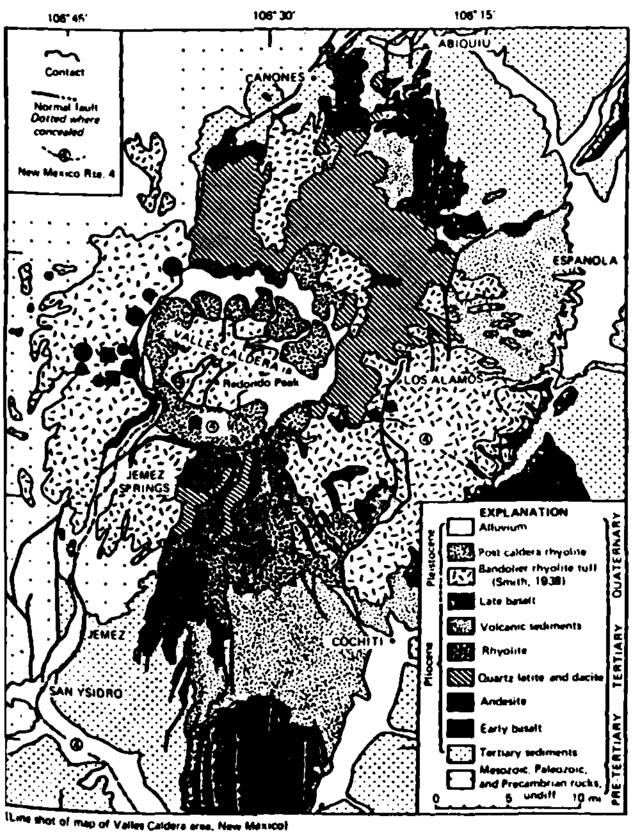

Figure 1. Generalized geologic map of the Jemez Mountains region showing locations of shallow temperature-measurement holes (small circles), intermediate-depth heat-flow holes (large circles), and deep exploratory holes (squares) (Smith, 1974).

at a depth of 785 m, and GT-2, completed in 1974 at a depth of 2928 m.

In 1973, a detailed study was completed of the existing faults and the earthquake history of the area of experimental interest west of the caldera (Slemmons, 1975). No large or active faults were found within several kilometers of the locations of GT-1 and GT-2, and there was no record of any earthquake centered in the area. It was concluded that the risk was very small that significant seismic activity could be triggered by hydraulic-fracturing and fluid-injection experiments there, or by the subsequent development of an experimental energy extraction system.

Because of its accessibility and inherent geologic interest, the region of the Valles Caldera has been studied intensively for many years by the U.S. Geological Survey, the New Mexico Bureau of Mines and Mineral Resources, the University of New Mexico, New Mexico Institute of Mining and Technology, and many other organizations and individuals. As a result, a great deal of geological, geophysical, and hydrologic information is available concerning the area, most recently from hydrologic studies by the U.S. Geological Survey (Trainer, 1974), from deep electrical resistivity studies by the University of New Mexico and LASL (Jiracek and Kintzinger, 1975), and from seismic and microseismic investigations and monitoring by LASL (Kintzinger, 1974; Newton, 1974). The general geology, hydrology, and fault structure of the region west of the caldera is now reasonably well understood. Unexplained magnetic and resistivity highs and lows have been mapped. Depth to the Precambrian surface has been estimated, and it has been established that at some distance below this surface the resistivity of the Precambrian granitic rocks becomes high. In fact, however, no convincing criterion other than actually drilling deep exploratory holes has yet been established for predicting whether or not dry hot rock will be encountered in a particular area at a drillable depth. Locations of the two deep exploratory holes so far drilled for this project were selected on the bases of (1) the general geology and volcanic history of the region; (2) the absence of nearby faults or earthquake activity; (3) geothermal gradients measured in shallow holes; (4) heat flows measured in somewhat deeper ones; (5) availability of the land for experimental use; (6) environmental considerations; (7) accessibility with regard to transportation, communications, and electrical power; and (8), in the case of the second exploratory hole, the very encouraging results of experiments conducted in the first one.

Stratigraphy and Core Studies

Exploratory hole GT-1 was drilled in Barley Canyon about 3 km west of the ring fault representing the western geologic boundary of the Valles Caldera. It penetrated 49 m of surface tuffs, 277 m of Permian sediments, 315 m of Pennsylvanian limestones and shales, and reached the Precambrian surface at 641 m depth. It was then extended 143 m into the crystalline Precambrian basement rock, encountering chiefly gneissic granodiorites, granites, and amphibolites (Purtymun, 1974). It was lined with 12.7-cm-diam casing to a depth of 732 m, leaving 53 m of uncased granitic rock exposed at the bottom of the hole for experiments.

Exploratory hole GT-2 was drilled on Fenton Hill, a flat-topped mesa, about 2.5 km south of GT-1 and also about 3 km west of the ring fault bounding the caldera.

It penetrated 137 m of volcanics, 238 m of Permian "red beds," 355 m of Pennsylvanian rocks, and reached the Precambrian surface at 733 m depth. It has since been extended in stages to a final depth of 2928 m, through gneissic granodiorites, granites, amphibolites, monzonites, quartz monzonites, gneisses and schists (Purtymun, 1974). The final 1000 m or so of the hole were drilled through a relatively uniform, substantially equiaxed, gray quartz monzonite containing well-developed biotite flakes. The hole was cased at 0.27 m diam to a depth of 773 m, about 43 m into the granitic basement rock, and was left uncased below that depth. However, a 0.178-m-diam steel liner was temporarily installed in the depth interval 1917 to 1981 m to facilitate experiments at and just below those depths. It has since been removed and a similar liner cemented in place in the interval 2731 to 2917 m for the same general purpose.

Cores were taken at intervals throughout the Precambrian sections of both exploratory holes and are being used for petrographic studies, geochemical investigations, property measurements, geochronology and geothermometry. In general the cores have shown several families of natural fractures which, however, at most horizons, have been tightly filled with calcite, quartz, muscovite, epidote, and occasional clays (Laughlin, 1974). In one interval in GT-2, around 1100 m depth, a region of unsealed, water-filled fractures was encountered. Elsewhere the natural fractures have been well sealed, and there appears to be a tendency for them to become less frequent and more tightly closed as the Precambrian column is descended.

Permeabilities

Permeabilities of the exposed crystalline basement rock in the uncased bottom section of GT-1 were measured at several levels of pressure from 13 to 177 bars above surface hydrostatic. With increasing pressure they ranged from 5×10^{-8} to 6×10^{-3} darcy, increasing by a factor of 10 for each pressure increase of about 40 bars (West, 1974). However, this pressure dependence of permeability has not been observed in GT-2.

In GT-2, permeabilities measured in the Precambrian section by drill-stem testing have ranged from 4×10^{-7} to 10^{-5} darcy (West, 1974). Permeabilities of freshly exposed fracture surfaces in the uncased region around 2820 m depth appear to be near the lower limit of this range. No satisfactory measurements have so far been made in the region of unsealed fractures around 1100 m, where a somewhat higher permeability is expected. It is of interest, however, that since the hole was completed, the mean permeability of the uncased Precambrian section between the bottom of the casing and the top of the liner—which includes this region of unsealed fractures—has diminished steadily to a present value of less than 10^{-9} darcy. This is apparently a result of plugging of the initial porosity either by mineral alteration or by fine particles of drill cuttings or alteration products suspended in the water filling the hole.

Except perhaps in the zone around 1100 m, the permeabilities measured in the granitic rocks in both exploratory holes have consistently been in the range generally considered to represent "dry" or "impermeable" rock. At least at depths below about 1200 m, the crystalline rocks underlying the experimental area appear competent to contain pressurized water with acceptably low leakoff rates. As is described below, this is true even of fresh fracture surfaces which expose relatively large granitic sections extending outward from the borehole.

Temperature Gradients and Heat Flow

The bottom-hole temperature in GT-1 is 100.4°C at a depth of 785 m. With considerable uncertainty because of the relatively short section of uncased granite exposed, the geothermal gradient in the crystalline basement rock is estimated to be about 50°C/km.

Special apparatus and techniques were developed for measurement of bottom-hole temperature in GT-2 during interruptions in drilling, over periods of time long enough to permit confident extrapolation to an equilibrium rock temperature (Albright, 1975). Temperatures so determined are plotted as a function of depth in Figure 2. Temperatures in the water-filled hole appear, since drilling has been terminated, to be slowly approaching the values indicated by this curve.

From temperature measurements in intermediate-depth holes and thermal-conductivity measurements on cores from those holes, it was estimated that terrestrial heat flow at the Fenton Hill site was 5 to 6 hfu. This was verified in the sedimentary section penetrated by GT-2 and—with an assumed value for the thermal conductivity of granite—was used to predict that a rock temperature of 200°C would be reached at a depth of about 1.5 km. In fact, however, heat flow in the Precambrian section of GT-2 is only about 3 to 4 hfu, and it was necessary to drill to a depth of about 3 km in order to reach a temperature approaching 200°C. It appears that there is a horizontal flow of warm water near the Precambrian surface, perhaps through the cavernous Pennsylvanian limestone encountered just above it, and that this has augmented heat flow through the overlying sediments and volcanics. In any case, the geothermal gradient in the upper part of the Precambrian section is only about 50°C/km. This increases to about 60°C/km at greater depth, presumably because of changes in rock type and a reduction in the thermal conductivity of granite that results from an increase in its temperature.

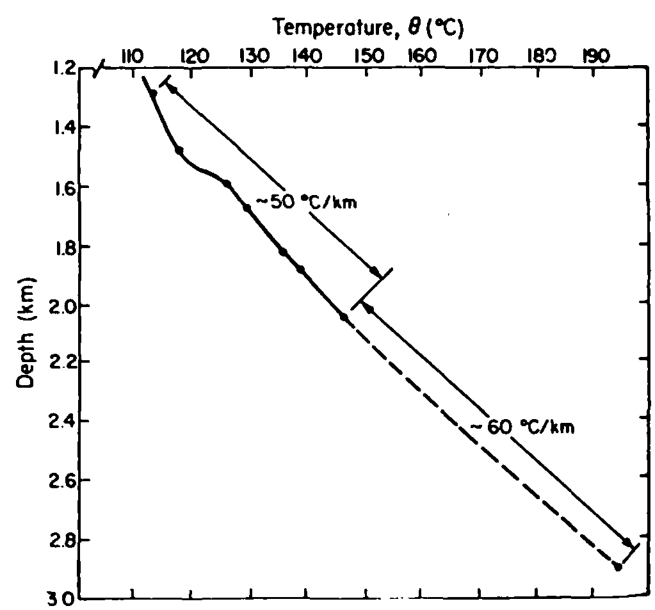

Figure 2. Geothermal temperatures and temperature gradients in GT-2 (Albright, 1975).

Logging

Standard geophysical logs have been run repeatedly in both GT-1 and GT-2. Of these, the caliper logs have been particularly useful in selecting relatively smooth sections of hole in which open-hole packers could be set successfully for hydrologic studies; the spectral-gamma log in mapping changes in lithology; and the sonic-velocity logs in locating zones containing unsealed fractures. Except perhaps in the more mafic rocks, density logs have been found to correlate well with densities measured in the laboratory on core samples, and elastic properties deduced from sonic-velocity logs have agreed well with laboratory measurements made on core samples.

Much of the commercial logging equipment has given trouble as downhole temperatures approached 150°C, and most of it has been unreliable at temperatures approaching 200°C.

Fracturing and Earth Stress

Hydraulic fractures were produced in the uncased bottom section of GT-1 at pumping pressures (measured at the surface) of about 100 to about 150 bars. Only a few sharp "breakdowns" were observed, suggesting that the initial fracturing event at the borehole wall was usually the reopening of a natural fracture sealed with a relatively weak mineral such as calcite. Fracturing pressure increased with the apparent competency of the rock as indicated by cores and downhole logs, and also with the pumping rate used to fracture. As would be expected, the pressure required to extend a crack was found to decrease steadily as the crack radius increased. Even after extensive fracturing, permeability of the uncased Precambrian section exposed in GT-1 remained very low.

When GT-2 had been drilled to a depth of 1937 m, drilling was interrupted for a series of successful hydrologic measurements and largely unsuccessful hydraulic-fracturing attempts. The hole was sufficiently oversize and its wall sufficiently rough so that commercial open-hole rubber packers did not seal successfully against the fluid pressures required for fracturing. Therefore the hole was deepened, eventually to 2042 m, to expose "fresh" rock, and a steel liner 64 m long was cemented in place about 60 m above the bottom of the hole. Commercial casing packers were set successfully within this liner, and a long series of experiments was completed in the uncased hole below it. The liner was then perforated about 40 m above its lower end, and additional experiments were conducted through the perforations.

When the uncased section of hole below the liner was first pressurized, it began to accept fluid at a pumping (surface) pressure of about 150 bars. With continued injection of water at a constant rate of 454 liters/min, the pumping pressure increased to a maximum of 172 bars and, with no indication of a formation breakdown, leveled off at that value. This behavior suggests that a pre-existing natural fracture began to open at a downhole pressure of approximately 340 bars. Subsequent pressurizations at a variety of flow rates and repeated observations of the decay of shut-in pressure have confirmed that the least principal earth stress at this depth is in the range 330 to 340 bars.

Spinner surveys, used to measure fluid velocity as a function of position in the hole during subsequent repumping operations, indicated the existence of two closely spaced parallel fractures in the borehole wall, one in the depth interval 1989 to 1993 m and the other in the interval 1998 to 2002 m. As shown by later impression-packer results, both fractures were vertical within 1 degree and were oriented N 35° E ±5°. They were offset horizontally by about 67 cm because in this section the borehole is inclined 4.5 degrees from the vertical; and, from their behavior during pressurization and depressurization experiments, it is speculated that they join in a single fracture not far from the borehole wall.

Twenty pumping experiments were performed on this fracture system with progressively increasing quantities of injected water, and the volumes of fluid returned were measured as the crack was permitted to deflate. The largest volume of water injected was 136 000 liters. When the system was vented, return of fluid from the unpropped fracture was relatively slow and the fraction of the injected fluid returned depended on the shut-in time before venting, but was as high as 84%. After the fracture was propped with 4300 kg of sand, fluid return was much more rapid and returns as high as 92% were observed.

Permeability measurements in the fracture were somewhat uncertain because of uncertainties concerning its actual area. If k is permeability and A is the total area of both surfaces of the fracture, a value of $\sqrt{k}A = 19\ cm^3$ was deduced from the rate of pressure rise when fluid was injected at a constant rate of 132 liters/min. Using an area calculated from the assumption that the sand proppant formed a monolayer, the calculated permeability is 6 microdarcys (μd). However, the fluid-return behavior of the system during fracture deflation indicated that the fracture was to some degree self-propping. This suggests relatively rough fracture surfaces, an actual area larger than that assumed above, and a true permeability significantly less than 6 μd.

The cemented-in liner above this uncased region was perforated with 80 1-cm-diam holes in the region from 1941 to 1945 m. A commercial bridge packer was set to straddle the perforated zone, with a clock-driven pressure gauge suspended below the lower packer to record pressure continuously in the uncased region below the liner. When the perforated zone between the packers was pressurized at a flow rate of 477 liters/min, a hydraulic fracture was initiated at a pumping (surface) pressure of 275 bars. With some shut-ins and flow reductions, the fracture was extended by injecting a total of 11 000 liters of water in a period of 42 min. A leak rate of 4 liters/min was observed past the upper packer into the annulus around the pressurizing line. Subsequent examination of the pressure record from the bottom of the hole indicated that there was no significant leakage past the lower packer.

When this fracture was initiated through the perforated liner, a small pressure rise—corresponding to injection of about 1 liter of additional fluid—occurred in the uncased section of hole below the lower liner. Since the fracture produced in the uncased section was vertical and had a calculated radius of 200 m, it should have extended to some level above that of the perforations through which the second fracture was produced. If the second fracture was also vertical it should, because of the inclination of the borehole, have been separated from the first fracture by a horizontal distance of 3.8 m. The observed communication between the two fractures could be explained if they were separated by a slab of rock having a permeability of about 50 μd and a uniform thickness of 3.8 m. Evidently the fractures did not intersect and were not directly connected through any open natural fractures.

The cemented-in liner in this part of the hole was removed, the hole deepened to 2928 m, and a similar liner cemented in place in the interval 2731 to 2917 m. Approximately 30 individual pumping experiments have now been completed in the 11-m-deep section of uncased hole below this liner. A single hydraulic fracture was produced there at a pumping (surface) pressure of about 120 bars. It has since been extended in stages to an apparent volume of 5700 liters and a calculated radius of 57 m. Total permeation loss during growth of this fracture is estimated to have been 3800 liters. The permeability of the freshly fractured rock is estimated to be about 0.3 μd, which is consistent with a value of 0.15 μd given by Brace (1968) for Westerly granite at similar stress levels. No measurement of the initial pore pressure was made at this depth. However, an increase of 62 bars in poor pressure adjacent to the fracture increased the fracture-extension pressure (measured at the surface) from 103 bars to 109 bars. Fluid recoveries substantially greater than 80% have been recorded from deflation of unpropped fractures with volumes of 2000 to 6000 liters.

These experiments have yielded measured values of the least principal earth stress of 355 to 375 bars at a depth of about 2920 m, obtained from the analysis of both pressure vs total flow curves and shut-in pressure vs time curves. These values are lower than those which would be predicted from the measurements noted above, which were made at about 2040 m depth in the same hole, and may indicate some relaxation of tectonic stress at greater depth.

CONCLUSIONS

A great deal of additional analysis will be required before the results already obtained in exploratory holes GT-1 and GT-2 are completely understood, and many more experiments will be conducted in these holes before they are abandoned. However, the engineering information already collected from them is extremely encouraging with regard to the probability that the world's first dry hot rock geothermal energy extraction system can be built and operated successfully at the LASL Fenton Hill Site in northern New Mexico. It has already been demonstrated that dry hot rock at commercially useful temperature exists there at accessible depths; that this rock can be drilled and hydraulically fractured without unusual or unexpected difficulty; that its permeability is low enough to contain pressurized water with acceptably low leak-off rates; and that the stress condition of the rock, particularly after its pore pressure has been increased locally by permeation from the fracture system, is such that a hydraulic fracture can probably be held open by fluid pressure alone without becoming unstable.

Although experiments of several types are continuing in GT-2, these results are sufficiently convincing with regard to the engineering feasibility of creating and operating a pressurized-water energy extraction loop so that construction of the demonstration system shown in Figure 3 has already been initiated. Drilling of the first hole, identified as EE-1, has started at a location about 75 m from GT-2. It is expected to reach a depth of about 3800 m and a rock temperature of about 250°C. When it has been completed, it is planned to drill a second hole ("EE-2") about 60 m from EE-1, connect the two holes at depth through the hot granite by means of a hydraulic fracture having a radius of about 500 m, and complete the circulation loop through a 100 MW air-cooled heat exchanger at the surface. It is hoped that this system can be completed and fluid circulation initiated in it during 1976.

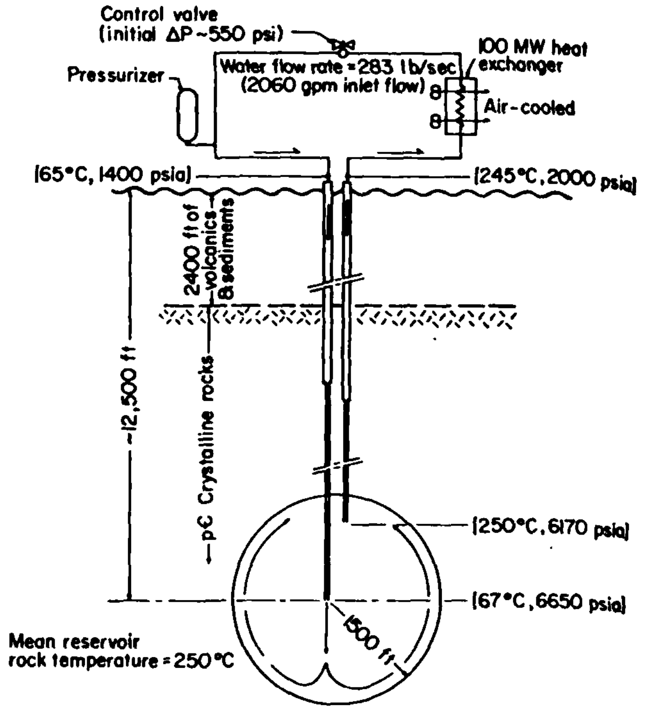

Figure 3. Proposed LASL demonstration system for geothermal energy extraction from dry hot rock.

This work is being done under the auspices of the United States Energy Research and Development Administration.

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MICROFRACTURES IN ROCKS FROM TWO GEOTHERMAL AREAS

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Core samples from the Dunes, California, and Raft River, Idaho, geothermal areas show diagenesis superimposed on episodic fracturing and fracture sealing. The minerals that fill fractures show significant temporal variations. Sealed fractures can act as barriers to fluid flow. Sealed fractures often mark boundaries between regions of significantly different physical properties. The fracture porosities measured on several samples are less than 0.1%. This low value indicates that fractures are effectively sealed or that fracturing is confined to the relatively few large fractures visible within the samples. Fracture sealing and low fracture porosity imply that only the most recently formed fractures are open to fluids.

1. Introduction

... namic geothermal system responsible for the ... ed fracturing and hydrothermal alteration of ... has been suggested by several workers, in... Elders and Bird [1], Helgeson [2], Facca and ... [3], and Elder [4]. In the model, cold, dilute, ... water descends along one limb of a convecting cell ... increases in temperature. As it does, it precipitates carbonates and sulfates and dissolves silica, K_2O, Na ... and varying amounts of other compounds. As the ... convects either upwards or laterally, along ... limb of the cell, it cools and precipitates such ... as quartz, chalcedony or silica, adularia, pyrite ... analcime. In this way, the system forms a self-sealed cap rock. This cap rock is brittle and subject to repeated fracturing. We suggest that the fractures contain information on the past histories and the current state of the system.

Cracks present in rocks from two geothermal areas, the Dunes, California, and Raft River, Idaho, were studied using recently developed techniques [5–7]. We have examined the fracture porosity, chemistry, and morphology. The standard petrographic microscope when used with 100 μm thick "crack sections" shows fracture and mineral distributions and spatial relationships. The scanning electron microscope is used to give a detailed view of fracture morphology. The electron microprobe gives the fracture and interstitial chemical compositions and spatial variations in compositions. Differential strain analysis (DSA), based on high-precision measurements of linear strain as a function of pressure, allows the determination of both the total fracture porosity and anisotropy in fracture orientation or distribution.

The Dunes area is located 15 km north of the U.S.–Mexico border in the Salton Trough of southern California (see Fig. 1). The samples come from a 612-m test well. The rocks consist of terrigeneous detritus of the Colorado River Delta (see Fig. 2). These rocks range in texture from shales to arenites to conglomerates which probably represent lacustrine, deltaic and dune, and alluvial sedimentary environments respectively. The rocks range from friable, poorly compacted sands to highly indurated silicified sands. Extensive petrologic studies have been done on these rocks by Elders and Bird [1]. Four samples were obtained for our study from rocks that were both within silicified zones and extensively fractured.

The Raft River area is located in southern Idaho approximately 9 km north of the Idaho–Utah border and south of the Snake River plain. The samples come from a 435-m well. The lithology ranges from silty and argillaceous sandstones and conglomerates to sandy shales, siltstones and claystones. The rocks represent almost exclusively an alluvial depositional environment.

