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THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
LAUREL MARYLAND

DIRECT APPLICATIONS OF GEOTHERMAL ENERGY IN THE EASTERN UNITED STATES AND ESTIMATES OF LIFE CYCLE COSTS

ABSTRACT

This brief paper was written to summarize the Department of Energy's program on the geothermal energy along the Atlantic Coastal Plain, and to indicate that there are other areas in the east which may also have potential for geothermal energy.

The paper outlines the form of the geothermal energy resulting in higher than normal thermal gradients. The method of withdrawing the resulting warm water is outlined and a preliminary estimate is made of the amount of thermal water that can be withdrawn with down-hole pumps.

The use of a peaking plant to ensure that any resource independent of its temperature may be used for space heating or industrial heat energy. The use of the peaking system to increase the utilization of the geothermal well when used for space heating is outlined.

Finally, the average cost of geothermal energy is calculated for various housing types with resource temperature as a parameter. These costs are compared to the cost of conventional fuels.

SIGNIFICANCE OF THIS PAPER

The form of this paper is significant to the understanding and education of the public and interested individuals. The determination of the cost of geothermal energy, the simplicity of applications engineering required and the comparison with conventional energy forms are questions asked first in any dialog with potential user.

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By

F. C. Paddison
C. S. Leffel, Jr.
W. J. Toth
R. S. P. Weissbrod

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F. C. Paddison[1], C. S. Leffel, Jr.[1],
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I. INTRODUCTION

This paper discusses the application of geothermal energy, as found in the eastern United States, to meet moderate-temperature energy demands. The development of geothermal energy resources in the eastern U.S. and its application are rather new and, accordingly, this paper will illustrate the concepts involved. Life-cycle costs for any complicated system require detailed engineering data. In the case of geothermal energy, such data are not as yet available on either the resource or the equipment required to extract the thermal energy. Accordingly, this paper can only estimate the life-cycle costs based on reasonable estimates of the resource and proposed application system parameters. The geothermal costs are compared with costs incurred when using more conventional, i.e., fossil, fuels. The resources assumed here are deep hydrothermal resources with higher-than-normal temperature increase with depth. It is too early to estimate costs for lower-than-normal gradient resources or for the exploitation of hot dry rock (HDR). The Department of Energy, Division of Geothermal Energy (DOE/DGE), has a balanced program to locate and define the higher-than-normal gradient geothermal resource parameters and desired engineering characteristics of systems to transfer thermal energy to the user. This program for the eastern region of the U.S. is currently in an advanced state and some definitive answers should be at hand in CY 1979. The Department of Energy also has an active program on HDR applied to the eastern U.S. However, it is a more difficult technical problem on a longer time scale and is not discussed in this paper. The DOE/DGE Eastern Hydrothermal Program is

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[1] The Johns Hopkins University, Applied Physics Laboratory, Laurel, Maryland 20810

[2] The Center for Metropolitan Planning and Research, The Johns Hopkins University, Baltimore, Maryland 21218

under the direction of Mr. Bennie DiBona and Dr. David B. Lombard. This paper is an outgrowth of work for that office.

II. SUMMARY

A brief description and location of hydrothermal resources in the eastern U.S. is presented together with an outline of the DOE/DGE Eastern Hydrothermal Program. The application of geothermally heated water from deep aquifers on the Atlantic Coastal Plain is illustrated for space heating of new communities of several different densities. The minimum cost of a million Btu's of geothermal energy delivered at the wellhead heat exchanger is calculated as a function of the available resource temperature. These are summarized as follows, assuming a 500 gallon per minute well operating year round.

Differential Temperature (°F)	Cost Per Million Btu at Wellhead ($)
110	1.70
90	2.06
70	2.64
50	3.68

The number of 1800 sq ft residences that can be heated with a 500 gallon per minute well are calculated. The utility and desirability of an auxiliary peaking system (fossil fuel or electric) to match any geothermal resource to the user demand is shown. An optimum exists for each resource dependent upon the choice of ambient temperature when the peaking plant begins to operate. This optimum is quite broad and is illustrated. The costs of the peaking system, the distribution system, and the local requirements lead to the overall cost per million Btu of energy delivered to the home. These are shown for several densities of residences for a representative case in the Delaware area.

