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# AHUACHAPAN GEOTHERMAL FIELD

# AFTER A YEAR OF OPERATION

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## SUMMARY

This work attempts to report the present conditions of some of the physical-chemical characteristics of the Ahuachapan geothermal field after a year of intensive operation; also presented are some hypotheses about the changes that are taking place in the production characteristics and in the chemical composition of the discharged fluids.

## 1. INTRODUCTION

The Ahuachapan geothermal field presently being worked covers an area of approximately 3 km2 and is found located to the west of El Salvador on the north limb of the quatenary volcanic range that crosses the whole country almost without interruption following the direction of the main graven. This graven is full of volcanic materials discharged by the quatenary volcanic centers.

The area being worked seems to be only one part of a more complex hydrothermal system that probably extends towards the East for a distance of about 10 kms. Currently exploratory drilling is being conducted with the purpose of investigating this area; temperatures greater than 200°C at 400 meters depth having been found.

The surface manifestations of the Ahuachapan hydrothermal system are characterized by having a fumarolic character in the limbs of the volcanic system, accompanied by extensive areas of hydrothermal alternation and springs of an acidic character, and in the areas below the volcanic mass by hot springs of a $Cl-HCO_3$ type, that drop off in T and salinity in a northerly direction; see Figure 1.

Presently 24 deep wells have been drilled in the area of which 11 are producers, 4 are reinjection and 9 exploratory with some type of production in some of them. The producing wells discharge a mixture of water-steam in proportions of 11 to 46%. The producing stratum that has been found has thicknesses up to 300 M, the maximum measured temperature is 239° C. The production rate is from 102 to 550 ton/hour of mix.

On the basis of the good results in the drill holes 2 units ~~with~~ at an average pressure of 5.5 with a generating capacity of 30 MW each, which are fed ~~with~~ through a steam separator from 9 holes with an average of 8.8 MW per hole, have been installed. The operation of the first unit began in June 1975 and the second in June of 1976. Presently the studies for the ~~implantation~~ INSTALLATION of the 3rd ~~programmed~~ generating unit ~~[illegible]~~ is ~~planned~~ ~~scheduled~~ for 1979 with a capacity of 35 MW.

In view of the need to study the conditions of the reservoir being worked, a programmed control of measurements and of fluid sampling has been established in order to detect and evaluate any changes in the physical-chemical conditions of the reservoir. This control basically consists of measurements of the pressure head, volume of water flow, volume of steam flow, input of fluid samples, measurements of production, and records of temperature and pressure.

The variations that have been detected have been:

-increase in total salinity
-decrese in the Na/K ratio
-decrease in hydrostatic levels
-variation in the production characteristics of some wells

All these variations have greater incidence in the major operation area.

Presently said changes are being evaluated in order to establish possible causes and effects.

## 2. GEOLOGICAL FEATURES

The geology of the Ahuachapan geothermal field has been widely studied. For the purposes of this work a vertical cut of the field has been worked in which it is possible to study the stratographic succession that basically consists of:

| | |
|---|---|
| -lavatic tuffaceous formation | |
| -young agglomerate | Quaternary |
| -Ahuachapan andesitic formation | |
| -old agglomerates | Tertiary |

### 2-1 Lavatic Tuffaceous Formation (Figure 2)

This basically is made up of two components (tuffaceous formation with lavatic intercalations). It does not have importance from the point of view of the internal reconstruction of the reservoir. It shows thicknesses up to 500 meters.

### 2-2 Young Agglomerate

It has thicknesses along the order thus of 200-400 M and is a quite impermeable volcanic formation, [illegible] by overlaying the Ahuachapan andesitic formation, serves as an effective seal for the reservoir.

### 2-3 Ahuachapan Andesitic Formation

A formation made up predominantly of wash with intercalations of tuffaceous materials. It constitutes the producing formation of the field. It is quite fractured although not uniformly, showing an increase in its secondary permeability in its contacts with the young agglomerates and with the deep substratum. The condition top of the roof of the andesitic formation is presented in the report prepared by Engineers Jimenez and Campos at this symposium.

### 2-4 Old agglomerate

This forms the base of the andesitic formation. It ~~will occasionally~~ usually contains intercalations of breccia and [illegible] lavas. In some holes this stratum shows certain secondary permeability.

## 3 Hydrogeologic Condition

On the basis of the studies in hydrology and geochemistry and with the verification of the results in the deep drill holes it was possible to confirm the existence of 3 main aquifers:

### 3-1 Shallow Aquifer

This is located ~~on~~ at the surface in recent geological formations made up of tuff, pumice and fluvials that lie on the wash of the Laguna Verde Volcanic Group. It is fed by surface percolation of meteoric water. The chemical composition of the waters of this aquifer show that they are predominantly carbonated, showing high concentrations of sulfates, when they are heated by underground steam.

### 3-2 Saturated Aquifer

This aquifer circulates in the ~~wash~~ lavas and pyroclastics that make up the lavatic tuffaceous formation and has a bed ~~the~~ highly impermeable young agglomerates. The water that circulates in this aquifer originates from the more or less deep infiltration of precipitation water. This aquifer feeds the domestic wells and gives certain thermality in some areas, produced by conduction by means of young agglomerates, showing having waters with high contents of calcium and sodium bicarbonates, or by mixing with the waters of the deep saline aquifer producing waters with a high content of sodium chloride and bicarbonates of Ca and Na.

### 3-3 Saline Aquifer

Located in the andesitic formation of Ahuachapan, it has an upper seal of the impermeable young agglomerate formation and as a base massive tertiary agglomerates. This aquifer circulates through the zones of secondary permeability which exist in the andesites.

Its actual expanse is to the South and West of the field, its boundaries on the South and East are not known with exactitude, but apparently it stretches in an easterly direction towards the Chipilapa region. The chemical characteristics are high salinity that basically consists of sodium, potassium, and calcium chlorides, accompanied by a wide variety of lesser constituents Li, Sr, Cs, Rb, I, Br, As, B.

The piezometric data and the geological characteristics suggest that the recharging zone of this aquifer is found in the volcanic groups located to the south of the field, where the craters facilitate the deep infiltration of water, that has been shown to be of a predominantly meteoric origin.

The natural outlet of this aquifer seems to be the series of springs located to the north of the field (El Salitre, La Ceiba, San Lorenzo) which show atomic ratios similar to those of this aquifer although the absolute concentrations are less than that of the water of the saturated aquifer. The massive extraction of fluids from this aquifer in the main part of the geothermal field area has produced a flow

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inversion, in the direction of the major working area, producing a dip in the piezometric level, this is accompanied by an invasion of water than tends to replace what has been extracted; the characteristics of this water seems to have the greatest heat content and saline content.

## CHEMISTRY OF THE FLUIDS

### 4-1 Generalities

The water discharged by the wells of the Ahuachapan geothermal field are characterized by being predominantly sodium chloride content, but also containing as major constituents potassium, silica, calcium, & boron. See table 1.

The material discharged at atmospheric as pressure has a slightly alkaline pH between 7.10 and 7.80 as found at the boiling point. The extension of the saline aquifer that feeds the producing wells of the area is presently undefined, with only two of its boundaries known to date: towards the West as indicated by the results of well Ah-15 which does not show salinity and the results of wells Ah-11 and Ah-12 to the north of the field which show a substantially reduced salinity. This rapid decrease in salinity in those directions clearly tells us the limits of the saline aquifer in that direction a fact that has been verified by the low permeability and temperatures in the area of said wells.

In the other directions where the extension of the high temperature aquifer cannot be determined we have a concentration effect in a S-SW direction as indicated in the map of the isocentration of chlorides (Figure 4).

Everything seems to indicate that the saline water of the aquifer being worked has a common source although the possibility of mixes with high temperature water of lower salinity cannot be excluded. To date a salinity gradient in a vertical direction has not been detected since there are nearby wells drilled at the same depth with different concentrations, but the existence of a horizontal concentration gradient in a S-SW direction is evident. The existence of this gradient tells us that the migration of fluids in the producing stratum is horizontal and that the wells with the highest concentrations (wells Ah-7, Ah-16) would be closer to the reservoir feed.

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Apparently the fall of the piezometric levels of the producing aquifer caused by the operation are causing a more rapid migration of the water with greatest salinity and temperature towards the center of the field. This fact is verified by the increment of concentrations that have been made in wells Ah-1, Ah-4, Ah-6 as well as by a decrease in the Na/K ratio in some wells (Figure 4).

The atomic ratios of Cl/B, Cl/As, Cl/F, Cl/Br, Cl/I also indicate that the saline water has a common source.

## 4-2 Na/K Ratio

This ratio, whose importance due to its dependence on temperature is well known, has in the fluid discharged by the Ahuachapan wells a range between 12.5 and 8.76 which corresponds to a temperature range between 222 and 274°C (White 1970) -- that differs in its upper limit with the maximum temperature measured at the reservoir which is 239°C in well Ah-22. We can contend that the Na/K ratio hasn't reached its balance in the area of the field where there are great differences between the T measured and the T calculated by the Na/K ratio; these differences can be observed in the following table in which the values for the maximum temperature measured and the temperature calculated by the Na/K ratio are reported:

| Well | Max T°C | T Na/K °C | Difference |
|---|---|---|---|
| Ah-1 | 232 | 255 | 23 |
| Ah-4 | 234 | 233 | -1 |
| Ah-5 | 230 | 222 | -8 |
| Ah-6 | 231 | 257 | 26 |
| Ah-7 | 230 | 274 | 44 |
| Ah-20 | 225 | 256 | 31 |
| Ah-21 | 233 | 258 | 25 |
| Ah-22 | 239 | 226 | -13 |
| Ah-26 | 232 | 241 | 9 |

From the preceding table and the map of Na/K temperatures compared with the maximum temperatures, it can be seen that these values move away from the temperatures measured in a S-Sw direction culminating in well Ah-7 which shows the greatest difference. This indicates that the sodium potassium hasn't reached its balance with the rocks of the reservoir in that direction and that it reaches the balance when it circulates in a N-NE direction. This fact is important for inferring the possible feeding zone of the reservoir. There is also the possibility that the low ratios reported in that direction are an indication that the water that feeds the reservoir has been in contact with rocks of higher temperature in a deeper zone not necessarily near the reservoir being worked and that the balance in the feeding zone adjoining the reservoir hasn't managed to be established yet. Up to now temperatures greater than 239°C have not been detected in the drilling area.

This ratio also confirms the possible extension of the reservoir in a S-SE direction and its N and NW boundaries coming from the working field.

The map of Na/K temperatures seems to indicate, together with that of maximum temperatures, and with that of the isoconcentration of chlorides, and with that of the concentration of Si02 that the feeding zone is found to the south of the working field and that the circulation of fluids has a lateral direction with a tendency towards the N-NE.

## 4-3 Concentrations of $SiO_2$

The concentrations of $SiO_2$ correspond very accurately to those expected for balanced quartz water to those measured from the reservoir. The map of silica isoconcentrations shows an obvious tendency to increase towards the south of the field, and this correlates with the maximum measured temperatures and with the Na/K ratios. All the evidence indicates that the flow has a N-NE direction previously converging in the center of the area of greatest operation (Figure 5)

If we calculate the heat content of the water in the reservoir using the $SiO_2$ concentrations in the discharged water, it will be seen that the values are much smaller than those calculated by means of measurements. This fact provides evidence that a certain quantity of steam generated in the reservoir is being expelled with the mix.

## 4.4 Cl/B, Cl/As, Cl/Br, Cl/I Ratios (Table 2)

This series of ratios show themselves to be quite constant in the waters discharged by the producing wells, confirming only one source for the water that feeds the saline aquifer. It should be noted that the Cl/B ratio stays within the average range even in the Ah-14 and Ah-16 wells, considered to be bordering the working area. This fact is important because it enlarges the extension of the saline aquifer to the S-SE at the same time that it suggests a possible communication with the saline aquifer existing in the Chilapa area.

The Cl/Br, Cl/I ratios are quite low compared to those found in similar fields and the source of the high concentrations of Br (40 ppm) and I (8 ppm) has not yet been explained.

The variation in the absolute concentrations of B, As, Br, and I seem to be related to a process of dilution of the feed water in the reservoir in a N-NE direction although to date it isn't possible to detect this process in ~~[illegible]~~ any way.

## 5. PHYSICAL STATE OF THE AHUACHAPAN FIELD

Beginning in 1975, a~~s~~ designed ~~[illegible]~~ ~~operation~~ EXPLOITATION of ~~in~~ considerable proportions was started in the Ahuachapan geothermal field. To date the total quantity of extracted mass is along the order of 26 x $10^3$ ?. This artificial extraction of mass has provoked caused changes in the physical conditions of the aquifer that supplies the Ahuachapan geothermal zone.

The change in the original physical conditions has been detected by a program of routine measurements that include: records of pressure and temperature, measurements of production and control of discharged water.

The original condition of the aquifer, before starting the extraction programs on a large scale for the purpose of generation, was as expected ~~was~~ that determined by the saturation condition. The evidence that supports the saturation condition, ~~that~~ is the existence of only one phase; it is also possible ~~[illegible]~~ to get it from the pressure ratios measured in the well together with the saturation pressures for the measured temperatures. Figures 6 and 7 show us these ratios for wells Ah-6, Ah-7, and Ah-20 in 1974. These wells were selected because they are representative of two field sites: Ah-6 and Ah-20 are located in the main working area and Ah-7 because of its being a well quite removed from the area and it has demonstrated not to be sensitive to many of the observed variations.

In said figures we see how the saturation condition was generalized for the 3 selected wells, with only one change in this condition occurring when the hydrostatic pressure surpassed the saturation pressure. The same ratios have been graphed for the current state of said wells, in which one can clearly observe how the saturation condition has been ruptured in the Ah-6 and Ah-20 wells while it has stayed ~~[illegible]~~ about the same in the Ah-7 well.

The similarity of the ratios before the extraction process indicates to us a s turation condition in the original aquifer in 1974, while the variations observed for 1976 indicate that in the zone of influence notable changes have occurred in the condition of the aquifer and that these changes have not affected the wells located outside of the major extraction area.

These pressure ratios together with the saturation pressure suggest the probability of a steam phase in the reservoir, that would be explainable on the basis of a decrease in the hydrostatic level.

With the mass extractions, without yet making suppositions about the existence of a recharge mechanism, a decrease in the water level of the reservoir has been produced which necessarily implies a fall in pressure. This fall in pressure should be accompanied by a drop in temperature until the point where the water reaches a balance in the temperature of the rocky formation, The saturation condition will then cause a decrease in pressure until saturated steam pressure corresponding to these balanced temperatures is reached. Below the water level, the pressure will drop with depth until the point where the pressure is greater than the saturation pressure and will dispose of heat from this depth to the water level. This available heat will theoretically cause a steam phase that will fill the formation and will keep the pressure above the water level more or less equal to the pressure of said level.

At this point changes in the heat content of the discharge of individual wells, since the steam produced by the 'flash' in the interior of the well will add to the existing steam in the reservoir; a fact that has already been detected for some wells. Basically, its from this point of view that the hypotheses about the present discharges of the Ah-4 and Ah-6 wells, that are wells located in the center of the working area, the production conditions that are listed in Table 2 have been observed and they have been compared with the characteristics of the discharge of well Ah-7 situated a little further away from the zone affected by the operation; these are characteristics which typify the discharge of a well in which the percentage of steam in the total discharge is only due to the 'flash' process starting with water saturated at 222°C.

A reasonable alternative to the hypothesis of the probability of a steam phase in the interior of the reservoir would be to consider an increase in the interior of the well, that is, a decrease in the 'flash' level. On the other hand, a quite considerable increase would be needed in order to explain the indicated ratios of liquid-steam, an increase that seems to us not to be justified on the basis of given thermodynamic variations.

Some considerations about the hypothesis of a recharge system are left to be done but up to now the only evidence in this direction is qualitative and was obtained during the withdrawal of the first unit in the months of Dec/75 to Jan/76. This was a period in which a recovery in the pressure of the same was observed which exceeded the errors in measurement.

In another part of this report it will be seen that the chemical composition of the waters in the field also lead to establishing the existence of a recharge. Therefore, it remains established that the behavior of the Ahuachapan geothermal field is one corresponding to a field where the discharges of the individual wells are of the water-steam type, that originally it was set up by a liquid phase and has been changed by working to a state of 2 phases: water-steam.

## 5-1 Temperatures

On the basis of the data obtained from the 24 presently drilled wells, it has been possible to draw a map of the maximum measured temperatures for the reservoir (Fig. 8). On said map one can observe an area of higher temperatures (220-239°C) found situated in an area of 1 km2 that includes all the wells presently in production. The boundaries of the hyperthermal zone are well defined in a northerly direction by the wells Ah-11 and Ah-12 and to the West by well Ah-15. In the South and S-SE the area seems to extend as far as the Chipilapa region, according to what has been shown by the results of the deep well CH-1 and the exploratory wells currently being drilled. This fact would extend the hyperthermal area to approximately 8-10 km2 which gives us an idea of the potentiality of the system.

One fact that has been made clear is that the widening of the area of highest temperatures due to intensive working is probably due to a greater movement of high temperature fluid towards the extraction zone.

Also, it should be noted that the wells located in the high part of the reservoir show the highest temperatures; this probably confirms that the primary feed of the reservoir occurs in a southerly direction.

The vertical distribution of temperatures measured after ~~the~~ thermal stabilization, from the formations, is characterized by a gradual increase in gradient until it reaches the roof of the reservoir, after which there is a notable tendency to maintain values that oscillate between 230-239°C. Generally an inversion occurs upon reaching the massive agglomerates.

PRODUCTION CAPACITY

The present production capacity of the field, considering only the 9 producing wells connected to the Geothermal Station, is around 1630 T/hr of mix which separated at an average pressure of 5.9 kgr/cm2 results in 493 t/hr of steam and 2137 T/hr of water, giving an average ratio of steam/water of 0.23. From the wells previously considered, (Ah-4 and Ah-21) these are found to be restricted due to the smaller capacity of the cyclonic separators.

Later on the production characteristics of the producing wells are reported (Table 3)

The curves of the production characteristics, measured by the critical pressure method, can be seen in graphs 9 and 12. In these we can observe the general production characteristics of each well.

Because of the intensive working of the field, a certain general tendency to an increase in the steam/water ratio has bee noted, that in some wells has been more pronounced, as is the case of well Ah-6, which by its location and depth seems to be the most sensitive to ongoing variations in production.

From the table on production characteristics we can observe 2 significant facts:

1. The production rate of the wells ~~is~~ are quite large, a fact that is intimately related to the distribution of secondary permeability in the field which has been shown to be totally unpredictible. We can see that the wells with greater capacity are those situated in a S-SE direction in the topographically elevated part of the field.

2. A wide range of heat content in the mix that goes from values of 211 kcal/kgr for well Ah-5 to values of 395 kcal/kgr for well Ah-26. This fact seems to indicate that with extensive operation a steam phase has been formed in the central part of the field. This subject was discussed in a previous chapter.

