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LOW-TEMPERATURE GEOTHERMAL RESOURCE ASSESSMENT OF THE UNITED STATES

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Introduction

Geothermal resource assessment is the estimation of the amount of thermal energy that might be extracted from the earth and used at costs competitive with other forms of energy at a foreseeable time under reasonable assumptions of technological improvement. A regional or national resource assessment provides a framework for long-term energy policy and strategy decisions by government and industry. A resource assessment is not intended to establish specific reserve figures for short-term investment and mdrketing decisions, but instead to give an overall perspective at a particular time, using uniform methodology and data.

The first systematic effort to estimate the geothermal resources of the United States was published in 1975 as U.S. Geological Survey Circular 726 (White and Williams, eds., 1975). This assessment and a followup assessment published in 1979 as Circular 790 (Muffler, ed., 1979) focused on the quantities of geothermal energy available in regional conductive environments, igneous-related geothermal systems, hydrothermal convection systems, and geopressured-geothermal systems. Estimates were given of the thermal energy recoverable from hydrothermal convection systems at temperatures above 90°C and geopressured systems. In addition, the 1979 assessment included a compilation of data on the occurrence of low-temperature geothermal water less than 90°C (Sammel, 1979), but no attempt was made to estimate the quantities of thermal energy associated with such occurrences.

Low-temperature geothermal resources occur in two types of geohydrologic environments. These include hydrothermal convection systems, commonly involving upward flow of thermal water along faults in areas of above-normal heat flow, and conduction-dominated areas such as sedimentary basins where aquifers of large areal extent occur beneath a thick insulating blanket of rocks having low thermal conductivity. As discussed by Sammel (1979), low-temperature geothermal resources occur throughout the United States, with some at relatively shallow depths, and appear to have the potential for significant utilization in space heating and agriculture on a local basis.

To provide estimates of the quantities of thermal energy stored in and recoverable from low-temperature reservoirs in the United States, the Geological Survey has made a new assessment based on an updated inventory of low-temperature geothermal occurrences and on the development of new methodology for estimating recoverable energy. We have been aided in this task by the data gathered under programs of many state agencies and several private contractors which are supported by the State Coupled Geothermal Program of the Department of Energy's Division of Geothermal Energy. The assessment is nearly complete; results will be published as a USGS circular in 1982. We present here an outline of the methods used and general descriptions of the results obtained.

Methods fo Assessing t Geothermal Resources

Assessment of geother... resources involves a two-step process of first determining the location, extent, and geohydrologic characteristics of each resource area and then estimating the amount of thermal energy stored in each reservoir (the resource base) and the amount of energy which can be produced at the land surface (the resource). Identified resource areas ideally should meet the criteria that a reservoir exists with sufficient permeability to supply long-term production and that reservoir temperatures exceed some minimum temperature-depth relation. As depicted in figure 1, we have used a lower-temperature limit which is 10°C above the mean annual air temperature at the surface and increases at a rate of 25°C/km with depth. This avoids consideration of the enormous quantity of cool, shallow groundwater while enabling us to include areas with anomalous concentrations of heat associated with hydrothermal convection systems and deep sedimentary basins or coastal embayments where temperatures increase relatively rapidly with depth.

The resource base for each low-temperature area identified in this assessment is calculated as:

$$q_R = \rho c \cdot a \cdot d \cdot (t - t_{ref}) \qquad (1)$$

where:

q_R = resource base (stored thermal energy)
ρc = volumetric specific heat of rock plus water (2.6 $J/cm^3 {}^\circ C$)
a = reservoir area

d = reservoir thickness
t = reservoir temperature
t_{ref} = reference temperature (15°C)

Statistical methods outlined in Circular 790 were used to quantify the uncertainty in these calculations and to provide probability distributions for total resource base, resource, and beneficial heat estimates. For each reservoir, estimates were made of the minimum, maximum, and most likely characteristic values for various parameters; these values were then used to form triangular probability densities from which the mean and standard deviation for each parameter and for the various energy quantities were calculated.

The approach used in previous assessments to estimate recoverable energy, or wellhead thermal energy, was to assume a recovery factor of 25 percent of the stored thermal energy. This value is based on a process involving injection of cold water into the reservoir to replace hot water withdrawn during production and to sweep out the energy stored in the rock. In uniformly-permeable reservoirs, up to 50 percent of the stored energy can be recovered before cold-water breakthrough occurs (Nathenson, 1975); 25 percent recovery was assumed to account for commonly-encountered non-uniform permeability conditions.