The minimum overall cost per million Btu's of delivered energy to a community for space heating for both a high temperature and moderate temperature resources is as follows.

1. Suburban community - 2500 residences/sq mi

Resource ΔT	Min. Cost Per Million Btu
110° F	$5.80
50° F	$8.70

2. Town house community - 10,000 residences/sq mi

Resource ΔT	Min. Cost Per Million Btu
110° F	$4.20
50° F	$7.20

3. Garden community - 17,000 residences/ sq mi

110° F	$3.40
50° F	$6.40

Traditional Alternatives

One important method of estimating the economic prospect for geothermal based space heating is to compare with other more traditional fuels. In Appendix A, using available data, such as the published rate schedules for electricity and gas, we estimate typical per million Btu costs and these are as follows:

Fuel	$/Million Btu's
Oil	5.00
Natural gas	4.00
Electric space heating	11.00

Even though we worked with published tariffs, the blocked structure of the tariff required that we chose typical consumption in order to arrive at per million Btu cost. These estimates are in agreement with national averages.

In summary, geothermal energy costs under suitable conditions can easily match and in some cases are lower than traditional fuels.

III. WHAT IS GEOTHERMAL ENERGY

The temperature in the crust of the earth increases with depth, with an average gradient of about 1.4° F/100 ft or 25° C/km. This rate of temperature increase cannot be constant to the center of the earth, but insofar as is known, is constant for the first 10 to 20 km of the earth's crust; that is, beyond any depths now accessible to technology. Since the earth is over four billion years old and it continually radiates heat away, the present high temperature cannot be remanent from the earth's formation, but can only be explained by the heat generated in the core and crust by the radioactivity decay of certain elements, primarily uranium, thorium and potassium.

The amount of energy stored in the first 10 km of the earth's crust under the U.S., at temperatures over 15° C, is estimated (in the U.S. Geological Survey (USGS) Circular 726[3]) to be about 32 million quad (1 quad = 10^{15} Btu). Since the present energy consumption of the U.S. is about 80 quad per year, this is a substantial source of energy, but for reasons that will be discussed later, DOE does not classify geothermal energy resources as inexhaustible. However, with present and near current technology, the same reference states that only about 0.01 percent of this energy is recoverable without regard to cost. Furthermore, the bulk of the energy is at a relatively low temperature and thus cannot serve all purposes, e.g., the production of electricity. At the present time, the only significant output of geothermal energy in the U.S. is at the Geysers in California, where electricity production from geothermal steam is now approaching that of a 800 MW nuclear plant.

Geothermal resources can be divided into the following categories:

a. Hydrothermal convective systems
    (1) Vapor dominated
    (2) Hot water
    (3) Warm water
b. Hot igneous systems
    (1) Hot dry rock
    (2) Molten magma (rare)

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[3] USGS Circular 726, "Assessment of Geothermal Resources of the United States, 1975"

c. Conduction dominated systems

(1) Warm volumes in the crust, caused by high heat flow from local radiogenic heat production and a cover of low conductivity rock.

d. Geopressured areas

The eastern U.S. has examples of several of these categories except for vapor-dominated. Hot Springs National Park probably represents a warm water hydrothermal system. HDR can be found anywhere at sufficient depth, but the only DOE experiment to attempt to utilize this energy source is near Los Alamos, New Mexico, a much more favorable locale than any known in the eastern part of the country. The geopressured regions in Texas and Louisiana are now the object of a relatively large DOE effort. Conduction dominated systems are found in may sedimentary basins in the east; for example, the Michigan, the Illinois-Indiana, the Appalachian and Champlain Basins. Other promising areas are the Atlantic Coastal Plain and Gulf of Mexico Plains. The location of some of these presumed conduction dominated regions are shown in Fig. 1.

This paper will discuss what is known about the geothermal resources in the Atlantic Coastal Plain only, how moderate temperature waters may be used for space heating, the estimated costs for this type of usage, and the current federal program in this area. The standard reference for geothermal resources in this country is the USGS Circular 726. This circular concentrates on the more promising western resources, but is scheduled to be updated in the near future as Circular 790, putting more emphasis on the east.