## TABLE 2

## COMPARISON OF THE DISCHARGES OF WELLS Ah-4, Ah-6, and Ah-7

| | Well Ah-4 | WellAh-6 | Well Ah-7 |
|---|---|---|---|
| -Separation Pressure (kg/cm$^2$) | 6.2 | 5.9 | 5.8 |
| -Total flow (T/hr) | 472 | 224 | 228.6 |
| -Water flow (T/hr) | 385.92 | 164.6 | 198 |
| -Steam flow (T/hr) | 85.75 | 59.4 | 30.6 |
| -Heat content of the mix (Kgal/Kg) | 251.1 | 291.6 | 224.87 |
| -Percentage of steam calculated by the separation pressure | 18.18 | 26.55 | 13.8 |
| -Percentage of separation expected for saturated water* | 15.91 | 15.7 | 13.9 |
| -Difference (f) - (g) | 2.27 | 10.85 | 0.1 |

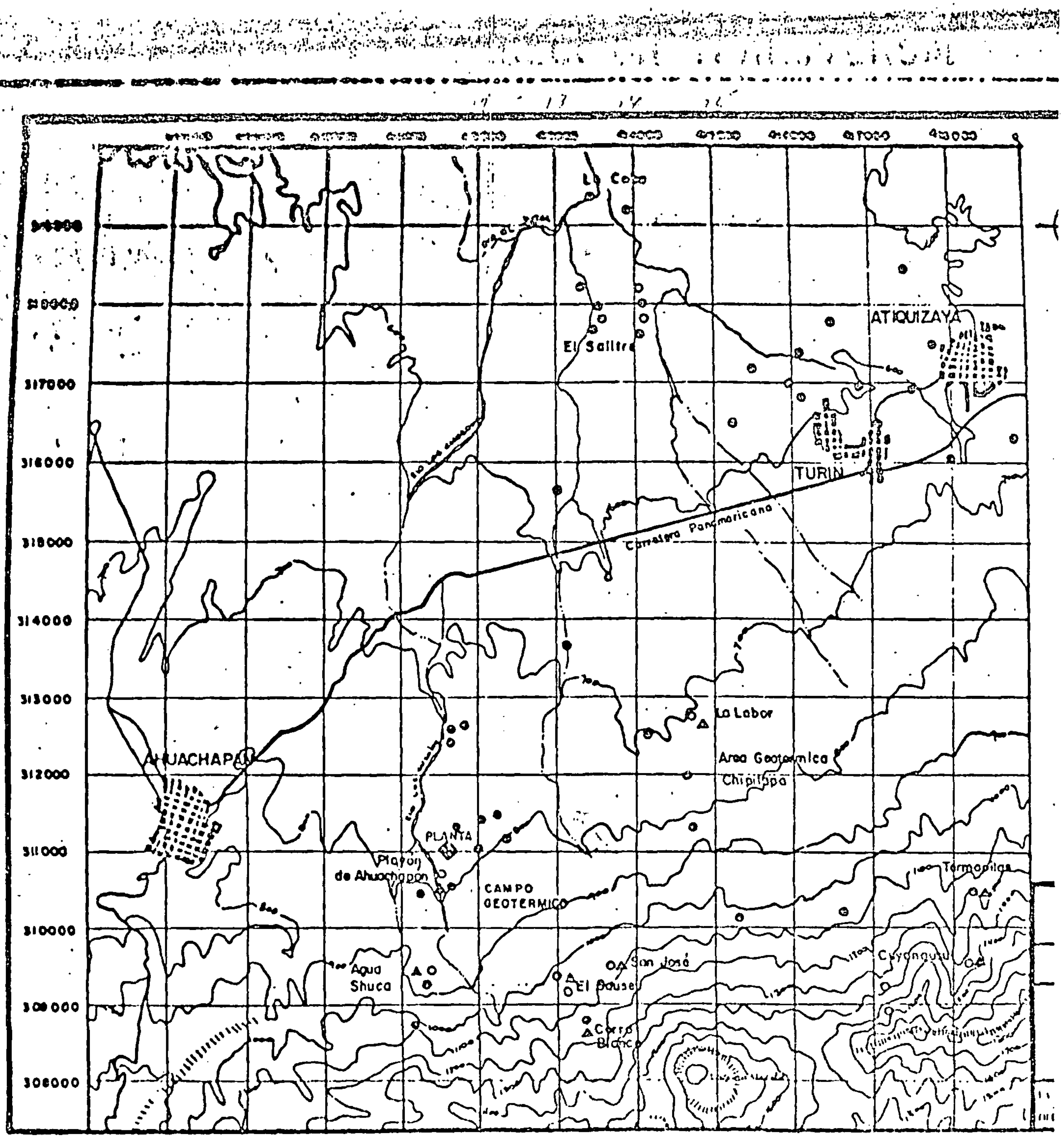
*In order to calculate (g) the heat content of the water at the temperature recorded in the well is taken as a base.

# PRODUCTION CHARACTERISTICS

| Wells | S.P. Kgr/cm$^2$ | Total Flow T/hr | Water Flow T/hr | Steam Flow T/hr | Percent of separation | Heat Content | Est MW |
|---|---|---|---|---|---|---|---|
| **Ah-1** | **5.8** | **344** | 298 | 46 | 13.37 | 224 | 7 |
| **Ah-4**** | 6.2 | 472 | 386 | 86 | 18.2 | 251 | 13 |
| Ah-6 | 5.9 | 224 | 165 | 59 | 26.6 | 291 | 9 |
| Ah-7 | 5.8 | 229 | 198 | 31 | 13.8 | 225 | 5.5 |
| Ah-5 | 5.6 | 239 | 213 | 26 | 10.8 | 211 | 4 |
| Ah-20 | 5.5 | 226 | 183 | 43 | 19.0 | 251 | 6.5 |
| Ah-21* ** | 5.9 | 502 | 423 | 82 | 16.3 | 220 | 12.5 |
| Ah-22 | 5.9 | 293 | 221 | 72 | 24.5 | 281 | 10 |
| Ah-26 | 5.8 | 102 | 54 | 48 | 46.8 | 392 | 9 |

*Estimated computation

**Restricted well



LEGEND

● Thermal sources

○ Fumaroles

▲ Gas leak

Edge of crater

Fig. 1

AHUACHAPAN GEOTHERMAL AREA

CROSS SECTION

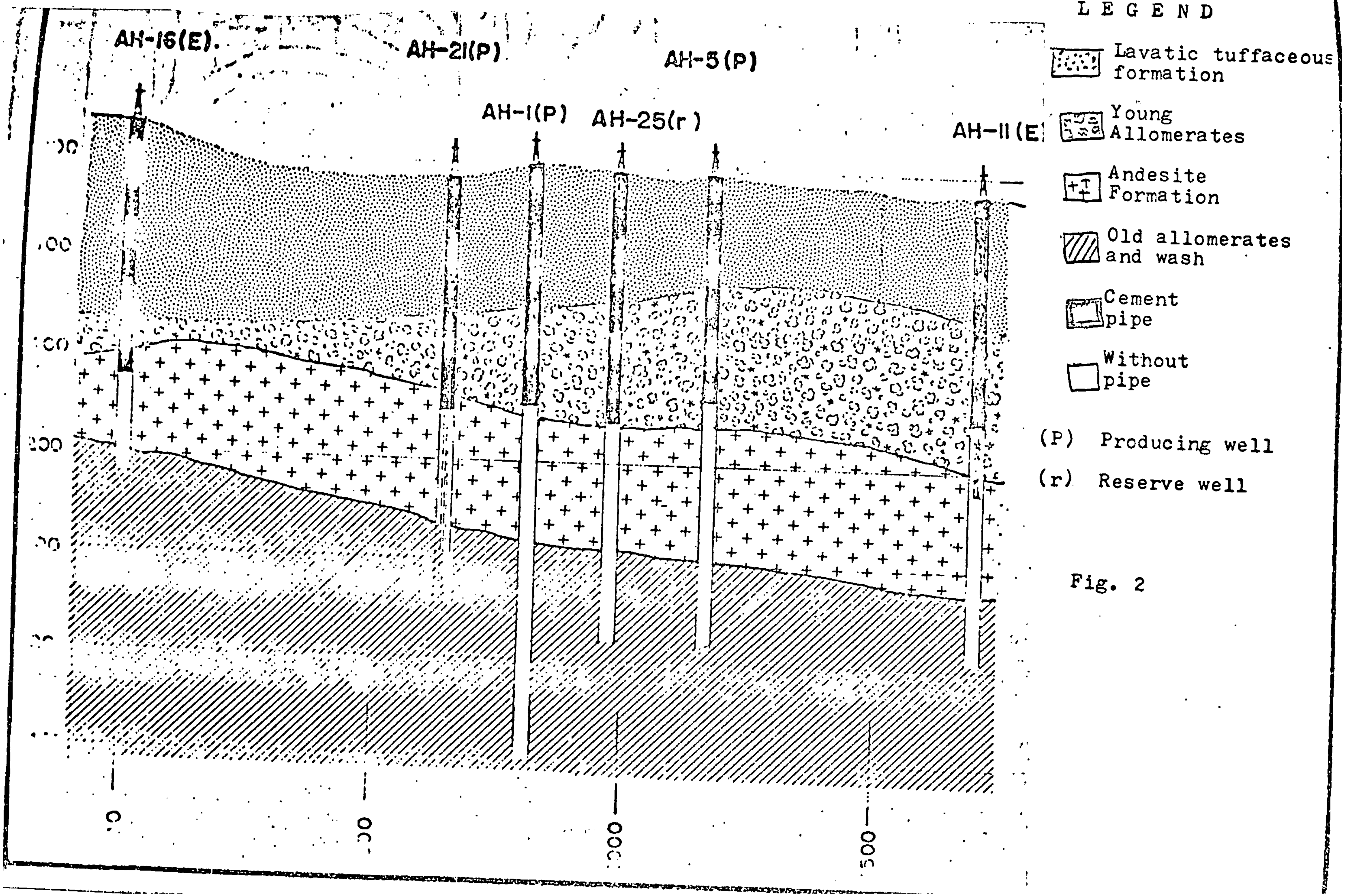
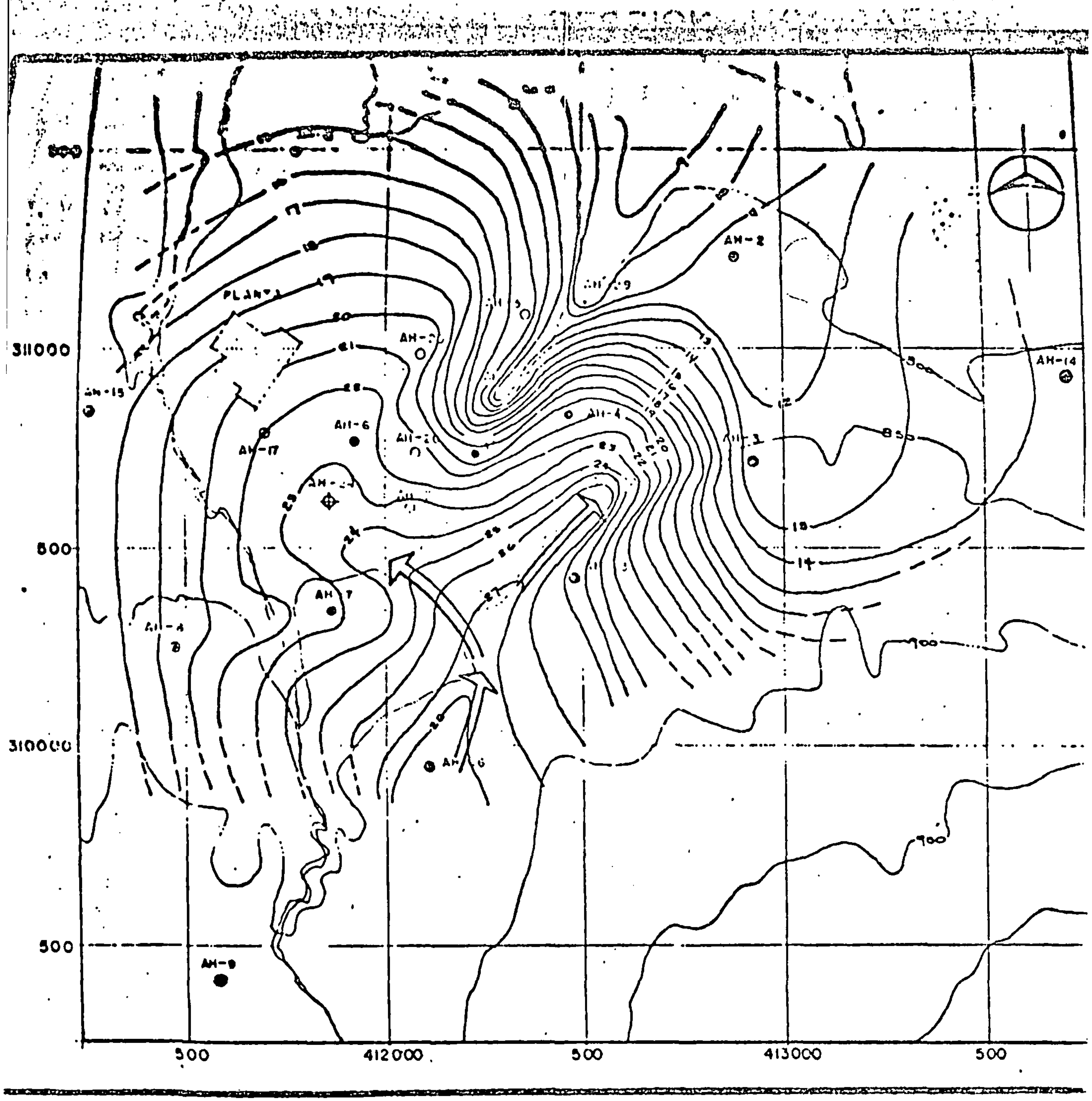


Fig. 2



## AHUACHAPAN GEOTHERMAL FIELD

SYMBOLOGY

● Wells 1a Unit

○ Wells 2a Unit

⊙ Reinjection wells

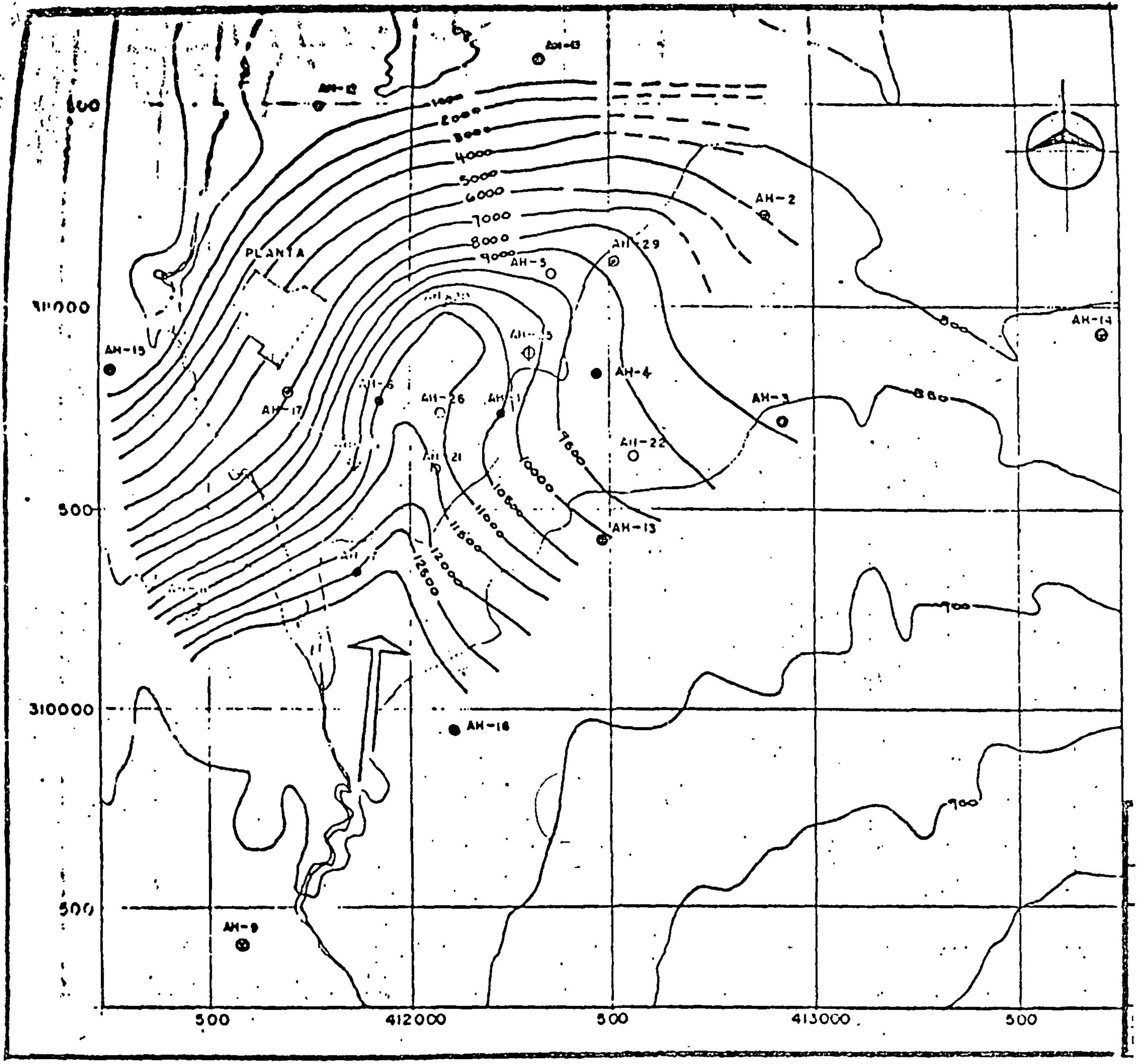
⊘ Exploratory wells

⊕ Reserve wells

Pressure map at elevation 450

# AHUACHAPAN WATER WELLS

| POZO | Cl/B | Cl/As | Cl/SO$_4$ | Cl/F | Cl/Br | Cl/I | Na/K | Na/Li | Na/Sr | Na/Ca | K/Rb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AH-1 | 22.05 | 2070 | 932 | 3755 | 534 | 4604 | 9.86 | 94.05 | 4911 | 23.75 | 276 |
| H-4 | 19.22 | 1909 | 717 | 3753 | 588 | 4983 | 11.49 | 95.54 | 4187 | 21.75 | 289 |
| H-5 | 20.19 | 1941 | 605 | 3850 | 554 | 4671 | 12.50 | 101.35 | 3354 | 19.77 | 293 |
| -6 | 21.38 | 1982 | 994 | 3332 | 588 | 4611 | 9.71 | 95.74 | 5080 | 23.78 | 277 |
| -7 | 20.85 | 1884 | 1411 | 3647 | 558 | 4720 | 8.76 | 99.00 | 5294 | 23.63 | 328 |
| -20 | 21.50 | 1916 | 978 | 3690 | 550 | 4617 | 9.81 | 97.30 | 5080 | 23.20 | 286 |
| -21 | 20.81 | 2056 | 769 | 3684 | 551 | 4660 | 9.69 | 95.81 | 5269 | 1663 | 300 |
| -22 | 22.19 | 2401 | 763 | 3811 | 538 | 4905 | 12.16 | 101.60 | 4083 | 20.23 | 297 |
| -26 | 21.82 | 1943 | 621 | 3871 | 492 | 4291 | 10.52 | 96.00 | 4700 | 22.66 | 270 |
| -11 | 19.46 | n.d. | 9.2 | n.d. | n.d. | n.d. | 48.49 | n.d. | 29464 | 81.28 | n.d. |
| -12 | 3.98 | n.d. | 1.5 | n.d. | n.d. | n.d. | 23.42 | n.d. | 15180 | 230 | n.d. |
| -14 | 18.71 | n.d. | 20.4 | 707 | n.d. | n.d. | 7.20 | n.d. | n.d. | 30.57 | n.d. |
| -16 | 18.94 | n.d. | 53.0 | 3978 | n.d. | n.d. | 10.26 | n.d. | 3295 | 16.14 | n.d. |