In the present assessment, wellhead thermal energy calculations were made both for a recovery factor of 25 percent for small systems and for a development plan involving production wells discharging for 30 years in the absence of cold-water injection for large systems. In this production model, wellhead thermal energy is given by:

$$q_{WH} = (\rho c)_f \cdot N \cdot Q \cdot (30 \text{ years}) \cdot (t - t_{ref}) \qquad (2)$$

where:

q_{WH} = energy recovered at the wellhead over 30 years
$(\rho c)_f$ = volumetric specific heat of fluid (4.1 J/cm3 °C)
N = number of production wells
Q = average discharge rate of each well

This approach is believed to yield more realistic estimates of recoverable energy for most low-temperature areas, where lower energy content of the resource fluid and relatively large reservoir areas make the economics of injection much less attractive than for higher-temperature geothermal areas.

Limited hydrologic data precluded determination of optimum values for N and Q in equation (2) for most of our identified low-temperature reservoirs. Instead, we selected a production plan involving evenly-spaced wells discharging at 0.0315 m^3/s (500 gpm) for 30 years with a maximum drawdown of 152 m (500 ft). Then for a range of realistic values of reservoir transmissivity and storage coefficient and of confining-bed properties, we developed corresponding curves relating reservoir area to well area, defined as the square of the well spacing. An example, calculated using the leaky-aquifer solutions of Hantush (1960) with confining-bed properties considered typical for sedimentary basins, is presented in figure 2.

The curves in figure 2 show several significant features of a production model which does not involve injection. Most notable is the fact that as reservoir area increases the appropriate well spacing increases because of drawdown interference between wells. Only for very large-area reservoirs, such as the Madison limestone and Dakota sandstone in the northern Great Plains, does the well spacing become constant with reservoir area thereby permitting the number of wells to increase in proportion to the size of the reservoir. For smaller reservoir areas, the number of wells a reservoir can support does not increase in proportion to the size of the reservoir. Consequently, under this production plan, the energy recoverable from a 100 km^2 reservoir is only about 1.5 times that from a 10 km^2 reservoir with the same hydraulic characteristics. Equivalent recovery factors with this production stratagy vary from about 0.1 percent for the largest-area reservoirs in sedimentary basins to 25 percent for the smallest-area reservoirs associated with thermal springs. The 25 percent figure is approached for small reservoir areas where breakthrough of cold, induced recharge from surrounding regions rather than drawdown interference limits energy recovery.

Curves such as those in figure 2 can be used to estimate minimum, maximum, and most likely values for the well area, a_w, which define the corresponding triangular probability density and the mean value $\bar{a}_w$. The assumption was made in developing these curves that each reservoir area was uniformly transmissive. The uncertainty associated with this assumption is treated in a manner similar to that used with the recovery factor approach by assigning a correction factor k to the estimated number of production wells with minimum, maximum, and most likely values of 0, 1, and 0.5, respectively. The effects of this correction factor are to decrease the estimate of N and to increase the confidence limits on estimates of q_{WH} and beneficial heat. The mean value for N is then given by $(\overline{ka}/\bar{a}_w)$ and the mean wellhead thermal energy becomes:

$$\bar{q}_{WH} = (\rho c)_f \cdot (\overline{ka}/\bar{a}_w) \cdot M \cdot (\bar{t}_{WH} - t_{ref}) \qquad (3)$$

where:

M = (0.0315 m^3/s)·(30 years) = 3 x 10^7 m^3
$\bar{t}_{WH}$ = mean wellhead temperature (≃ mean reservoir temperature).

For small-area reservoirs, our resource estimates based on equation (3) are close to those based on a recovery factor of 25 percent, but for large-area reservoirs the well-spacing calculation yields a much smaller value. Differences between these estimates reflect the importance of time-scale over which production continues and the choice of injection versus no-injection developments. Maximum recovery fractions are obtained with an efficient injection plan designed to give cold-water breakthrough at the end of the designed life of the development. If cold water is not injected, high recovery fractions can still be attained for small-area reservoirs over a 30-year period, but for large-area reservoirs production would have to continue for much longer times to obtain high recovery fractions. Despite low recovery fractions, total energy recovery from sedimentary basins could be large because the estimated reservoir areas are so large.