IV. THE GEOTHERMAL ENERGY RESOURCES ALONG THE ATLANTIC COASTAL PLAIN

1. Heat Flow and Geothermal Gradient

The average heat flow from the interior of the earth to the surface q is about 1.2×10^{-6} cal/cm^2 sec (1.0×10^{-6} cal/cm^2 is called a heat flow unit, HFU). The Atlantic Coastal Plain is an area of average to slightly above average heat flow. Figure 2 shows the heat flow for the Atlantic Coastal Plain and Piedmont on an enlarged scale.

These data from from Ref. 4.

The thermal gradient dT/dZ is the heat flow q divided by the conductivity K, of the crustal rock, $dT/dZ = q/K$. The direct measurement of heat flow is extremely difficult and reported results are usually derived from measurements of the thermal gradient in deep wells and the thermal conductivity of cores taken from the well boring.

Thermal gradient data of limited accuracy are available where extensive oil or gas drilling has occurred, since the bottom hole temperature (BHT) of these holes has often been recorded. The accuracy of this measurement is often questionable since the drilling process itself generates heat, the water and mud circulated for drill lubrication cools the well, and the setting of the cement holding the casing in place produces heat. Thus the BHT takes periods on the order of weeks to reach equilibrium. The average geothermal gradient as defined by the oil drillers is:

$$\text{Thermal gradient} = \frac{\text{BHT - mean surface temperature}}{\text{Depth to bottom of hole}}$$

The American Association of Petroleum Geologist (AAPG) and the USGS have calculated and mapped the thermal gradient contours for the North American Continent from existing oil and gas well data, Ref. 5.

Figure 3 show areas in the eastern U.S. where the gradient exceeds 1.6° F/100 ft. These areas represent the most promising regions to explore, either for hot hydrothermal resources or HDR. For a hydrothermal source, it must be assumed that water bearing sedimentary strata exist at sufficient depth and that useful amounts of water can be extracted.

2. The Effect of Local Radiogenic Intrusives

In an area, such as the Eastern Coastal Plain, where very little deep well information is available, it is

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[4] Near Normal Geothermal Gradient Workshop, ERDA-76-11, UC 66A, March 10 and 11, 1975

[5] AAPG and USGS 1975 Geothermal Gradient Map of North America, USGS Scale 1:5 million

necessary to use some model to calculate temperature at depth and, from these calculations and what geologic information is available, decide what areas are most promising for further exploration. In USGS Circular 726, Diment et al, summarize the conventional model of heat flow for the U.S. In this model, the heat flow q_o, at the surface is given by

$$q_o = q* + DA$$

where $q*$ is the heat flow from the lower crust and mantle, and DA is the heat produced in the upper crust where D is a depth scale factor and A is the radiogenic heat production term. For the eastern U.S., it has been determined that

$$q* = 0.8 \times 10^{-6} \text{ cal/cm}^2 \text{ sec and}$$

$$D = 7.5 \text{ kilometers.}$$

The changes in q_o are then due to the radiogenic heat production term A. A must be a decreasing function with depth and is ofter taken to be of the form,

$$A = A_o e^{-Z/D}$$

where A_o is a local constant in the range of 2 to 20 x 10^{-13} cal/cm^3 sec (2 to 20 heat generation units, HGU). From $dT/dZ = q/K$, where q and K are both positive and increasing functions of depth, the temperature as a function of depth can be calculated.

Figure 4 shows the results of such calculations where A_o is assumed to be zero, i.e., there is no radioactive heat generation and the rock conductivity K to be 7.0 x 10^{-3} cal/cm sec °C, a value typical for granitic rock. Also shown is the temperature for the case of A_o = 10 HGU and granitic conductivity. If the granitic basement is overlain by a lower conductivity layer of sedimentary rock, K = 3.5 x 10^{-3} cal/cm sec °C, and A_o in the granitic basement is 10 HGU, the temperature variation with depth is as shown on the third curve.

On the basis of this model, the easy geothermal resource to exploit is one where a relatively thick insulating layer of sedimentary strata overlay granitic intrusion of greater than ordinary radiogenic heat production. This has been the foundation for DOE strategy on the Atlantic Coastal Plain.