AHUACHAPAN GEOTHERMAL FIELD

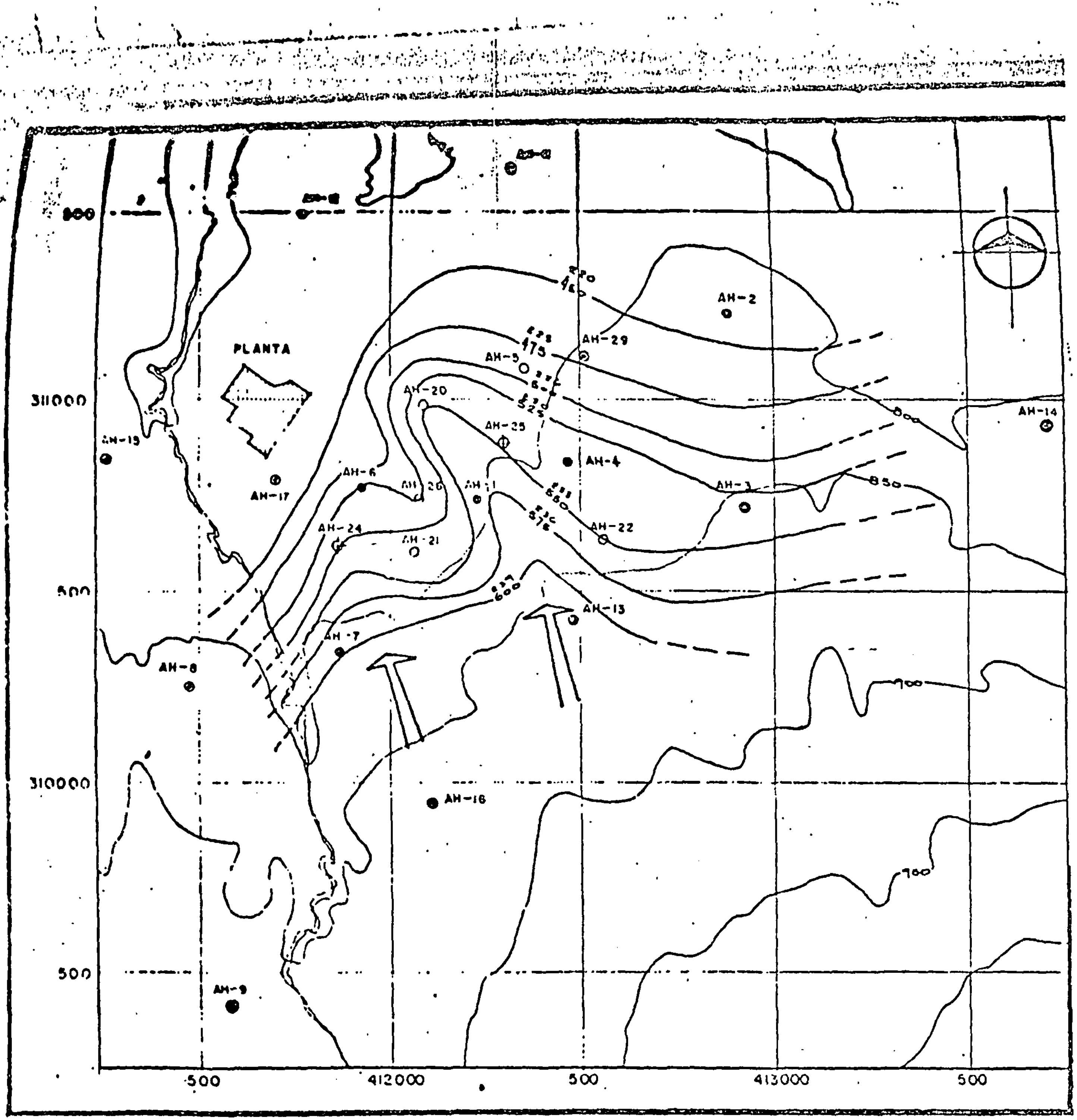
Symbology

- ⊗ Wells 1a Unit
- ○ Wells 2a Unit
- ⦿ Reinjection wells
- ⊙ Exploratory Wells
- ⌖ Reserve Wells

Fig. 4

Map of chloride iso-concentrations in p.p.m.

## AHUACHAPAN GEOTHERMAL FIELD



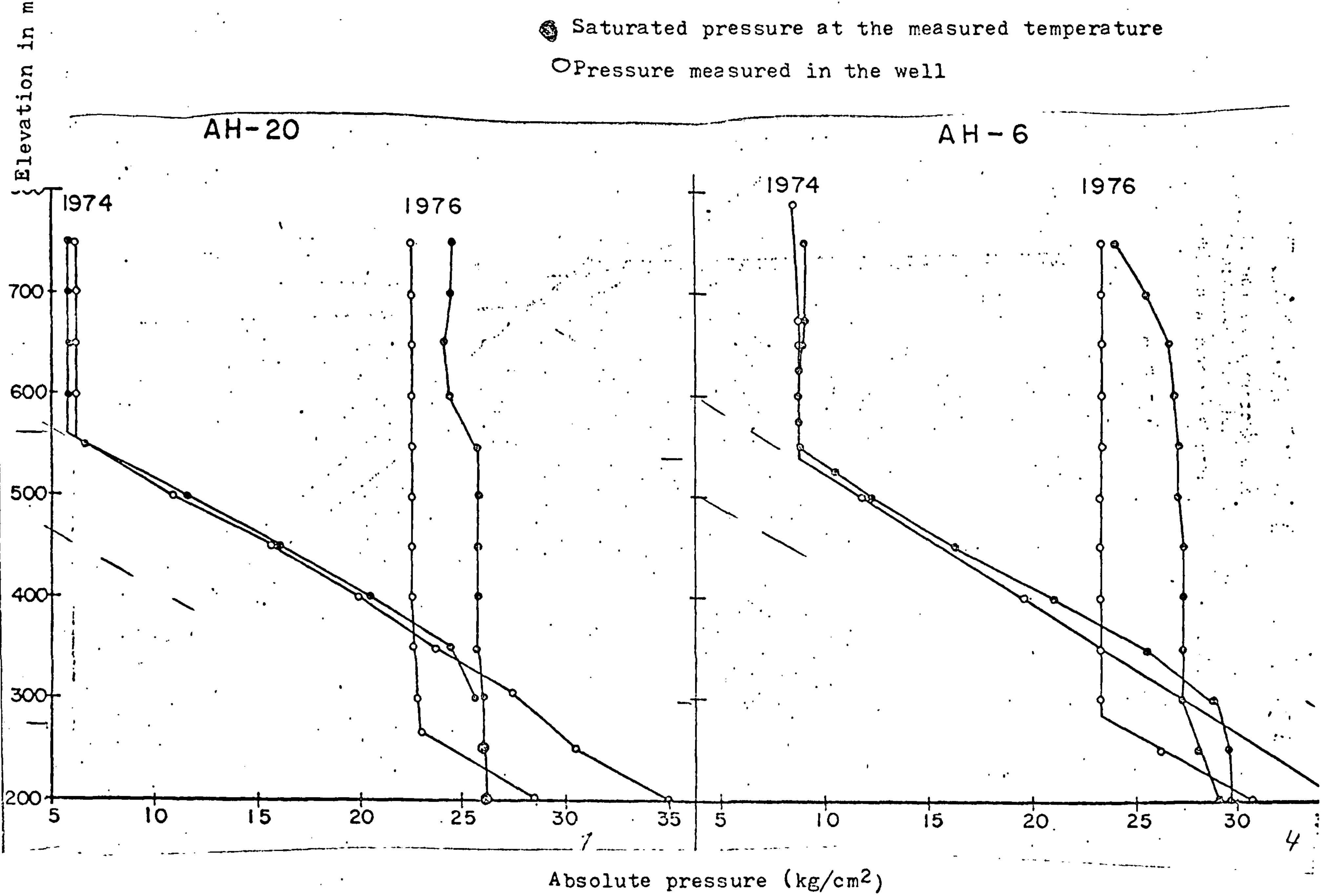
Symbology

- ● Wells 1a Unit
- ○ Wells 2a Unit
- ⊙ Reinjection wells
- ⊕ Reserve Wells
- ◎ Exploratory Wells

Map of silica isoconcentrations in p.p.m.

Fig. 5

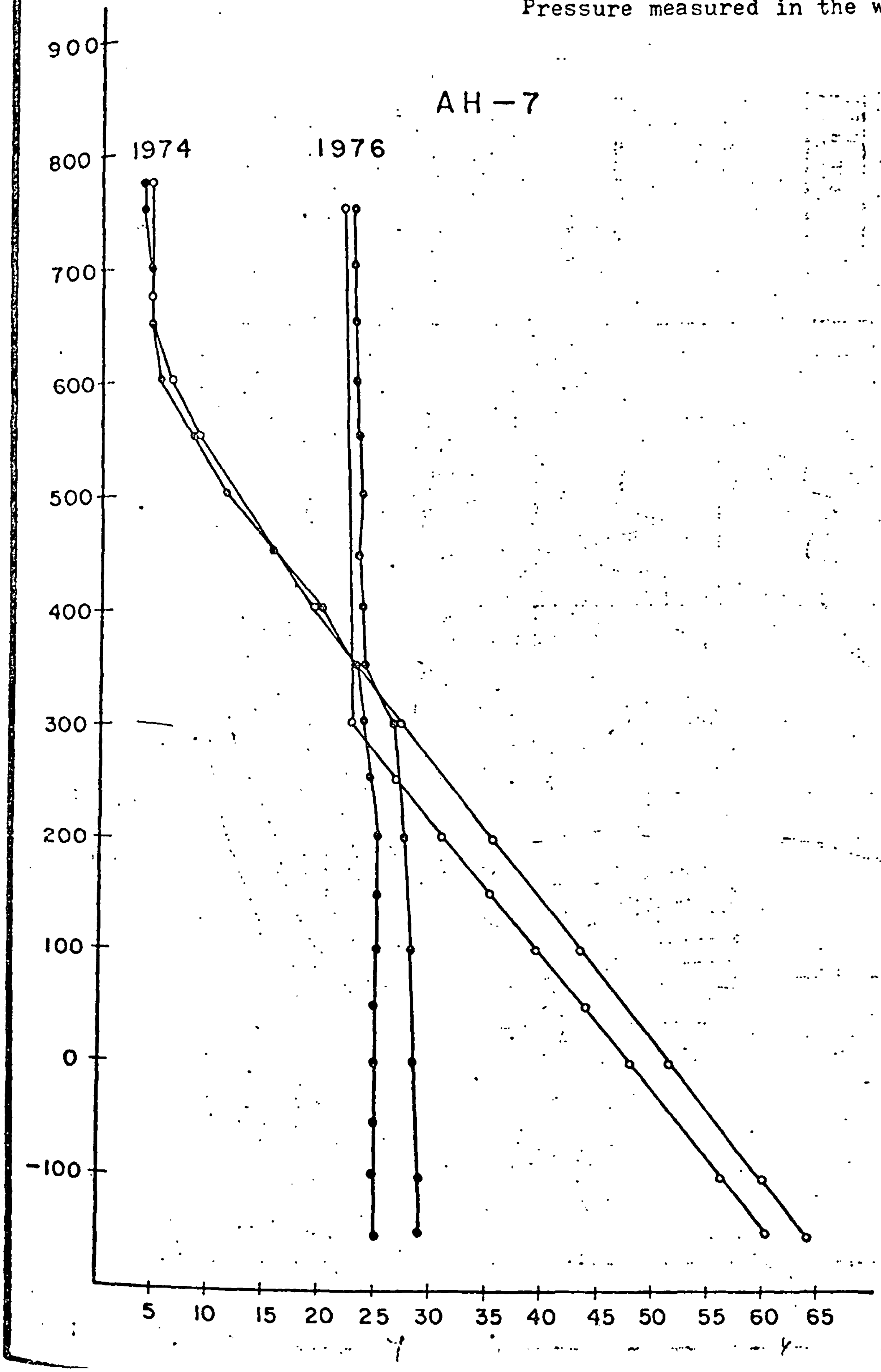
PRESSURE RATIOS Fig. 6

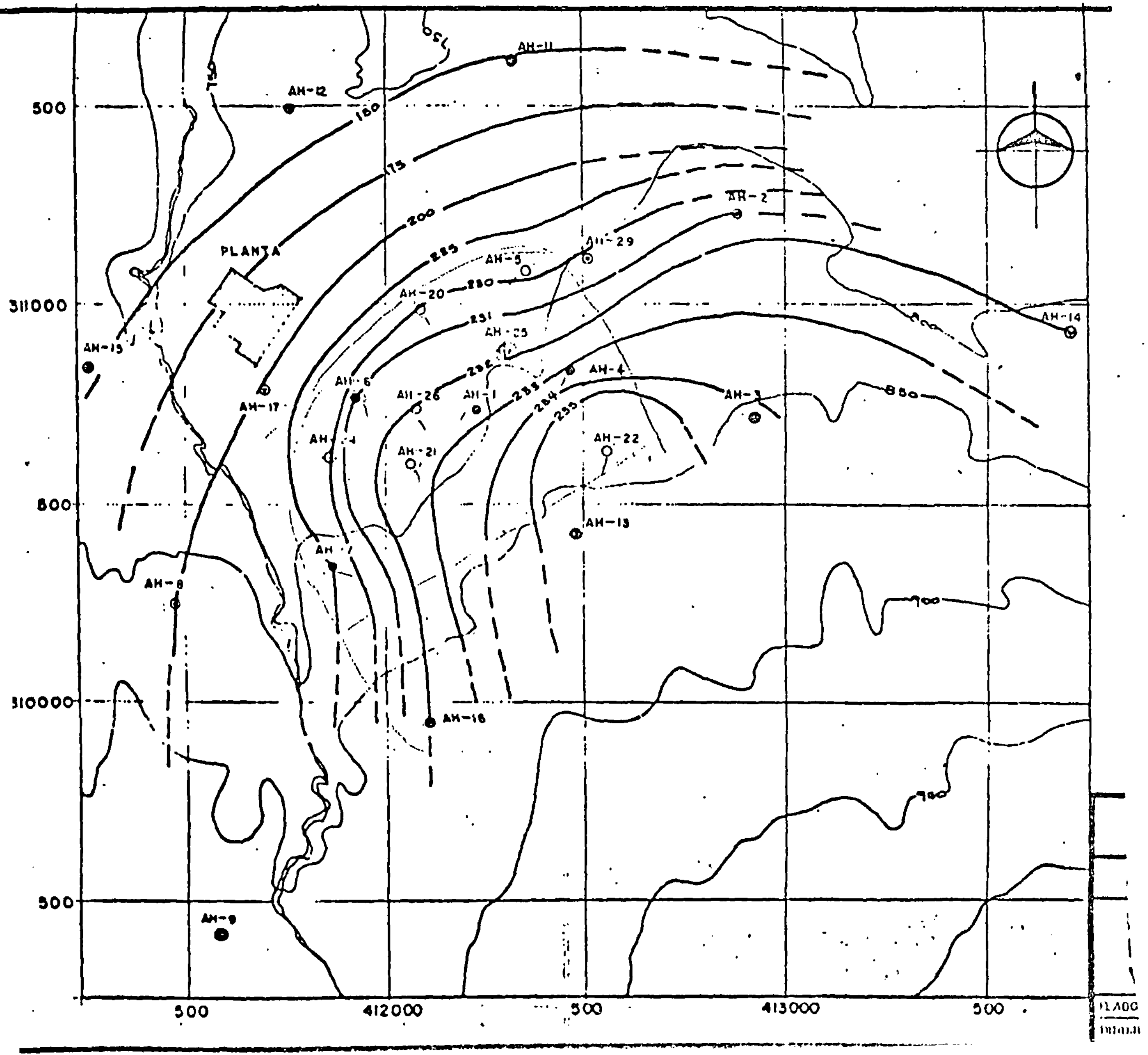


PRESSURE RATIOS

Saturation pressure at the measured temperature

Pressure measured in the well



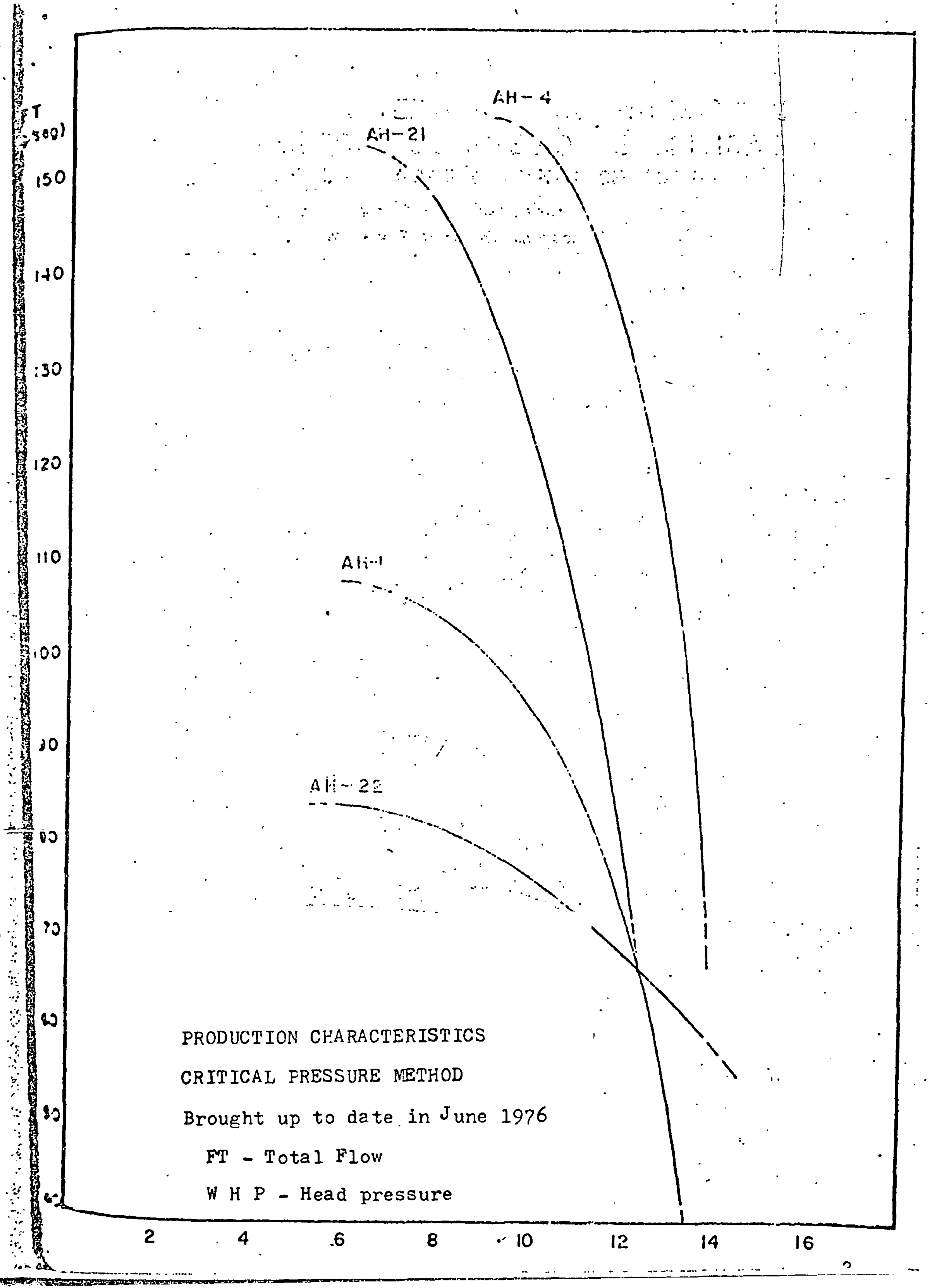


## AHUACHAPAN GEOTHERMAL FIELD

Symbology

- ● Wells 1a Unit
- ○ Wells 2a Unit
- ⊙ Reinjection Wells
- ○ Exploratory Wells
- ⊕ Reserve Wells