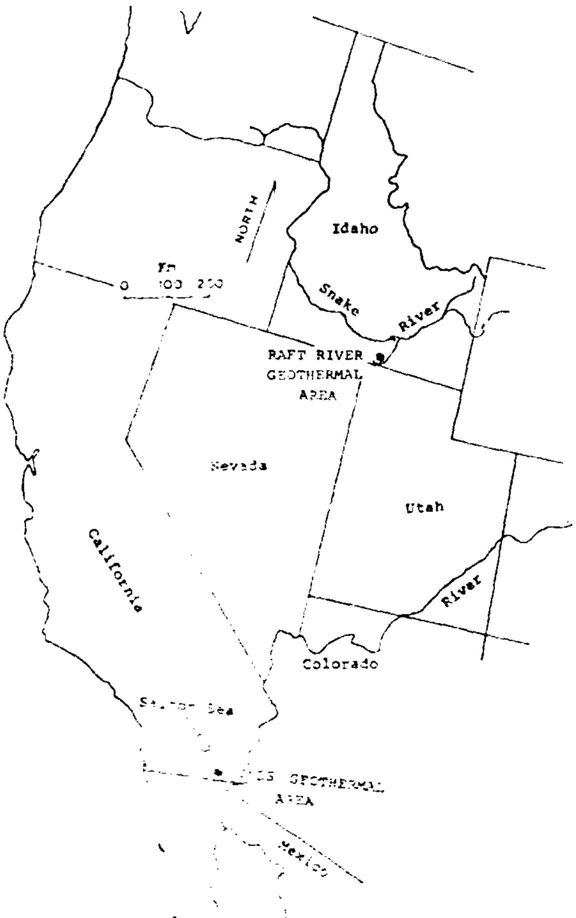


Fig. 1. Index map of sample locations.

The rocks range from friable and pliable uncompacted sediments to rocks of moderate induration and silicification. Preliminary petrographic work is being done by Paul Williams and Harry Covington (of the U.S.G.S.). Five samples were obtained for our study from indurated rocks with fracturing.

The samples studied are *not* representative of the entire rock column. They were chosen specifically on the basis of their indurated nature and high degree of fracturing. Although our sample is biased for such purposes as determining average rock type or composition and measuring general physical properties, we believe that the set is an excellent one for the initial application of our techniques to the study of geothermal systems.

Rocks from the Dunes and Raft River geothermal areas both show diagenesis superimposed on episodic fracturing and fracture sealing. The chemistry of the fracture and interstitial mineralogy reflects the bulk composition of the surrounding rocks. The Dunes area rocks consist mostly of quartz and feldspathic arenites and wackes. The interstitial and fracture minerals are predominantly quartz and adularia. The Raft River area rocks consist of argillaceous sandstones and conglomerates and sandy claystones. The fracture minerals consist mostly of calcite, analcime, and, in one case, chlorite. The chemistry of the fluids can change significantly in time. In a Dunes area sample, the fluids change from quartz to adularia supersaturation and from reducing to oxidizing. In a Raft River area sample, the fluids change from calcite to analcime supersaturation and then to calcite undersaturation. The fracture porosities of the matrix of these rocks are surprisingly low, usually less than 0.1%. This value is extremely low and is most likely due to either the self-sealing nature of the system or the concentration of fracturing into relatively few large fractures.

In this paper, a fracture or crack is any place where a formerly continuous solid has been broken. Fractures are "healed" when the broken crystal lattice reforms across the fracture. Fractures are "sealed" when precipitated materials fill the void created by the fracture. A geothermal area is the location of unusually high heat flow or thermal gradient. A geothermal system refers to the entire physical and chemical make-up of a geothermal area, including rocks, fluids, and thermodynamic properties.

2. Observations and data

2.1 Fracture history, morphology, and mineralogy

In this section, we present the fracture history of each rock sample and the relationships among fracturing events. The relationships will also be determined between the fracturing and the local fluid properties as reflected in the fracture and interstitial mineralization. These histories are subsets of the history of each geothermal area as a whole. The results of the examination with the optical microscope, the scanning electron microscope (SEM), and the electron microprobe are presented graphically in Fig. 3. Only three samples, D 380, RR 1132, and RR 1107 will be described in

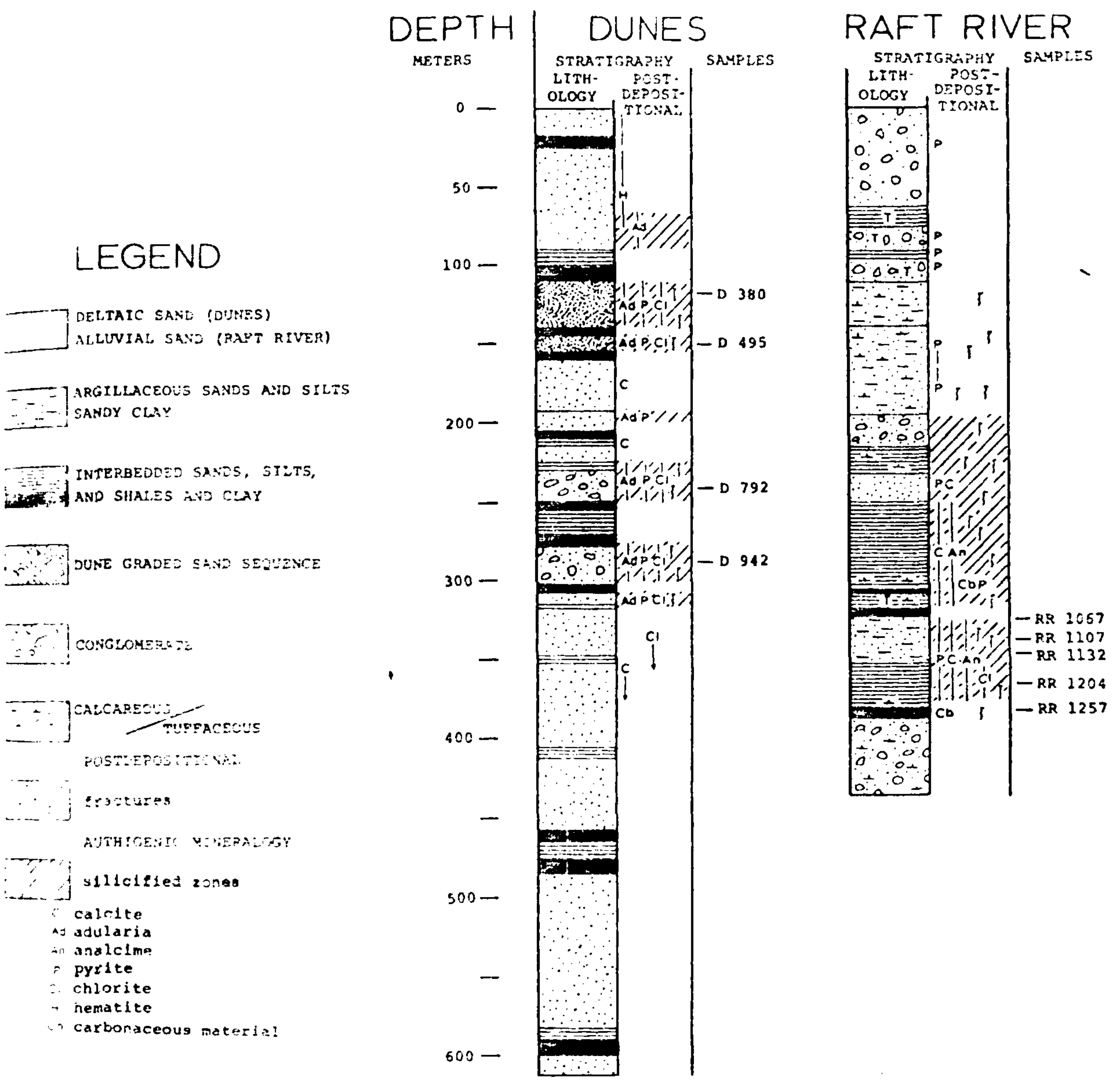


Fig. 2. Stratigraphic setting. The Dunes area data is from Elders and Bird [1]. The Raft River data is compiled from Crosthwaite et al. [13].

detail as they exemplify best the relationships involved and the methods of investigation.

All the samples show compaction, alteration, and interstitial mineralization as the result of diagenesis. In the Dunes area rocks, quartz grains usually have developed quartz overgrowths and feldspar, clay, and lithic fragments commonly have either adularia or quartz overgrowths. Euhedral pyrite grains are common both interstitially and within lithic fragments. In the Raft River area rocks, large percentages of clay make the intergrain relations difficult to determine. Some of these rocks are moderately indurated by silici-

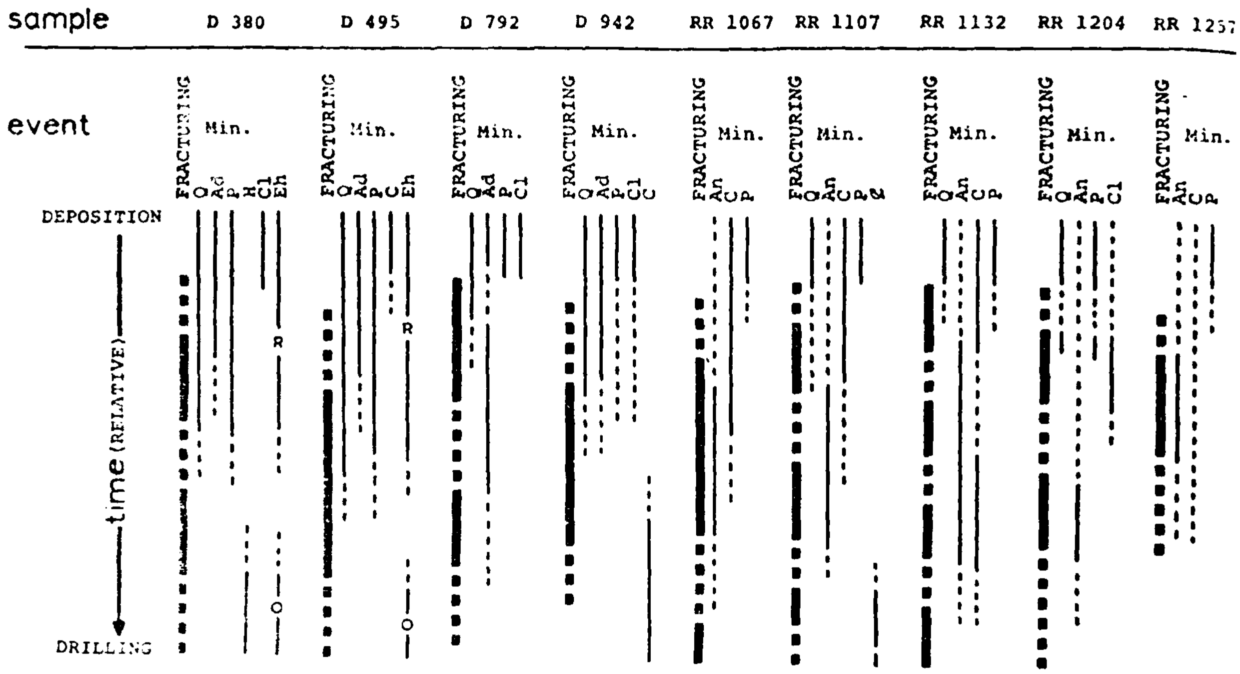


Fig. 3. Schematic fracture histories. The time scale is relative and indicates time relationships within each sample and not between samples. Dashed lines indicate that relationships are uncertain. "Min." represents precipitated minerals both interstitial and within fractures. "Eh" represents oxidation condition; R = pyrite stable (reducing conditions), O = pyrite oxidizing. "C" represents conditions under which calcite was undersaturated with respect to the surrounding fluids.

Fracture and interstitial minerals: Q = quartz (or silica), Ad = adularia, An = analcime, P = pyrite, C = calcite or carbonate, Cl = chlorite, H = hematite.

fication and most of the rocks show interstitial growths of calcite and pyrite crystals (see Fig. 2).

Several fracture origins are possible in these sedimentary rocks. Grains may have been fractured at their source or in transport and deposition. Fractures can be produced in such processes of sampling and specimen preparation as drilling, shaping, cutting, and thin-sectioning. Of course, hammering on a specimen and dropping it can also produce fractures and should be avoided. The fractures of interest are those produced by the geothermal processes.

Several lines of evidence allow us to determine the temporal relationships among fractures. Overgrowths enclose older fractures but are transected by fractures younger than the overgrowth, as can be seen in Plate 1. Fractures also show cross-cutting relationships. Younger fractures often terminate on older ones. Progressive changes in fracture mineralogy can be used to date particular fractures. However, possible ambiguities can arise. Refracturing events can complicate the relations. New fractures often follow old lines of weakness. These lines of weakness can be old fractures or partially healed fractures as seen in Plate 2. Complex fracture shapes, usually at grain boundaries, can be misleading, particularly after refracturing events.

2.2. *Sample D 380*

Sample D 380 is a medium-grained, well-sorted feldspathic arenite. This sample is dull gray-red in color and is well indurated. An intergrown grain boundary texture results from almost all grains being enclosed by overgrowths. Sample D 380 shows several steeply dipping, open fractures to the unaided eye. These fractures are as wide as 1 mm.

Plate 3A and B contains evidence for four distinct

Plate 1. Fracture cutting relationships. Older fractures are surrounded by overgrowth. "New" fracture cuts overgrowth.

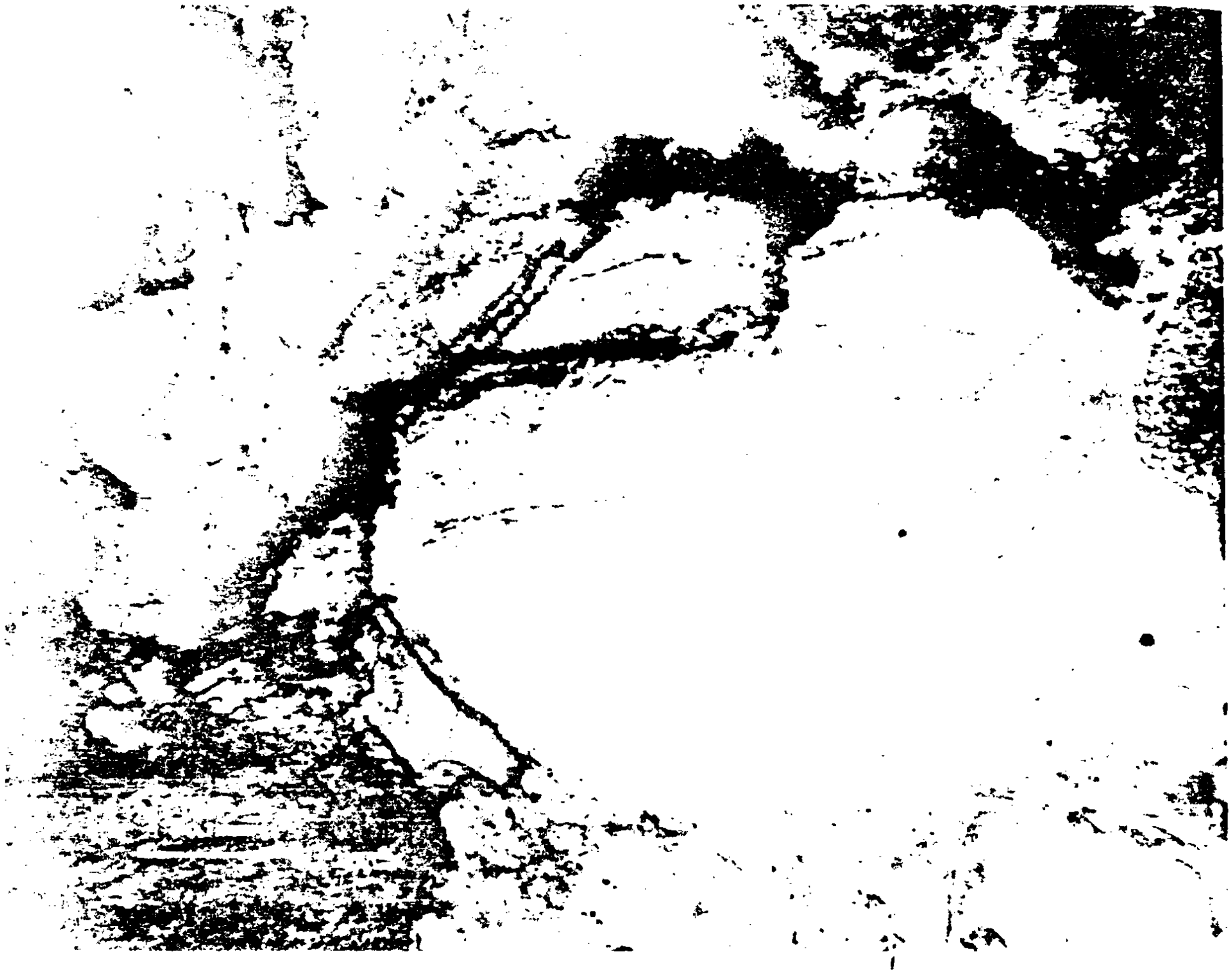


Plate 2. Refracturing. New fractures follow old lines of weaknesses. Here, healed fractures in the form of bubble planes are weaknesses.

episodes of fracturing. The episodes start with the major fracture *f1* and end with a minor fracture *f4*, possibly due to drilling. All but *f4* show same signs of healing or sealing by mineral precipitation. Examples of healing on fractures *f2* and *f3a* are shown at *healed f2* and *healed f3a* respectively. An example of fracture sealing by mineral precipitation is shown at *sealed f1*.

An ambiguity in the temporal relationships between fractures is seen along fractures *f2*, *f3b*, and *f3c*. Apparently, *f2* formed first, followed by *f3b* and *f3c*. The similarity of morphologies and merging near *D* of *f3b* and *f3c* indicates that they are the result of the same fracturing event. Fracture *f3c* terminates on fracture *f2* at location *K*. This termination indicates that *f3b* is younger than, or at least the same age as, *f2*. However, *f3b* and *f2* merge at *L*. Here at *L*, *f3b* most likely represents refracturing of *f2*.

The minerals sealing the major fracture *sealed f1* are mostly quartz with the addition of a few pyrite grains. Other fractures are either open or mineralized with quartz. The sharp, unetched nature of the fracture boundaries within quartz grains indicates that the fluids were always silica-saturated.

Sample D 380 shows the effects of time-varying fluid chemistry. The fluids in the rock were in the process of oxidizing pyrite. Both oxidized rims around

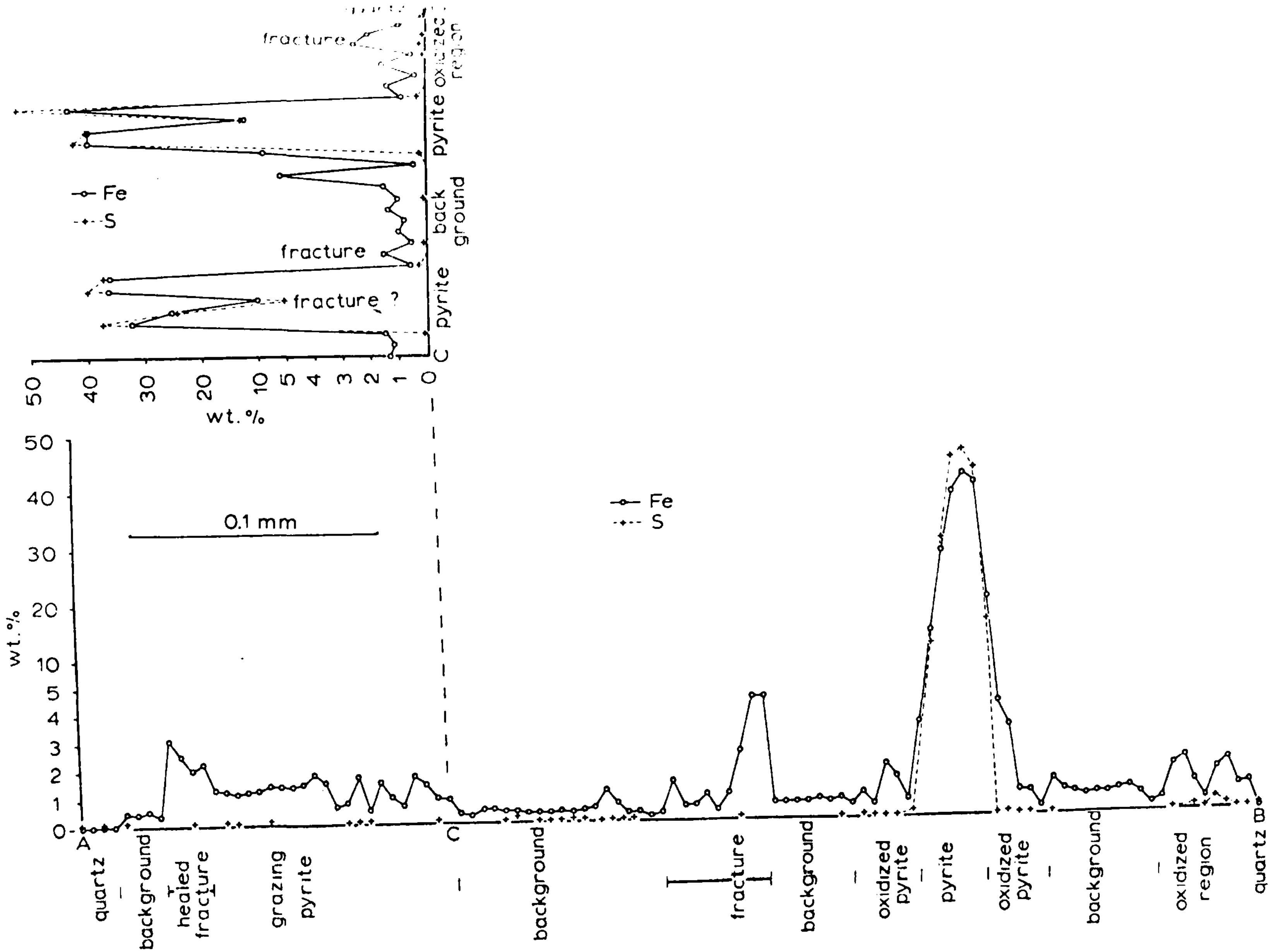


Fig. 4. Sample D 380. Microprobe traverses A–B, C–D. See Plate 3.