3. Department of Energy Program to Define Geothermal Resources on the Atlantic Coastal Plain

A DOE program for the Atlantic Coastal Plain has been carried out by the Virginia Polytechnic Institute and State University (VPI&SU) under the direction of Dr. John K. Costain, Ref. 6. Possible locations of relatively youthful granitic intrusions have been identified by gravitational and magnetic anomalies. Using basement depth data, available petrology and stratigraphic information, estimates of radioactivity, and what well data were available, VPI&SU has selected about 50 sites from New Jersey to Georgia for the drilling of wells 1000 to 1800 ft deep for gradient measurement. The actual drilling program is nearly completed[7]. When the wells have reached thermal equilibrium, they will be logged and the conductivity of the extracted cores measured. Following this analysis and the acquisition of data on the basement structure, as derived by seismic measurements, a decision will be made in early 1979 as to where to drill one or more deep wells to basement, i.e., into the pluton itself or its edges. The deep well program is designed to confirm the calculated temperatures and determine the quality and quantity of the water than can be pumped from the well at the selected site.

In addition to estimating and verifying the energy available in an area of promise, it is necessary to examine the possible use of geothermal energy for that area. The current and projected energy demand at temperatures below 250° F for each potential resource area is being examined by the Applied Physics Laboratory of The Johns Hopkins University (APL/JHU). Further, for each possible resource area, a scenario is being written to identify what steps must be taken by the entities involved in the development of the resource and to schedule these steps.

Figure 5 shows the areas along the Atlantic Coast under study. Figure 6 shows the depth of sedimentary sequences in the areas.

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[6] VPI&SU, Blacksburg, Virginia 24061, "Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States," Series of Quarterly Progress Reports VPI&SU 5103-1 through 6 to present

[7] The drilling was done by Energy Services under the direction of Gruy Federal, Inc. of Houston, Texas

V. THE RECOVERY OF GEOTHERMAL ENERGY

1. Ground Water to Transfer Geothermal Heat to Surface

Existing oil field equipment and technology are directly applicable to the recovery and eventual disposal of the geothermal waters. Similarly, current circulating hot water technology and equipments are adequate for transferring heat, while keeping separate the geothermal water (often very aggressive) and the clean circulating water.

There are other techniques either applied or in development for transforming thermal energy. For example, peaking systems and heat pumps can be used to increase the temperature of the water if the resource does not match the user's needs.

Circulating water is a convenient method for distributing thermal energy from a central heat exchanger to the individual user. Here non-corrosive water can be circulated directly into convective radiators, or through a heat exchanger in a forced hot air system.

2. Water Availability under the Atlantic Coastal Plain

The Atlantic Coastal Plain has been selected as an area of concentrated geothermal effort since 1) it is near large demographic and energy load centers, 2) it may have areas of higher than normal gradients, and 3) the coastal plains usually have large amounts of removable ground water, even at substantial depths.

Figure 7 shows a typical cross-sectional view of coastal plain; it is similar to that found anywhere along the Atlantic from New Jersey to Georgia. The Plain results from the accumulation of sediments eroded from the once majestic Appalachian Mountains. The Plain is gently sloping from its mountain region to the edge of the continental shelf. It begins at the "fall line," i.e., the place where the granite basement is first seen at the surface, and the usual elevation difference between the basement rock and the coastal plain causes water falls. A portion of the surface rain and ground water on the Plain enters the ground and travels out to sea underground in the more porous strata. Frequently sedimentary sequences, representing different geologic time periods, will be sealed one from the other with nearly impervious layers of clays and shale, and the underground water flow is accordingly channeled in an "aquifer". Coastal plain aquifers however, are frequently not well sealed, and the deeper waters can be forced up to shallower aquifers. Normally the flow of water at depth is extremely slow and it can be thousands of years from the time it enters to the time it reaches deep aquifers at the coast. During this time, the water leaches many minerals from the strata it has passed through and will have reached thermal equilibrium with the local rock.

3. The Geothermal Well - Flow Rates and Drawdown

If a deep well is drilled into a well sealed and highly permeable aquifer, the water will normally rise to a level to equal the elevation of recharge of that aquifer. If the recharge area is at an elevation higher than the top of the well, then the water will flow automatically out of the well through artesian pressure. The elevation of the areas shown in Fig. 7 where sediments are deep enough for interest as a geothermal resource are lower than the recharge areas. Regardless of whether or not deep wells on the Atlantic Coastal Plain are artesian, the deep wells will have to be pumped to maximize the thermal output of the well in order to defray the substantial capital cost of the well and its associated equipment.