The amount of each resource that can be directly applied to non-electric uses is termed beneficial heat, q_B. Whereas wellhead thermal energy, q_{WH}, represents energy above a reference state, beneficial heat represents energy that can be applied to specific processes such as heating air. Estimates of beneficial heat from geothermal fluid can be compared with thermal energy obtainable from other fuels. Selection of appropriate uses for low-temperature geothermal water depends partly on the reservoir temperature, and different uses involve different rejection temperatures for the geothermal waste water. We have used the following equation to calculate the mean temperature drop, Δt, as a function of mean wellhead temperature:

$$\Delta t = 0.6 \cdot (t_{WH} - 25°C) \qquad (4)$$

From this, mean values for beneficial heat are calculated as:

$$\overline{q_B} = (\rho c)_f \cdot (\overline{ka/a_w}) \cdot M \cdot 0.6 \cdot (\overline{t_{WH}} - 25°C) \qquad (5)$$

Note that for values of $\overline{t_{WH}} \leq 25°C$ in equations 4 and 5 the useful Δt and the beneficial heat are zero. This limit is obtained both from defining low-temperature resources as being at least 10°C above the mean annual air temperature, which averages 15°C across the United States, and from consideration of heat-pump applications for which ground-water temperatures above 25°C significantly improve coefficients of performace.

Estimates of Resource Base, Resource, and Beneficial Heat

Preliminary results of our assessment of low-temperature resources in the United States indicate that the total recoverable thermal energy at temperatures less than 90°C (based on our well-spacing calculations) is of similar magnitude to corresponding estimates from previous assessments for identified intermediate-temperature (90° to 150°C) and high-temperature (above 150°C) hydrothermal convection systems. These totals are each on the order of 200 x 10^{18}J (about 200 Quads).

The major portion of the identified low-temperature resource occurs within the sedimentary basins east of the Rocky Mountains. Among these are portions of the Powder River and Williston Basins in Wyoming, Montana, North Dakota, and South Dakota where regional aquifers with resources at temperatures of 40° to 90°C exist in Paleozoic rocks of the Madison Group (limestone) and Cretaceous rocks of the Dakota Group (sandstone). Although the reservoir areas involved in these basins are large, the methods used in this assessment to estimate recoverable thermal energy appear to yield realistic results. For example, our preliminary estimate of recoverable energy for the Madison limestone in the Powder River and Williston Basins in Montana is 20 x 10^{18}J. This estimate involves 1800 production wells spread over an area of about 180,000 km^2. An alternative calculation, involving smaller-scale developments at each of about 60 population centers within this region, yields the same resource total for individual well fields with 30 wells per town.

In terms of total numbers of identified low-temperature areas, most areas occur in the western United States and are associated with hydrothermal convection systems of various kinds. We have identified approximately 1,900 individual areas in the United States; roughly 1,850 of these occur west of the Rocky Mountains. In most of these areas, evidence for the existence of a geothermal reservoir consists mainly of the presence of a single thermal spring or spring group, commonly along one or more active normal faults. In such cases a most likely reservoir volume of 1 km^3 and a thermal energy recovery factor of 25 percent were assigned. The resource estimate for such a system,-with a reservoir temperature of 70°C, is 4 x 10^{16}J.

There are, however, numerous areas involving hydrothermal convection systems where sufficient information exists to delineate a larger reservoir size. Most notably, in portions of Idaho's Snake River Plain, thermal water moves upward along marginal faults and leaks laterally through permeable strata at relatively shallow depths towards the center of the Plain. Our preliminary estimate of the total recoverable energy for 24 low-temperature areas within the Snake River Plain is approximately 2 x 10^{18}J.

Low-temperature areas identified within the Eastern United States include the warm spring areas in the Appalachian Mountains of Virginia, West Virginia, and North Carolina in the south and of New York and Massachusetts in the north. Other warm spring areas in Arkansas and Georgia were identifed as containing resources, and portions of the Atlantic Coastal Plain in Delaware, Maryland, Virginia, and North Carolina were also included as low-temperature areas. The western side of the Allegheny Basin in Pennsylvania contains a thick section of Devonian shale having low thermal conductivity, but it is not known if aquifers exist below the shale to form a geothermal reservoir. Outside these areas, however, the generally low crustal heat flow and low thermal gradients appear to restrict the occurrence of significant low-temperature resources.

Limited geohydrologic data requires us to treat many areas which appear favorable for the existence of low-temperature reservoirs as containing undiscovered, rather than identified resources. Undiscovered resources were assumed to be associated with 1) aquifers in sedimentary basins and coastal embayments where existing data could not support a quantitative assessment, 2) halos around identified intermediate and high-temperature systems, and 3) thermal energy in systems whose locations are as yet unknown. Estimates of the total undiscovered resource base, resource, and beneficial heat for various geologic provinces will be included in the final report along with estimates for identified areas.