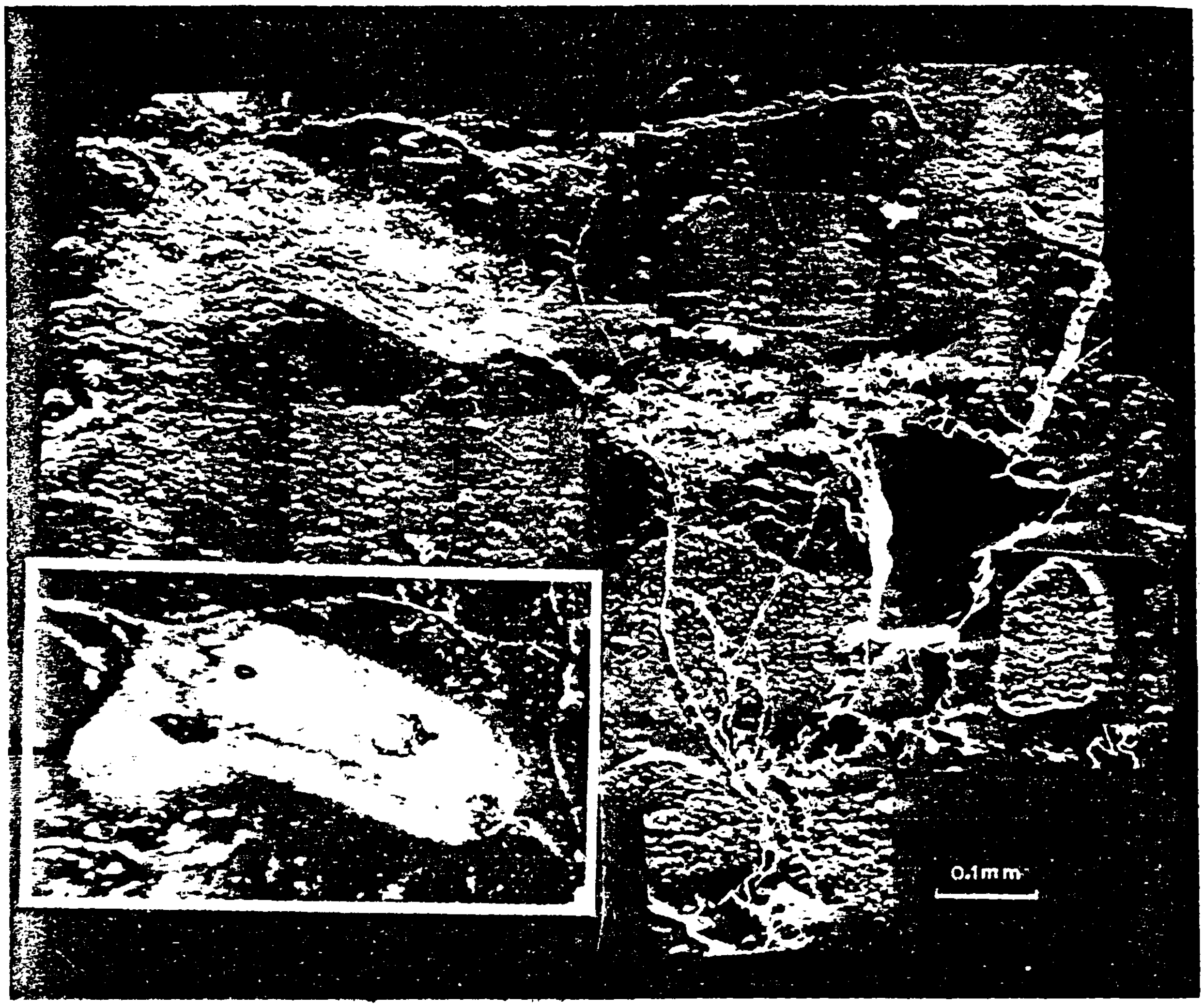
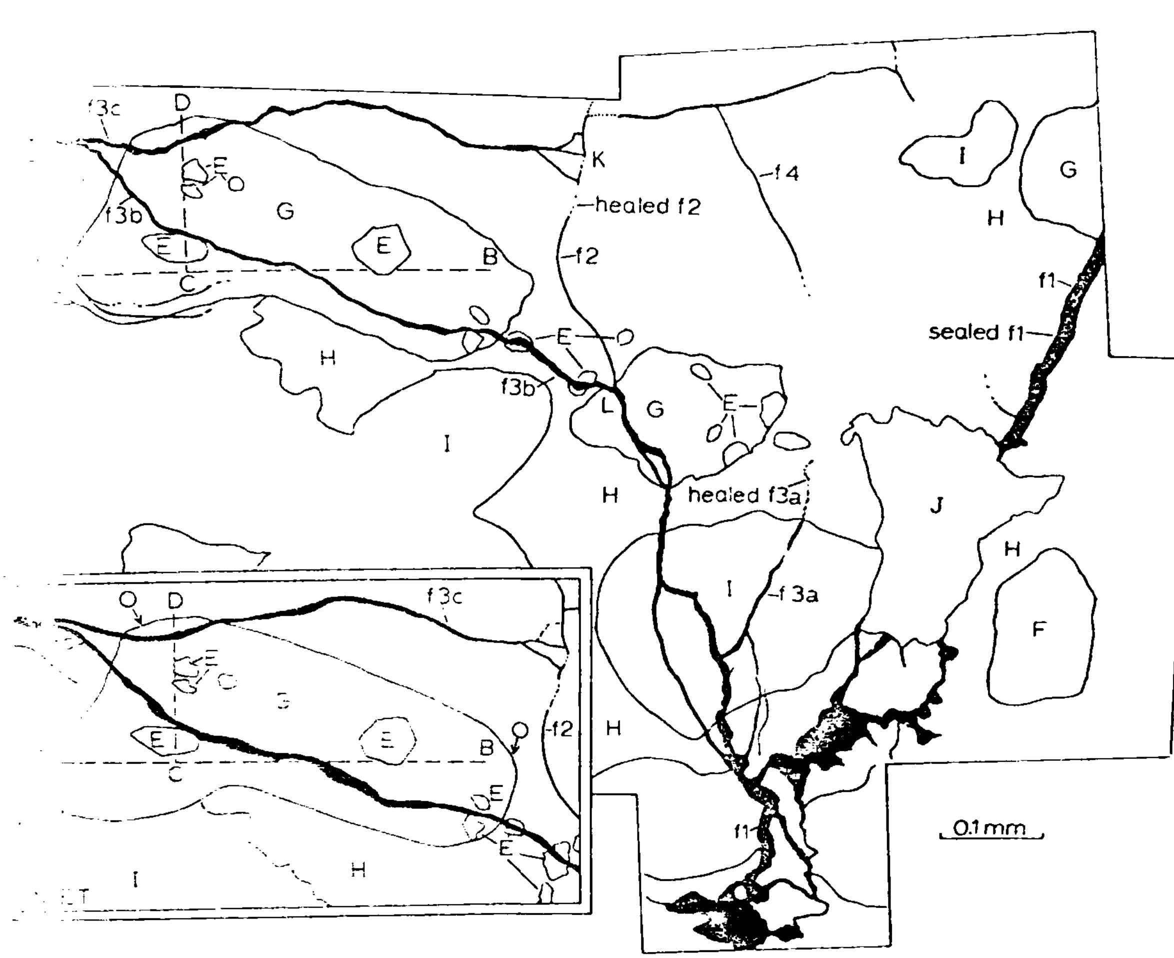


Plate 3A. Sample D 380. Scanning electron photomicrograph mosaic of an area of fracture intersections. The hummocky topography is a result of milling the sample surface with ionized argon. See also Fig. 4. In the inset, the feldspar is viewed with an optical microscope using reflected light.

many pyrites and varying degrees of pyrite oxidation exist throughout the sample. At some locations within the major fracture *f1*, pyrite grains are almost completely altered to hematite. At other locations within this same fracture, unaltered euhedral pyrite grains still exist. Hence, fluid flow is restricted to specific sites within the fracture.

The progressive oxidation occurs in a particularly significant form within the altered clay (*A*–*B*, *C*–*D*). The oxidation reaction is poorly understood. Apparently, pyrite is oxidized to hematite and a highly soluble sulfate or hydrogen sulfate complex [8]. The sulfate is removed from the sample in solution. The hematite coats the pyrite grains and, more importantly, is distributed along the fractures. The active fractures, or fractures open to oxidizing fluids, appear as an abrupt rise in the iron background in microprobe analysis.

This correlation is seen in the microprobe traverse *A*–*B* in Fig. 4. Proceeding from *B* to *A* there is an abrupt rise in the iron content when crossing the first



... Index sketch of the principle features of plate 3A. $A-B$, $C-D$ = microprobe traverse lines through altered feldspar; ... grains; F = lithic fragment; G = altered clay fragment; H = authigenic quartz overgrowth; I = interior of detrital quartz ... void now filled with epoxy; K, L = fracture intersections; $f1$ to $f4$ = fractures (see text).

... *f3b*. The traverse then parallels the fracture ... at 0.04 mm. This juxtaposition results in the ... decrease in iron to the left side of the peak. ... active fractures can be recognized on the ... the local iron content. The iron in the fracture ... be due to broken pyrite grains emplaced there ... grinding because the sulfur content remains essentially zero within the fracture.

... of progressive oxidation can also be seen. ... appear as shaded areas (brick red in color) in the ... indicated in the inset of Plate 3. The $A-B$ traverse across the pyrite grain (E) shows a slight flaring ... the iron content which represents a coating ... hematite. The pyrite near C in traverse $C-D$, however, shows no such flaring. Fracture *f3b* crosses the traverse $C-D$ on the upper boundary of the pyrite grain near C. The fracture *f3b* here only slightly increases the background iron content. The decrease in the iron and sulfur contents near the center of the pyrite grain may be due to a small "healed" fracture. The relative increase of iron with respect to sulfur indicates that both this healed fracture and *f3b* are localized areas of oxidation. The presence of strong oxidation gradients within the feldspar ($A-B$, $C-D$) is interpreted to mean that ozidizing fluids are restricted to the vicinity of fractures.

In brief, the fracture history of sample D 380 is one of repeated fracturing events superimposed on time-varying fluid chemistry. Fracturing occurred, followed by precipitation of quartz and pyrite. In turn, periods of fracturing and then oxidation followed. Varying degrees of oxidation show that, at any one time, different portions of the same fracture can be both open or closed to the circulating fluids.

2.3. Sample RR 1132

Sample RR 1132 is a gray-green, argillaceous, poorly sorted sandstone (see Fig. 2). Pyrite grains are visible throughout the sample. Bedding is indicated by several centimeter-wide dark bands with shallow dips. The high clay content makes observation by transmitted light impossible except for areas of translucent fracture mineralization.

In sample RR 1132, several sealed and unsealed fractures are visible to the unaided eye. The sample is divided by the fractures into two regions. One region is well indurated with siliceous cement and minor carbonate cement. The other region is friable and easily crumbles when handled. This division indicates that the sealed fractures have acted as effective boundaries to the circulating fluids responsible for the induration. Continuity of bedding across fractures indicates that there has been no significant movement along fractures.

SEM photomicrographs of an area of intersecting fractures are shown in Plates 4, 5, and 6. Five episodes of fracturing are indicated. The first to occur, fracture *f1* in Plate 4, is now filled with calcite. The calcite tends to grow inward in small tablets perpendicular to

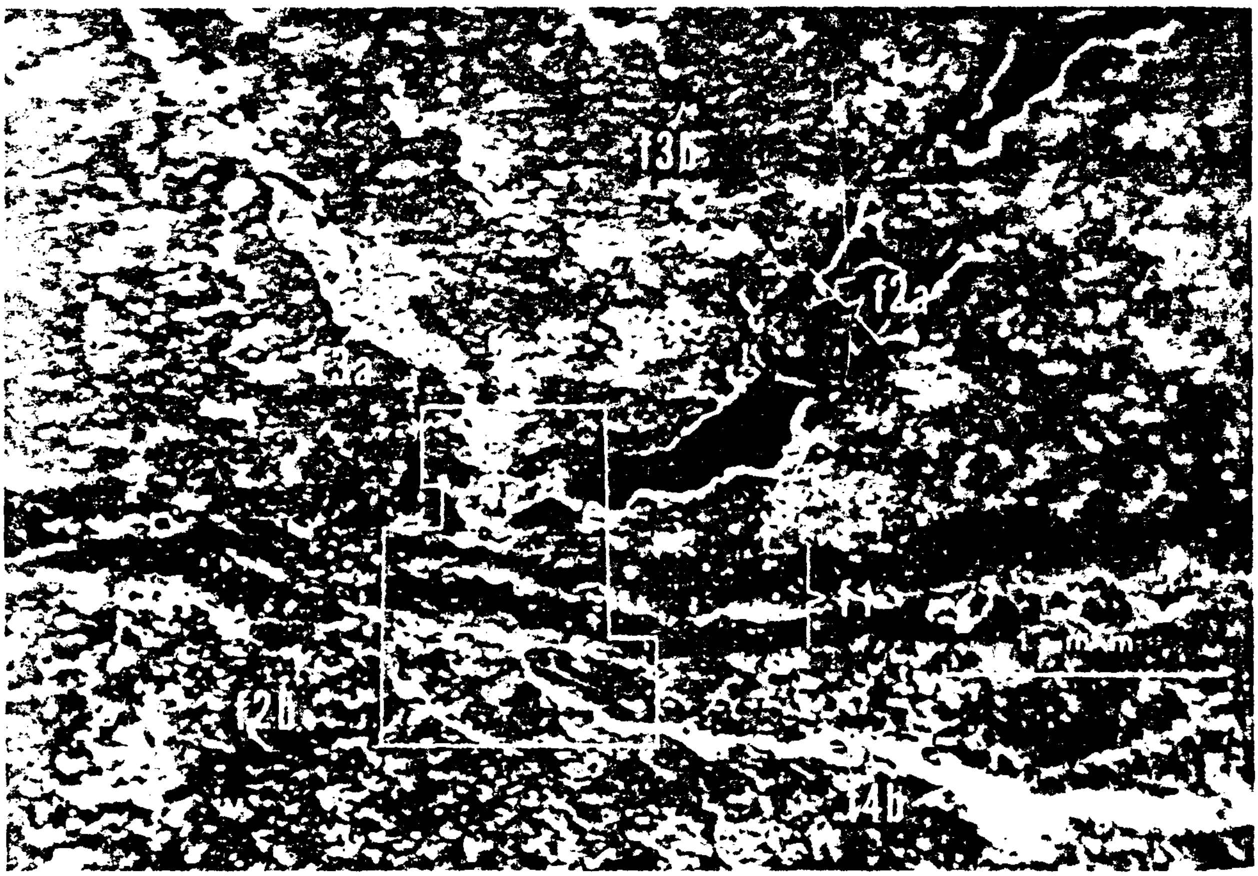


Plate 4. Sample RR 1132. SEM photomicrograph. *f1* to *f4b* = fractures (see text). See Plate 5 for enlargement of outlined portion.

Plate [illegible]. Sample RR 1132. SEM photomicrograph (mosaic). Enlargement of the outlined portion of Plate 4. *B* = calcite plates (?) in [illegible]. *C* = calcite; *D* = analcime; *E* = void; *F* = void now filled with epoxy; *f1* to *f4c* = fractures (see text). See Plate 6 for enlarge-[illegible] outlined area.

the fracture walls. The sealing is complete except for a discontinuous chain of cavities at the center.

A second series of fracturing, *f2a*, angles down from the upper right-hand corner of Plate 4 to join *f1* at the center of the plate. Fracture *f2a* then continues toward the left, paralleling and crosscutting *f1*. Fracture *f2b* most likely occurred during the same fracturing episode that produced *f2a*. The evidence for this similarity in relative ages is that *f2a* and *f2b* trend in the same general direction, but are perpendicular to the later set of fractures, *f3a* and *f3b*. Fracture *f2b* is completely sealed with analcime, reflecting a change in the fluid chemistry from calcite to analcime supersaturation. Fracture *f2a* is lined with euhedral growths of analcime. The sealed and ingrown natures are clearly shown in Plate 5. Fractures *f3a* and *f3b* in Plate 4 occurred next, propagating downward from the upper left until terminating on *f2a*. Fractures *f3a* and *f3b* are partially filled with analcime.

A more substantial change in the fluid chemistry is recorded in fractures *f4a, f4b,* and *f4c* of Plate 5. These cross-cut *f1* and *f2b*. Much of the lengths of *f4a, f4b,* and *f4c* are open cavities. They conspicuously narrow when cutting the analcime of *f2b*. Fracture *f4b* appears only as a "hollow" or shallow valley in Plate 6. This valley is paralleled by the more recent fracture *f5*. The fluids within *f4a, f4b,* and *f4c* have become undersaturated with respect to calcium carbonate. This undersaturation may be due to a number of things, including a decrease in fluid pH or fluid temperature. The undersaturation does not affect the analcime already deposited in *f2b* but causes large voids in the clayey matrix

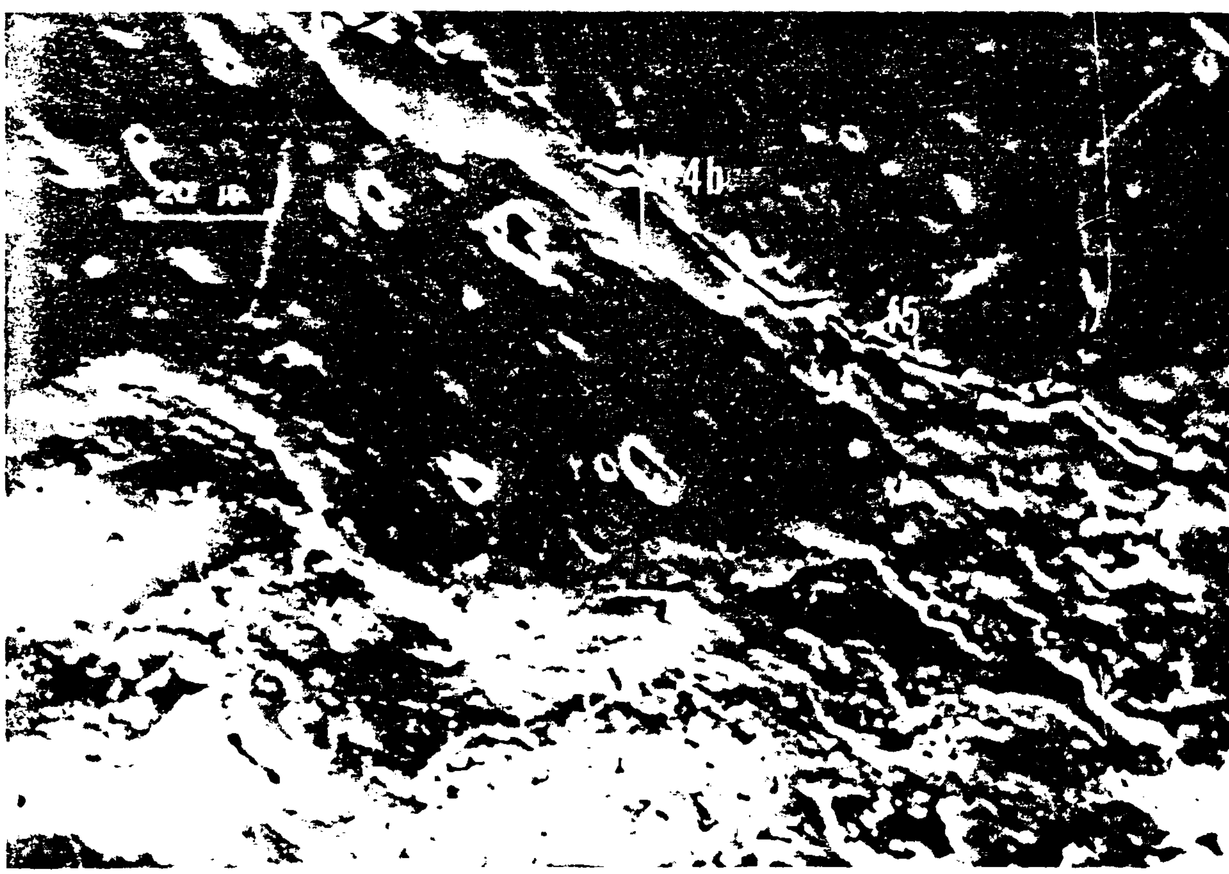


Plate 6. Sample RR 1132. SEM photomicrograph enlargement of a portion of Plate 5 (see text).

Plate 7. Sample RR 1107. Photomicrograph of an area of intersecting faulting and fracturing. Reflected light. (See text.) See Plate 8 for enlargement of outlined area.

by etching out any calcite cement. In Plate 6, fracture *f4b* is probably a zone of weakness in the calcite more readily attacked by the ion milling process. This zone may be due to the calcite "healing" across the fracture, or to a zone of lattice weakness due to the introduction of the undersaturated fluids. Fracture *f5* parallels this plane of weakness and may be due to drilling. This hollow is not due to the effects on ion milling on the open fracture *f5*.

In brief, the fracture history of rock sample RR 1132 is again one of repeated fracturing events superimposed on time-varying fluid chemistry. The fluid reactions usually involve fracture sealing. The fluid chemistry changes in time from calcite supersaturation to analcime supersaturation to calcite undersaturation. Pyrite crystals remain unaltered indicating continuous reducing conditions.

2.4 Sample RR 1107

Sample RR 1107 shows many sealed faults and fractures. Drag folding and offset bedding indicate at least 1 cm of movement along a faulted zone. The sealed faults and fractures form a boundary between well-indurated and poorly indurated regions of the sample. The sample is a gray-green, sandy claystone with siliceous and carbonate cement. Unaltered pyrite grains are present throughout the rock. Sample RR 1107 is very similar to sample RR 1132.

Sample RR 1107 is massively fractured and faulted in a narrow zone 3 mm wide. As can be seen in Plate 7, this fault zone (*f1*) consists of several wavy and broken bands. These bands consist of calcite and analcime. The wavy and broken texture is evidence for intermittent periods of calcite and analcime precipitation within fractures followed by further faulting and fracturing. The matrix surrounding fault *f1* contains many calcite and analcime shards. A later fracture, *f2*, along *f1*, marked the end of significant movement as is demonstrated by the sinuous and unbroken vein of analcime now filling *f2*.

Another episode of fracturing, *f3*, cross-cuts both *f1* and *f2*. A more detailed view of *f3* is shown in Plate 8. The mineralization within *f3* consists of both calcite and analcime and demonstrates the dependence of mineral precipitation on the micro- or local environment. Analcime fills *f3* where it crosses the analcime of *f2*. Calcite fills *f3* where it cuts the calcite-rich matrix. In turn, *f5* is cross-cut by *f4*. Fracture *f4* is narrow, open, parallels *f1*, and extends down the center of *f2*.

Sample RR 1107 again exemplifies the episodic fracturing and sealing histories seen in both the Dunes and Raft River geothermal areas.

3. Fracture (crack) porosity

The flow of fluids through fractures depends, in part, on fracture porosity. Fracture or crack porosity can be determined through its effect on rock compressibility. We use differential strain analysis (DSA), a high-precision technique, to study the shape and spatial orientations of fractures [6]. Axial and radial linear differential strains were measured on each core sample.

The effects of fractures on the compressibility of rocks have been well documented. For a dry sample, the graph of strain versus pressure often shows two characteristic regions as in Fig. 5a. The "straight" portion of the curve at higher pressure (βP) is a result of the intrinsic compressibilities, β, of the constituent minerals. The increase of compressibility, represented by the "curved" portion of Fig. 5a, is due to crack closure. At the junction of these "curved" and "straight" portions, all fractures have closed. Walsh [9] demonstrated that the crack porosity, η_c in Fig. 5a, is the amount of volumetric strain between the origin and the zero pressure intercept of the "straight" portion (βP) of the stress-strain curve. Morlier [10] showed that the *distribution* of crack shapes could be obtained from the compression curves.

DSA is a new technique for measuring linear strain with a precision of 2×10^{-6} [6]. DSA is essentially the difference in linear strain between the sample and a fused silica standard exposed to the same high-pressure environment. The process of plotting differential strains transforms a curve such as the one in Fig. 5a to the form shown in Fig. 5b. In the transformation, the fracture porosity remains the strain between the origin and the zero pressure intercept of the "straight" intrinsic compressibility ($\beta' P$) portion of the DSA curve.

The precision of the DSA technique allows the fine structure of the linear stress-strain curves to be observed. Curves made up of straight line segments separated by discontinuities in slope, as in Fig. 5c, have been observed in some igneous samples. If the penny-shaped

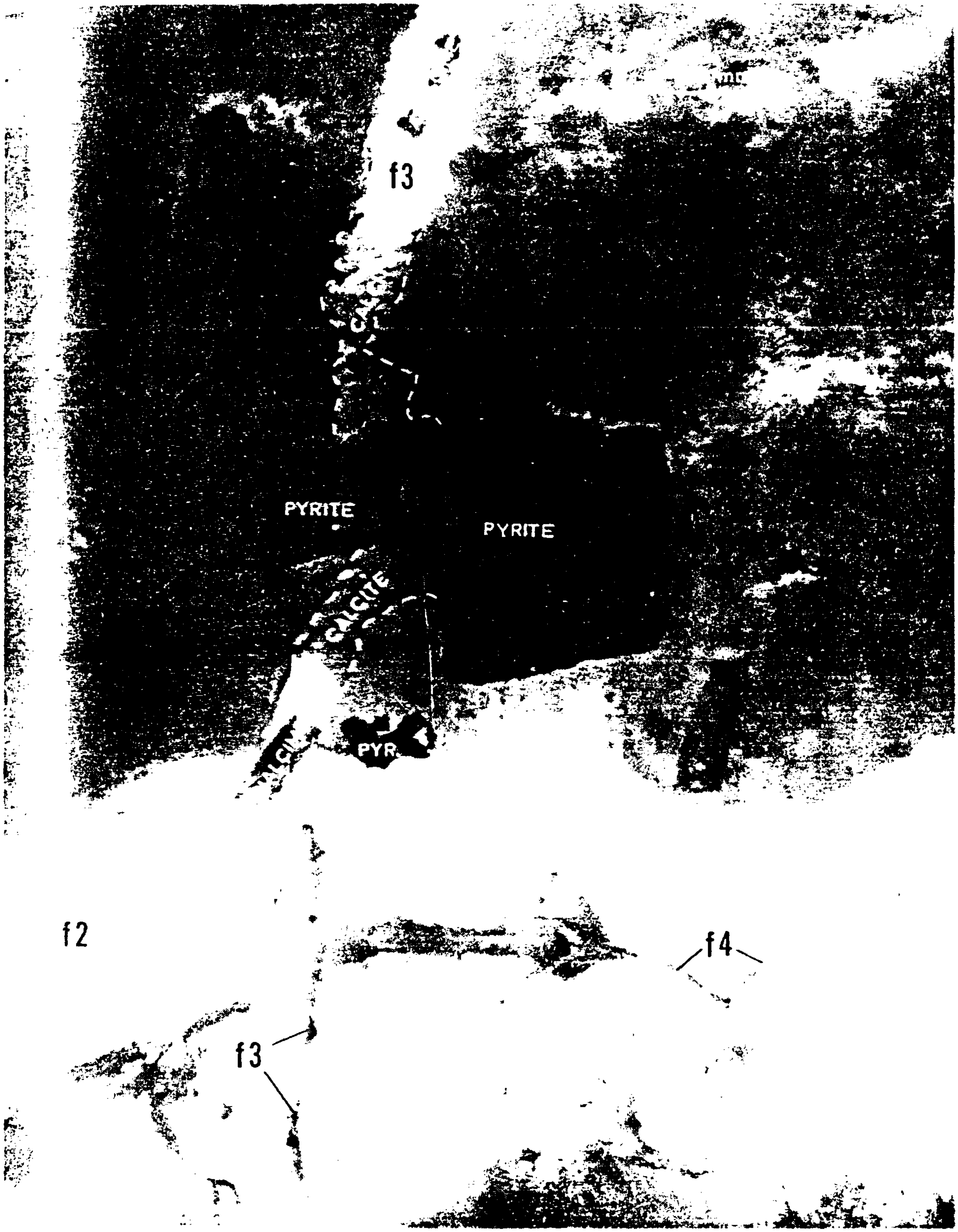


Plate 8. Sample RR 1107. Photomicrograph enlargement of a portion of Plate 7. Transmitted light (see text).