The oil industry has developed down hole pumps of large capacity which are placed at depth in a well to raise the water to the surface. The pump must be placed at a depth in the well below the drawdown level of the water. During pumping the drawdown S is determined by the following equation. The units of S are length.

$$S \doteq \frac{528\ Q \operatorname{Log} R/r}{T_w}$$

where Q is the volumetric withdrawal rate of water, T_w is the transmissivity of the aquifer and is the product of the vertical thickness and permeability of the aquifer, R is the radius of influence and r is the well diameter. Figure 8 shows the pressure head drawdown around the well.

The radius of influence R is the radial distance from the center of the well where the local recharge equals the water withdrawal. It is a function of aquifer transmissibility, leakage from adjacent aquifers, and the aquifer pressure. The value of R is usually assumed from prior experience; 5000 ft or more is typical of an artesian aquifer; see Ref. 8. The only parameters presently available to the system design are the withdrawal rate Q already discussed and the well radius r. In the case of the assumed coastal plain characteristics a doubling of r is equivalent to only a 6% increase in Q. For a particular aquifer at 7450 ft beneath the coastal plain of the Delmarva Peninsula, a well producing 500 gallon per minute would have a predicted drawdown of approximately 4650 ft. This means that the water level in the well while pumping at this rate will be 4650 ft below the surface, whereas at zero flow rate it would be at the surface, Ref. 8.

The inlet to the down-hole pump must be located below the drawdown level of the water and the diameter of the well and its casing must be of sufficient diameter to accommodate the pump at that depth. The required minimum inside diameter is at least eight inches, depending on the manufacturer of the down-hole pump. A systems designer would select the largest capacity down-hole pump available. The largest down-hole pumps available are those in the 750 to 1000 horsepower range.

4. The Geothermal Well - Temperatures Available

Each geothermal resource will produce water temperatures unique to that resource. Further the temperature at the top of the well will be slightly lower than that at the bottom of the well depending upon the withdrawal rate, the depth of the well and the local geology. Since the resource temperature is so significant in determining the cost of geothermal energy, it will be treated as a variable in this analysis. Temperatures at the top of the well, delivered to the input of a central heat exchanger ranging from 135°F to 195°F in steps of 10°F will be used.

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[8] Ground Water and Wells, Johnson Division UOP, Inc., St. Paul, Minnesota 55165

5. Disposal of Geothermal Fluids

There are three considerations which dictate the method of disposal of geothermal fluids: the chemistry of the geothermal fluid, the potential for compaction of the aquifer and the resulting potential subsidence if water is withdrawn in large quantities.

The physical properties of the aquifer rocks, the depth of the aquifer and the characteristics of the overburden dictate whether appreciable subsidence will occur. If this possibility is significant, then the water should be returned to the same aquifer after being cooled. In this case the chemical equilibria of the two fluids in the formation must be examined to ensure that, in their subsequent mixing, precipitation of minerals and clogging of pore spaces will not occur.

If the geothermal fluid is non-potable or contains chemicals in amounts considered harmful, then it must be reinjected at a depth below potable ground water. For many areas in the Atlantic Coastal Plain this is 2000 to 3000 ft.

Where the chemistry permits the geothermal fluid can be added to ocean water, if the resource is close to the coast. Environmental analysis of the effluent in the specific environment would be necessary.

VI. THE USE OF MODERATE TEMPERATURE GEOTHERMAL ENERGY

There follows a discussion of the application of moderate temperature geothermal water to space heating and a brief listing of other possible uses in the eastern U.S. The system required for each application and its costs vary and, accordingly, this paper limits itself to consideration of a newly constructed residential space heating system. This is not to say that this is the best or the least costly application. Data on the cost and application to other uses will be evolved as part of the on-going DOE/DGE Eastern Regional Development Program.

1. Space Heating with Geothermal Water

a. System Block Diagram

The use of geothermally heated water for space heating may incorporate several supply wells depending on the needs of the community and considering the costs. To focus on these costs, we present the case of a single well system and the varying conditions and costs under which it serves different markets and demand areas. The temperature of the resource and the usage density are both important parameters which have a pronounced effect on the cost of geothermal energy. To illustrate these points, seven different resource temperatures and three residential densities will be used in the calculations. Table I defines the residential densities assumed.