References

Hantush, M. S., 1960, Modification of the theory of leaky aquifers: Journal of Geophysical Research, v. 65, n. 11, p. 3713-3725.

Muffler, L. J. P., ed., 1979, Assessment of geothermal resources of the United States--1978: U.S. Geological Survey Circular 790, 163 p.

Nathenson, Manuel, 1975, Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas: U.S. Geological Survey Open-file Report 75-525, 35 p.

Samnel, E. A., 1979, Occurrence of low-temperature geothermal waters in the United States, in Muffler, L. J. P., ed., Assessment of geothermal resources of the United States--1978: U.S. Geological Survey Circular 790, p. 86-131.

White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the United States--1975: U.S. Geological Survey Circular 726, 155 p.

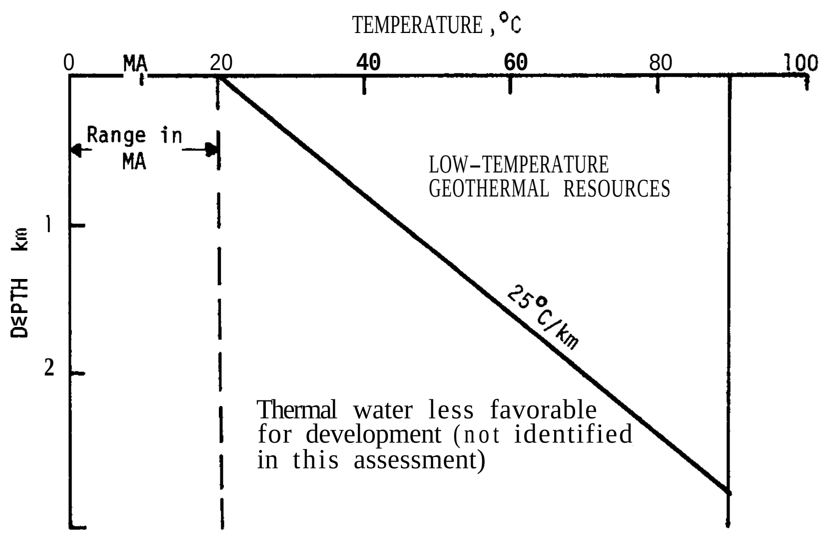

Figure 1. Diagram of temperature-depth criteria used to identify low-temperature geothermal resources. MA = mean annual air temperature. Maximum temperature limit = 90°C. Minimum temperature limit given by line with slope of 25°C/km and intercept of MA+10°C. Heavy solid line shows minimum temperature limit for example case MA = 10°C.

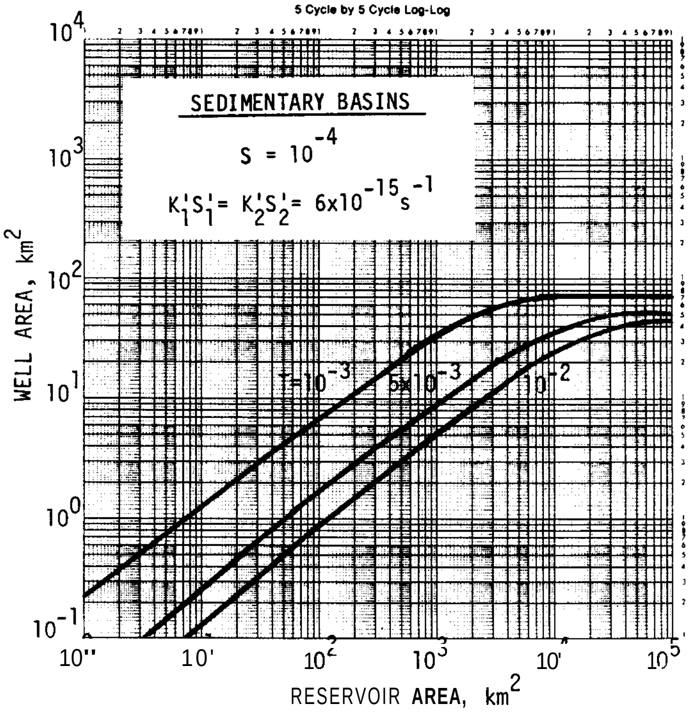

Figure 2. Curves of well area (well spacing squared) versus reservoir area developed for a production plan involving evenly spaced wells discharging for 30 years at 0.0315 m^3/s (500 gpm) with a maximum drawdown of 152 m (500 ft). T = reservoir transmissivity (m^2/s), S = reservoir storage coefficient, K' = hydraulic conductivity of confining beds (m/s), and S' = specific storage of confining beds (m^{-1}).