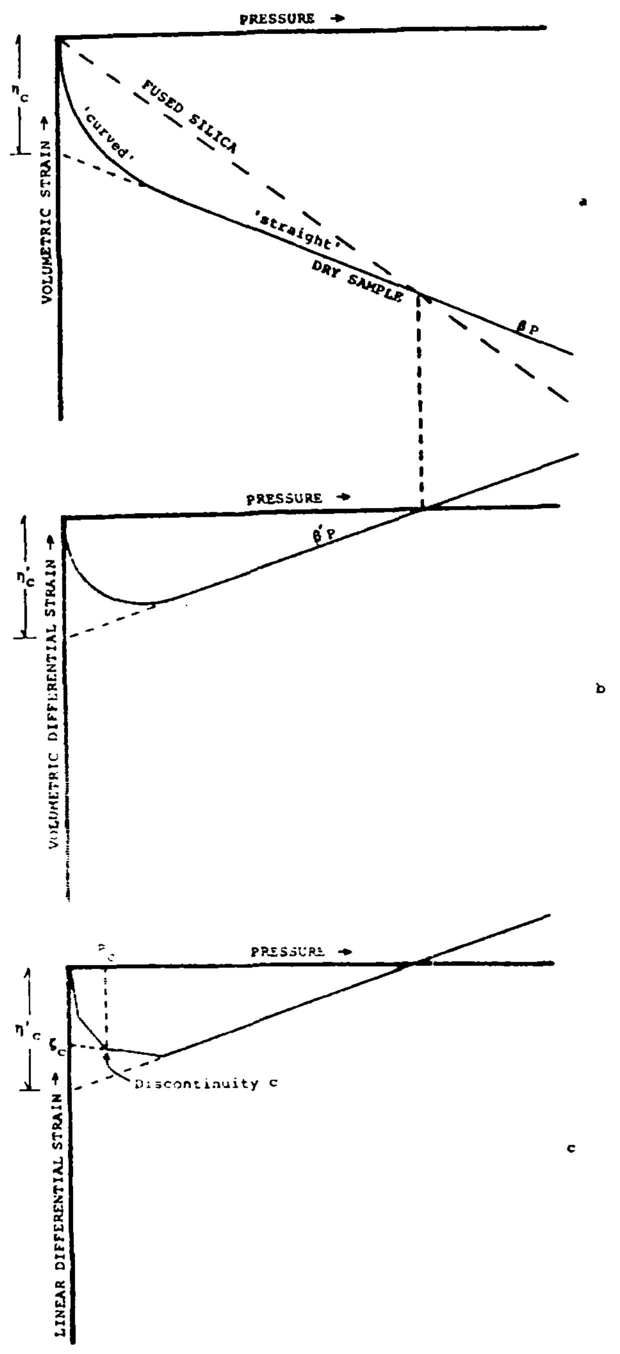


Fig. 5. Schematic stress–strain relationship. Symbol definitions: η_c = crack porosity, η'_c = linear differential strain due to fracture closure, P_c = pressure at closure discontinuity c, ζ_c = zero pressure intercept of linear segment beyond closure discontinuity c, β = compressibility, β' = differential compressibility, P = pressure. (a) Standard stress–strain curve. (b) Differential strain analysis (DSA) curve. (c) Segmented DSA curve.

crack model of Walsh [9] is used, then this segmented curve can be interpreted as being due to sharp peaks in the number of cracks with a particular aspect ratio (the ratio of width to length). Rocks with a continuous distribution of aspect ratios will have an appearance similar to Fig. 5b. In Fig. 5c, no cracks close completely over straight lined segments. At discontinuity c, all fractures with aspect ratio $\alpha = 4P_c(1-\nu^2)/\pi E$ close, where ν and E are Poisson's ratio and Young's modulus respectively. This value of α is strongly dependent on the fracture model. To avoid this model-dependency, Simmons et al. [6] have used the experimentally determined values P_c and ζ_c as in Fig. 5c. P_c is the pressure at discontinuity c. ζ_c is the strain due to all the cracks that close *by* discontinuity c. The contribution to the total strain due to the fractures that close *at* discontinuity c is $\zeta_{c-1} - \zeta_c$. There exists a complete range of rocks that have a stress-strain curve such as Fig. 5c and those with one like Fig. 5b.

Previous experience in interpreting DSA data has been confined to dense, low-porosity, igneous rocks from the earth and to lunar samples. For the interpretation of DSA curves on sedimentary rocks, several modifications are needed. Compaction of rocks, particularly those rich in clay, results in a curve like that of Fig. 6a (note that strain is two orders of magnitude larger than the strain typical of igneous rocks). Initially, the rate of change of differential strain with pressure increases. Note that in Fig. 6a the intrinsic compressibility of the sample is greater than that of fused silica at all pressures so that the DSA curve does not recross the pressure axis. A similar, but less pronounced, effect occurs when the material is crushed in the vicinity of intergranular contacts. This effect may also occur due to the crushing of "bridges" or material spanning open fractures. Crushing appears as a downward offset of the DSA curve as shown in Fig. 6b. Crushing has also been observed in aggregates by Talwani and Nur [11]. The effect of small amounts of water within samples is shown in Fig. 6c. This effect was first noticed in igneous rocks [12] and may be the result of water movement in the crack network during compression. All of these effects are present to some degree in each of the Raft River area samples. Only "crushing" is observed in the Dunes area samples.

The preparation of DSA samples must be done with care to prevent the introduction of new fractures. Surfaces are cut parallel and perpendicular to the core

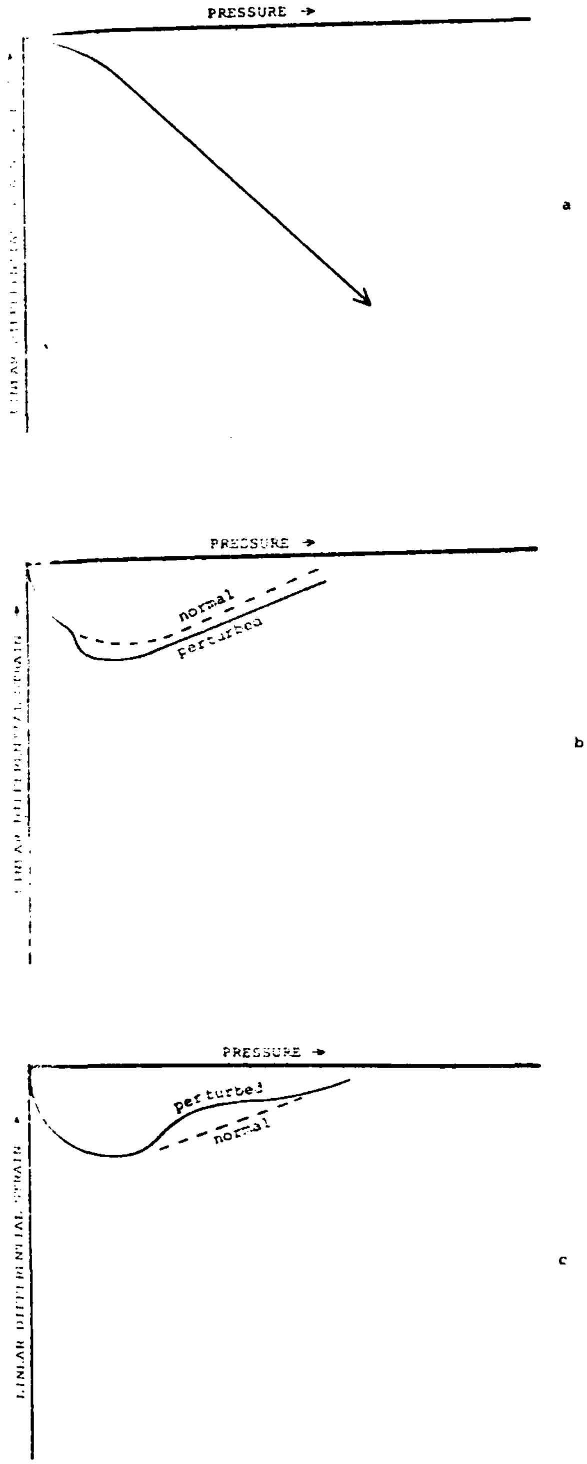


Fig. [illegible]. Variations on a theme. (a) Effects of compaction; characteristic of clay-rich samples. (b) Effects of "crushing" (see text). (c) Effects of water.

axes and then ground. Samples are dried for 24 hours at room temperature and in a vacuum of less than 10^{-3} torr. For samples of low porosity, foil strain gages are attached directly to the sample with Tra-Con 2101 epoxy. The epoxy is allowed to cure completely. The sample is then encapsulated in Dow-Corning Sylgard to exclude the pressure medium. However, for highly porous rocks, both Sylgard and strain gages can be forced into pores under high pressures. The only method found to prevent entry into pores was a 1 mm thick coating of epoxy applied to the sample surface after drying but before further preparation.

Differential strain analyses were made on each sample. Strains were measured parallel (axial) and perpendicular (radial) to the core axis as a function of pressure to 2000 bars in increments ranging from 20 bars at low pressures to 100 bars at high pressures. The results are summarized in Table 1. Representative results for D 380, D 792, RR 1067, and RR 1107 will be described in detail.

3.1. Sample D 380

Sample D 380, described above, has several open, steeply dipping macroscopic fractures. The DSA curves, shown in Fig. 7, differ significantly in the radial and axial directions, an indication of strong anisotropy in physical properties. This anisotropy may be due to the preferred orientation of the fractures parallel to the core axis. The DSA results also indicate that not all the fractures are closed by 2000 bars.

For the radial direction, the DSA curve consists of four linear segments, each of which represents a specific crack shape. The results for the radial direction are shown in Table 1. The segment assumed to be the intrinsic compressibility curve was picked on the basis of only two points and has a large possible error. This "intrinsic" segment gives a minimum value of the differential strain due to total crack closure of $+162\mu$, where μ represents the factor 10^{-6}. The zero pressure residual differential is 18μ. For the axial direction, the DSA curve varies smoothly. By extrapolating the line defined by the last two points at high pressure, a minimum linear strain due to fracture closure of 183μ is obtained. There was no residual strain in the axial direction.

The DSA curves for axial and radial directions are quite different in both shape and values. The different

TABLE 1

Differential strain analysis results (errors in closure pressure are ±5 bars, in strain and fracture porosity are ±5% of the values reported)

Sample No.	Direction/ (location)/	[segment]	Closure pressure (bars)	Linear fracture strain (μ)	Total fracture porosity *	Remarks
D 380					0.0507%	
	radial	[1]	525	16		
		[2]	1300	66		discrete dis **
		[3]	1840	80		
	total			162		
	axial		1900?	183		continuous dis
D 495					0.0340%	initial grain crushing
	radial	[1]	1000	52		continuous dis
		[2]	1750	75		discrete dis
	total			127		
	axial	[1]	475	20		discrete dis
		[2]	1350	66		discrete dis
	total			86		
D 792					0.0371%	
(see text)	radial	(X)	1600	135		
		(YC)	1650	70		
		(YE)	1750	94		continuous dis
	axial	(AC)	1700	166		
		(AE)	1500	169		
D 942					0.0392%	
	radial		1400	106		
	axial		1600	180		continuous dis
RR 1[illegible]					0.0610%	
	radial		1350	220		
	axial		600	170		
RR 1132					0.0710%	
	radial		700	210		
	axial		900	290		
RR 1107						
RR 1204						compaction effects predominate
RR 1257						

* Except for D 792, the total fracture porosity is based on the assumption of radial symmetry. Total fracture porosity then equals axial strain + 2 × radial strain.

** The abbreviation dis is used here for "distribution of crack closure pressures".

slopes at the higher pressures imply differences in the intrinsic compressibilities in these directions. The large differences in strain at each pressure imply that the cracks are anisotropically oriented.

The presence of linear segments in the compression curve for the radial direction and their absence for the axial direction are particularly interesting. The linear segments can occur only if no cracks close completely over the pressure range for each segment. However, the curves with continuously varying first derivatives can occur only if some cracks close completely at each pressure over the same range. If the spatial distribution

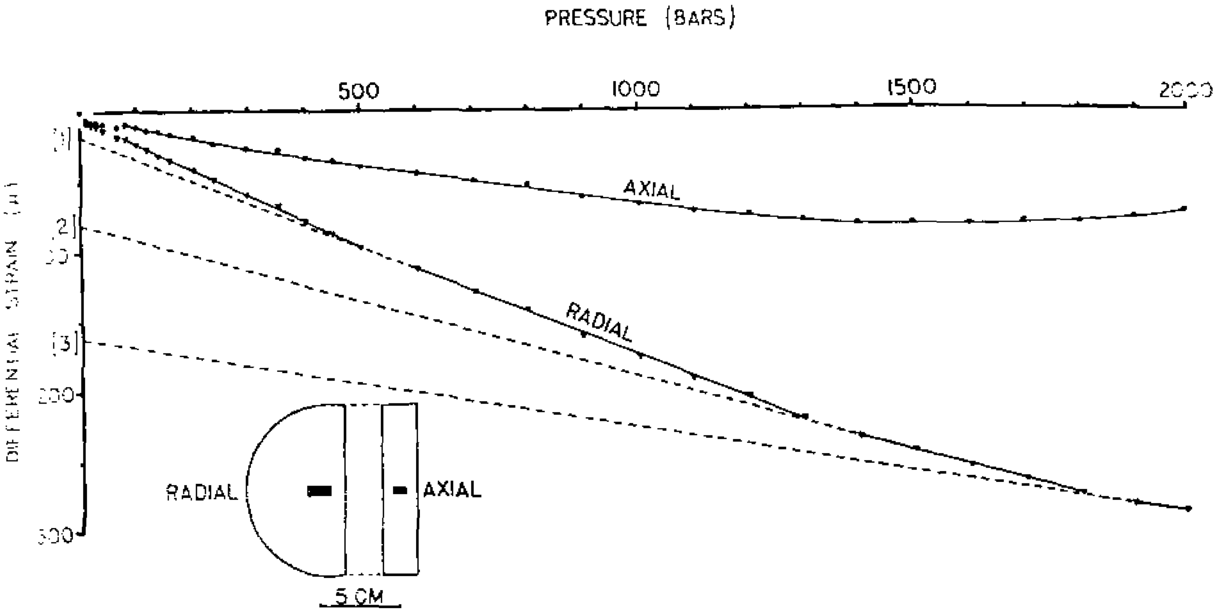


Fig. 7. Sample D 380. differential strain analysis. Sample size and shape is represented at lower portion of figure. The dark rectangles represent the size, position, and orientation of the strain gages.

of cracks in the sample is homogeneous, then linear segments in one direction and curved segments in other directions can occur only if the sets of cracks with continuous distribution of closure pressures are normal to the directions in which the curved segments are measured. The set of cracks with a discrete distribution of closure pressures may be isotropically oriented. If we assume then that the DSA data in Fig. 7 fit such a model, then total crack porosity is twice the radial value plus the axial value, 0.0507%.

3.2 *Sample D 792*

DSA was performed for several directions and at several locations on sample D 792. The DSA curves and strain gage locations are shown in Fig. 8. This rock is a medium-grained, well-sorted sandstone showing no bedding. The sample has many steeply dipping fractures that apparently penetrate about 2 cm into the core. These fractures may have been caused by drilling. The upper boundary of the sample is formed by surfaces coated with fine adularia crystals.

The DSA curves on sample D 792 are smooth and show no straight segments within our experimental error, about 2μ. Each curve shows some irregularities at low pressure. The irregularities are probably due to the "crushing effect". The DSA curve for the axial direction at the edge of the core (*AE*) parallels the curve for the axial direction at the center (*AC*), but is greater in magnitude by 50μ at higher pressures. The greater magnitude of strain at the edge is perhaps due to an increased number of fractures near the drilled surface. The stress due to drilling would tend to produce tensional cracks with surfaces perpendicular to the core axis. The total strain due to crack closures at 2000 bars for *AC* is $+166\mu$.

In the radial direction, strain was measured in two perpendicular directions x and y (see Fig. 8). The differential strain curves for the y direction at the center (*YC*) and edge (*YE*) differ only by 26μ at 2000 bars. The total strain at *YC* due to the closure of cracks at 2000 bars is 70μ. The differential strain for the x direction at the center (*X*) is greater in magnitude by 95μ than *YC*. This difference is not due to sample preparation and must be due to sample anisotropy. The differential strain at *X* due to crack closure is 135μ.

The linear differential strains due to cracks in the three mutually perpendicular directions at the center

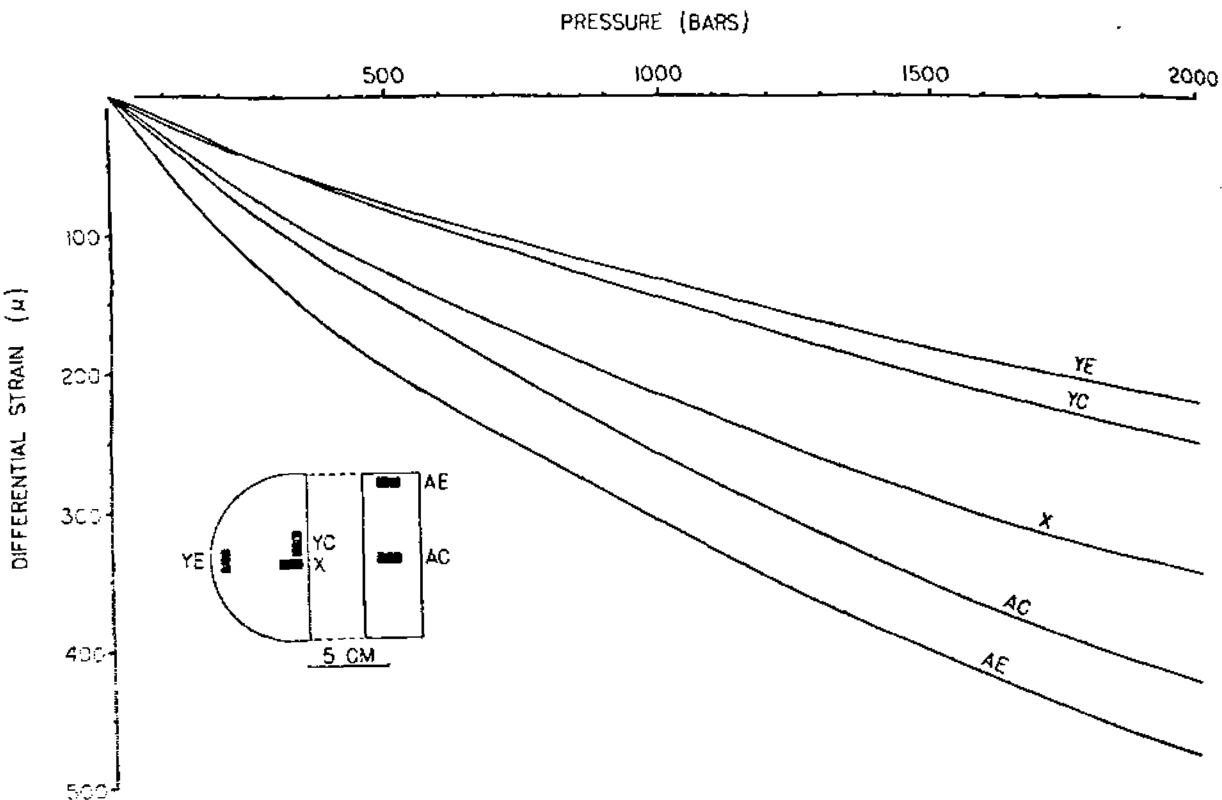


Fig. 8. Sample D 792, differential strain analysis. Data points have been omitted for clarity. Datum point location and scatter are similar to Fig. 7.

of the sample allow the calculation of the total crack porosity at the center. The total crack porosity is the sum of these linear strains, 0.0371%.

3.3. Sample RR 1067

Sample RR 1067 is a gray sandy claystone and is well indurated with siliceous and carbonate cement. Many fractures cross-cut the rock in apparently random directions. These fractures are filled with analcime and minor amounts of calcite. Several clay lenses cross the sample perpendicular to the core axis.

The DSA curves for sample RR 1067 are shown in Fig. 9. These curves consist of "curved" low-pressure portions and "straight" high-pressure portions. The curved portions require a continuous distribution of crack aspect ratios. Note, however, that the differential strains are much larger than in the Dunes area rocks. The compressibility for the axial direction in sample RR 1067 is greater than that for the radial direction. The axial differential strain differs from the radial by 520μ at 2000 bars. Also, at high pressures, the axial curve is deflected downwards. This deflection is probably due to compaction and intergranular crushing. The strains due to crack closure in the axial and radial directions are 170μ and 220μ, respectively. This anisotropic behavior may be due to cracks introduced perpendicular to the core axis during the drilling process. The sample appears to possess radial symmetry. The total crack porosity is then 0.061%. At zero pressure, residual differential strains of 52μ and 44μ remained in the axial and radial directions, respectively.