Table I

Density of Communities for Geothermal Space Heating

Type of Community	Density Residences/ 200 x 400 Block	Residences/ sq mi
Suburban	7	2,535
Town Houses	30	10,140
Garden	51	17,000

Figure 8 illustrates a geothermal community heating system. Here the geothermal water goes through a central heat exchanger and then, depending on the quality of the water and the locale of the system, to some form of surface or subsurface disposal.

The water on the other side of the heat exchanger circulates through the community in a closed system where water chemistry and corrosive properties can be controlled. The system that is posed in this paper may require a topping subsystem after the heat exchanger depending on whether housing units heating demand is completely satisfied by the geothermal resource or if it needs to be supplemented.

The individual residence accepts the heated circulating water and either circulates it directly through radiators or it goes through a small individual heat exchanger, delivering the heat to circulating air. The cost of this latter type of system is estimated.

b. The Wellhead Heat Exchanger

The wellhead heat exchanger is used to transfer the thermal energy from the geothermal water to the local water that will carry the energy to the community. Like many physical devices, its efficiency may be improved through a more expensive design. Since the correct balance between economic efficiency and engineering efficiency is project specific, the heat exchanger costs and performance figures in this report are a compromise.

The variable which best illustrates performance is the differential temperature (ΔT) between the input and output on the community side of the heat exchanger or between the input and exit on the geothermal well side of the heat exchanger, see Table II.

Table II

Definition of Differential Temperatures (ΔT) to Community

	Geothermal Water Temperatures		Circulating Water Temperature	
Differential Temperature	Top of Well Input to Central Heat Exchanger	Exit from Heat Exchanger	Output of Heat Exchanger	Input to Heat Exchanger
ΔT °F	°F	°F	°F	°F
110	195	85	190	80
100	185	85	180	80
90	175	85	170	80
80	165	85	160	80
70	155	85	150	80
60	145	85	140	80
50	135	85	130	80

Given varying ΔT's the cost of the central heat exchanger for the above performance with a maximum flow rate of 500 gallon per minute through the exchanger has been calculated and is presented in Table III.

Table III

Cost of Central Heat Exchanger

Sized to Requirements of Table II at 500 gallons per minute

ΔT °F	Cost ($)	Btu per Min Delivered
110	118,000	459,000
100	107,000	417,000
90	96,000	376,000
80	86,000	334,000
70	75,000	276,000
60	64,000	250,000
50	54,000	209,000

c. The Peaking System

The topping plant plays a most significant role in a community heating system during the peak heating period. This plant, fired most probably by fossil fuel, provides a small increment of temperature to the circulating hot water. The topping system must be capable of large heating rates to augment the geothermal system for the very short duration when outside temperatures are below the design point, which occurs typically less than 10% of the heating season. The presence of the peaking system allows the system designer to increase the number of residences that can be served by a given well. This is achieved by selecting some moderate design ambient temperature and allocating the geothermal energy available to as many houses as can be served by the well's output. For the short duration of time when the outside temperature is lower than this design point, then the peaking system increases the circulating water temperature accordingly. The result is that the utilization of the geothermal well is increased and the resultant savings in capital debt service on a per million Btu basis more than compensates for the cost of the peaking plant and its fuel. A minimum cost per million Btu exists and its character is illustrated later.

The peaking system has several other advantages. These are: it provides a method of matching very moderate temperature resources to many user requirements; it serves as a limited emergency backup, if required, particularly when and if the geothermal well or associated equipment require maintenance during the heating season.

The cost of peaking systems with the peak thermal capacities discussed in this analysis is assumed to be $26,000 per million Btu per hour heating rate. This cost includes boilers, building, controls, and plumbing. The life expectancy of a peaking system at this cost is 15 years for 50% utilization and more than double that (30 years) for the utilization factors assumed here.

d. Home Heat Exchanger

As has been previously mentioned, the home heat exchanger is assumed to be a circulating hot water to air exchanger. The detailed design of the exchanger and costs must be done when specific temperatures and heat loads are known. For this paper, a cost of $100 to $350 appears reasonable to handle the maximum heat loads for an average house at the temperatures supplied by the geothermal and peaking plant.

e. Space Heating System Requirements

The heating and refrigeration industry has developed rules of thumb for estimating the peak heating load and the total annual energy required for a typical residence. These are as follows for a reasonable insulated single story home of 1800 sq ft (Ref. 9).