Map of maxium temperatures measured in the reservoir



PRODUCTION CHARACTERISTICS

CRITICAL PRESSURE METHOD

Brought up to date in June 1976

FT - Total Flow

W H P - Head pressure

PRODUCTION CHARACTERISTICS

CRITICAL PRESSURE METHOD

Brought up to date in June 1976

Fv - Volume of steam

Whp - Head pressure

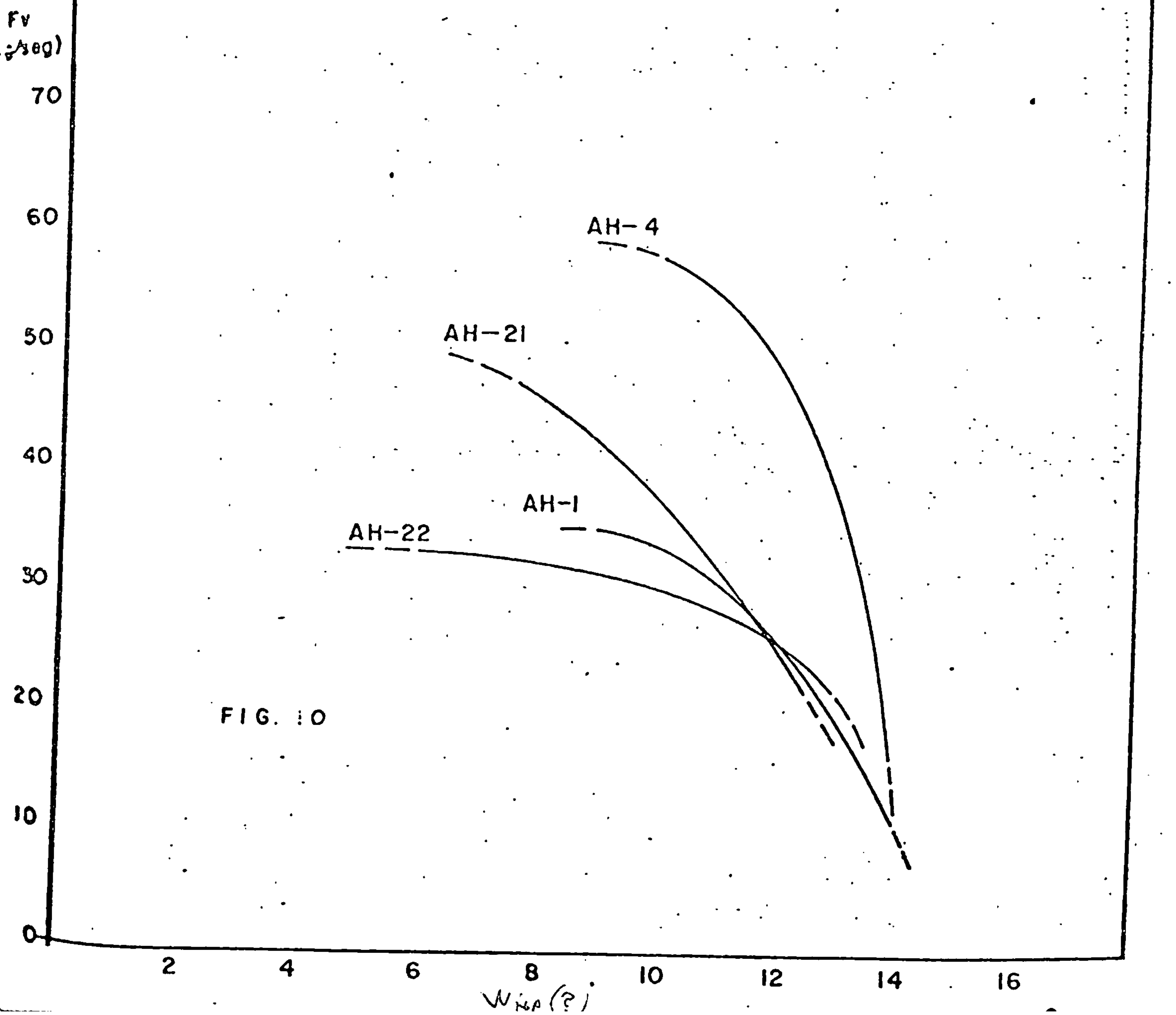


FIG. 10

## PRODUCTION CHARACTERISTICS

## CRITICAL PRESSURE METHOD

Brought up to date in June 1976

FT - total flow

WHP - head pressure

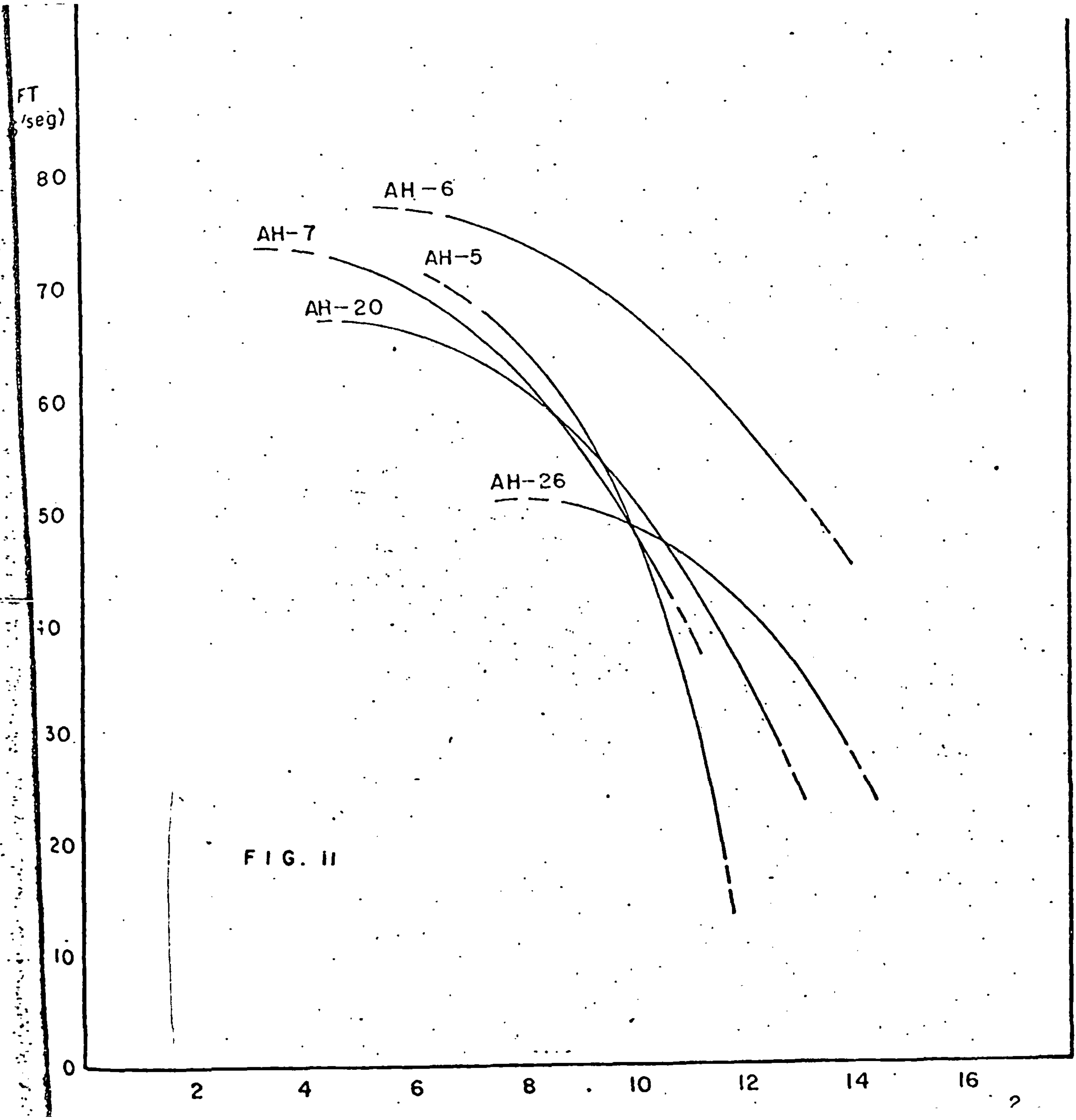


FIG. 11

PRODUCTION CHARACTERISTICS

CRITICAL PRESSURE METHOD

Brought up to date in June 1976

Fv - Volume of steam
WHP - head pressure

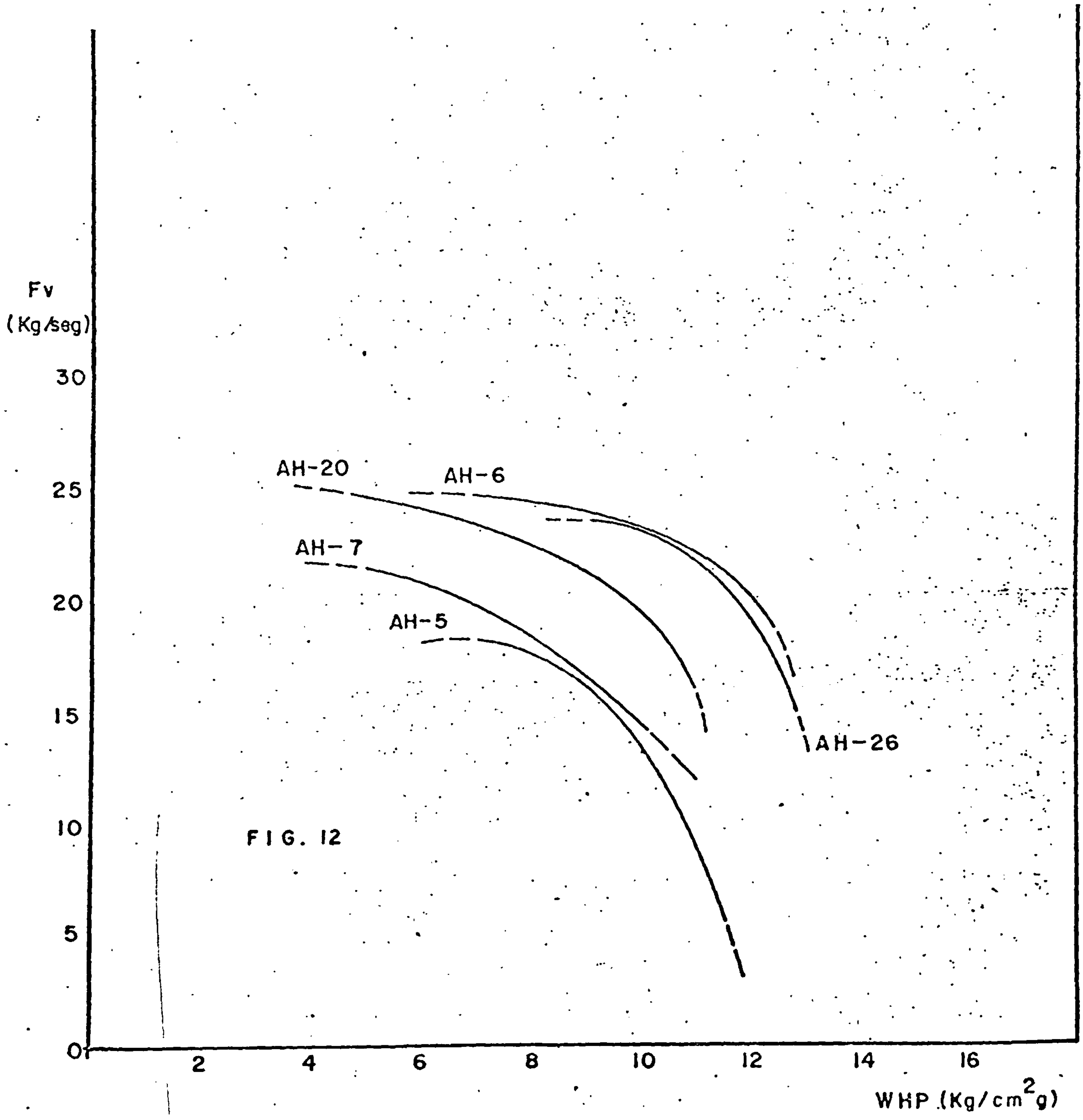


FIG. 12

# APPLICATIONS OF MODERATE-TEMPERATURE GEOTHERMAL RESOURCES

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## ABSTRACT

Moderate-temperature hydrothermal resources will, in time, be the "bread and butter" of the hydrothermal industry. Estimates indicate that thirty-seven states in the U.S. have geothermal resources that may be presently economically exploitable. The medium- and low-temperature (50 to 150°C) hydrothermal resource contains about five times as much recoverable energy as the high-temperature (above 150°C) resource. Direct use of the energy from the resource, in process and space heating, is viable today. Economic electrical production using fluids in the 150°C range is possible in the near-term future.

## INTRODUCTION

The upper 10 kilometers of the earth's crust may contain more than 8 x $10^{24}$ calories of heat; however, the majority of this heat is too diffuse to be economically exploitable as an energy source. Estimates indicate that thirty-seven states in the U.S. have geothermal resources that may be presently economically exploitable. The medium- to low-temperature (50 to 150°C) hydrothermal resource contains about five times as much recoverable energy as the high-temperature (above 150°C) resource when extraction practices are limited to current or near-term technology (Figure 1). The direct application of geothermal energy is a viable technology that already is in worldwide use. Commercial and government cooperative projects are now underway which will expand the use of direct applications in the United States.

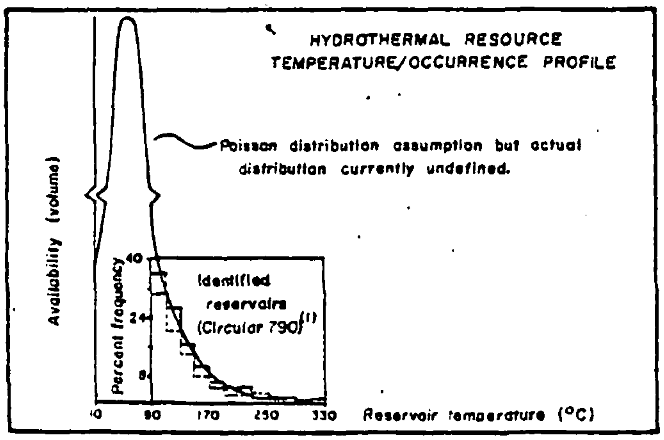

Figure 1

## DIRECT APPLICATIONS

The practices employed in the direct use of geothermal energy encompass a wide spectrum. At one end is the age-old balneological use, while at the other is the use of geothermal energy for refrigeration. Applications range from melting snow to providing the thermal energy requirements for a modern food dehydration plant.

It is startling to realize that the commercial use of geothermal energy is older than the commercial use of natural gas. District space heating by the Artesian Hot and Cold Water Company of Boise, Idaho, was initiated in 1893. This system at one time serviced a peak of 400 customers. Currently, the space heating requirements of approximately 200 homes are met by the system. The largest known, and probably the most economical, district heating system is in Reykjavik, Iceland. It supplies a total population of about 90,000 with space and domestic water heating. The present capacity for the system is 350 MW (th). The average cost of heating is about 30% below oil heating costs.(2)

The earliest utilization of geothermal energy in modern industrial processing is not well documented, but appears to have been initiated in the early 1950's. The Italians used steam at Larderello in the early 1800's for evaporator heating. A compilation of the types of industrial processes and the country in which they are currently utilized is presented in Table 1.

Hydrothermal resources are now being employed for industrial processing in the United States. The first of these operations was the Medo-Bel Creamery in Klamath Falls, Oregon. Medo-Bel has been using this energy source since 1973 for milk pasteurization. Geothermal Food Processors have recently initiated onion and celery drying operations at Brady Hot Springs, Nevada. In addition, the DOE field demonstration (PON) program has stimulated industrial developments in potato processing, grain drying, aquaculture, agribusiness, and sugar processing.

Table 1

CURRENT INDUSTRIAL PROCESSES USING GEOTHERMAL ENERGY(3)

| Application | Country | Description of Application |
|---|---|---|
| Wood & Paper Industry | | |
| Pulp & Paper | New Zealand | Processing and a small amount of electrical power generation. Kraft process used. |
| Timber Drying | New Zealand | Kiln operation. |
| Washing & Drying of Wood | Iceland | Steam drying. |
| Mining | | |
| Diatomaceous Earth Plant | Iceland | Production of dried diatomaceous earth recovered by wet-mining techniques. |
| Chemicals | | |
| Salt Plant | Japan, Philippines | Production of salt from sea water. |
| Sulphur Mining | Japan | Sulfur extraction from the gases issuing from a volcano. |
| Boric Acid, Ammonium Bicarbonate, Ammonium Sulphate, Sulphur | Italy | Includes recovery of substances from the volatile components which accompany the geothermal steam. |
| Miscellaneous | | |
| Confectionary Industry | Japan | |
| Grain Drying | Philippines | Geothermal steam heats rotary kiln dryer. |
| Brewing & Distillation | Japan | |
| Stock Fish Drying | Iceland | Fish drying in shelf dryers. |
| Curing Cement Building Slabs | Iceland | Curing of light aggregate cement building slabs. |
| Seaweed | Iceland | Drying seaweed for export. |
| Onion Drying | United States | Dehydration of onions. |
| Milk Pasteurization | United States | Milk processing using low-temperature resource. |

Industrial use represents 40% of our national energy consumption, the single largest share, with residential space conditioning and water heating using 20%, commercial space conditioning and water heating using 15%, and transportation accounting for the remaining 25%.