3.4. Sample RR 1107

The DSA curves for sample RR 1107 are shown in Fig. 10. This sample exemplifies the effect on DSA curves of the compaction of a clay-rich rock. This effect

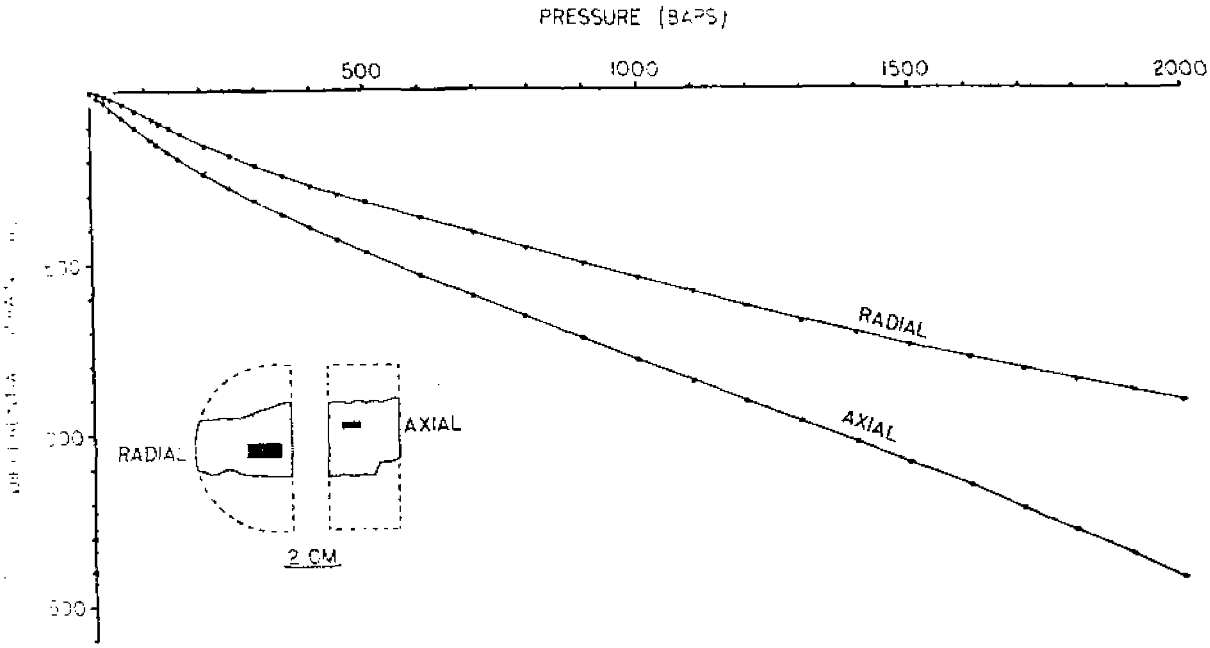


Fig. 9. Sample RR 1067, differential strain analysis.

makes the determination of fracture porosity impossible. The differential strain in the axial direction is much less than in either the radial direction in this rock or in any other sample previously discussed. These DSA curves clearly show that bias in the data results when only well-indurated locations within the samples are used.

Sample RR 1107 shows a large change in compressibility over the 2000 bar pressure range. On an expanded scale similar to those of the previously described samples, the first portion of the DSA curve for

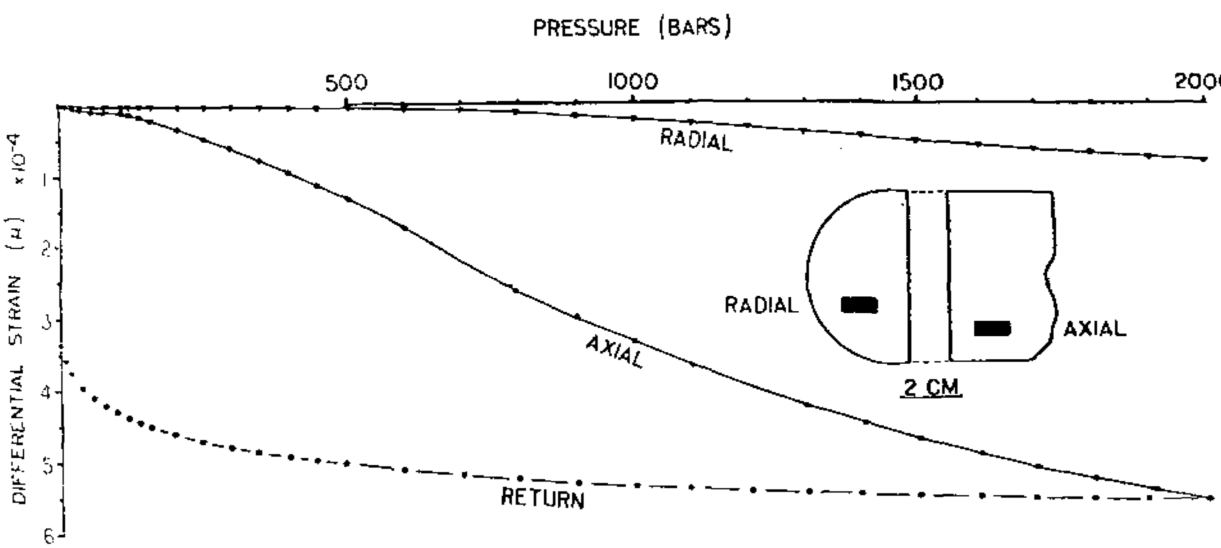


Fig. 10. Sample RR 1107, differential strain analysis.

the axial direction in sample RR 1107 looks similar to the curves of RR 1067. However, above 175 bars the compressibility becomes more than 60 times greater than the compressibility of any previously described sample. This large increase is probably due to the crushing and rotation of clays within the sample. The strain measurements during the return to zero pressure are shown to indicate how the sample is permanently affected. The maximum differential strain recorded is 56,000μ at 2000 bars. The residual at zero pressure is 33,500μ. For an isotropic region, this strain would indicate a volumetric change of about 10% (indicating irreversible changes in the sample). The radial DSA curve for this sample is similar to the axial curve but much smaller in magnitude. The rock is strongly anisotropic and the results are dependent not only on the direction but also on the location where the measurements are made. As can be seen, the compaction effects of such poorly indurated clay-rich rocks completely obliterate the effects due to microfractures.

4. Conclusions

This preliminary study of cores from two geothermal areas demonstrates the potential of combined scanning electron microscopy, optical microscopy, and differential strain analysis for the study of geothermal areas.

The geothermal system involves the interplay among the fractures, rocks, and interstitial and fracture fluids. Both the Dunes and Raft River rocks show multiple periods of fracturing. Both areas had fluid chemistries that varied in time and usually resulted in fracture sealing. The two areas differ in their specific fracture mineralogy which is caused by the differences in bulk composition of the rocks. The feldspathic sandstones in the Dunes area develop quartz and adularia within fractures and interstitial areas. The clay-rich rocks of the Raft River area have interstitial and fracture minerals consisting mostly of calcite and analcime. Vertical variations in fracture mineralogy as well as the existence of impermeable shale beds indicate that lateral fluid movement is significant and may predominate.

Rock compressibilities indicate a low crack porosity even though large fractures are present in all samples. The low crack porosity is probably due to fracture sealing or fracturing being confined to a few large fractures. Fractures occur even in highly compactable clay-rich rocks. If drilling produces fractures, they are probably oriented with surfaces perpendicular to the core axis. Such drilling fractures apparently do not significantly increase the total fracture porosity. Fracturing and fracture sealing can alter the rock bulk physical properties greatly over distances as small as a few millimeters.

Due to the self-sealing nature of the geothermal system, geothermal areas will tend to develop dense impermeable cap rocks. Only the most recently formed fractures will remain open to fluid circulation. Sealed fractures can act as effective barriers to fluid movement through rocks. We speculate that fracture sealing will result in high heat flow and low electric resistivity only over regions of recent fracturing because new, open fractures conduct both fluids and electric currents.

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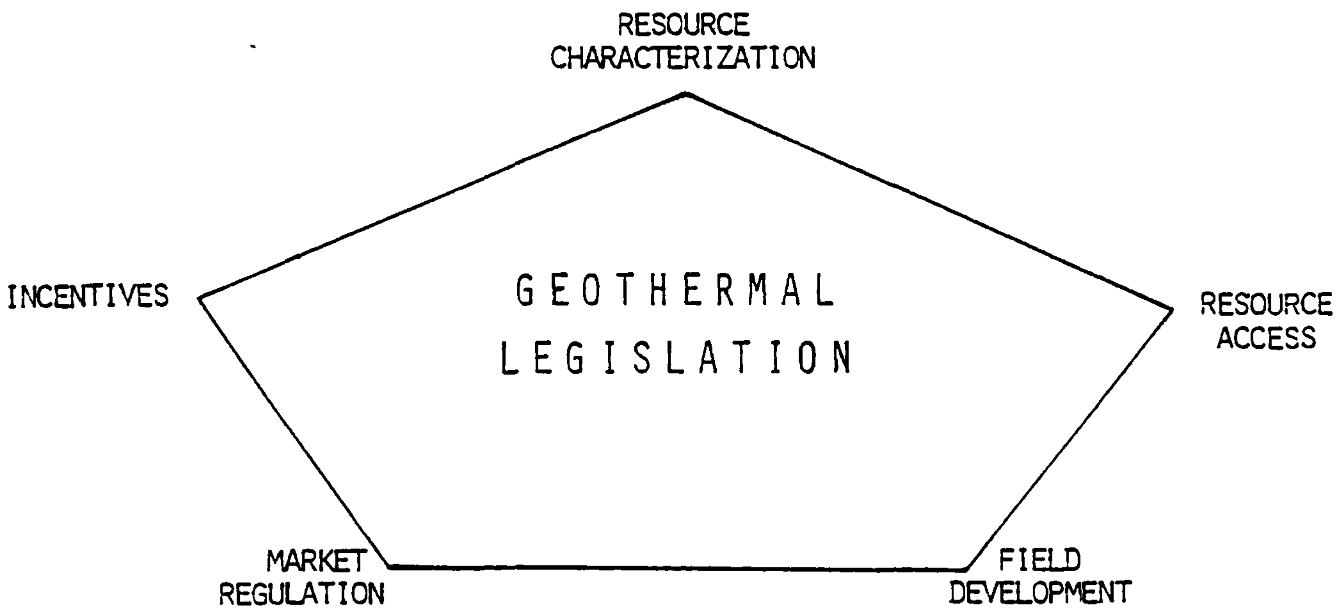
ISSUES IN GEOTHERMAL LEGISLATION



GEOTHERMAL POLICY PROJECT
NATIONAL CONFERENCE OF STATE LEGISLATURES
1405 CURTIS STREET, SUITE 2300
DENVER, COLORADO 80202

JULY 1978

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ISSUES IN GEOTHERMAL LEGISLATION

INTRODUCTION

Geothermal resources have significant potential as an alternative energy source. High-temperature geothermal fields can be tapped for electrical generation, while lower-temperature reservoirs find their utility in various "direct use" applications: industrial process heat, space heating and cooling, greenhousing, crop drying, food processing, aquaculture, snow removal, balneology. The United States is the current leader in electrical generation but trails other countries in direct use of the resource. In both cases, only a small fraction of the geothermal potential is being realized.

Geothermal resources are especially attractive because development promises to be less environmentally damaging than exploitation of fossil and nuclear fuels. In addition, some geothermal fields may comprise "income" energy sources--that is, virtually inexhaustible or potentially renewable. These advantages, plus the extent of the resource, present a unique opportunity for future energy development. And, since geothermal exploitation is in preliminary or initial stages, the scope for policymaking remains great.

A clear understanding of the nature of geothermal development is the first requirement for effective legislation. Geothermal resources have distinctive characteristics which should be recognized in state laws and regulations. Regulatory experience with other resources is an important reference, but may be misleading when applied to geothermal development. Indeed, current state and federal geothermal policies are often criticized for excessive reliance on oil and gas or water law precedents.

NATURE OF THE RESOURCE

Geothermal resources are a complex mix of elements. Natural heat from the earth's interior is the central energy component--but fluids, dissolved minerals and gases, and pressure also may be resource constituents. Geothermal systems occur in a variety of geologic settings, including hydrothermal and geopressured reservoirs, hot dry rock and magma chambers. Only hydrothermal systems (vapor or fluid dominated) are presently in production. Development of hot dry rock, magma chambers and geopressured reservoirs awaits further technological advances to insure economic viability.

The commercial value of geothermal systems is dependent on numerous factors. Most important are reservoir temperature, size and depth, fluid quality and quantity, associated resource constituents and access to geothermal markets.

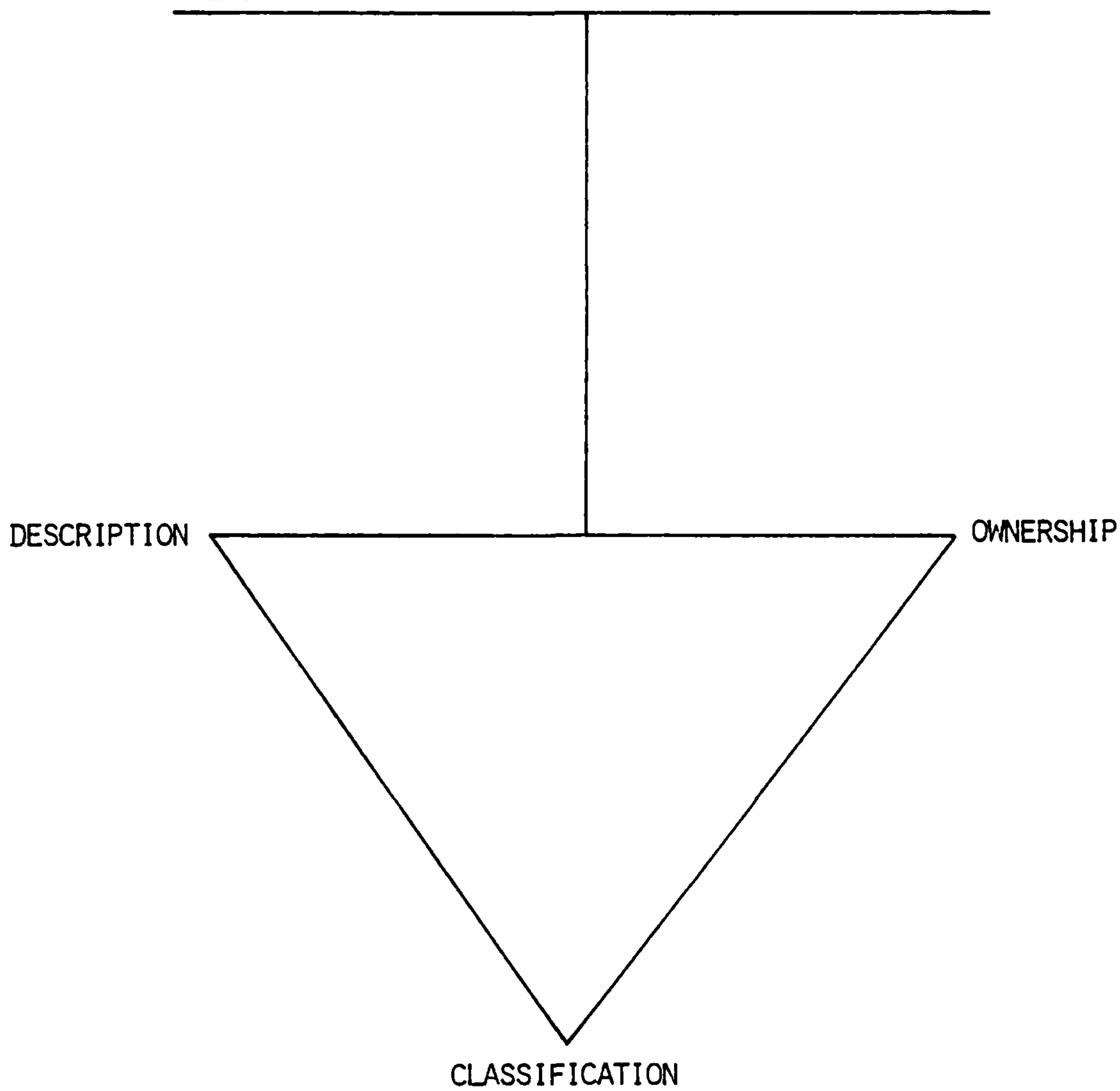
The location of a geothermal reservoir is a vital factor affecting its commercial potential. Heat energy (enthalpy) cannot readily be stored or transported over long distances. The wide market enjoyed by fossil and nuclear fuel producers, therefore, is not available to geothermal suppliers. Geothermal operations are tied to local buyers who can utilize a specific resource (temperature, flow rate, salinity, etc.) near the producing field. Recovery of resource constituents ("by-products") may enhance the value of geothermal prospects.

STATE POLICIES

Geothermal resources are a novel energy source of diverse character. Exploration, production, and marketing pose unique problems to a growing geothermal industry. State legislators also are faced with a major challenge. Resource characterization and determination of ownership rights, resource distribution, regulation of field development and production, facility siting and utility commission regulations, taxation, capital formation and market expansion all are subject to legislative initiative. For geothermal resources to supply their full potential, policies must be established in these areas providing prompt access and secure rights to the resource, efficient regulatory procedures, equitable tax treatment, investment incentives and a substantial market.

The remainder of this paper describes potential legislative actions to encourage the efficient development of geothermal resources. For each area, policy objectives and legislative options are outlined. The issues presented are generic in nature, and the range of options may not be suitable for every state.

RESOURCE CHARACTERIZATION



RESOURCE CHARACTERIZATION

Geothermal resources are similar in some respects to water, minerals and gas. As a result, considerable disagreement--including litigation--has arisen over the essential nature of the resource and corresponding ownership rights. This climate of uncertainty impedes geothermal development and makes resource characterization a major issue. As long as the nature of geothermal resources remains unclear, ownership also will be uncertain. As a result, geothermal entrepreneurs face the difficult task of negotiating with all possible lessors for access rights. Legislative concerns include the definition of resource elements, designation of ownership rights and the relationship of geothermal resources to other resource categories, especially water.

OBJECTIVE: IDENTIFICATION OF THE GEOTHERMAL RESOURCE AND ITS CONSTITUENTS

This is a matter of statutory definition. The definition identifies just what resource is subject to geothermal legislation and serves as an important reference for the courts in resolving disputes and as a model for private contracts.

Issue: Does the definition adequately identify geothermal systems and elements?

Options: A broad, general definition may be adopted. Alternatively, characteristics of the various resource forms (hydrothermal, geopressured, etc.) may be specified. Subsurface heat energy, a transfer medium and associated byproducts are essential elements of the geothermal resource. Pressure is another possible component. Minimum temperature and depth levels may be employed for greater specificity. Byproducts may be described generally or listed--many states exclude hydrocarbons and helium.

OBJECTIVE: DETERMINATION OF THE LEGAL STATUS OF GEOTHERMAL RESOURCES

Determination of the legal relationship of geothermal resources to established resource categories and the corresponding application of existing law--including implications for ownership--often have been left to the judiciary. However, a legislative assignment has several advantages. Unlike courts, legislatures are not precedent bound, nor are they limited to the factual dispute at hand. Rather, they may examine a wide range of facts and make decisions on the basis of public policy.

Issue: How should geothermal resources be classified?

Options: Geothermal resources have generally been classified, if at all, as water, mineral or *sui generis* (unique). Constituents (heat, fluid or vapor. dissolved minerals and gases, pressure) may perhaps be classified individually.

Issue: What is the legal relationship between geothermal fluids and groundwater?

Options: Geothermal fluids may be considered groundwater and regulated accordingly. However, existing water allocation procedures--especially in the water short western states--may impose considerable constraints on development. To minimize the problem, requirements for water rights may be limited to consumptive use (fluid not reinjected, additional cooling water). Also, geothermal appropriations might be "perfectable" as "developed" water--not ordinarily part of the general supply.

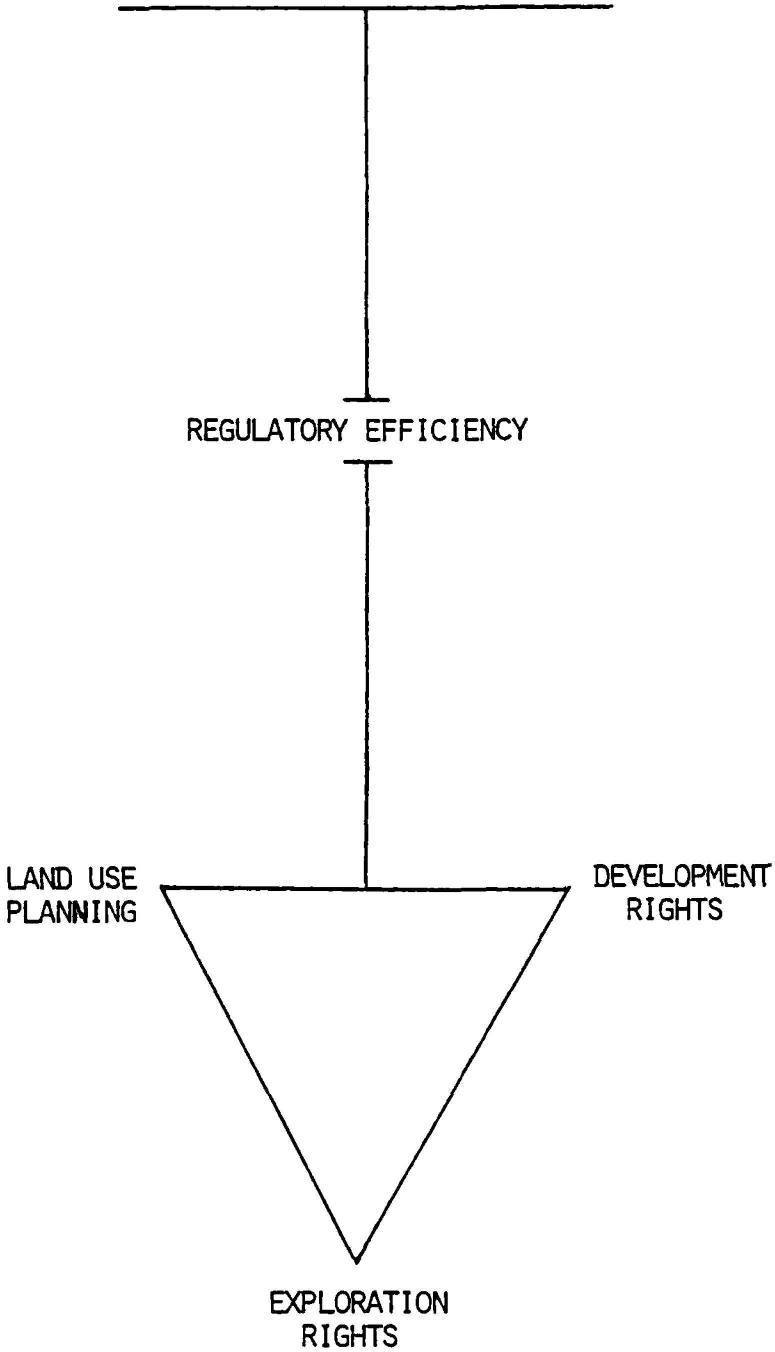
Geothermal fluids may be distinguished from groundwater in at least two ways. A distinction may be drawn according to the depth and/or temperature of the producing horizon. Alternatively, a "use" definition may be adopted, whereby fluids withdrawn for their heat content are designated geothermal--not water--resources. A conflict between geothermal and water rights may arise under this approach, requiring a determination of their relative status. Superiority might be assigned according to temporal priority or to a scale of preferred ("beneficial") uses.

Finally, geothermal fluid production may be exempted from water laws unless interference with groundwater aquifers is indicated. Such an exemption can be designated a "rebuttable presumption" so that the initial burden of proof does not fall on geothermal developers. This would recognize that geothermal reservoirs are probably most often distinct from groundwater aquifers.

Issue: Has geothermal ownership been clarified?

Options: Classification of geothermal resources may determine ownership as well. Mineral rights are usually in subsurface estates, while water rights are usually in surface estates. In the western states, water rights, especially to groundwater, may be in the public domain. Legislative manipulation of these rights can produce various mixes of public and private ownership: as water (public domain) a state could claim all geothermal resources; as water (surface estate) a state would possess all geothermal resources underlying state lands; as mineral (subsurface estate) a state would own all geothermal resources where it possesses the mineral estate, including those under state lands and those under private lands where the state retains a mineral reservation. A *sui generis* designation could be assigned to any of these estates.

RESOURCE ACCESS



RESOURCE ACCESS

Access for exploration and development is a fundamental requirement for geothermal legislation. The access system influences the rate of exploration and development, protects public and private interests and controls fragmentation and monopolization of the resource. Many regimes are possible, but it is vital that the process chosen be streamlined and efficient, with coordination of access procedures for state, federal and private lands. As a first step, it would be helpful to identify land available for geothermal development.

OBJECTIVE: LAND USE PLANNING FOR GEOTHERMAL DEVELOPMENT

Some lands may be deemed unsuitable for geothermal development due to environmental, social, economic, or other reasons. It is important to delineate available lands so that entrepreneurs can concentrate their exploration efforts in the appropriate areas. The planning mechanism for these decisions should not impose a barrier to development through excessive delay in review periods.

Issue: How should geothermal areas be delineated?