Peak Energy Demand

The peak energy demand occurs during the coldest period of the year, and the size of the peak may be estimated using local historical data available from Ref. 10. The peak energy demand in Btu per hour is the difference between 65° F, the point at which heat may first be supplied, and the selected design ambient temperature, multiplied by 1200 or:

Peak Btu per hour = 1200 x (65 - design ambient temperature).

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[9] DOE Idaho Operations Office, Idaho Falls, Idaho 83401 "Rules of Thumb and Geothermal Space Heating Publications"

[10] NOAA National Climate Center, Asheville, North Carolina 28801, "Frequency of Hourly Temperatures, Period 1951 to 1960 for 138 Cities in the USA"

The geothermal resource may be designed to meet 100% of this peak, or, as is suggested in this paper to meet some higher temperature, which allows the resource to be shared by additional residences. The difference between the peak demand and the design ambient temperature demand would be supplied by a peaking system.

Table IV lists the peak Btus required and the percent utilization of the geothermal resource as a function of the design ambient temperature for the Delaware area. Two degrees Fahrenheit is assumed to be the lowest temperature. Note that at a design ambient temperature of 35° F afforded by the use of a peaking system, the utilization of the geothermal well is doubled from the approximate 22% if it were used without a peaking system to heat a smaller community.

Annual Energy Demand

Figure 9 shows the annual ambient temperature versus duration for the Delaware area. These data are 10-year averages for 5° F temperature increments. The energy demand is determined from the difference between 65° F the point at which heat may first be supplied, and the selected design ambient temperature, as has been discussed. The total annual energy requirements are the integration of these demands over the heating season. This value is frequently expressed as Degree Days. In the case of the Delaware area shown in Fig. 9, there are 4983 Degree Days on the average. To obtain the total annual number of Btu's for a 1800 sq ft residence, multiply the number of Degree Days by the constant 28,800, which comes to 143 million Btu's per residence per annum, Ref. 10.

f. System Performance

The Number of Residences That Can Be Heated by One Geothermal Well

Table IV shows the maximum heating rate that must be supplied by the community heating system to each residence as a function of design ambient temperature. If the maximum delivery rate of the geothermal well were used to supply the peak heat rate, then it could supply fewer residences than if it were used to supply the lower peak rate of a higher design ambient temperature, the difference being supplied by the peaking system. The thermal output of the well is equal to the flow in gallons per minute Q times the thermal content per gallon. The latter is equal to the specific heat (unity) times the temperature differential times the number of pounds per gallon (i.e., Btu's per minute = Q x 8.4 x ΔT). Table IV lists the number of residences that can be supplied for different design ambient temperatures and geothermal well differential temperatures.

Table IV

The peak heating rate, number of residences in the Delaware area that can be supplied by 500 gallon per minute geothermal well, and the utilization factor of the geothermal well as function of design ambient temperature.

Outside Design Ambient Temperature	Peak Heat Rate Demanded	Number of Residences Supplied for a Differential Temperature Available from Well ΔT				Utilization of Well
		110	90	70	50	
°F	Btu/hour					Percent
2	75,000	363	298	231	165	22
10	66,000	416	340	265	189	25
15	60,000	458	375	291	208	27
20	54,000	509	416	324	231	30
25	48,000	573	468	364	260	34
30	42,000	654	535	416	297	39
35	36,000	763	625	486	347	46

2. Other Uses

In addition to residential space heating, there are the following other potential uses of geothermal energy on the Atlantic Coastal Plain. Each of these has its own unique temperature requirement, annual energy demand cycle and economics, as indicated in Fig. 10.

Although not discussed in this paper, community domestic hot water heated from the geothermal waters is practical for high density communities.