The energy used by industry can be broken into the following categories:

| | |
|---|---|
| Process Steam | 40.6% |
| Electric Drive | 19.2% |
| Electrolitic Process | 2.8% |
| Direct Process Heat | 27.8% |
| Feedstocks & Chemicals | 8.8% |
| Other | 0.8% |

Process steam and direct process heat account for 68.4% of the total industrial use of energy, much of which can potentially be supplied by hydrothermal energy. Today, high-temperature processing is being practiced in many cases only because those are the temperatures naturally achieved when fossil fuel is consumed. A study by Intertechnology Corporation(4) reviewed in excess of 75 processes and defined the associated heat requirements. Typical processes which can be operated in the low to moderate range, together with the percentage of the process energy needs as a function of maximum temperature required, are given in Table II. It should be noted that the methodology of the study considered the process temperature required, not the temperature supplied. However, in many processes, time and temperature can be traded-off to permit the use of lower temperature energy sources. Thus, there are potentially many additional processes which can be adapted to low-temperature energy sources.

Although a national market analysis has not been completed, an analysis of ten Rocky Mountain states shows that space conditioning and industrial processing are prime market sectors for the direct applications of hydrothermal energy. Currently, greater than 75% of the energy requirements of these market sectors is met by fossil fuel consumption, with electricity claiming the majority of the remaining sales. Energy competition projections for the referenced states indicate a future higher dependence upon coal, which may encounter environmental or other growth constraints.

Table II

TYPICAL INDUSTRIAL PROCESS HEAT REQUIREMENTS

| | 40°C-60°C | 60°C-80°C | 80°C-100°C | 100°C-120°C | 120°C-140°C | 140°C-160°C | 160°C-180°C | 180°C-200°C | 200°C |
|---|---|---|---|---|---|---|---|---|---|
| Dehydrated Fruits & Vegetables | 0 | 100% | → | → | → | → | → | → | → |
| Concrete Block - Low-Pressure | 0 | 100% | → | → | → | → | → | → | → |
| Autoclave | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100% | |
| Frozen Fruit & Vegetables | 0 | 0 | 39% | 100% | → | → | → | → | → |
| Poultry Dressing | 100% | → | → | → | → | → | → | → | → |
| Meat Packing | 0 | 99% | 100% | → | → | → | → | → | → |
| Prepared Feeds - Pellets | 0 | 0 | 100% | → | → | → | → | → | → |
| Alfalfa Drying | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100% |
| Plastic Materials | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100% |
| Dairy Industry - Cheese | 23% | 100% | → | → | → | → | → | → | → |
| Condensed Milk | 0 | 63% | 63% | 93% | 100% | → | → | → | → |
| Dried Milk | 0 | 0 | 42% | 66% | 71% | 71% | 71% | 100% | → |
| Fluid Milk | 0 | 0 | 100% | → | → | → | → | → | → |
| Soft Drinks | 61% | 100% | → | → | → | → | → | → | → |
| Soap | 0 | 0 | 0 | 1% | → | → | → | → | 100% |
| Detergents | 0 | 0 | 0 | 52% | → | → | → | → | 100% |

A cross matching of the hydrothermal resources, as known today and projected for the future, on a county-by-county basis with the potential user sectors, has defined the prime commercial sectors that could most effectively convert to hydrothermal energy. This analysis reveals that all ten states under study have significant resources which correlate with potential energy market areas, and that the majority of the industrial and population centers are co-located with hydrothermal resources. The current energy use, considering all potential uses of direct heat, is $362 \times 10^{12}$ Btu/yr, with a growth potential, by the year 2020, of $3980 \times 10^{12}$ Btu/yr.

The largest single user segment is space conditioning and water heating. The current energy use for this is $288 \times 10^{12}$ Btu/yr, and this could grow to $2504 \times 10^{12}$ Btu/yr by 2020.

Many of the major industrial energy consumers in the states studied can use low to moderate heat sources to meet a portion, if not all, of their energy needs. These industries include food and kindred products processing, wood and lumber products, mining and minerals, chemical processing, and the concrete industry. Table III lists the top prospect industries that are matched by counties with hydrothermal resources.

The energy requirements of the industrial sector are somewhat smaller than the energy needs for residential/commercial space conditioning, but the ten-state area growth potential is excellent. In addition, it appears that the market can be more readily penetrated in the industrial sector since industrial applications are energy intensive (therefore decreasing the delivered cost per Btu), require less public acceptance, and have favorable tax benefits for investors. Current industrial energy use in the low to moderate heat processing sector which can be served by hydrothermal energy is $74 \times 10^{12}$ Btu/yr, with a growth potential to $1476 \times 10^{12}$ Btu/yr by the year 2020.

Table III

TOP 20 INDUSTRIAL PROCESS HEAT APPLICATIONS DIRECTLY MATCHED(a) FOR GEOTHERMAL ENERGY REPLACEMENT IN THE RMB&R REGION
(x $10^{12}$ BTU/HR)

| Industry | Matched 1975 Energy Use(b) |
|---|---|
| Dehydrated Fruits & Vegetables | 11.80 |
| Concrete Block | 7.10 |
| Frozen Fruits & Vegetables | 5.24 |
| Poultry Dressing | 4.82 |
| Meat Packing | 4.45 |
| Prepared Feeds | 3.65 |
| Plastic Materials | 3.63 |
| Dairy Industry | 3.24 |
| Soft Drinks | 2.91 |
| Soaps | 1.24 |
| Inorganic Chemicals | 1.06 |
| Ready-Mix Concrete | .98 |
| Gypsum | .97 |
| Canned Fruits & Vegetables | .97 |
| Beet Sugar | .82 |
| Treated Minerals | .69 |
| Cotton Seed Oil Mills | .34 |
| Prepared Meats | .34 |
| Pharmaceuticals | .25 |
| Furniture | .21 |

(a) Industries matched by co-location with resources and compatible process temperatures in those counties having hydrothermal resources.

(b) Regional consumption of direct heat energy in 1975 replaceable by hydrothermal energy from co-located and temperature-matched resources.

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Market growth projections for hydrothermal energy in the ten-state area analyzed present an attractive profile. From the data illustrated in Figure 2, it is evident that a substantial portion of the region's energy needs can be satisfied by hydrothermal energy. Competition from conventional energy sources, as well as other alternative energy types (solar, biomass, etc.) result in the choice of conservative market penetration rates, as shown by the estimated penetration (bottom) curve.

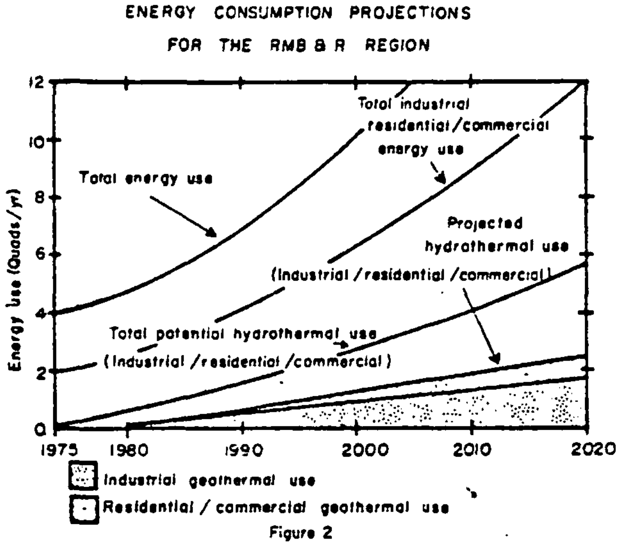

Figure 2

In the U.S., direct applications of hydrothermal energy are minimal, a result of our former abundant, inexpensive fossil fuel supply. However, with reduced fossil fuel supplies and increasing energy requirements, the nation can no longer delay implementing the significant contributions that the direct utilization of geothermal resources can make to meeting energy demands. Reducing resource uncertainties, assisting industry in developing confidence in the applications of hydrothermal fluid, removing unnecessary barriers, solving environmental issues, demonstrating uses, and providing incentives are necessary activities if the objective of widespread utilization of geothermal resources is to be attained. Many applications of geothermal heat are considered straightforward applications of existing technology, but there are applications, such as industrial drying with low- to medium-temperature geothermal fluids, where technical issues remain to be resolved by experiment, demonstration, or analysis. Small-scale and pilot testing are important incentives to demonstration and full-scale applications of industrial processes.

At the Raft River Geothermal Test Site in southcentral Idaho, a highly successful aquaculture experiment has demonstrated the desirability of raising aquatic species directly in geothermal fluids, a fluidized-bed geothermal dryer has converted potato wastes into high protein fish food, and an agriculture/irrigation experiment has explored the benefits and detriments of raising field crops with spent geothermal fluids. In addition, the first U.S. geothermal-powered air conditioner cools a Raft River office building; on-line building space heating is being examined, and new heat exchanger designs are being evaluated for highly corrosive and scaling water applications.

To further promote the development and early commercialization of direct applications, the Department of Energy has issued two Program Opportunity Notices for field experiments. Currently, eight projects are in progress and an additional fourteen are in the contract negotiation stage. The projects are listed in Table IV.

## Table IV

## GEOTHERMAL DIRECT USE FIELD EXPERIMENTS

| Project | Location | Application |
|---|---|---|
| Utah Roses, Inc. | Salt Lake City, UT | greenhouse space heating |
| Utah Energy Office | Salt Lake City, UT | space & water heating |
| Montana Energy & MHD Research & Development Institute, Inc. | Butte, MT | space heating |
| Madison County Energy Commission | Rexburg, ID | district heating & industrial food processing |
| Chilton Engineering | Elko, NV | space & water heating |
| Town of Pagosa Springs | Pagosa Springs, CO | district heating |
| City of Boise | Boise, ID | district heating |
| Haakon School | Philip, SD | space & water heating |
| South Dakota School of Mines | Diamond Ring Ranch, SD | space heating & agribusiness |
| St. Mary's Hospital | Pierre, SD | space heating |
| Ore-Ida Foods, Inc. | Boise, ID | space heating & industrial food processing |
| Monroe City | Monroe, UT | district heating |
| City of Klamath Falls | Klamath Falls, OR | district heating |
| Torbett-Hutchings-Smith Memorial Hospital | Marlin, TX | space & water heating |
| Klamath County YMCA | Klamath Falls, OR | space & water heating |
| City of El Centro | El Centro, CA | space heating & cooling |
| TRW, Inc. | Redondo Beach, CA | industrial food processing |
| Navarro College | Corsicana, TX | space & water heating |
| City of Susanville | Susanville, CA | district heating |
| Geothermal Power Corp. | Novato, CA | space heating & agribusiness |
| Hydrothermal Energy Corp. | Reno, NV | space & water heating |
| Aquafarms International, Inc. | Mecca, CA | aquaculture |

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Each project, with minor variations, is organized to include the following major phases:

a) Environmental Report Preparation
b) Resource Assessment
c) Well Drilling
d) Well Evaluation
e) Corrosion Evaluation
f) Water Disposal Method Decision
g) System Design
h) System Construction
i) System Monitoring

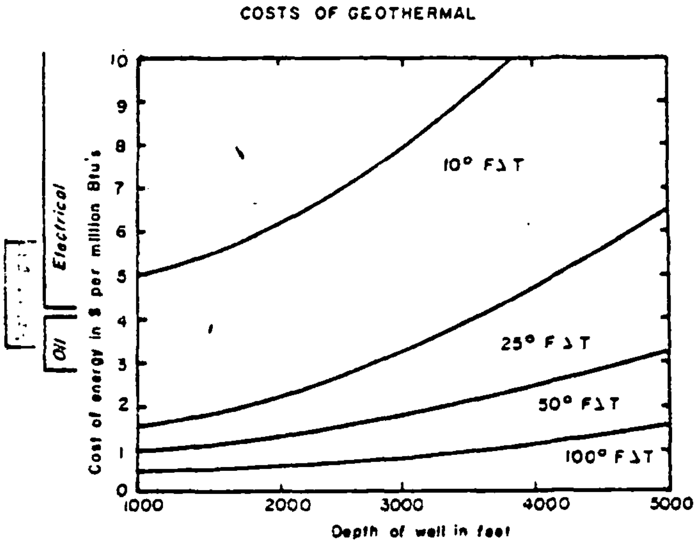
The type and complexity of the current projects vary from space heating and grain drying (Diamond Ring Ranch) to food processing (Ore-Ida Foods, Inc.). While only existing technology is being employed to carry out the projects, they will provide an excellent baseline for future commercial development.

Valuable environmental, technical, operational and economic information will be generated as a result of these projects. In addition, institutional barriers will be tested, private firms and organizations will gain experience, and public awareness of hydrothermal energy will be increased.

Since it is difficult to discuss direct application economics except in a generic manner, these projects are especially important to the development of the hydrothermal market. Economics are extremely site and application dependent. Major factors which determine the economics are:

a) Depth of Resource
b) Geophysical Surveys Required
c) Utilization Factor
d) $\Delta T$ Available
e) Pumping Costs
f) Disposal Method Required
g) Fluid Transmission Distance
h) Water Quality
i) Heat Exchanger Surface Area Required
j) Cost of Investment Capital
k) Taxation Position of Developer/User

Figure 3 illustrates the importance of using as much of the energy as possible. If only a 10°F ΔT is available for use, the resource must be shallow and near its utilization point, whereas the project economics are greatly improved if ΔT's of 50 to 100°F can be obtained. Estimates from the field experiments program and actual cost data from several private developments yield energy cost rates from $.46/MBtu to $5.83/MBtu.



Plot assumes 500 gpm production and one mile of main distribution pipe

Figure 3

ELECTRIC APPLICATIONS

The lower temperature limit for economic electric power generation approaches 170 to 180°C. Since many of the presentations at this symposium will discuss power cycles, power economics, resource definition and reservoir engineering for electric power production, only a brief description of the research being performed to include the moderate-temperature resources into the "economic" power production range is discussed herein.

As one of the initial steps in the application of moderate-temperature hydrothermal resources to electrical power production, a prototype power plant, rated at 60 kW, was constructed in Idaho's Raft River Valley. This was the first time a binary cycle generated electricity from medium-temperature geothermal fluid and supplied power to a commercial grid. Isobutane is being used as the working fluid in this system. The primary function of this facility is to test advanced components and systems, and to gain actual operating experience.

Attempts to find less expensive devices to transfer heat are also continuing. Both fluidized-bed and direct-contact heat exchangers have been developed. Models of fluidized-bed exchangers, which use a bed of floating sand to scrub the scale from heat-exchanger tubing, were tested to analyze their flow-distribution characteristics. It now appears, however, that component development will center on direct-contact exchangers in which the secondary fluid mixes with the hot geothermal fluid.

A second prototype system, a 500 kW direct contact heat exchanger pilot plant, is being designed by Barber Nichols Company for the Lawrence Berkeley Laboratory. This system will be tested at Raft River in the fall of 1979. It will be the first test of a binary geothermal system with heat exchangers large enough to eliminate size effects.

As an outgrowth of this research and development work, a 5 MW(e) binary cycle pilot plant is being built at Raft River, Idaho. This plant will utilize state-of-the-art components, but will employ a dual boiling power cycle using isobutane as a working fluid. It is designed to take maximum advantage of the valley's low seasonal temperatures which are typical of the intermountain west. Design work was completed in January of 1978, and construction initiated in August, 1978. The facility should begin operation by mid-1980.

The 5 MW(e) plant will require about 2250 gallons per minute of 143°C geothermal fluid. The Raft River well field has four deep production wells. These wells will produce a flow of approximately 2850 gallons per minute, which is sufficient to operate both the power plant and auxiliary experiments. The production wells range in depth from 5000 to 6500 feet, and draw geothermal water from a zone of fractures 3750 to 6000 feet deep.

To protect the shallow groundwaters, and to prevent subsidence or ground settling, the expended hydrothermal fluid will be injected back into the ground. The Raft River well field contains three medium-depth injection wells. Tests are presently being conducted to determine their ability to accept long-term injection.

This research and development work, coupled with industry participation, will be instrumental in determining the economic and technical feasibility of the use of moderate-temperature resources for electric power production.

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GEOPHYSICS, VOL. 47, NO. 12 (DECEMBER 1982); P. 1716-1723, 11 FIGS., 1 TABLE

# Bottom-hole temperature stabilization with continued circulation of drilling mud

M. F. Middleton*

## ABSTRACT

Determination of true formation temperature from measured bottom-hole temperature (BHT) is important for well log interpretation and geothermal studies, especially with the current realization of the role of temperature in hydrocarbon maturation. A "bulk" thermal diffusivity of the borehole-rock system of approximately 0.003 $cm^2/sec$, initially suggested by Leblanc et al (1982), is confirmed by comparison with a two-media borehole model. In general, time-consecutive BHT measurements exhibit slower stabilization than those predicted by thermal conduction models. A simple model of thermal stabilization of a borehole with continued circulation after cessation of drilling is proposed. By modeling the thermal sink due to continued circulation of drilling mud as an exponentially decaying sink, thermal stabilization curves more consistent with observation are obtained. A good estimate of true formation temperature can be obtained by a curve-matching technique where the observed BHT data are well behaved and the physical conditions in the borehole closely match the assumed model. However, it is virtually impossible in some cases to obtain a precise estimate of true formation temperature with BHT measurements from well log runs with current BHT stabilization models.

## INTRODUCTION

Determination of true formation temperature from measured bottom-hole temperatures (BHT) is important for well log analyses, geothermal investigations, and hydrocarbon maturation studies. One such method for determining true formation temperature was presented by Middleton (1979) using a square borehole model. Leblanc et al (1982) discussed BHT stabilization in a circular cross-section hole. The method used to determine true formation temperature from measured BHTs is a curve-matching technique in which thermal stabilization is assumed to be due to radial conduction of heat into the borehole. Leblanc et al (1982) found a "bulk" thermal diffusivity $k_b$ of about 0.003 $cm^2/sec$ to approximate physically the thermal properties of the rock-mud medium of the cylindrical borehole filled with drilling mud and surrounded by rock of thermal diffusivity about 0.01 $cm^2/sec$.

These models assume simple heat conduction from a radial or square borehole, initially with a mud temperature some tens of degrees less than the formation temperature of the surrounding rock. In many cases, however, this model poorly explains observed BHT stabilization with time, possibly a result of continued circulation of drilling mud for several hours after drilling has ceased or short-period variations in groundwater circulation.

This paper examines the thermal properties of saturated porous rock and drilling mud in order to test the validity of using a bulk thermal diffusivity for the rock-mud borehole thermal system. A model of thermal stabilization with continued slow circulation of drilling fluids in the borehole after circulation has ceased is also presented. Continued circulation of drilling fluids is modeled as an exponentially-decaying thermal sink of arbitrary time constant; using a bulk thermal diffusivity for the rock-mud borehole system allows considerable simplification of the mathematical analysis. This model explains commonly observed BHT stabilization which does not appear to conform to predicted thermal stabilization by thermal conduction alone.