Options: Land use and zoning plans should address potential geothermal development. Local agencies can prepare a geothermal element to a general plan, and areas unsuitable for development may be withdrawn from entry. KGRA (Known Geothermal Resource Area) designations may be employed for land categorization, according to various criteria: presence of a producing well, geology, well data and competitive interest.

Issue: Does an adequate land use planning mechanism exist?

Options: Determination of the respective roles of state and local planning agencies is required. Local control over small facility siting, especially for direct use, may be desirable. On the statewide level, designation of a lead agency or creation of an inter-agency task force are streamlining options. Adequate funding and administrative expertise are necessary, and appropriations for resource assessment may be worthwhile.

OBJECTIVE: DISTRIBUTION OF ENTRY AND DEVELOPMENT RIGHTS

Distribution of exploration and development rights through permits, patents, leases or appropriation is the basic task in this area. In order to stimulate development, costly delays, burdensome requirements and overlapping jurisdictions must be minimized at all stages of the distribution process.

Issue: How should entry rights for resource exploration be granted?

Options: Entry rights should correspond to the ownership regime in effect and the type of land (state/private, KGRA/non-KGRA) in question. For geothermal "public domain" resources, access to both state and private lands would need to be addressed. For geothermal "surface" resources, access to state lands would be necessary. For geothermal "mineral" resources, access to state mineral estate (public) and mineral reservation (private) lands would be required.

Leases may be issued for exploration purposes, particularly when the lands are in a KGRA. Leasing provides security for discovery investments but may reduce ease of access due to review requirements. An alternative system might employ exploration permits, possible as an exclusive right.

Ease of access can be influenced by minimizing environmental and other agency review processes at the exploration phase. If permits are used, security for investments can be provided through conversion privileges (preferential rights to a lease) or by allowing exploration expenditures to be credited against lease bids. Permit duration, rentals, work commitments and surface use stipulations are additional concerns.

Issue: What mode of resource access should be adopted?

Options: Three models are familiar options for resource distribution on public lands: patents (hard rock minerals), appropriation (water) and leases (oil and gas, coal, common minerals). Patents commit surface and resource ownership to developers; leasing and appropriation provide for surface occupation and production rights while retaining surface and resource ownership in public hands.

Issue: How would a patent system work?

Options: After obtaining entry rights and locating a commercially viable geothermal resource, explorers would be entitled to apply for a patent. Some state constitutions or enabling acts may prohibit disposition of state lands at less than full market value. Environmental review might be appropriate before granting a patent.

Issue: How would an appropriation system work?

Options: After gaining entry, entrepreneurs would be authorized to divert (appropriate) a specific quantity of discovered geothermal resources, probably in conjunction with a surface occupation license. The quantity authorized would be related to the intended use of the resource. Environmental review would probably occur prior to actual production.

Issue: How would a leasing system work?

Options: Convertible exploration permits would lead to non-competitive leasing for the subject lands. A more flexible approach is possible with other types of entry rights. For instance, a "two-tier" leasing system could be employed, whereby lands with high geothermal potential (KGRA) are leased competitively (by bid) and other areas are leased non-competitively (by application). Possible bidding factors include cash bonuses, royalties or profit shares, rentals and work commitments. Environmental review might be required prior to lease issuance.

Lease terms should balance public and private interests in the resource. Public interests include fair return of resource value, efficient production and protection of surface lands. Private interests include security of tenure, flexibility in development and profitability. Relevant terms address lease duration, renewal, rentals, bonding, stipulations (work commitments, environmental conditions, covenants for surface restoration), royalties or profit shares and renegotiation.

Issue: Does the access regime address fragmentation and monopolization of the resource?

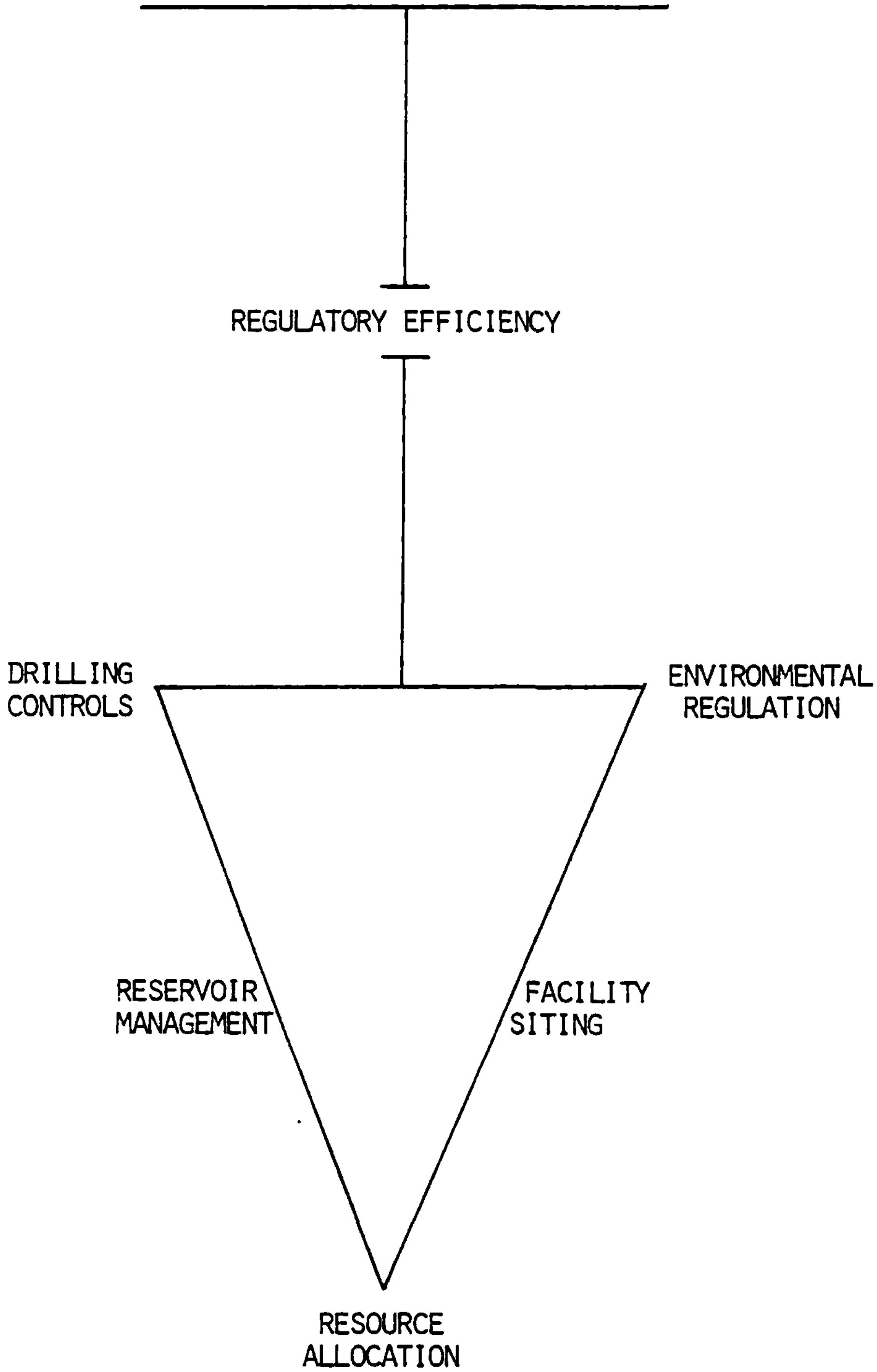
Options: Many states have adopted acreage limitations. Minimum acreages are set for individual parcels, while maximum acreages are applied to both individual and total holdings. Maximum number of parcels or number of townships occupied are other options for limiting total holdings.

Acreage limits should correspond to the needs of geothermal development. Minimum acreages that are too high may inhibit small-scale projects, while maximum acreages that are too low may impede exploration and prevent developers from securing their investments in a reservoir.

Issue: Is the access regime a streamlined process?

Options: This is an important area for policy initiatives and is essentially a cost-free method of stimulating development. Burdensome requirements should be minimized. For instance, environmental review should correspond to the level of activity in question. Overlapping jurisdictions can be dealt with by allowing single reviews, permits and bonds to satisfy multiple jurisdictions and by designating lead agencies. Costly delays can be reduced by specifying time periods for agency review processes.

FIELD DEVELOPMENT



REGULATION OF FIELD DEVELOPMENT

Regulation of field development can generally be achieved through existing regulatory mechanisms, with specific geothermal modifications as required. Drilling controls, reservoir management and allocation of production rights, facility siting and environmental regulation are areas of concern. Of prime importance is the institution of a streamlined regulatory effort. Coordination of state and federal efforts is an important avenue to be pursued.

OBJECTIVE: ADOPTION OF GEOTHERMAL DRILLING CONTROLS

Most states have relied on their oil and gas agencies to regulate geothermal drilling. Prevention of groundwater contamination (faulty drilling may establish pathways between previously isolated aquifers) is of central concern. Blowouts are a potential problem with high-temperature/pressure geothermal wells.

Issue: What drilling controls should be authorized?

Options: Information on geothermal drilling will assist in the institution of controls. Legislatures may mandate that well logs be maintained and made available to the appropriate agency. Information on temperature gradients and bottom-hole temperatures also will aid resource assessment.

States should authorize the responsible agency to require appropriate drilling practices. Special attention is usually paid to reinjection and well abandonment. Blowout prevention equipment (BOPE) and adequate well casing are other regulatory concerns. Stringent controls appropriate for deep, high-temperature wells may be unnecessary for shallow, low-temperature wells.

OBJECTIVE: RESERVOIR MANAGEMENT AND ALLOCATION OF PRODUCTION RIGHTS

Geothermal fluids are "migratory" or "fugitive" in nature, similar to oil and gas or groundwater. Withdrawal at one site may reduce production potential at other sites on the same reservoir. Therefore, when a reservoir is shared by competing developers, allocation of production rights may be required to avoid a wasteful race to produce the resource.

Various reservoir management techniques and allocative schemes have evolved to control overdrilling and inefficient withdrawal of petroleum and water. These also may be adapted to geothermal production; however, the unique aspects of geothermal development should be observed when promulgating such regulations.

Issue: What reservoir management techniques should be authorized?

Options: A well-spacing plan is the most common method of governing withdrawal rates on a reservoir. Pooling of tracts is usually employed as well to avoid inequities to small parcel owners who might otherwise be prevented from drilling. Other measures also may be necessary, such as production restrictions and unitized operations (voluntary or mandatory). Geothermal unit development, however, raises anti-trust questions, and the quantitative allocation of reservoir heat content is a difficult task.

Issue: How should production rights be apportioned among competitive interests?

Options: Existing models of resource allocation in petroleum and groundwater reservoirs include "rule of capture," "reasonable use," "correlative rights" and "appropriation." Efficient resource management will be difficult where state, federal and private leases exist in the same reservoir, unless allocative methods are integrated.

The rule of capture is essentially non-allocative: whatever can be reduced to possession becomes the property of the producer. The resulting race to "capture" the resource can have detrimental effects (mining) on reservoir performance. Production restrictions or unit operations can mitigate this problem.

The doctrine of reasonable use, whereby production is unlimited for the benefit of the drilling parcel, also could result in mining of the resource. Reasonable use prohibits transportation of fluids off the drilling parcel if the common supply would suffer. This prohibition on transport could be a serious impediment to geothermal marketing. Unitization or production restrictions might again be necessary to avoid reservoir deterioration.

Correlative rights to a resource are assigned on a pro rata basis, while seeking to keep total withdrawal within reservoir capacity. This would require information on reservoir characteristics. The allocation of enthalpy would be of particular concern under this approach.

The appropriation doctrine would grant exclusive rights to a specific quantity of geothermal fluid, defined by "beneficial use" (volume marketed) and accorded a temporal priority. Subsequent operations would be licensed only if prior rights were unimpaired. Under existing laws, not all states would recognize energy production as a beneficial use of water (geothermal fluid).

OBJECTIVE: ESTABLISHMENT OF FACILITY SITING PROCEDURES

Facility siting is bound up with land use and environmental issues. Regulatory efficiency is again the prime concern. Long lead-times for permitting energy facilities will seriously delay return on geothermal investments.

Issue: Do appropriate facility siting procedures exist?

Options: States may incorporate geothermal facility siting under existing statewide procedures. Lead agency designation or creation of an inter-agency task force are streamlining options. Alternatively, since local utilization of geothermal energy is necessary, county or municipal level agencies may be best suited to perform the review functions.

These approaches may be mixed according to the type of facility in question. For instance, is the facility for electric generation or heat transmission? If electric, is its capacity over a certain megawattage? If direct use, are associated pipelines over a certain diameter and length? Under any approach, attention should be paid to eliminating redundant permitting and bonding requirements and to avoiding costly delays.

OBJECTIVE: INSTITUTION OF APPROPRIATE ENVIRONMENTAL REGULATION

While geothermal development promises to be comparatively harmless to the environment, certain specific hazards should be addressed. Construction and drilling entail surface disturbance which may create erosion problems, destroy habitat and impair aesthetic values. Air pollution, water pollution (surface and groundwater), noise pollution, solid waste disposal and subsidence/seismicity effects also should be examined. Impact review prior to development and regulation of actual operations are two modes of environmental management. A streamlined process is imperative.

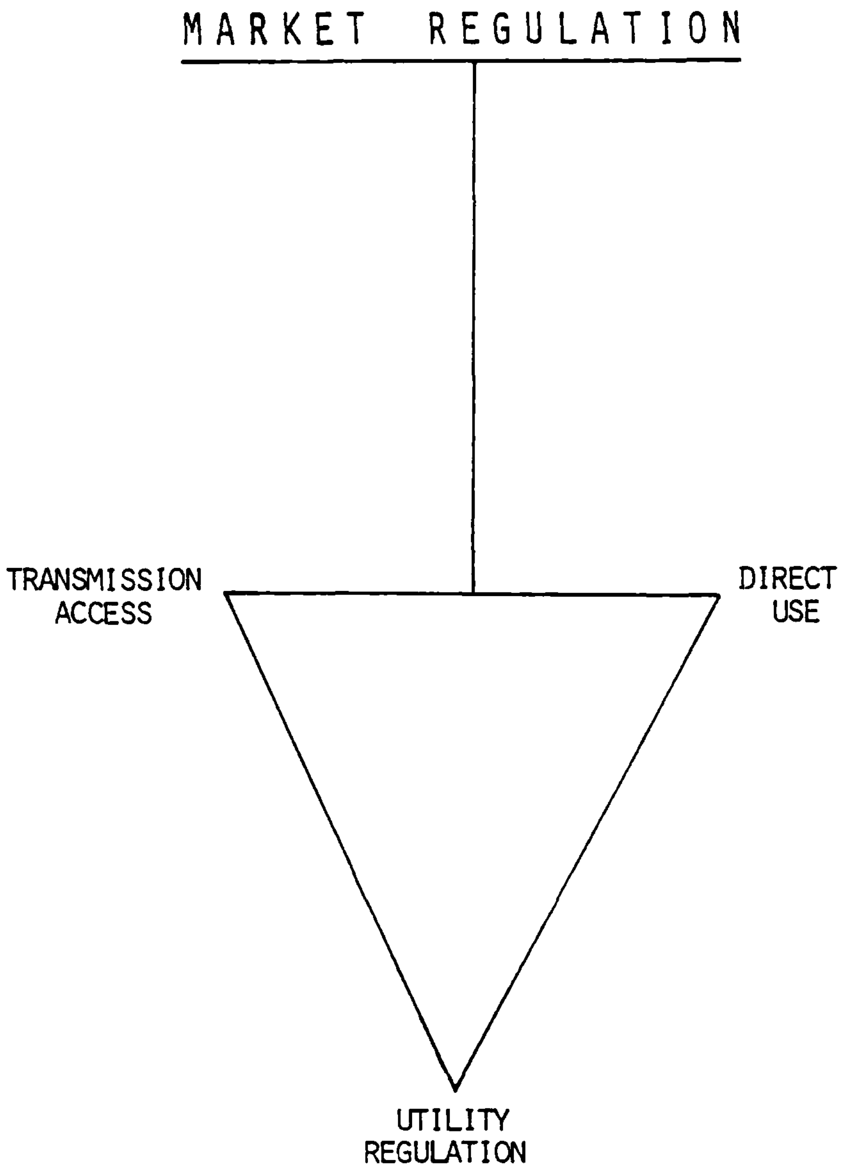
Issue: When is impact review applicable to geothermal development?

Options: Many states have enacted "little NEPA's" which require environmental impact review of proposed state actions (lease or permit issuance, facility siting license). Formal review prior to a commitment to commercial production may be a hindrance to development. The scope of review at this stage may be limited to exploration impacts. Acquisition of baseline data during the exploration phase, however, may expedite later full impact review and subsequent permitting for operation. Generally, a lead agency will prepare impact review documents, with participation from other involved agencies and private parties. Streamlining options include limits on agency review periods, public participation and judicial appeals.

Issue: How should geothermal operations be regulated?

Options: Licensing of equipment, environmental bonds and lease stipulations, monitoring requirements and waste discharge permits are various approaches to environmental regulation. Pollution standards (emission or ambient) may be required as part of a federally approved or managed system under the various national pollution statutes. Reinjection is generally seen as the answer to brine disposal, although groundwater protection must be addressed.

A lead agency approach would be particularly valuable to coordinate regulatory activities regarding air, water, noise, solid waste and subsidence/seismicity. Permits and bonds applicable to multiple jurisdictions would help make environmental regulation more simple and less time consuming.


MARKET REGULATION
TRANSMISSION ACCESS
DIRECT USE
UTILITY REGULATION

MARKET REGULATION

The availability of geothermal markets will ultimately determine the pace of development. Many legislative initiatives are available to clarify the geothermal market situation. Of major importance are utility regulatory issues, such as access to transmission systems and rate regulation. Novel market structures for direct use of geothermal resources should be considered as well.

OBJECTIVE: CLARIFICATION OF THE GEOTHERMAL-UTILITY INTERFACE

Utilities, traditionally conservative institutions, may be reluctant to participate in geothermal development due to its novelty and inherent uncertainty. If geothermal developers themselves generate electricity, questions arise concerning access to existing transmission systems and rate regulation of electrical sales. Investor-owned utilities may be reluctant to interconnect with non-utility or publicly-owned geothermal projects--especially if the power is to be delivered (wheeled) to other than the utility's own customers. Private geothermal generation facilities may not offer an adequate return on investment if electrical sales are rate regulated by utility commissions.

Issue: How can geothermal transmission access be provided?

Options: States can mandate utilities to interconnect with and wheel geothermal electricity, as long as the geothermal developer is willing to bear the cost of extra facilities, and system reliability is preserved. Designation of transmission systems as "common carriers" (available to all electrical producers at equitable prices) is another approach. The utility provisions of the National Energy Act (under Congressional consideration) may grant jurisdiction in this area to the Federal Energy Regulatory Commission (FERC).

<u>Issue: Should geothermal electrical sales be rate regulated?</u>

<u>Options</u>: State may exempt small power producers from utility-style rate regulation if electricity is merely marketed to existing utilities for resale or is used by industries at the production site. Negotiation with the FERC may be necessary since wholesale of electricity is subject to federal jurisdiction. (FERC has not, however, exercised its jurisdiction over cogeneration plants selling excess power to utilities in the Pacific Northwest.) The National Energy Act may authorize the FERC to exempt small power producers (especially from alternative energy sources) from utility regulation.

<u>OBJECTIVE: CONSIDERATION OF DIRECT USE MARKET STRUCTURES</u>

The utility status of geo-heat facilities should be decided, and transmission access is again an issue. Heating district formation is an avenue which should be examined. The scope for legislative innovation is great in this area due to the limited development of geothermal direct use to date.

<u>Issue: Should geo-heat distribution be rate regulated?</u>

<u>Options</u>: To encourage the development of alternative energy sources such as

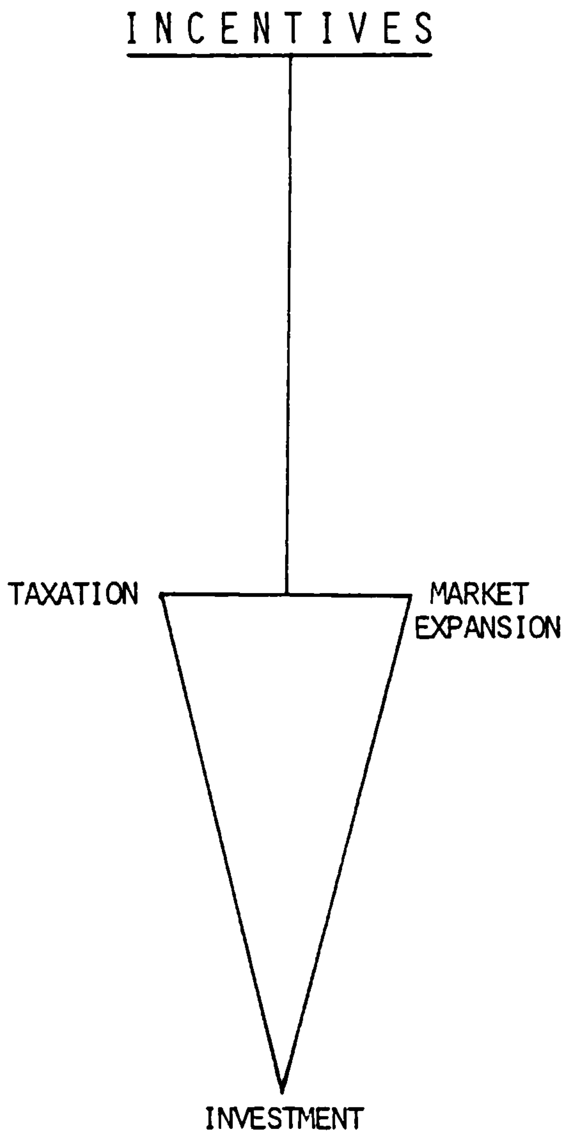
geothermal, exemption from utility-style rate regulation may be a worthwhile option. This would allow geo-heat to find its natural competitive position with respect to other heating methods.

Issue: How can transmission access for geo-heat be provided?

Options: Electrical transmission corridors may be the logical choice for geo-heat distribution. Legislative easements for pipelines would guarantee access to such corriders. Eminent domain authority for geo-heat distributors also may be necessary in order to complete transmission systems.

Issue: What market structures will facilitate direct use of geo-heat?

Options: Zoning for geothermal operations (industrial parks, etc.) is a valuable tool for stimulating development. Heating district formation is another promising avenue. Existing special districts may have their charters expanded or special geothermal districts created. Easements, power of eminent domain, bond authority and power to levy special assessment taxes are relevant to district heating.


INCENTIVES
TAXATION
MARKET EXPANSION
INVESTMENT

INCENTIVES

Resolution of the issues raised in the previous sections would constitute a potent incentive to geothermal development. There are, however, additional factors within the purview of state legislatures. Geothermal resources must compete in an artificially priced and subsidized energy market. Moreover, the uncertainty surrounding such a novel resource inhibits capital formation and market development. Policymakers should consider measures to equalize the competitive position of geothermal resources and stimulate market development.

OBJECTIVE: EQUALIZATION OF THE COMPETITIVE POSITION OF GEOTHERMAL RESOURCES

Producers of most energy fuels are accorded various tax benefits. The extension of comparable benefits to geothermal resources should be considered. Early institution of tax benefits will avoid the need for major adjustments in the flow of tax dollars at a later date.

Issue: How can equitable tax treatment of geothermal development be achieved?

Options: Deferral of *ad valorem* assessment until commercial production begins (or substitution of a well-head tax) is an important property tax option. Otherwise geothermal producers face a significant tax burden during the long years of field and market development. Exemption from property taxes (or a refund) on non-productive tracts may be another worthwhile option.

In the income tax area, depletion allowances and deductions for current (exploration/development) expenses can be extended to geothermal operations as with other energy fuels. Investment tax credits are a further possibility to encourage development.

Finally, various gross-receipts, excise, severance, conservation and franchise taxes may be applicable to geothermal development. To facilitate investment decisions, the application (or exemption) and levels of such taxes should be defined.

OBJECTIVE: STIMULATION OF GEOTHERMAL INVESTMENT AND MARKET DEVELOPMENT

Uncertainties and delays in development may make utilities and other investors reluctant to commit capital to the geothermal industry. Due to its novel character, public acceptance of geothermal energy may be slow to develop. Private investment in geothermal equipment may appear non-competitive with other energy systems unless life-cycle costing is performed, or tax benefits are available. Various policy options are available to ameliorate this situation.

Issue: How can investments for geothermal development be increased?

Options: A geothermal loan guarantee program has been established on the federal level. Securities Commission rulings that geothermal investment is "sound" or "prudent" could open the way for institutional participation. Public funding for exploration, resource assessment and demonstration projects may be considered.

Utility investments in geothermal development may be encouraged by allowing costs to be expensed (as for research and development costs), included in the rate base (even if the field or facility fails) or allowed a higher rate of return. States may require utilities to purchase geothermal power if the cost is reasonable.

Issue: How can the geothermal market be expanded?

Options: Public acceptance can be influenced through education, funding of demonstration projects (such as geo-heating state buildings) and offering tax benefits. Examples of the latter include property tax exemptions for geothermal improvements and income tax credits or deductions for investments in geothermal equipment, whether retrofitted or original. The availability of risk insurance on field longevity and facility performance may influence potential customers. Life-cycle cost analysis for energy systems in new or renovated state buildings also may be mandated, so that geothermal heating or cooling is adopted whenever it proves economically competitive.

CONCLUSION

Geothermal reserves are a major new energy resource, representing a secure domestic supply with relatively minor environmental dangers. Innovative state legislation can provide a substantial impetus to geothermal development. While comprehensive policymaking would focus on all the outlined areas, a step-by-step approach would still be valuable. In any case, new policies should be monitored and revised as necessary to insure effectiveness in operation.

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SHALLOW WELL COST REVIEW

IDAHO OFFICE OF ENERGY

John V. Evans, Governor

Prepared for the United States Department of Energy, Division of Geothermal Energy

SHALLOW WELL COST REVIEW

October, 1980

By

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Office of the Governor
Governor John V. Evans

Prepared for the United States Department of Energy,
Region X Office; Seattle, WA

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SHALLOW WELL COST REVIEW

Introduction

In a paper delivered to the annual meeting of the Geothermal Resources Council in September of 1979 Robert Chappell of the Idaho Falls office of the Department of Energy did a statistical analysis of deep well costs and suggested two things: 1) that cost variation with depth is different for shallow wells and, 2) that the importance of shallow well costs to direct use of geothermal energy makes such a study important.

This study of shallow well costs attempts to follow up on both suggestions by assembling data from various sources for wells under 5000 feet deep, by statistically describing that assemblage of data, and by comparing the analytical result with other available sources of data on well costs.

Data Base

Data on well costs was assembled from a variety of people thought to have access to such information. All usable data on past well costs is included in TABLE I. Excluded from TABLE I was disaggregated drilling bid data which did not seem comparable to the aggregate cost data most readily available from already-drilled wells.

Some of the data in TABLE I was available in a form which made it possible to detail casing costs, logging cost, mobilization costs, etc. Some of the data was available only in aggregate form, with no breakdown of individual cost items. Rather than provide an incomplete and mismatched comparison of individual cost items for each well it was decided to concentrate on aggregate well costs. These total costs include drilling, casing, and logging.

Data presented in TABLE I is for 18 different wells, 3 of which were temperature gradient holes, 1 of which was a bid for a well presently being drilled, and 2 were for injection wells. Only the Newcastle, Sturm #1, Bluffdale, Cascade, and Roystone wells were privately-funded drilling efforts. The remainder, the obvious majority, were funded under various DOE direct-use demonstration projects and PON programs.

We are well aware, and were reminded by each of our several data sources, that there is no such thing as an "average" well, that we must expect terrific variance, even in the cost associated with wells of the same depth in the same area.

TABLE I
TOTAL WELL COSTS

	DESCRIPTION	YEAR DRILLED	WELL HEAD TEMPERATURE (°F)	DEPTH (FEET)	CASING DIAMETER (INCHES)/DEPTH (FEET)	ORIGINAL COST ($1000s)	INFLATION FACTOR	COST (1980) (1000s)	COST/FT.
1	Sturm #1 Occidental Fremont Cnty, Idaho	1979	----	4000'	10 3/4" to 4000' gradient	$ 395	1.14	$ 450	$112.50
2	Raft River #1 Idaho	1975	281°	5007'	13 3/8" to 3624'	$ 910	1.92	$ 1747	$350.00
3	Raft River #4A Idaho	1977	248°	2840'	13 3/8" to 1820' injection	$ 330	1.48	$ 488	$172.00
4	Raft River #5 Idaho	1978	265°	4925'	----	$1,200	1.30	$ 1560	$317.00
5	Raft River #6 Idaho	1978	155°	3888'	13 3/8" to 1698'	$ 325	1.30	$ 423	$109.00
6	Raft River #7 Idaho	1978	165°	3858'	13 3/8" to 2044' injection	$ 275	1.30	$ 358	$ 93.00
7	Utah Roses #1 Utah	1979	120°	5009'	8 5/8" to 2322' 6" liner to 3860'	$ 386	1.14	$ 440	$ 88.00
8	Warm Springs Hospital #1 Montana	1979	160°	1498'	12½" to 900' 8 5/8" to 1498'	$ 186	1.14	$ 212	$142.00
9	Madison County HTW 1, Idaho	1979	65°	1259'	6" to 440' 1½" to 1195' gradient	$ 95	1.14	$ 108	$ 86.00
10	Madison County HTW 2, Idaho	1979	74°	1534'	6 5/8" to 516' 1½" to 1531' gradient	$ 63	1.14	$ 72	$ 47.00
11	Haakon County School District South Dakota	1979	157°	4266'	10 3/4" to 1000' 9 5/8" to 3800' 5" to 3900'	$ 317	1.14	$ 361	$ 85.00
12	Monroe City MC3, Utah	1979	165°	1500'	16" to 690' 7 5/8" to 1313' slotted 7 5/8" open to 1500'	$ 245	1.14	$ 279	$186.00
13	St. Mary Hosp. #1, South Dakota	1979	106°	2176'	10 3/4" to 800' 7" to 2176'	$ 320	1.14	$ 365	$168.00
14	Madison County Idaho	1980	----	5000' (bid)	----	$ 540	----	$ 540	$108.00
15	Roystone Idaho	1980	160°	500'	12" uncased	$ 21	----	$ 21	$ 42.00
16	Cascade Idaho	1980	----	1135'	8" hole cased to 720'	$ 15	----	$ 15	$ 13.00
17	Newcastle Utah	1979	215°	502'	----	$19.75	1.14	$22.50	$ 45.00
18	Bluffdale Utah	1979	198°	410'	12' to 87' 8" to 190' 6" to 410'	$25.84	1.14	$29.50	$ 72.00

While remaining aware of the difficulties involved in analyzing data with such a degree of possible variability we are even more aware of the need to come to grips with how best to estimate well costs. Estimation of such costs is a job which must be done, so publishing and analyzing as much data as possible is a necessary step in improving such techniques. Broadening the available data base has got to be a first step in improving our knowledge of the actual dimensions and range of drilling costs.

In addition to the inherent variability of drilling cost presented by the underlying geology we have inflation as a factor to be reckoned with in estimating drilling cost. To compare wells drilled in different years we must have some way to adjust for cost differences which result from mere changes in the overall price level.

The level of disaggregation of our data did not permit satisfactory construction of our own weighted index for price change. We do know that drilling costs have been rising faster than the overall inflation rate and we have seen, in Chappell's paper, that his inflation correction factor closely matched that calculated in the Oil and Gas Journal each year. To simplify matters, then, we have borrowed the 14% per year inflation rate calculated from the Oil and Gas Journal's annual survey of drilling and completion costs. That 14% per year figure has been used to adjust upward the cost of wells drilled prior to 1980. The inflation factor is $(1+i)^n$, where i = the interest rate expressed as a decimal and n = the number of years between the date of drilling and 1980.

Year	Inflation Factor
1979	1.14
1978	1.30
1977	1.48
1976	1.69
1975	1.92

Well costs adjusted for inflation to 1980 values are found in the extreme right column of TABLE I. Those inflation-adjusted figures were used in all further cost analysis exploring the relationship between well cost and drilling depth.

Range of Well Cost Data

The 18 wells numbered in TABLE I had an actual average cost per foot of depth of $152 in 1980 dollars. This overall average is considerably upward biased by the presence of wells #2 and #4, each with costs over one and one half million dollars.

Without these two high cost wells the average cost per foot of depth of the remaining 16 wells is $106. The eight shallow wells (numbers 8,9,10,12,15,16,17,18) are all 1500 feet or under and their average cost is but $91 per foot. Without the four very cheap wells (number 15-18) the average for all the remainder is $158 per foot. The average cost for the four very cheapest wells (Number 15-18) is only $34 per foot of depth. The twelve wells left after elimination of the 2 very expensive (numbers 2 and 4) and the 4 very cheap (Numbers 15-18) have an average cost of $112 per foot. The two most expensive wells have an average cost of $333 per foot.

The range of values for different combinations of wells shows great variability, with the most expensive wells at an average cost just over twice the average for all wells and the least expensive wells averaging about 30% of the average for all wells. For individual wells the costs ranged from $13 per foot to $349 per foot with the mean cost at about $123 per foot. This variability means problems for anyone interested in estimating well costs.

Relationship of Well Cost to Depth

While for limited purposes the average cost per foot of depth may be useful, for purposes of prediction a more complete specification of the nature of the relationship between well cost and depth is in order. To specify this relationship we have used a linear regression model with straight-line, expotential, and power functions which can be statistically fitted to the 18 sets of well cost and depth data.

These functions specify the mathematical relationship between well cost and depth and enable us to predict well cost values for certain depths. After fitting the data to the three types of functions we have calculated the coefficient of determination, a term which describes the closeness of the relationship between well cost and depth. High coefficients (those close to 1.00) indicate a close correlation between well cost and depth as defined by each function type. Calculation of a t-statistic was done in each case to test whether the relationship found to exist could have been due to chance. In all regression equations tested the correlation coefficients were significant at the 95% confidence interval.

Table II presents a comparison of well costs for 1000 foot intervals of depth from 1000 to 5000 feet, estimated from various well cost equations. Footnotes to Table II detail the exact form of the estimating equations used and the sources from which they were taken. The APL series of estimates and both the X series of estimates seem very much out of the range of the others, being especially low at the 4000 and 5000 foot depths. Even for the others there is a substantial range of variation shown for particular depths.

TABLE II

WELL COST ESTIMATES COMPARED

Depth	NMEI[1]	APL[2]	Battelle[3]	O.I.T.[4]	X[5]	EG&G[6]	EG&G[7]	IOE-A[8]	IOE-B[9]	IOE-C[10]
1000	50,350	62,820	148,000	150,000	399,100ig 249,400sed	90,000	88,806hd 130,916sft	58,112	142,017	66,887
2000	148,717	121,834	296,000	225,000	462,400 262,600	240,000	250,488 268,262	118,423	322,729	190,054
3000	280,223	189,999	444,000	311,000	568,700 284,600	365,310	459,431 408,144	241,325	503,440	350,089
4000	439,259	202,695	592,000	470,000	715,600 315,400	477,000	706,527 549,699	491,781	684,152	540,023
5000	622,505	358,613	740,772	750,000	905,500 355,000	633,250	986,520 692,512	1002,166	864,864	755,824

[1] Well cost equation, $1.033957 \times \text{depth}^{1.5625}$, from New Mexico Energy Institute's BTHERM model.

[2] Well cost equation, $dx^4 + cx^3 + bx^2 + ax$, where $d = -4.17 \times 10^{-11}$, $c = 1.00 \times 10^{-6}$, $b = -3.83 \times 10^{-3}$, $a = 28.0$, from Johns Hopkins Applied Physics Lab, escalated to 1980 dollars from 1976 at their suggested rate of 25.8%.

[3] $100 per foot estimated in 1977, escalated to 1980 at 14% per year, from Battell Northwest study.

[4] Rough estimates derived from graph on page 3-21 in Direct Utilization of Geothermal Energy - A Technical Handbook GRC Special Report No. 7.

[5] Two equations, one for igneous rock, $.378 + .0211\ \text{depth}^2$, and one for sedimentary rock, $.245 + .0044\ \text{depth}^2$, from October, 1979 DOE contract ET-78-S-02-4713A001, author unknown.

[6] $90 per foot for 1000, $120 per foot for 2000, then depth $(189.35 - .0375\ [\text{depth}] + 4.994 \times 10^{-6}\ [\text{depth}]^2$, from Geothermal Space Heating Cost Simulation Model notes.

[7] Two equations, one for hard rock, cost $= 2.887(\text{depth})^{1.496}$, and one for soft rock, cost $= 102.8\ (\text{depth})^{1.035}$, derived from 32 geothermal wells and escalated to 1980 base.

[8] Idaho Energy Office estimated exponential curve, cost $= 28517(e)^{.0007\ \text{depth}}$. Coefficient of determination = .861.

[9] Idaho Energy Office estimated linear regression, cost $= -38695 + 181(\text{depth})$. Coefficient of determination = .680.

[10] Idaho Energy Office estimated power curve, cost $= 2.02(\text{depth})^{1.5066}$. Coefficient of determination = .895.

TABLE III

ESTIMATED AVERAGE COST PER FOOT FOR VARIOUS DEPTHS

Depth	NMEI	APL	Battelle	O.I.T.	X	EG&G[6]	EG&G[7]	IOE-A	IOE-B	IOE-C
1000	50	62	148	150	399	90	89 131	58	142	67
2000	74	61	148	113	231 131	120	125 134	59	161	95
3000	93	63	148	106	284 94	122	153 136	80	168	117
4000	110	51	148	117	179 79	119	177 137	123	171	135
5000	124	72	148	150	181 71	127	197 138	200	172	151
Overall Average	90	62	148	127	255 125	116	148 135	104	163	113

NOTE: Sources and estimating equations are same as in Table II.

The IOE-A estimate, the exponential curve, had a high coefficient of determination but was itself an outlier from the rest in that it was very low at 1000 feet and then very high at 5000 feet. The IOE-B estimate started high and remained uniformly high compared to the others. Also, it had a very low (.680) coefficient of determination. For both these reasons it was decided to recalculate all forms of the IOE estimate based on 16 rather than 18 wells. Wells number 2 and 4 had extremely high costs relative to the other wells and for that reason were deemed atypical.

Table III presents average cost figures estimated from the cost equations in Table II. Averages have been computed for costs at 1000 feet intervals to a depth of 5000 feet. This allows comparison of costs per foot for various depth intervals as well as calculation of an overall average cost per foot for a 5000 foot well using each of the various estimating equations.

Recalculation of the three forms of the IOE equations based on 16 wells resulted in uniformly high coefficients of determination for all three equations and gave predicted costs for the range of depths which seemed more commensurate with the other estimates. Table IV details the comparison between the two sets of IOE equations, one based on all 18 wells and the other based on just 16 wells. The new estimating equations and coefficients of determination are found in the footnotes. Table IV also includes one non-linear equation estimated in the form, $y=a_0+a_1x+a_2x^2$. This equation, dubbed IOE-D[16], had a very high coefficient of determination but as is obvious from the estimates at 1000 foot intervals, the increments added to cost with depth are decreasing. This counter-intuitive conclusion led to rejection of the non-linear form of estimating equation. Table V was constructed to test Chappel's hypothesis that cost variation with depth is different for shallow wells. In this case comparison of estimating equations is done between those for all wells under 5000 feet, shown in Table IV and those 8 wells under 1500 feet, shown in Table V. The coefficients of determination for the very shallow well estimating equations are all below .78, while those for all wells are all above .82 indicating a nicer fit of the data with the regression line as more data points and thus more deep holes are considered. Considering the coefficients of the equations themselves there seems to be considerable difference between the very shallow holes and the entire sample of holes up to 5000 feet. This is corroborated when any two of the equations are graphed for comparison. For the very shallow holes costs rise much faster than for all holes. There appear to be two distinct relationships. Extrapolation of the very shallow curve to depths beyond 1500 feet appears unwarranted since the very steep slope of this line leads quickly to considerable overestimate of actual drilling costs.

TABLE IV

IOE WELL COST ESTIMATES COMPARED

DEPTH	IOE-A[18]	IOE-A[16]	IOE-B[18]	IOE-B[16]	IOE-C[18]	IOE-C[16]	IOE-D[16]
1,000	58,112	59,825	142,017	110,775	66,877	66,261	104,892
2,000	118,423	114,280	322,729	213,945	190,054	170,325	262,992
3,000	241,325	218,300	503,440	317,115	350,089	295,884	374,492
4,000	491,781	417,002	684,152	420,286	540,025	437,819	439,392
5,000	1,002,164	796,568	864,864	523,456	755,824	593,322	457,692

IOE-A[18], IOE-B[18], IOE-C[18], have the same form indicated in footnote to Table II.

IOE-A[16], exponential curve, cost = $31319(e)^{.00647\,(\text{depth})}$
Coefficient of determination = .819.

IOE-B[16], linear regression, cost = 7604 + 103(depth).
Coefficient of determination = .891.

IOE-C[16], power curve, cost = $5.43\,(\text{depth})^{1.3620}$
Coefficient of determination = .887.

IOE-D[16], non-linear, cost = $-99808 + 228(\text{depth}) - .233(\text{depth})^2$.
Coefficient of determination = .846.

TABLE V

IOE WELL COST ESTIMATES FOR VERY SHALLOW WELLS

(less then 1500 feet)

DEPTH	IOE-B[8]	IOE-A[8]	IOE-C[8]
500	17,588	22,085	24,018
1000	88,853	52,049	62,976
1500	160,118	122,668	110,678
	r = .704	r = .754	r = .707

IOE-A[8], exponential curve, cost = $9371(e)^{.00171\,(depth)}$

IOE-B[8], linear regression, cost = -53677 + 143 (depth)

IOE-C[8], power curve, cost = $.707\,(depth)^{4.2375}$

We feel it unwise to use the very shallow hole equations since they appear to lead to considerable underestimation at very shallow depths and overestimation in the more normal range of drilling for direct uses in our area.

Figure 2 compares the three IOE equations specified in previous tables with the equation Chappell derived in his 1979 study. What is most interesting about the graphical comparison is that the equation most favored in previous discussion and defined in Table IV, IOE-B^{16} (based on all wells except the two high cost ones), just about parallels Chappell's line though on a lower plane. This seems to suggest that while the level of cost is indeed different for shallow versus deep holes the general relationship between cost and depth is remarkably similar, that is, the slopes of the functions are very nearly the same.

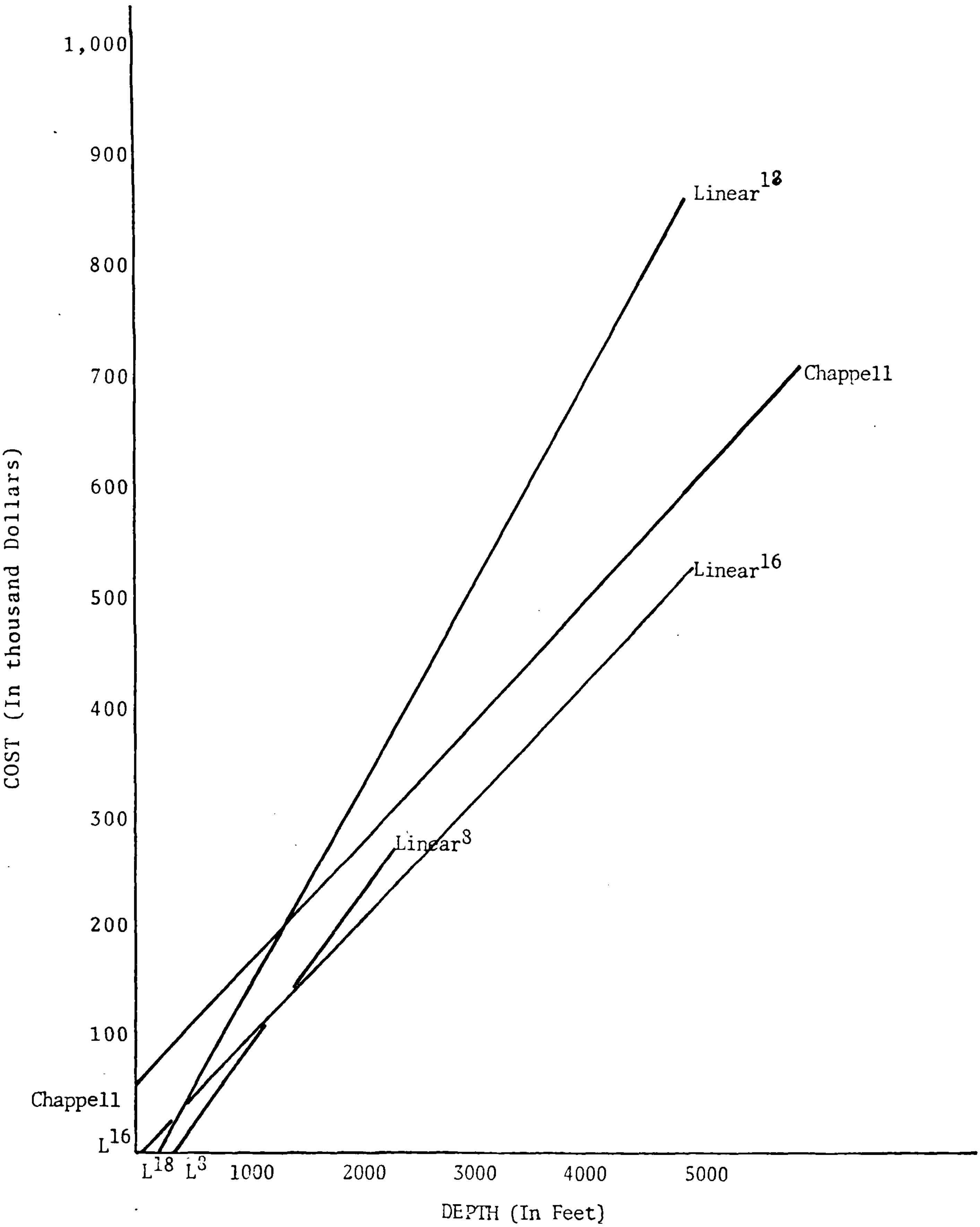
Conclusion

All the equations fitted to the available data seem to corroborate Chappell's suggestion: that cost variation with depth is different for shallow wells. However, not too much should be made of this conclusion since it is difficult to decide what should be the meaning of different. If different is restricted only to the relationship between cost and depth, then in the linear function (IOE-B^{16}) which was picked as most representative of the sample of wells used there is no appreciable difference from Chappell's work on deeper wells. Of course the average cost per foot is greater for deep wells, but the cost-depth relationship, the slope of the function, is pretty much the same.

The difference between shallow and deep wells in the cost-depth relationship is not so clear cut as to admit a simple and obvious conclusion. The real differences vary with the form of estimating equation used and the exact nature of the sample.

The real importance of this study is in providing an equation (or a variety of equations) which can be used to provide a preliminary estimate of well cost for shallow wells. IOE-B^{16} will be used extensively in the future by the Idaho Office of Energy in estimating well costs for direct-use geothermal applications in our area.

Figure 2


1,000
900
800
700
600
500
400
300
200
100
COST (In thousand Dollars)
Linear18
Chappell
Linear16
Linear8
Chappell
L16
L18
L3
1000
2000
3000
4000
5000
DEPTH (In Feet)

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INVERSION MODELING OF MULTIPLE GEOPHYSICAL DATA SETS FOR GEOTHERMAL EXPLORATION

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Introduction: Program Description and Objectives

A geothermal area is often characterized by the anomalous behavior of several geophysical parameters at depth, such as density, seismic velocity, electrical conductivity and porosity. The goal of an ideal exploration method is to determine all of the relevant subsurface parameters based on an integrated interpretation of several geophysical data sets measured at the earth's surface. As a step toward this goal, we have developed a joint geophysical data set inversion program based on generalized linear inverse theory. The program determines the three-dimensional subsurface structure from a multiple geophysical data set. This kind of a combined interpretation is an extremely cost-effective approach to geothermal exploration since it uses all data sets acquired and results in an earth model that will have the greatest impact on drilling strategy in a resource area.