## OBSERVED BOREHOLE STABILIZATION

Typical plots of BHT stabilization data in deep petroleum exploration wells from the Cooper basin in central Australia are shown in Figure 1. Several temperature readings were taken in conjunction with geophysical well log runs less than 40 hours after drilling ceased, although the majority were taken within 20 hours. Figures 1a and 1b show what may be termed good thermal recovery data where the consecutive BHTs converge with time toward the true formation temperature. Figures 1c to 1f show less well-behaved data. Measurements particularly difficult to interpret were those made less than 20 hours after the cessation of drilling (Figure 1d) and those exhibiting slow onset of recovery toward the true formation temperature (Figure 1f).

A thermal stabilization model assuming a bulk thermal diffusivity of approximately 0.003 $cm^2/sec$ was proposed by Leblanc et al (1982) to explain BHT stabilization by thermal conduction. For a cylindrical borehole with a bulk thermal diffusivity $k_b$, the temperature $BHT(t)$ at the center of the borehole of radius $a$ which is initially at drilling mud temperature $T_m$ and surrounded by rock of formation temperature $T_f$ is given by:

$$BHT(t) = T_m + \Delta T[\exp(-a^2/4k_b t)]. \tag{1}$$

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Manuscript received by the Editor October 22, 1981; revised manuscript received May 26, 1982.

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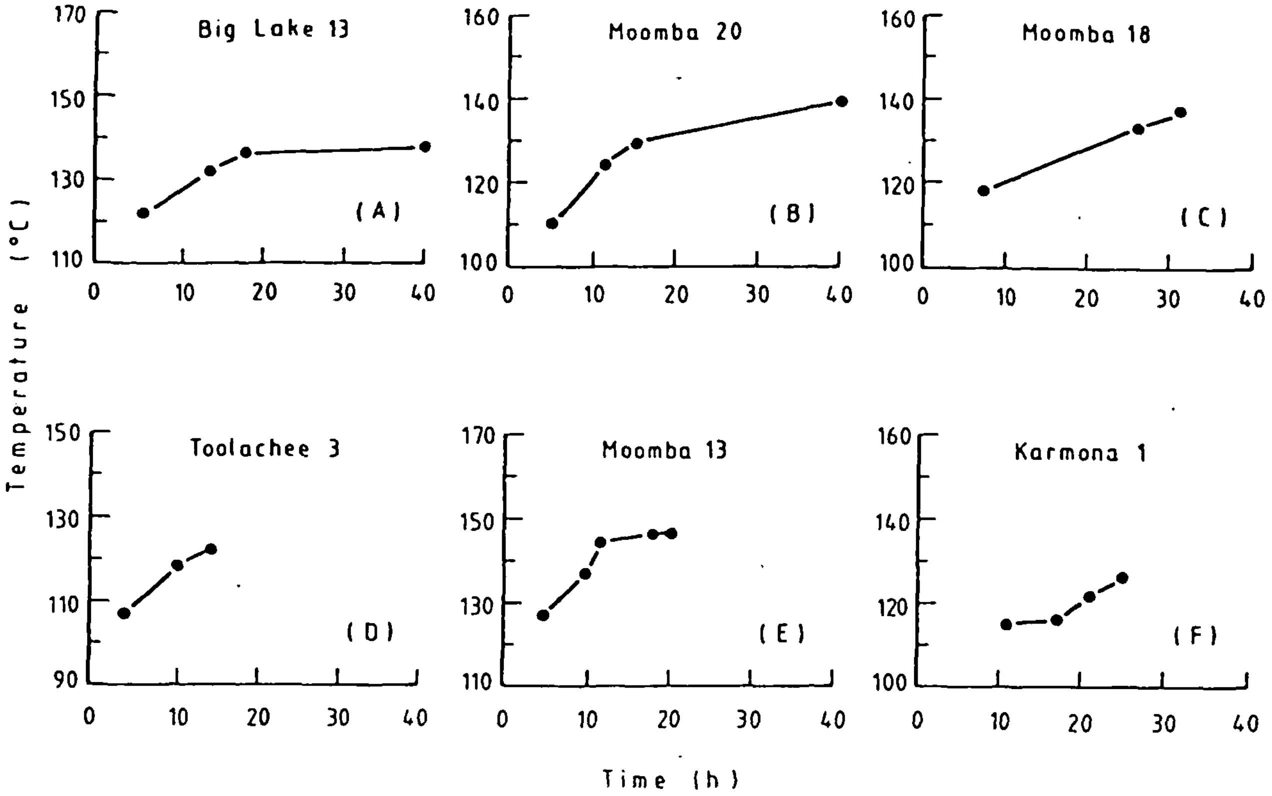

FIG. 1. Observed BHT stabilization data from deep petroleum wells in the Cooper basin, central Australia.

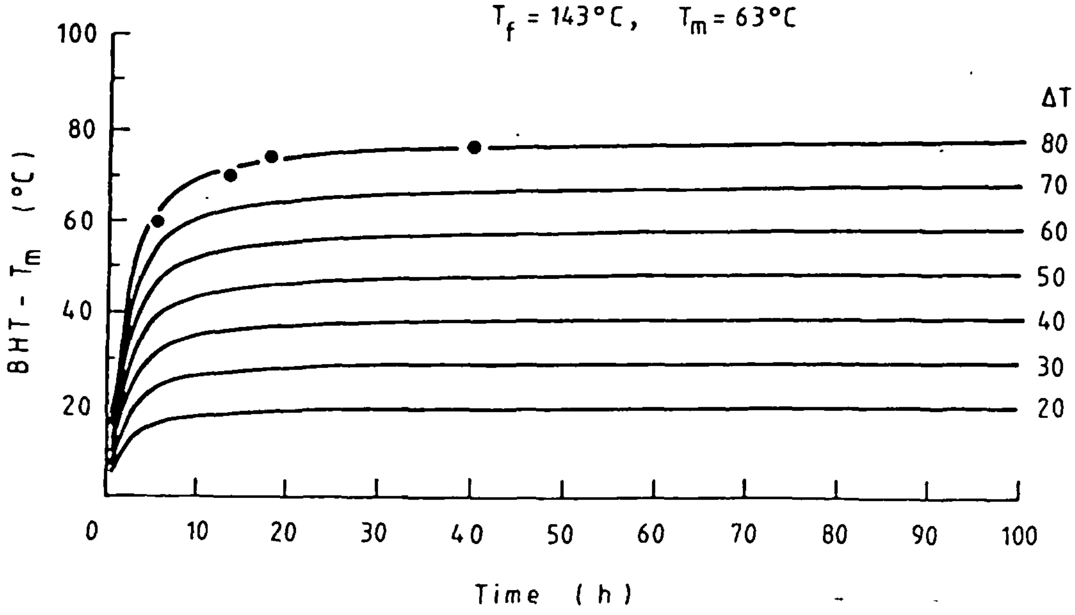

FIG. 2. Set of thermal stabilization curves based on equation (1) for various values of $\Delta T$, with Big Lake 13 data included.

where $t$ is the time after cessation of drilling and $\Delta T = T_f - T_m$.

Figure 2 shows a set of curves of $(BHT - T_m)$ versus time after drilling has ceased, based on equation (1) for various values of $\Delta T$, with borehole radius of 10 cm and a $k_b$ of 0.003 cm$^2$/sec. Figure 2 also shows data from Big Lake 13 well which have been matched by eye to the $\Delta T = 80°C$ model curve with $T_m$ = 63°C and $T_f$ = 143°C. Figure 2 demonstrates that, provided the assumption of a $k_b$ of 0.003 cm$^2$/sec is correct, data of the type shown in Figure 1a are explained by the conduction stabilization model. The conduction model indicates rapid thermal recovery in the first 10 hours after drilling has stopped. However, observed BHTs often exhibit a slower rate of recovery (Figures 1b to 1f). Continued circulation of drilling fluids appears to play a significant role in temperature stabilization.

## THERMAL PROPERTIES OF THE ROCK-MUD BOREHOLE SYSTEM

Four important physical quantities to be considered in the thermal recovery problem are thermal conductivity $K$, specific heat $c$, density $\rho$, and thermal diffusivity $k$. These quantities are related by the equation:

$$k = K/\rho c. \tag{2}$$

In the case of the thermal recovery of a borehole, the bulk characteristics of the formation rocks and borehole should be determined. Bear (1972) and Leblanc et al (1982) suggested the following relationships for saturated porous media:

$$K_b = K_w \phi + K_s(1 - \phi), \tag{3}$$

$$c_b = c_w \phi + c_s(1 - \phi), \tag{4}$$

and

$$\rho_b = \rho_w \phi + \rho_s(1 - \phi), \tag{5}$$

where $\phi$ is porosity, the fraction of pore volume to the total volume, and the subscripts $b$, $w$, and $s$ represent bulk, fluid, and solid, respectively. Thus the bulk physical property is a linear (or series) combination of the fluid and solid components. Bear (1972) suggested parallel and other combinations of the fluid and solid components; these other bulk determinations give values very similar to those calculated by equations (3) to (5). The nonlinear expression for $K_b$ of Sass et al (1971) gives similar values as equation (3). However, the consistent set of linear equations relating $\phi$ to the above physical parameters [equations (3) to (5)] is adopted here. Bulk thermal diffusivity is determined by substituting equations (3) to (5) in equation (2). It is important to note that the bulk thermal diffusivity determined in this fashion is that of either rock or mud, but not of the whole borehole system. The bulk thermal diffusivity of the borehole system is determined by varying $k_b$ in equation (1) to obtain the optimum match, with the thermal stabilization model using true values of the rock (formation) thermal diffusivity $k_f$ and mud thermal diffusivity $k_m$. The two-media stabilization model and subsequent comparison with equation (1) to determine $k_b$ is presented in the following section.

For water at 100°C, $K_w$ = 0.0016 cal cm$^{-1}$sec$^{-1}$°C$^{-1}$, $c_w$ = 1.0076 cal g$^{-1}$°C$^{-1}$, $\rho_w$ = 0.9584 g/cm$^3$, and $k_w$ = 0.0017 cm$^2$/sec (Kappelmeyer and Haenel, 1974, p. 223). Drilling muds have densities in the range 1.1 to 1.2 g/cm$^3$. A bentonite mud has a porosity range from equation (5) of 0.86 to 0.77, assuming the density of the bentonite clay to be 2.0 g/cm$^3$. The mud bulk thermal parameters are shown in Table 1 for porosities 0.86 and 0.77. Similarly, the thermal properties of saturated porous rock are described by equations (2) to (5). Deep bores commonly bottom in rock of porosity in the range 10 to 20 percent (Athy, 1930). Table 1 shows rock bulk thermal parameters for porosities 0.10 and 0.20 with the tabulated values of fluid and solid component parameters.

Table 1. Assumed parameters.

| Physical parameter | Mud | | Rock | |
|---|---|---|---|---|
| | $\phi = 0.86$ | $\phi = 0.77$ | $\phi = 0.10$ | $\phi = 0.20$ |
| $K_b$(cal cm$^{-1}$sec$^{-1}$°C$^{-1}$) | 0.0021 | 0.0024 | 0.0065 | 0.0059 |
| $c_b$(cal g$^{-1}$°C$^{-1}$) | 0.90 | 0.82 | 0.28 | 0.36 |
| $\rho_b$(g/cm$^3$) | 1.10 | 1.20 | 2.48 | 2.31 |
| $k_b$(cm$^2$/sec) | 0.0021 | 0.0024 | 0.0094 | 0.0071 |

| Parameter | Value |
|---|---|
| $\rho_w$(g/cm$^3$) | 0.9584 |
| $c_w$(cal g$^{-1}$°C$^{-1}$) | 1.0076 |
| $K_w$(cal cm$^{-1}$sec$^{-1}$°C$^{-1}$) | 0.0016 |
| $\rho_{clay}$(g/cm$^3$) | 2.00 |
| $c_{clay}$(cal g$^{-1}$°C$^{-1}$) | 0.20 |
| $K_{clay}$(cal cm$^{-1}$sec$^{-1}$°C$^{-1}$) | 0.005 |
| $\rho_s$(g/cm$^3$) | 2.65 |
| $c_s$(cal g$^{-1}$°C$^{-1}$) | 0.20 |
| $K_s$(cal cm$^{-1}$sec$^{-1}$°C$^{-1}$) | 0.007 |

For the two-media borehole model, the drilling mud is assumed to have thermal conductivity $K_m$ of 0.002 cal cm$^{-1}$ sec$^{-1}$°C$^{-1}$ and thermal diffusivity $k_m$ of 0.002 cm$^2$/sec, and the formation is assumed to have thermal conductivity $K_f$ of 0.006 cal cm$^{-1}$ sec$^{-1}$°C$^{-1}$ and thermal diffusivity $k_f$ of 0.008 cm$^2$/sec.

## TWO-MEDIA CYLINDRICAL BOREHOLE MODEL

The two-media cylindrical borehole stabilization model is physically similar to the model presented by Leblanc et al (1982), with the added assumption of different thermal properties inside and outside the borehole. This type of problem was discussed by Carslaw and Jaeger (1959, p. 345–346) who gave the solution to the specific problem of the stabilization of a cylindrical region initially at a temperature $V$ surrounded by an infinite region initially at zero temperature. The present problem is the reverse of that situation; the region $0 \le r < a$ is initially at the (cooler) mud temperature $T_m$ and the region $r > a$ is initially at the (hotter) formation temperature $T_f$. The problem is treated using the Laplace transformation, and full analysis is given in the Appendix.

The temperature at the center of the borehole is given by:

$$T(0, t) = T_f - \frac{4(T_f - T_m)}{\pi^2 a} \int_0^\infty \exp(-k_m t u^2) \cdot \frac{J_1(ua)\,du}{u^2[A^2(u) + B^2(u)]}, \tag{6}$$

where

$$A(u) = (K_m/K_f)^{1/2} J_1(au) J_0(\kappa a u) - \kappa (K_f/K_m)^{1/2} J_0(au) J_1(\kappa a u), \tag{7}$$

$$B(u) = (K_m/K_f)^{1/2} J_1(au) Y_0(\kappa a u) - \kappa (K_f/K_m)^{1/2} J_0(au) Y_1(\kappa a u), \tag{8}$$

$$\kappa = (k_m/k_f)^{1/2},$$

with $J_0(x)$, $J_1(x)$, $Y_0(x)$, and $Y_1(x)$ as the Bessel functions of order zero and 1.

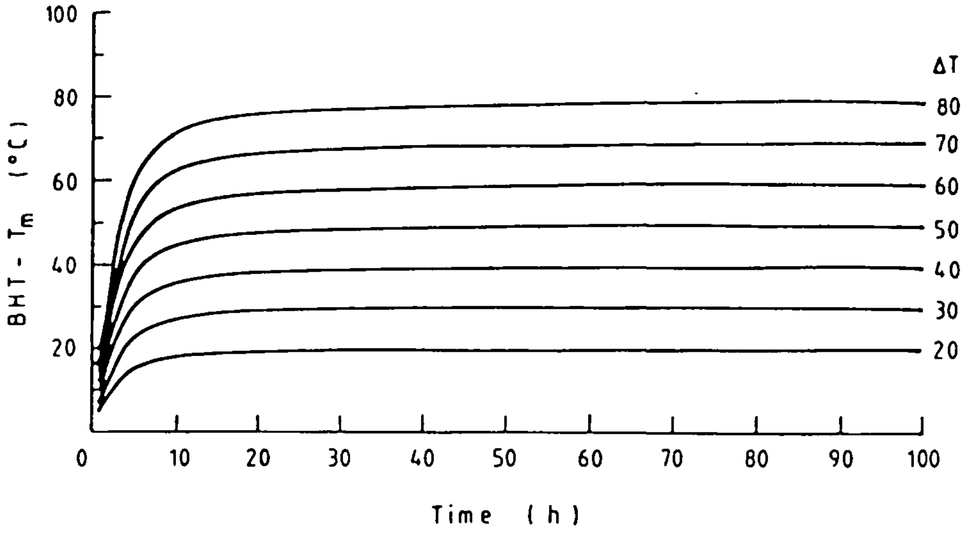

FIG. 3. Thermal stabilization by conduction of a two-media borehole as a function of time after cessation of drilling, based on equation (6), for various values of $\Delta T$ and typical mud and rock thermal properties: $K_m = 0.002$ cal cm$^{-1}$sec$^{-1}$°C$^{-1}$, $K_f = 0.006$ cal cm$^{-1}$sec$^{-1}$°C$^{-1}$, $k_m = 0.002$ cm$^2$/sec, and $k_f = 0.008$ cm$^2$/sec.

Figure 3 shows the thermal stabilization of a borehole as a function of time after cessation of drilling, using this model for various values of $\Delta T = T_f - T_m$ and assuming $a = 10$ cm, $k_m = 0.002$ cm$^2$/sec, $K_m = 0.002$ cal cm$^{-1}$sec$^{-1}$°C$^{-1}$, $k_f = 0.008$ cm$^2$/sec, and $K_f = 0.006$ cal cm$^{-1}$sec$^{-1}$°C$^{-1}$.

Figure 4 shows single-medium stabilization curves with bulk thermal diffusivities of 0.008, 0.003, and 0.002 cm$^2$sec$^{-1}$ compared with the two-media model in Figure 3 with $\Delta T = 60$°C. The model with a bulk thermal diffusivity of 0.003 cm$^2$/sec most consistently approximates the two-media model for times less than 15 hours when most BHT measurements are made. After 15 hours all models asymptotically approach stabilization. Figure 5 shows the difference between the 0.003 cm$^2$/sec bulk thermal diffusivity model and the two-media model for various values of $\Delta T$. Essentially, the 0.003 cm$^2$/sec bulk thermal diffusivity model provides a good approximation to the more physically correct two-media stabilization model. The simplification of using a bulk thermal diffusivity greatly reduces the complexity of the analysis of the borehole thermal recovery model with the continued thermal sink boundary condition.

## THERMAL RECOVERY WITH CONTINUED CIRCULATION

Some of the thermal recovery curves shown in Figure 1 are poorly explained by the simple thermal conduction stabilization

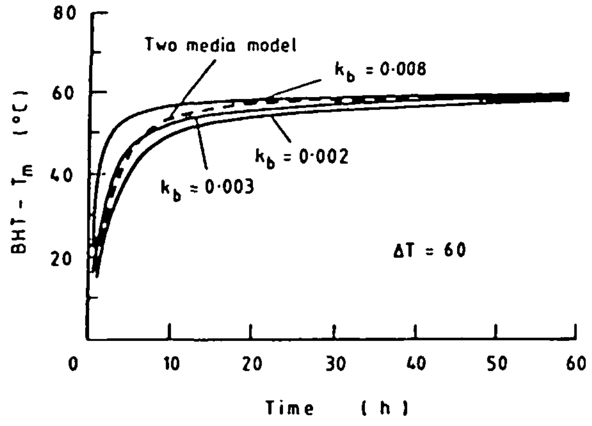

FIG. 4. Comparison of the two-media borehole stabilization curves with single-medium borehole stabilization curves, based on equation (1), with various values of $k_b$ for $\Delta T = 60$°C.

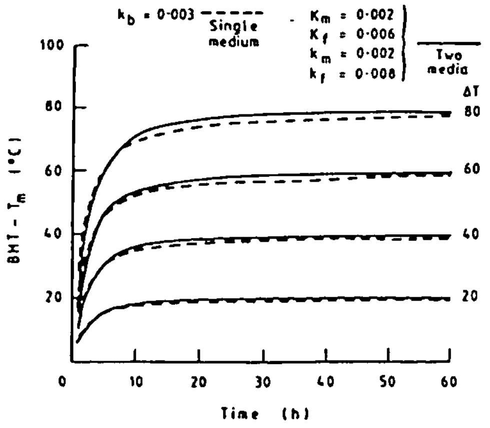

FIG. 5. Sets of thermal stabilization curves, based on equations (1) and (6), which describe the single medium and the two-media models, respectively.

model, and they may be more satisfactorily described by a model entailing continued circulation of drilling fluids after drilling has ceased, in which case the fluids prevent thermal stabilization of the borehole by conduction alone. Essentially, the circulating fluids maintain the cooler mud temperatures in the hole. Such behavior is similar to a thermal sink which decays with time. Because the behavior of settling of the circulating mud is unknown, for mathematical simplicity its effect is represented by an exponentially decaying thermal sink. The problem is approached by expressing the temperature distribution as the sum of (1) the temperature distribution due to instantaneous sources, and (2) the temperature distribution due to heat loss from the sink. A cylindrical borehole with radial transfer of heat is assumed (see Figure 6). Initial physical conditions are similar to those in the model presented by Middleton (1979).

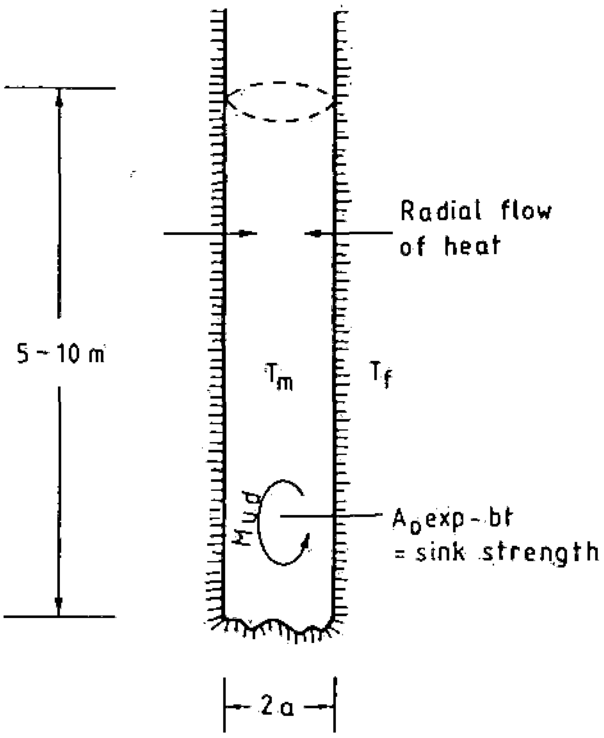

FIG. 6. Schematic diagram of the assumed physical model of the basal section of a borehole; $A_0$ is the initial sink strength and $b$ is the time constant of the decaying sink.

### Solution for instantaneous sources

This result was derived by Leblanc et al (1982) for the thermal stabilization of a cylindrical borehole by conduction of heat. The temperature distribution $T(0, t)$ at the center of the borehole ($r = 0$) is given by equation (1), where $\Delta T = T_f - T_m$ and $\mathrm{BHT}(t) = T(0, t)$.

### Solution for an exponential sink

The temperature distribution for a sink of exponentially decreasing magnitude is found by integration of the expression for the continuous point source over an infinite region.

The expression for a continuous point source is [Carslaw and Jaeger, 1959, p. 261, equation 10.4(1)]:

$$T(r, t) = \frac{1}{8(\pi k_b)^{3/2}} \int_0^t \frac{\phi(t')}{(t - t')^{3/2}} \exp[r^2/4k_b(t - t')]\,dt', \quad (9)$$

where $r^2 = (x - x')^2 + (y - y')^2 + (z - z')^2$, with the location of the sink at $(x', y', z')$, the location of observation at $(x, y, z)$, and $\phi(t)$ the strength of the transient heat sink. Equation (9) is expressed in cylindrical coordinates as

$$T(r, \theta, z, t) = \frac{1}{8\rho c(\pi k)^{3/2}} \int_0^t \frac{A(t') \exp\left[-\frac{(z - z')^2}{4k_b(t - t')}\right] \exp\left[-\frac{rr' \cos\theta'}{2k_b(t - t')}\right] \exp\left[-\frac{(r^2 + r'^2)}{4k_b(t - t')}\right]}{(t - t')^{3/2}} r'\,dr'\,d\theta'\,dz'\,dt', \quad (10)$$

where $\phi(t') = A(t')r'\,dr'\,d\theta'\,dz'/\rho c$. This point source is integrated over the infinite space; $-\infty < z < \infty$, $0 < \theta < 2\pi$, $0 < r < \infty$ with generation of heat only in the cylindrical volume $0 < r < a$, $-\infty < z < \infty$. The temperature distribution is now expressed by

$$T(r, t) = \frac{1}{2k\rho c} \int_0^t \frac{A(t')\,dt'}{(t - t')} \int_0^a I_0\left[\frac{rr'}{2k_b(t - t')}\right] \cdot$$

$$\cdot \exp\left[-\frac{(r^2 + r'^2)}{4k_b(t - t')}\right] r'\,dr', \quad (11)$$

where $I_0(x)$ is a modified Bessel function of zero order. Evaluating equation (11) on the axis $r = 0$ and performing the integration, the temperature distribution is

$$T(0, t) = (1/\rho c) \int_0^t A(t')\{1 - \exp[-a^2/4k_b(t - t')]\}\,dt'. \quad (12)$$

In the present problem $A(t)$ is assumed to be $A_0 \exp(-bt)$, where $b$ is the time constant of the decaying thermal sink. Equation (12) then becomes

$$T(0, t) = (A_0/b\rho c)[1 - \exp(-bt)] - (A_0/\rho c) \cdot$$

$$\cdot \exp(-bt) \int_0^t \exp(bu - \beta/\mu)\,du, \quad (13)$$

where $\beta = a^2/4k_b$. Equation (13) is the temperature perturbation due to the sink of magnitude $A_0 \exp(-bt)$. An equivalent sink temperature $T_s$ is defined as

$$T_s = A_0/b\rho c. \quad (14)$$

$T_s$ may be considered the temperature which is necessary to produce the sink of magnitude $A_0$ at time $t = 0$. The sink may be defined as

$$A(t) = b\rho c T_s \exp(-bt). \quad (15)$$

## THE COMPLETE SINK MODEL

The complete model is obtained by subtracting the temperature perturbation of the sink [equation (13)] from the temperature distribution due to stabilization by conduction [equation (1)]. The

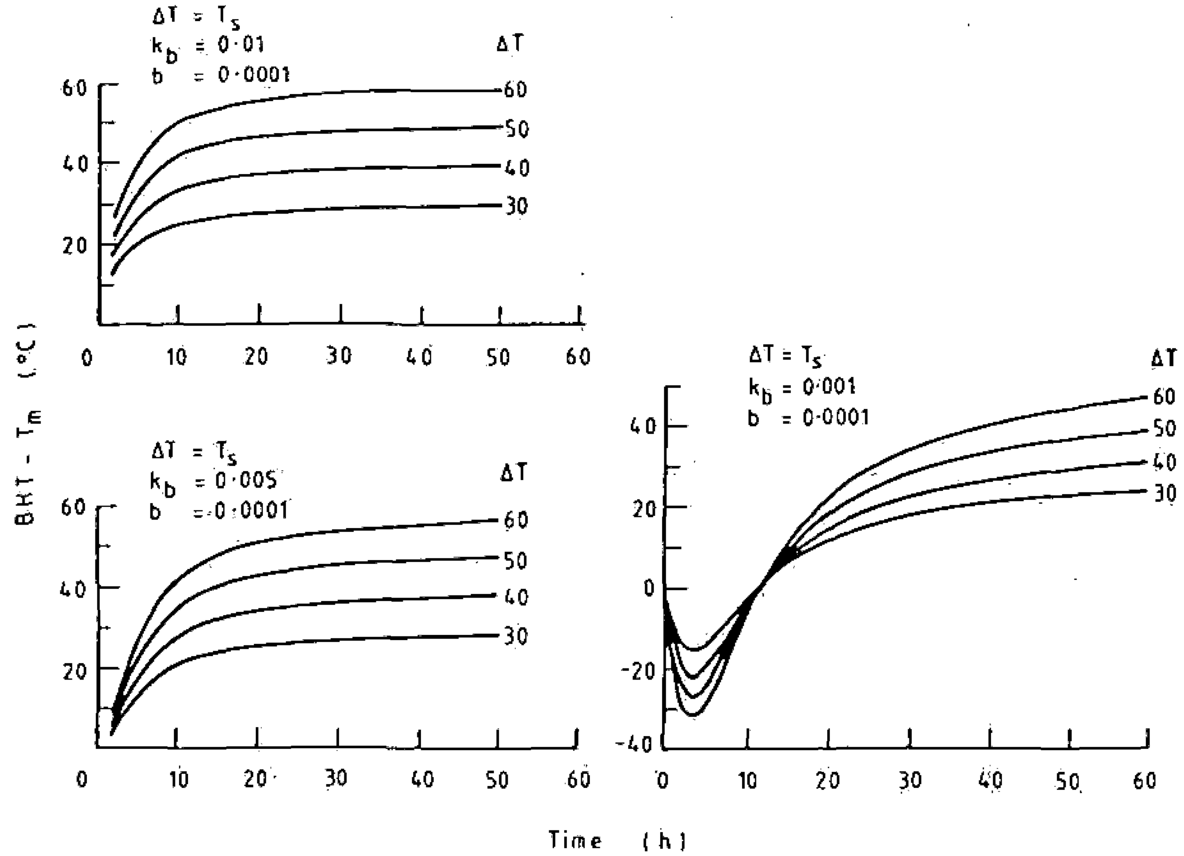

FIG. 7. A plot of (BHT $-$ $T_m$) versus time after completion of drilling, from equation (16), for various values of $\Delta T$ and $k_b$ with the assumption that $T_s = \Delta T$. The variable nature of stabilization for differing $k_b$ is clearly seen.

complete solution for the temperature at the center of the borehole ($r = 0$) as a function of time is

$$T(0, t) = [T_m - (T_f - T_m) \exp(-a^2/4k_b t)] - T_s[1 - \exp(-bt)] + bT_s \exp(-bt) \int_0^t \exp(bu) \exp(-\beta/u)\,du, \quad (16)$$

which must be evaluated numerically.

Figure 7 shows a plot of the BHT, given by equation (15), minus $T_m$ versus time after completion of drilling for various values of $\Delta T(=T_f - T_m)$, $k_b$, and $b$ assuming $T_s = \Delta T$. The assumption that $T_s = \Delta T$ may in many cases provide a good approximation of $T_s$. With $T_s \ll \Delta T$, the model approaches the conduction case in equation (1). With $T_s \gg \Delta T$, the model gives BHTs in the first 10 or so hours after completion of drilling approaching zero or less degrees which is physically unacceptable. Figure 8 shows the behavior of (BHT $-$ $T_m$) versus time after

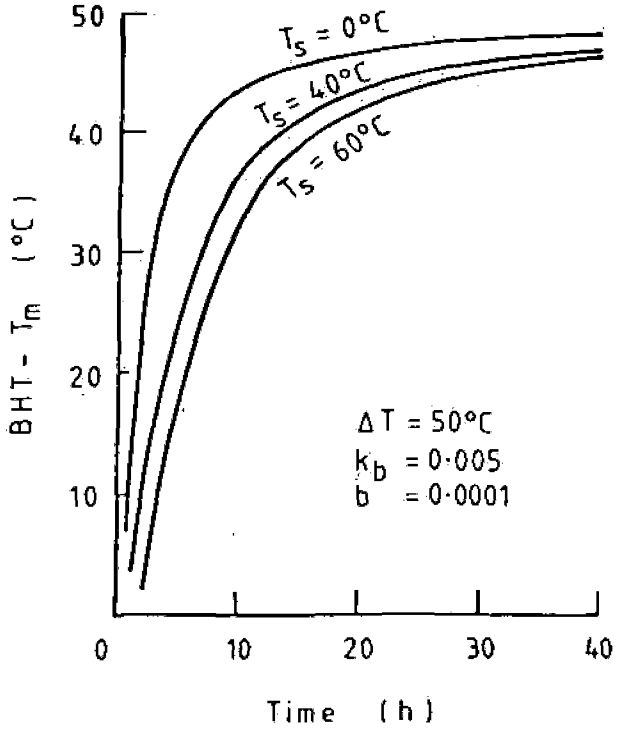

FIG. 8. A plot of (BHT $-$ $T_m$) versus time after completion of drilling for constant $k_b$, $\Delta T$, and $b$ with variable $T_s$, the magnitude of the thermal sink due to circulation. Considerable difference occurs between the simple conduction model ($T_s = 0$) and the circulation models in the time interval (5 to 20 hours) when BHT measurements are generally made.

completion of drilling for a constant $k_b$ (0.005 cm²/sec) and $b$ (0.0001 sec⁻¹) with $\Delta T = 50°C$ and various values of $T_s$. The assumption of $T_s = \Delta T$ appears reasonable from the present preliminary study.

Figure 9 shows the behavior of $(BHT - T_m)$ versus time after completion of drilling for $T_s = \Delta T = 60°C$ and $k_b = 0.003$ cm²/sec with various values of the thermal sink time constant $b^{-1}$. Large $b$ models a small duration of circulation after completion of drilling, and small $b$ models a large duration of circulation. Models with large $b$ approach the conduction stabilization model of equation (9). Figure 9 essentially demonstrates that a given amount of heat

$$\int_0^{\infty} c\rho T_s \exp(-bt)\,dt$$

per unit volume has less effect on the cooling of the borehole if released over a large period of time, that is, the $b = 0.0001$ sec⁻¹ curve most closely approaches the curve for conduction without a source $(A_0 = 0)$. For $b = 0.0001$ sec⁻¹, $A/A_0 = \exp(-1) = 0.3679$ after 2.78 hours. A $b$ value of 0.0001 sec⁻¹ is the most representative sink time constant, because $b$ values less than this have inordinately long circulation times, and higher $b$ values produce only slight variation in the stabilization curve.

Figure 10 illustrates the thermal sink model for the optimum $k_b$ value of 0.003 cm²/sec with $T_s = \Delta T$ and $b = 0.0001$ sec⁻¹ for various values of $\Delta T$. The curves in this figure approach the formation temperature more slowly than the simple conduction stabilization curves. Figure 11 shows the Toolachee 1 and Moomba 13 data matched to the curves plotted in Figure 10. These data appear to be consistent with the circulation model for $T_s = \Delta T$ and $b = 0.0001$ sec⁻¹.

## DISCUSSION

The present model, approximating the thermal sink effects of continued mud circulation after cessation of drilling as a decaying exponential sink, produces BHT stabilization curves consistent with the slower return to formation temperature common to many wells (Figure 11).

The very slowly stabilizing wells (for example, Figures 1c, 1e and 1f) can be explained by the very low bulk thermal diffusivity models ($k_b \leq 0.001$ cm²/sec) shown in Figure 7. The major unknown quantity in the present study is the initial magnitude of the thermal sink caused by circulation ($A_0 = b\rho cT_s$); this sink is a function of "equivalent sink temperature" $T_s$ and the sink thermal decay time constant $b$. Although these quantities are poorly known, this study points to $T_s$ being of similar order of magnitude to $\Delta T$, and $b$ on the order of 0.0001 sec⁻¹. Further studies are needed to determine the range of $T_s$ and $b$ values more precisely.

Figures 3 and 10 can be used to determine true formation temperature by the curve-matching technique described in Middleton (1979). Figure 3 is used in the case of no continued circulation, and Figure 10 is used when circulation after cessation of drilling is suspected. Often, intermediate cases of thermal stabilization occur between the two extremes of Figures 3 and 10. However, interpretation by curve matching to Figures 3 and 10 gives an interpretive range of true formation temperature for a particular set of data. Figure 2 gives a good example of data matching the case of no continued circulation, and Figure 11 gives examples of data consistent with continued circulation. However, many sets of time-consecutive BHT measurements are not well-behaved in the sense of following the predicted stabilization

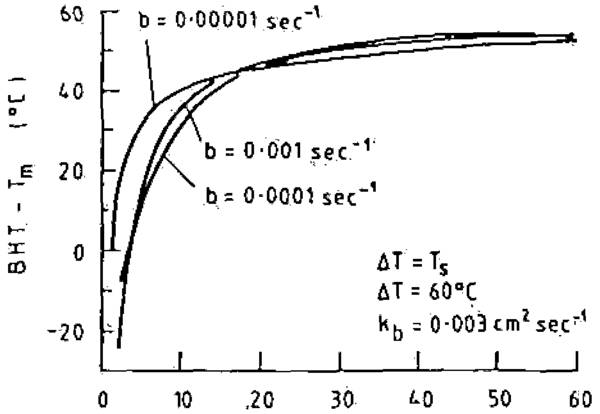

FIG. 9. A plot of $(BHT - T_m)$ versus time after completion of drilling for $T_s = \Delta T = 60°C$ and constant $k_b$ with variable thermal sink time constant $b$.

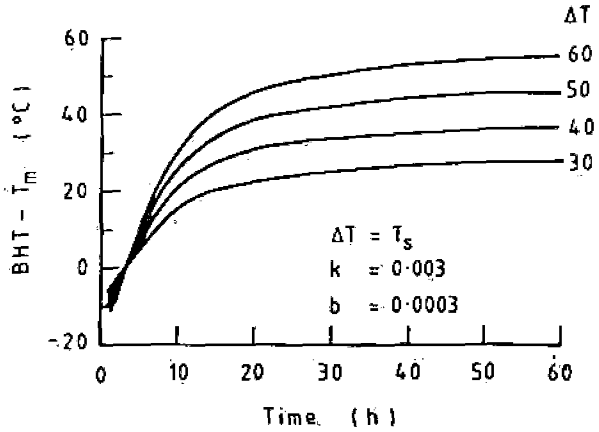

FIG. 10. Set of stabilization curves for the circulation model from equation (16). This set of curves may be used similarly to those of Figures 2 and 5 to determine $T_f$ from a series of BHT measurements. These curves are applicable to the situation of continued mud circulation for approximately 3 hours after drilling has ceased, and an "equivalent sink temperature" approximately equal to $\Delta T$.