To date we have applied the joint inversion method to seismic and gravity data from two geothermal areas: Yellowstone National Park, in a study supported by the University of Utah (Evoy, 1978); and the Imperial Valley, California, in a Department of Energy sponsored study (Savino, et al., 1977). The objectives of these studies were to determine the three-dimensional seismic velocity and density structures and identify the heat sources in each area. The specific data sets that were inverted are P wave travel-time residuals from teleseismic earthquakes recorded at a local seismic array and regional Bouguer-corrected gravity data. As evidenced from the final inversion models obtained for each of the study regions, both data sets are good indicators of the deep seated structural features associated with these geothermally active regions.

These initial applications were for delineation of relatively large scale subsurface (i.e., deep crust and upper mantle) features. This was dictated by the inherent resolving power of the particular data sets used; teleseismic P-wave travel times and regional gravity data. Our objective under the present project is to add to this existing three-dimensional modeling procedure the capability for including detailed surface and subsurface geologic information and higher resolution geophysical data sets, such as P-wave arrival times from local earthquakes. This approach will be tested using seismic and gravity data sets from Roosevelt Hot Springs, Utah and Leach Hot Springs, Nevada.

Inversion Method

Our joint or simultaneous inversion method is an application of the generalized linear inverse theory of Backus and Gilbert (1970), Wiggins (1972) and Jordan (1973). The method finds the simplest three-dimensional velocity-density model giving an acceptable fit to a combined set of observed P-wave residuals and gravity data. The uniqueness and accuracy of this optimal model are determined in terms of its standard error and spatial resolution at each point in the structure. In its treatment of the P-wave residual data, our inversion method is similar to that of Aki, et al. (1977). We have combined this method with a gravity inversion procedure to improve its effectiveness.

In linear inversion, the inverse problem is reduced to a system of simultaneous linear equations relating a vector of observed data to a vector of model parameters. In our problem, the data include gravity values from a grid of surface stations and travel-time residuals from either teleseismic or locally occurring events recorded by an array of seismograph stations.

The model parameters describe the velocity and density structure beneath the seismic and gravity arrays. We model the subsurface structure as a three-dimensional grid of homogeneous rectangular blocks extending to a maximum depth of about 50 to 300 km, depending upon whether we are using travel-times from local earthquakes or teleseismic events, respectively. The gravity data depend on the block densities, and these are the model parameters solved for directly in the inversion. The velocities of the blocks, on which the travel times depend, are determined implicitly through an assumed velocity-density relationship.

The processed gravity data and teleseismic residuals do not depend on the absolute values of density (ρ) and velocity (α), but only on their departure from a laterally uniform structure: $\Delta\rho$ and $\Delta\alpha$. We assume α and ρ obey Birch's law, implying $\Delta\alpha = c\Delta\rho$, where the c is prescribed. This relationship is used to determine the indirect dependence of travel-time residuals on density. It also determines a final velocity model from the density model found by the inversion.

An optimal solution to the inverse problem is a linear estimator having the form of a generalized inverse matrix operating on the observed data vector. The inverse matrix is chosen such that the final density model, and the corresponding velocity model, are the smoothest models giving an acceptance fit to both the gravity and travel-time data. We measure smoothness in terms of the lateral gradients in velocity and density, so that lateral variations on a scale of less than 50 km are restricted from the model unless they are required to fit the data.

Results to Date

Accomplishments to date under this project include the development of forward modeling theory and algorithms for inversion of travel time information from local earthquakes and the acquisition and processing of seismic and gravity data from the two test regions, in particular Roosevelt Hot Springs. Using geometrical ray theory a relationship was established among the P wave arrival time at a seismic station from a locally occurring earthquake, the origin time and location of the earthquake and the P-wave velocity distribution within the earth. Of particular importance was the development of a technique for separating the dependence of network arrival times on velocity structure from the dependence on earthquake location parameters. This technique offers two big advantages over the simultaneous inversion for velocity and location. First, one does not need to deal at any one time with as large an inverse problem or with a large parameter vector containing dissimilar items. Second, one can separately study the resolution and variance of the velocity model independently of the event locations.

Considerable effort was spent in acquiring and processing the seismic and gravity data sets prior to inversion. We have calculated theoretical reduced travel time curves for events (i.e., 163 earthquakes in the Roosevelt Hot Springs-Cove Fort area) at different focal depths and have generated a preliminary three-dimensional block sampling pattern for the model region. These two steps are required for definition of an optimal three-dimensional inversion grid.

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Appendix 1

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/Yr)
Group 10				
1. Copper Concentrate - 1021				
Drying	250*	(121)	1.7	(1.6)
Group 12				
2. Bituminous Coal - 1211				
Drying (including lignite)	150-250*	(66-104)	18.0	(19.0)
Group 14				
3. Potash - 1474				
Drying Filter Cake	250*	(121)	1.03	(1.09)
Group 20 - Food & Kindred Products				
4. Meat Packing - 2011				
Sausages and Prepared Meats - 2013				
Scalding, Carcass Wash and Cleanup	140	(60)	43.7	(46.1)
Edible Rendering	200	(93)	0.52	(0.55)
Smoking/Cooking	155	(68)	1.16	(1.22)
5. Poultry Dressing - 2016				
Scalding	140	(60)	3.16	(3.33)
6. Natural Cheese - 2022				
Pasteurization	170	(77)	1.28	(1.35)
Starter Vat	135	(57)	0.02	(0.02)
Make Vat	105	(41)	0.47	(0.50)
Finish Vat	100	(38)	0.02	(0.02)
Whey Condensing	160-200	(71-93)	10.2	(10.8)
Process Cheese Blending	165	(74)	0.07	(0.07)
7. Condensed and Evaporated Milk - 2023				
Stabilization	200-212	(93-100)	2.93	(3.09)
Evaporation	160	(71)	5.20	(5.48)
Sterilization	250	(121)	0.54	(0.57)
8. Fluid Milk - 2026				
Pasteurization	162-170	(72-77)	1.44	(1.52)

Appendix 1 (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10¹² BTU/Yr	(10¹² KJ/YR)
9. Canned Specialties - 2032				
Beans				
Precook (Blanch)	180-212	(82-100)	0.40	(0.42)
Simmer Blend	170-212	(77-100)	0.24	(0.25)
Sauce Heating	190	(88)	0.20	(0.21)
Processing	250	(121)	0.38	(0.40)
10. Canned Fruits and Vegetables - 2033				
Blanching/Peeling	180-212	(82-100)	1.88	(1.98)
Pasteurization	200	(93)	0.15	(0.16)
Brine Syrup Heating	200	(93)	1.02	(1.08)
Commercial Sterilization	212-250	(100-121)	1.67	(1.76)
Sauce Concentration	212	(100)	0.44	(0.46)
11. Dehydrated Fruits and Vegetables - 2034				
Fruit & Vegetable Drying	165-185	(74-85)	5.84	(6.16)
Potatoes				
Peeling	212	(100)	0.33	(0.35)
Precook	160	(71)	0.47	(0.50)
Cook	212	(100)	0.47	(0.50)
12. Frozen Fruits and Vegetables - 2037				
Citrus Juice Concentration	190	(88)	1.33	(1.40)
Juice Pasteurization	200	(93)	0.27	(0.28)
Blanching	180-212	(82-100)	2.26	(2.38)
Cooking	170-212	(77-100)	1.41	(1.49)
13. Wet Corn Milling - 2046				
Starch Dryer	120*	(49)	3.03	(3.20)
Steepwater Heater	120	(49)	0.77	(0.81)
Sugar Hydrolysis	270	(132)	1.89	(1.99)
Sugar Evaporator	250	(121)	2.74	(2.89)
Sugar Dryer	120*	(49)	0.16	(0.17)
14. Prepared Feeds - 2048				
Pellet Conditioning	180-190	(82-88)	2.28	(2.40)
15. Bread and Baked Goods - 2051				
Proofing	100	(38)	0.84	(0.89)

Appendix 1 (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12} BTU/Yr	(10^{12} KJ/YR)
16. Cane Sugar - 2062				
Mingler	125-165	(52-74)	0.59	(0.62)
Melter	185-195	(85-91)	3.30	(3.48)
Defecation	160-185	(71-85)	0.44	(0.46)
Granulator	110-130	(43-54)	0.44	(0.46)
Evaporator	265	(129)	26.39	(27.84)
17. Beet Sugar - 2063				
Extraction	140-185	(60-85)	4.63	(4.88)
Thin Juice Heating	185	(85)	3.08	(3.25)
Thin Syrup Heating	212	(100)	6.68	(7.05)
Evaporation	270-280*	(132-138)	30.8	(32.5)
Granulator	150-200	(66-93)	0.15	(0.16)
Pulp Dryer	230-280*	(110-138)	16.5	(17.4)
18. Soybean Oil Mills - 2075				
Bean Drying	160	(71)	4.05	(4.27)
Toaster Desolventizer	215	(102)	6.08	(6.41)
Meal Dryer	300*	(149)	4.36	(4.60)
Evaporator	225	(107)	1.62	(1.71)
Stripper	212	(100)	0.30	(0.32)
19. Shortening & Cooking Oil - 2079				
Oil Heater	160-180	(71-82)	0.72	(0.76)
Wash Water	160-180	(71-82)	0.12	(0.13)
Dryer Preheat	200-270	(93-132)	0.60	(0.63)
Cooking Oil Reheat	200	(93)	0.32	(0.34)
Hydrogenation Preheat	300	(149)	0.37	(0.39)
20. Malt Beverages - 2082				
Cooker	212	(100)	1.53	(1.61)
Water Heater	180	(82)	0.53	(0.56)
Mash Tub	170	(77)	0.60	(0.63)
Grain Dryer	300*	(149)	9.18	(9.68)
Brew Kettle	212	(100)	3.98	(4.20)
21. Distilled Liquor - 2085				
Cooking (Whiskey)	212	(100)	3.16	(3.33)
Cooking (Spirits)	320	(160)	6.27	(6.61)
Evaporation	250-290*	(121-143)	2.32	(2.45)
Dryer (Grain)	300	(149)	1.94	(2.05)
Distillation	230-250	(110-121)	7.69	(8.11)

Appendix 1 (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
22. Soft Drinks - 2086				
Bulk Container Washing	170	(77)	0.21	(0.22)
Returnable Bottle Washing	170	(77)	1.27	(1.34)
Nonreturnable Bottle Warming	75-85	(24-29)	0.43	(0.45)
Can Warming	75-85	(24-29)	0.52	(0.55)
Group 21 - Tobacco				
23. Cigarettes - 2111				
Drying	220*	(104)	0.43	(0.45)
Rehumidification	220*	(104)	0.43	(0.45)
24. Tobacco Stemming & Redrying - 2141				
Drying	220*	(104)	0.50	(0.26)
Group 22 - Textile Mill Products				
25. Finishing Plants, Cotton - 2261				
Washing	200	(100)	15.4	(16.2)
Dyeing	200	(100)	4.5	(4.7)
Drying	275	(135)	22.2	(23.4)
26. Finishing Plants, Synthetic - 2262				
Washing	200	(93)	35.9	(37.9)
Dyeing	212	(100)	15.2	
Drying & Heat Setting	<275	(135)	23.2	(24.5)
Group 24 - Lumber				
27. Sawmills & Planing Mills - 2421				
Kiln Drying of Lumber	200*	(100)	63.4	(66.9)
28. Plywood - 2435				
Plywood Drying	250	(121)	50.6	(53.4)
29. Veneer - 2436				
Veneer Drying	212	(100)	57.8	(61.0)

Appendix 1 (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12} BTU/Yr	(10^{12} KJ/YR)
Group 25 - Furniture				
30. Wooden Furniture - 2511				
Makeup Air & Ventilation	70	(21)	5.7	(6.0)
Kiln Dryer & Drying Oven	150	(66)	3.8	(4.0)
31. Upholstered Furniture - 2512				
Makeup Air & Ventilation	70	(21)	1.4	(1.5)
Kiln Dryer & Drying Oven	150	(66)	0.9	(0.9)
Group 26 - Paper				
32. Pulp Mills - 2611				
Paper Mills - 2621				
Paperboard Mills - 2631				
Building Paper - 2661				
Pulp Refining	150	(66)	175	(185)
Black Liquor Treatment	280	(138)	164	(173)
Pulp & Paper Drying	290	(143)	383	(404)
Group 28 - Chemical				
33. Cyclic Intermediates - 2865				
Styrene	250-300	(121-149)	35.0	(37.0)
Phenol	250	(121)	0.45	(0.47)
34. Alumina - 28195				
Digesting, Drying, Heating	280	(138)	113.2	(119.4)
35. Plastic Materials & Resins - 2821				
Polystyrene, suspension process				
Polymerizer Preheat	200-215	(93-102)	0.102	(0.107)
Heating Wash Water	190-200	(88-93)	0.067	(0.068)
36. Synthetic Rubber - 2822				
Cold SBR Latex Crumb				
Bulk Storage	80-100	(27-38)	0.179	(0.189)
Emulsification	80-100	(27-38)	0.086	(0.091)
Blowdown Vessels	130-145	(54-63)	0.865	(0.912)
Monomer Recovery by Flashing & Stripping	120-140	(49-60)	4.095	(4.319)

(continued on next page)

Appendix 1 (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12} BTU/Yr	(10^{12} KJ/YR)
36. Synthetic Rubber - 2822 (continued)				
Dryer Air Temperature	150-200	(66-93)	3.663	(3.864)
Cold SBR, Oil-Carbon Black Masterbatch				
Dryer Air Temperature	150-200	(66-93)	0.506	(0.534)
Oil Emulsion Holding Tank	80-100	(27-38)	0.090	(0.095)
Cold SBR, Oil Masterbatch				
Dryer Air Temperature	150-200	(66-93)	1.09	(1.15)
Oil Emulsion Holding Tank	80-100	(27-38)	0.090	(0.095)
37. Cellulosic Man-made Fibers - 2823				
Acrylic	<250	(<121)	23.5	(24.8)
38. Noncellulosic Fibers - 2824				
Rayon	<212	(<100)	37.8	(39.9)
Acetate	<212	(<100)	37.6	(39.7)
39. Pharmaceutical Preparations - 2834				
Autoclaving & Cleanup	250	(121)	18.85	(19.88)
Tablet & Dry-Capsule Drying	250	(121)	1.00	(1.05)
Wet Capsule Formation	150	(66)	0.05	(0.05)
40. Soaps & Detergents - 2841				
Soaps				
Various Processes in Soap Manufacture	160	(82)	0.50	(0.53)
Detergents				
Various Low-Temperature Processes	160	(82)	0.36	(0.38)
41. Organic Chemicals, N.E.C. - 2869				
Ethanol	200-250	(93-121)	6.0	(6.0)
Isopropanol	200-300	(93-149)	11.0	(12.0)
Cumene	250	(121)	1.0	(1.0)
Vinyl Chloride Monomer	250-300	(121-149)	9.0	(9.0)
42. Urea - 2873215				
Low-Pressure Steam-Heated Stripper	290	(143)	0.89	(0.94)

Appendix 1 (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
43. Explosives - 2892				
Dope (Inert Ingredients)				
Drying	300	(149)	0.006	(0.006)
Wax Melting	200	(93)	0.118	(0.12)
Nitric Acid Concentrator	250	(121)	0.070	(0.07)
Sulfuric Acid Concentrator	200	(93)	0.027	(0.02)
Nitric Acid Plant	200	(93)	0.223	(0.23)
Blasting Cap Manufacture	200	(93)	0.016	(0.01)
Group 29 -- Petroleum				
44. Petroleum Regining - 2911				
Alkylation	45-300	(7-149)	59	(62)
Butadiene	250-300	(121-149)	60	(63)
45. Paving Mixtures - 2951				
Aggregate Drying	275-300*	(135-149)	88.1	(92.9)
Group 30 - Rubber				
46. Tires & Inner Tubes - 3011				
Vulcanization	250-300	(121-149)	6.16	(6.52)
Group 31 - Leather				
47. Leather Tanning & Finishing - 3111				
Bating	90	(32)	0.094	(0.099)
Chrome Tanning	85-130	(29-54)	0.060	(0.063)
Retan, Dyeing, Fat Liquor	120-140	(49-60)	0.15	(0.16)
Wash	120	(49)	0.034	(0.036)
Drying	110*	(43)	2.05	(2.16)
Finish Drying	110*	(43)	0.13	(0.14)
Group 32 - Stone, Clay, Glass & Concrete Products				
48. Hydraulic Cement - 3241				
Drying	275-300*	(135-149)	8.0	(8.0)
49. Concrete Block - 3271				
Low-Pressure Curing	165*	(74)	12.29	(12.96)

Appendix 1 (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12} BTU/Yr	(10^{12} KJ/YR)
50. Ready-Mix Concrete - 3273				
Hot Water for Mixing Concrete	120-190	(49-88)	0.34	(0.36)
51. Gypsum - 3275				
Wallboard Drying	300	(149)	11.18	(11.79)
52. Treated Minerals - 3295				
Kaolin				
Drying	230*	(110)	12.7	(13.4)
Expanded Perlite				
Drying	160*	(71)	0.22	(0.23)
Barium				
Drying	230*	(110)	0.34	(0.36)
Group 33 - Primary Metals				
53. Ferrous Castings				
Gray Iron Foundries - 3321				
Malleable Iron Foundries - 3322				
Steel Foundries - 3323				
Pickling	100-212	(38-100)	151	(160)
Group 34 - Fabricated Metal Products				
54. Galvanizing - 3479				
Cleaning, Pickling	130-190	(54-88)	0.011	(0.012)
Group 36 - Electrical Machinery				
55. Motor & Generators - 3621				
Drying & Preheat	150	(66)	0.043	(0.045)
Baking	300	(149)	0.133	(0.140)
Group 37 - Transportation Equipment				
56. Motor Vehicles - 3711				
Baking-Prime & Paint Ovens	250-300	(121-149)	0.29	(0.31)

Note: SIC Groups 34, 35, 36, 37 utilize hot water for parts degreasing and washing in application temperatures of 80-180°F (27-82°C); total process heat used is not currently available.

*No special temperature required; requirement is simply to evaporate water or to dry the material.

LEASING POLICY FOR GEOTHERMAL DEVELOPMENT

Submitted by

Leasing Policy Development Office
of the
U.S. Department of Energy

November 27, 1979

GEOTHERMAL DEVELOPMENT AND LEASING POLICY

Geothermal energy development is in its infancy. As such it is undergoing rapid change in technology, government and private participation, and public awareness and attitudes. Due to its economic and environmental advantages geothermal energy will be developed. Geothermal's contribution may be small but it is one of the few alternative energy sources that can make an important contribution in the next decade. Geothermal energy could produce as much as 5 percent of total national energy needs by the year 2000 and a much higher percentage of regional needs in some areas. It may provide 80 percent of Idaho's non-transportation energy needs, and energy importers like Nevada could become energy exporters. However, due to uncertainty and institutional barriers this development may well be slow. Government initiatives and policy may be able to accelerate development significantly.

The above considerations plus the fact that the majority of the known geothermal resource is under federal lands highlight the need for concerted Federal effort in meeting our responsibilities in the development of geothermal energy. The Leasing Policy Development Office of the Department of Energy (DOE) and other offices in the Federal Government have been and are now performing work related to the development of geothermal energy. It is essential that there be coordination between the activities of everyone with responsibilities in geothermal energy to avoid duplication and to create a climate in which geothermal energy can and will be developed.

Section 302(b) of the Department of Energy Organization Act (DOE Act) transferred to DOE authority under the Geothermal Steam Act of 1970 to promulgate regulations applicable to federal leases which would (1) foster competition; (2) implement alternative bidding systems; (3) establish diligence requirements; (4) set rates of production; and (5) specify the terms, procedures and conditions for the acquisition and disposition of federal royalty interests taken in kind. The DOE Act explicitly reserves to the Department of the Interior (DOI) responsibility for the issuance and supervision of Federal leases and for the enforcement of all regulations applicable to Federal mineral leasing. While DOI will continue the day-to-day administration of federal leases -- i.e., setting their terms and conditions and issuing the leases -- Section 303(c)(1) of the DOE Act grants the DOE authority to review all proposed leases prior to issuance by DOI and to either approve or disapprove the terms and conditions therein which relate to the regulatory authorities transferred to the DOE under Section 302(b) of the DOE Act.

If adopted, pending amendments to the Geothermal Steam Act will change the approach to geothermal leasing in several respects. For example, it has been proposed to amend the definition of a Known Geothermal Resources Area (KGRA) to employ a stricter standard for designation of lands as KGRAs. In addition, the proposed legislation anticipates enhanced diligence requirements and a series of time frames for processing leases and permits. In light of these pending amendments and their potential impact on our areas of statutory responsibility, DOE feels it would be premature to propose any regulations prior to final passage and, accordingly, does not anticipate doing so.

DOE is, however, actively involved in preparing geothermal production goals and in analyzing areas in which the promulgation of regulations would encourage geothermal exploration and development. In the course of preparing production goals for geothermal energy, with interim goals scheduled to be ready by Spring 1980, several review papers have been written covering the status of various aspects of geothermal development. These include:

1. Status of the geothermal resource and its development;
2. Current federal leasing system and a history of federal geothermal leasing;

3. Listing of possible constraints to geothermal energy development;
4. Review of regulatory, legal, and legislative aspects;
5. Investigation of available sources of information on geothermal and determination of other agencies and offices involved in geothermal energy; and
6. Initial review and inventory of geothermal rig availability and technology.

Two additional studies are underway, one concentrating on electric generation from geothermal energy, and the other gathering available resource data and supply information on ownership to supplement the information we now have and enable us to determine exactly what part of the resource is federally controlled. The second study will also review non-electric commercialization, critiquing and enhancing existing studies to obtain forecasts for direct use of geothermal energy. DOE anticipates that the research undertaken in the development of production goals will provide a foundation for future regulatory activity.

As stated earlier, it is unlikely that specific regulations applicable to geothermal development would be promulgated by DOE before the final legislation is enacted. There are certain areas, however, that are being studied and in which we anticipate the eventual promulgation of regulations.

One such area is the use of alternative bidding systems. DOE is evaluating bidding systems other than the cash bonus bidding system to determine whether one or more alternative system might be particularly appropriate for geothermal leasing in light of our goal to increase participation and ease entry into the geothermal field.

The definition of a KGRA contained in one of the legislative proposals would limit the designation of KGRAs to those areas on which there is substantial physical evidence that the resource could be used to generate electricity in commercial quantities, or to areas in which there is demonstrated competitive interest. With respect to the latter standard, DOE anticipates promulgating regulations that will define what criteria must be met to designate an area as a KGRA because of competitive interest. It is expected that a narrower standard will be applied than is now used. One definition that has been proposed would also limit to once the number of times that an area designated as a KGRA because of competitive interest may be offered for sale under competitive bidding procedures. If this competitive sale attracted no bids, the lease would be offered to the original first applicant. We believe that these changes will decrease the amount of time required to obtain a lease and, in that respect, will encourage a more rapid development of geothermal resources.

In the area of diligence requirements, DOE believes a strict standard is needed to ensure that development actually takes place and that leases are not simply held indefinitely without any positive action being taken that would lead to production. There also exists the related problem of ensuring that, once production is reached, leases continue to produce at the maximum efficient rate. One approach that is being considered is to establish a diligence standard for the pre-production period and use a production rate requirement to ensure post-production diligence. DOE's flexibility in establishing a diligence standard is likely to be controlled by the pending legislative amendments. Hopefully, whatever diligence standard is mandated will provide sufficient flexibility for waiver of the requirements in appropriate cases.

Regulations providing authority for direct use of geothermal resources and setting an appropriate royalty rate are being considered and can be expected once the geothermal area is more fully developed.

The Department is very much interested in obtaining the views of those involved in the geothermal industry, as well as other interested parties, and toward that end we actively solicits comments, ideas and proposals on any of the areas related to the authorities transferred to DOE under the provisions of the DOE Act. In this regard the names, addresses, and telephone numbers of staff members of the Leasing Policy Development Office are provided below.

Diane Menefee - (202) 633-9437
John Broderick - (202) 633-8300
Dan Dick - (202) 633-9437

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