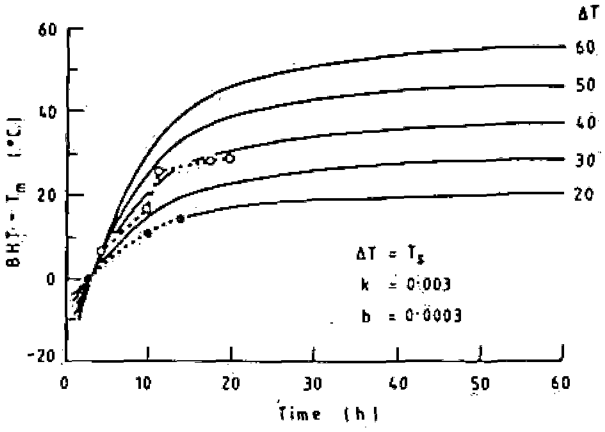

FIG. 11. The Toolachee 1 (•) and Moomba 13 (○) data matched to the curves plotted in Figure 10.

behavior (Figures 1e and 1f). In these cases the present model cannot be applied to give good approximations of true formation temperature, because other physical phenomena such as groundwater circulation or disruption of thermal conditions by well logging activities may apply which have not been considered.

This study shows that it is difficult to interpret a set of time-consecutive BHT measurements made less than 20 hours after drilling has ceased, due to lack of knowledge of the magnitude and duration of mud circulation in the well or borehole. However, estimates of true formation temperature from conduction only and circulation models indicate the range of values in which this temperature may fall for well-behaved data.

## ACKNOWLEDGMENTS

Dave Clark and Dr. John Knight are gratefully acknowledged for reading this manuscript. Support was provided under the National Energy Research, Development and Demonstration Program administered by the Commonwealth Dept. of National Development and Energy.

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## APPENDIX
## TWO-MEDIA CYLINDRICAL BOREHOLE THERMAL STABILIZATION MODEL

The region $0 \leq r < a$ in cylindrical coordinates is the borehole with thermal conductivity $K_m$, thermal diffusivity $k_m$, radius $a$, and initial temperature $T_m$. The region $r > a$ is the sedimentary formation of thermal conductivity $K_f$, thermal diffusivity $k_f$, and initial temperature $T_f$. The problem is to be solved using the Laplace transform; the solution is very similar to that of the special case described by Carslaw and Jaeger (1959, p. 346).

The temperatures in the regions $0 \leq r < a$ and $r > a$ are $T_1$ and $T_2$, respectively. The differential equations governing the present problem are

$$\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r}\frac{\partial T_1}{\partial r} - \frac{1}{k_1}\frac{\partial T_1}{\partial t} = 0,\ 0 \leq r < a,\ t > 0 \quad \text{(A-1)}$$

to be solved with $T_1 = T_m$ at $t = 0$, and

$$\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r}\frac{\partial T_2}{\partial r} - \frac{1}{k_2}\frac{\partial T_2}{\partial t} = 0,\ r > a,\ t > 0 \quad \text{(A-2)}$$

to be solved with $T_2 = T_f$ at $t = 0$. The subsidiary equations are

$$\frac{\partial^2 \bar{T}_1}{\partial r^2} + \frac{1}{r}\frac{\partial \bar{T}_1}{\partial r} - q_1^2\bar{T}_1 = -\frac{T_m}{k_m},\ 0 \leq r < a, \quad \text{(A-3)}$$

and

$$\frac{\partial^2 \bar{T}_2}{\partial r^2} + \frac{1}{r}\frac{\partial \bar{T}_2}{\partial r} - q_2^2\bar{T}_2 = -\frac{T_f}{k_f},\ r > a, \quad \text{(A-4)}$$

with $q_1 = (p/k_m)^{1/2}$, $q_2 = (p/k_f)^{1/2}$, and

$$\bar{T}(p) = \int_0^\infty \exp(-pt)T(t)\,dt.$$

The solution of equation (A-3), the temperature distribution inside the borehole, is

$$\bar{T}_1 = \frac{T_m}{p} - \frac{T_m K_f (k_m)^{1/2}}{pD} I_0(q_1 r)K_1(q_2 a)$$

$$+ \frac{T_f K_f (k_m)^{1/2}}{pD} I_0(q_1 r)K_1(q_2 a), \quad \text{(A-5)}$$

where

$$D = K_2(k_1)^{1/2} I_0(q_1 a)K_1(q_2 a) - K_1(k_2)^{1/2} I_1(q_1 a)K_0(q_2 a),$$

and $I_0(x)$, $I_1(x)$, $K_0(x)$, and $K_1(x)$ are Bessel functions.

The Laplace inversion theorem gives the following expression, which enables inversion of equation (A-5):

$$L^{-1}\left[\frac{VK_2(k_1)^{1/2} I_0(q_1 r)K_1(q_2 a)}{pD}\right]$$

$$= V - \frac{4V}{\pi^2 a}\int_0^\infty \frac{\exp(-k_1 u^2 t)J_0(ur)J_1(ua)\,du}{u^2[A^2(u) + B^2(u)]}, \quad \text{(A-6)}$$

where

$$A(u) = (K_1/K_2)^{1/2} J_1(au)J_0(wau)$$
$$- w(K_2/K_1)^{1/2} J_0(au)J_1(wau),$$
$$B(u) = (K_1/K_2)^{1/2} J_1(au)Y_0(wau)$$
$$- w(K_2/K_1)^{1/2} J_0(au)Y_1(wau),$$

$w = (k_1/k_2)^{1/2}$ and $J_0(x)$, $J_1(x)$, $Y_0(x)$, and $Y_1(x)$ are modified Bessel functions. Equation (A-5) is inverted to

$$T(0,\ t) =$$

$$T_2 - (T_2 - T_1)\frac{4}{\pi^2 a}\int_0^\infty \frac{\exp(-k_1 u^2 t)J_0(ur)J_1(ua)\,du}{u^2[A^2(u) + B^2(u)]}. \quad \text{(A-7)}$$

Equation (6) is obtained by evaluating equation (A-7) at $r = 0$ with $k_1 = k_m$, $T_1 = T_m$, and $T_2 = T_f$.

D. Foley

II

98TH CONGRESS
1ST SESSION

# S. 883

To amend the Geothermal Steam Act of 1970 (30 U.S.C. 1001 et seq.) to expedite exploration and development of geothermal resources.

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IN THE SENATE OF THE UNITED STATES

MARCH 22 (legislative day, MARCH 21), 1983

Mr. McCLURE (for himself, Mr. WARNER, Mr. LAXALT, Mr. HECHT, Mr. SYMMS, and Mr. WALLOP) introduced the following bill; which was read twice and referred to the Committee on Energy and Natural Resources.

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→ Wayne Hamilton

# A BILL

To amend the Geothermal Steam Act of 1970 (30 U.S.C. 1001 et seq.) to expedite exploration and development of geothermal resources.

*Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,* That the Geothermal Steam Act of 1970 (30 U.S.C. 1001 et seq.) is amended as follows:

SECTION 1. This Act may be cited as the "Geothermal Steam Act Amendments of 1983".

SEC. 2. Whenever an amendment or repeal contained in this Act is expressed in terms of amendment to, or repeal of, a section or other provision of "the Act", such reference shall be considered a reference to an amendment to, or repeal of, a provision of the Geothermal Steam Act of 1970 (30 U.S.C. 1001 et seq.; Public Law 91-581).

SEC. 3. Section 2(e) of the Act is amended to read as follows:

"(e) 'known geothermal resource area' means an area in which there is substantial physical evidence including but not limited to the geology or a discovery on such lands, which would, in the opinion of the Secretary, engender a belief in persons experienced in the subject matter that the prospects for extraction of geothermal resources for the primary purpose of generating electricity in commercial quantities warrant substantial expenditures for that purpose.".

SEC. 4. Section 3(2) of the Act is amended to read as follows: "(2) in any lands administered by another Federal agency or department, including public, withdrawn, or acquired lands.".

SEC. 5. Section 4 of the Act is amended—

(a) by deleting the first two sentences, and inserting in lieu thereof the following:

"SEC. 4. (a) If lands to be leased under this Act are within any known geothermal resource area, they shall be leased to the highest responsible qualified bidder by competitive bidding. Any lands so offered and receiving no bids shall be declassified and leased to the first qualified applicant: *Provided*, That the Secretary's authority to reclassify such lands as a known geothermal resource area at a later date on the basis of new evidence shall not be affected. The Secretary may offer not to exceed 5 per centum of all lands offered for sale in any year on a basis other than cash bonus bidding, employing those bidding systems set forth in section 8(a)(1) of the Outer Continental Shelf Lands Act, as amended (43 U.S.C. 1335). The provisions of this subsection shall expire on December 31, 1987.

"(b) If the lands to be leased are not within any known geothermal resource area, the qualified person first making application for the lease shall be entitled to a lease of such lands without competitive bidding, provided the lands applied for are not designated as a known geothermal resource area within one year of the application being filed and before a lease is issued. If an application is rejected due to a known geothermal resource area designation of the lands within one year of the application being filed, the applicant shall have the opportunity to match the highest competitive bid for the parcel when offered, provided the applicant submits a bona fide bid at the sale. However, the applicant or lessee responsible for the exploration resulting in the designation of lands as a known geothermal resource area shall be entitled to noncompetitive leases for all lands in the known geothermal resource area for which the applicant or lessee had first-filing applications on file prior to the approval of any plan of exploration or notice of intent to conduct geophysical exploration.".

(b) by inserting "(c)" before the word "Notwithstanding" at the beginning of the next sentence; and

(c) by redesignating subsections "(a)" through "(f)" as paragraphs "(1)" through "(6)".

SEC. 6. Section 5(a) of the Act is amended to read as follows:

"(a) a royalty of not less than 10 per centum or more than 15 per centum in the case of electrical generation, or of not less than 5 per centum or more than 10 per centum in the case of nonelectrical utilization, of the amount or value, as utilized, of steam, heat, or other form of energy derived from production under the lease and sold or utilized by the lessee or reasonably susceptible to sale or utilization by the lessee. The Secretary may defer royalty payments for nonelectric geothermal developments when it is deemed to be in the public interest, for municipal, cooperative, or other political subdivision lessees where legal limitations on front-end financing otherwise would prohibit or significantly deter development.".

SEC. 7(a). Section 6(a) of the Act is amended to read as follows:

"(a) Geothermal leases shall be for a primary term of ten years. If geothermal resources are produced or utilized in commercial quantities within this term, or any administrative extension thereof as provided pursuant to subsection (c), such lease shall continue for so long thereafter as geothermal resources are produced or utilized in commercial quantities.".

(b) Section 6(b) of the Act is deleted, section 6(c) is redesignated 6(b) and is revised to read as follows:

"(b) Any lease for land on which, or for which under an approved cooperative or unit plan of development or operation, actual drilling operations are commenced prior to the end of its primary term, or any administrative extension thereof as provided in subsection (c), and are being diligently prosecuted at that time shall be extended for five years and so long thereafter as geothermal resources are produced or utilized in commercial quantities.".

(c) Section 6(d) of the Act is redesignated 6(c) and amended to read as follows:

"(c) For purposes of subsection (a) of this section, production or utilization of geothermal resources in commercial quantities shall be deemed to include the completion of one or more producing or producible wells and either a bona fide sale for delivery to a facility or facilities installed or to be installed not later than fifteen years of the commencement date of the lease, or in the case of utilization by the lessee, proof of commitment to construct such utilization facilities. However, in the event construction of the facility or facilities has not been possible due to administrative delays beyond the control of the lessee or due to the demonstrated marginal economics of such a facility or facilities, and substantial investment in development of the lease has been made, the Secretary shall upon petition by the lessee, grant extensions totaling not more than fifteen years beyond the expiration date of the primary lease: *Provided,* That the lessee be required to submit annual reports detailing bona fide efforts to resolve the administrative delays or to bring the facility or facilities into economic production.".

SEC. 8. Section 7 of the Act is amended to read as follows:

"SEC. 7. (a) A geothermal lease shall embrace a reasonably compact area of not more than two thousand five hundred and sixty acres, except where a departure therefrom is occasioned by an irregular subdivision or subdivisions. No person, association, or corporation, except as otherwise provided in this Act, shall take, hold, own, or control at any one time, any direct or indirect interest in Federal geothermal leases in any one State exceeding fifty-one thousand two hundred acres.

"(b) At any time after twenty years from the effective date of the Geothermal Steam Act of 1970, the Secretary, after public hearings, may increase this maximum holding in any one State by regulation, not to exceed one hundred fifteen thousand two hundred acres.

"(c) Any leases which contain a well shown to be capable of commercial production and any lease operated under an approved operating, drilling, or development contract as authorized under section 18 of this Act shall be excepted in determining holdings or control under this section.".

SEC. 9. Section 8(a) of the Act is amended to read as follows:

"SEC. 8. (a) The Secretary may adjust the terms and conditions, except as otherwise provided herein, of any geothermal lease issued under this Act at not less than twenty-year intervals beginning twenty years after the date production is commenced, as determined by the Secretary. Each geothermal lease issued under this Act shall provide for such readjustment. The Secretary shall give notification of any proposed readjustment of terms and conditions, and, unless the lessee files with the Secretary objection to the proposed terms or relinquishes the lease within thirty days after receipt of such notice, the lessee shall conclusively be deemed to have agreed with such terms and conditions. If the lessee files objections, and no agreement can be reached between the Secretary and the lessee within a period of not less than sixty days, the lease may be relinquished by the lessee, or following appropriate judicial proceedings, canceled by the Secretary.".

SEC. 10. Section 15(b) of the Act is amended to read as follows:

"(b) The Secretary shall consult with the head of any other Federal agency or department with respect to lands under its jurisdiction to determine appropriate terms or conditions prior to issuing leases for such lands. However, as to acquired lands of other Federal agencies or departments, the Secretary shall not issue leases on those lands without the consent of the head of that agency or department. The head of the Federal agency or department which administers any land which is subject to a geothermal lease or which is available for geothermal leasing, shall, in making land-use decisions regarding such land or adjacent lands, consider their potential for geothermal resource development.".

SEC. 11. Section 15 of the Act is amended by adding a new subsection (f) to read as follows:

"(f)(1) The Secretary shall not issue any geothermal lease pursuant to this Act in the Island Park Known Geothermal Resource Area adjacent to Yellowstone National Park until the requirements of paragraph (2) have been met.

"(2) Within two years from the date of enactment of this Act, the Secretary is authorized and directed to complete a study to determine whether any thermal geological connection exists between the Island Park KGRA and the thermal features of Yellowstone National Park. In addition, the study shall include an evaluation of and recommendation for monitoring techniques and operating procedures which may be employed in conjunction with any geothermal leasing in the Island Park KGRA, to protect the thermal features of Yellowstone National Park. The study shall be conducted by the United States Geological Survey in consultation with the National Academy of Sciences and the National Park Service. Upon completion of the study, which shall include the findings and recommendations of the Geological Survey and comments by the National Academy of Sciences and the National Park Service, it shall be transmitted forthwith to the Senate Committee on Energy and Natural Resources and the House Committee on Interior and Insular Affairs and made available to the public;

"(3) Sixty days (not counting days on which the House of Representatives or Senate was adjourned for more than three days) after receipt of the study required by paragraph (2), by the appropriate committees the Secretary may issue geothermal leases in the Island Park KGRA, if he determines that: (A) a valuable geothermal resource exists; (B) development of the potential geothermal resource will not adversely affect the thermal features of Yellowstone National Park; and (C) after considering the finding and recommendations of the study, that such leasing will be consistent with the Secretary's duty to protect the thermal features of the park. Costs of any monitoring or operational procedures determined by the Secretary to be necessary shall be borne by the lessee or lessees;

"(4) Effective October 1, 1983, there are hereby authorized such sums as may be necessary to carry out the study provided for in paragraph (2).".

SEC. 12. Section 23 of the Act is amended by adding after subsection (b) the following:

"(c) Where the Secretary finds it in the public interest, the Secretary is authorized, subject to section 15(c), to issue permits for the use of geothermal resources in lands administered by him for any noncommercial application without requiring a lease or compensation therefor. No such free-use permit may be issued for the purpose of generating electricity in any amount.

"(d) In any case in which the Federal interest in any geothermal energy research and development facility, pilot plant, or demonstration facility which utilizes geothermal resources from lands subject to the provisions of this Act is transferred to any person, corporation, municipality, or agency, the Secretary is authorized, notwithstanding any other provision of this Act, to issue at no cost, a permit allowing necessary surface use and utilization of geothermal resources sufficient, in the Secretary's opinion, for the continued operation of such plant or facility for the operating life of the project.

"(e) The head of each Federal agency may develop for the use or benefit of such agency any geothermal energy resource within lands under its jurisdiction. The head of such agency shall determine in writing, with the concurrence of the Department of the Interior, that such utilization is in the public interest, and will not deter commercial development which might otherwise be more beneficial to the public if the lands were offered for leasing under this Act.".

SEC. 13. Section 24 of the Act is amended by designating the existing text as subsection (a) and adding the following:

"(b) The Secretary shall establish requirements for diligent operations which shall require that a plan of operations for exploration shall be filed within five years of the issuance of a lease. The diligence requirements shall also provide that drilling shall commence no later than four years after approval of such plan. The Secretary may provide for the aggregation of diligence requirements on lease tracts within a geothermal prospect. The running time of the diligence requirements established in this subsection shall be suspended for periods of unreasonable delay caused by a lessee's inability to obtain State or Federal permits (with the exception of permits issued by the Department of the Interior) through no fault of his own.".

SEC. 14. A new section is added to the Act as follows:

"SEC. 28. For purposes of section 4(d)(3) of the Wilderness Act of 1964 (16 U.S.C. 1131 et seq.), this Act, as amended, shall be deemed a law pertaining to mineral leasing.".

SEC. 15. The Act is further amended by making the following technical changes:

(a) Section 2(c) of the Act is amended by striking out "steam and associated geothermal" and by inserting after "brines" in the first place it appears, the following: "geopressured water, magma, and hot rock formations".

(b) Section 2(d) of the Act is amended by striking out "steam" in both places it appears and inserting in lieu thereof "resources".

(c) Section 3 of the Act is amended by striking out "steam and associated geothermal" in both places it appears.

(d) Section 5(d) of the Act is amended by striking out "steam and byproduct" and inserting in lieu thereof "resources".

(e) Section 6(a) of the Act is amended by striking out "steam is" in both places it appears and inserting in lieu thereof "resources are".

(f) Section 6(b) of the Act is amended by striking out "steam is" and inserting in lieu thereof "geothermal resources are".

(g) Section 6(c) of the Act is amended by striking out "steam is" in the first place it appears and inserting in lieu thereof "resources are," and by striking out "steam is" in the second place it appears and inserting in lieu thereof "geothermal resources are".

(h) Sections 6 (d) and (e) of the Act are amended by striking out "steam" in each place it appears and inserting in lieu thereof "resources".

(i) Section 6(f) of the Act is amended by striking out "steam and associated geothermal".

(j) Section 8 of the Act is amended by striking out "steam is" in both places it appears and inserting in lieu thereof "resources are".

(k) Section 9 of the Act is amended by striking out "steam" and inserting in lieu thereof "resources".

(l) Section 19 of the Act is amended by striking out "steam" and inserting in lieu thereof "resources".

(m) Section 23 of the Act is amended by striking out "steam and associated geothermal" in both places it appears.

(n) Section 25 of the Act is amended by striking out "steam and associated geothermal".

(o) Section 26 of the Act is amended by striking out "steam and associated geothermal".

(p) Section 27 of the Act is amended by striking out "steam and associated geothermal" in the three places it appears.

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