Space Cooling

In addition to space and water heating, space cooling can be performed wherever the geothermal resource is hot enough. Absorptive air-conditioning equipment powered by heat is not advertised to operate efficiently below 180° F-200° F. It is possible that in time these systems, or variations of these systems, may be driven by lower temperature geothermal heat and will be able to supply space cooling in addition to space heating, increasing the annual usage of the geothermal resource.

Poultry Industry

The year-round space conditioning of poultry brooding houses is a future potential if sufficient numbers of brooding houses can be located near a resource. In addition, poultry eviscerating plants use large quantities of water in the 125° F-180° F range year 'round, and thus offer a prime potential use of moderate temperature geothermal water.

Agricultural Use

The food-processing industry uses large volumes of water in the 120° F-200° F range for pasteurization, crop cleaning, vegetable peeling, blanching, and cooking. While many of these are seasonal, most large plants have several product lines which allows them to operate year 'round.

Greenhouses, growing either vegetables, cut flowers, or bedding plants, are currently a small industry on the Coastal Plain; however, reliable moderate cost energy for space heating would promise growth of that industry.

The drying of lumber, grain, and tobacco are all additional potential users of geothermal.

This list is not intended to be all-encompassing or complete but rather to illustrate those applications receiving study by DOE and industry groups.

VII. THE COST OF GEOTHERMAL ENERGY USED FOR COMMUNITY SPACE HEATING

The cost of geothermal energy used for space heating of a new community is determined by: 1) the costs associated with the geologic assessment of the resource and the determination of the engineering parameters for the specific geothermal resource under consideration; 2) the cost of drilling, casing and completing the well; 3) the costs of the geothermal well down-hole-pump used to deliver water to the surface, the wellhead heat exchanger; 4) drilling and completion of the reinjection well; and 5) the distribution system, the peaking subsystem, and the home radiators or heat exchangers.

The following sections discuss, first, the costs of the geothermal energy delivered at the wellhead heat exchanger. It is assumed that the prospective user is co-located with the geothermal well. In succeeding sections, the cost of geothermal energy delivered to the individual residence is shown. Finally, costs of available energy alternatives are listed.

1. Resource Assessment and Engineering

The costs associated with the definition of the size, character and engineering properties of a geothermal resource can be substantial, and, since they are so variable as a function of resource type and vary from area-to-area, no attempt is made to detail them here. In Europe and to some extent here in the U.S. the government does much of the resource assessment in developing the methodology and tools for reservoir engineering and management. In the case of the Atlantic Coastal Plain, the DOE/DGE is assessing the extent of the resource from New Jersey to Southern Georgia and will develop reservoir engineering data on some, if not most, of the promising areas on the Plain. These costs are not included in this paper.

2. Cost of One Million Btu of Thermal Energy Delivered at the Wellhead

The cost of one million Btu of energy delivered by the heat exchanger to the circulating water used for residential space heating involves both initial capital and recurring costs. For this paper it is assumed that the geothermal water must be reinjected by a second well and pump to an intermediate depth of 2000-3000 ft.

Initial Costs of a Geothermal Well

a. The cost of a 7500-ft geothermal well, completely equipped, in the Atlantic Coastal Plain is estimated to be approximately $475,000.

b. The reinjection well = $200,000

c. The heat exchanger = $125,000

d. The down-hole pump including cable and all additional equipment = $125,000

e. The costs of plumbing between wells and heat exchanger, the circulating pump and reinjection pump are all considered to be relatively insignificant and are not included here.

The total cost for this phase, therefore is $925,000. In the analysis, a capital recovery factor, using a 10% interest rate and amortization over 25 years, is 11%.

Operating Cost of a Geothermal Well

The cost of operating the down-hole pump and its maintenance is substantial.

For 100-percent operation, the cost of a 817 horsepower down-hole pump requiring an input power of 780 kilowatts amounts to $313,000 per year, assuming electrical power at $0.04/kw-hr.

The down-hole pumps have a finite life, after which time they must be removed and reworked. The average life for continuous operations in the expected down-hole environment of the Coastal Plain is approximately three years. The cost of removal and rework is 70% of the original cost. The pump cables and in-well equipment are assumed to be completely replaced every six years of continuous service.

This represents an additional operating cost which is hard to quantify at this point. It is not included in the following cost estimates because it probably will amount to less than 10% of the annual operating cost.

The wellhead cost of one million Btu's of geothermal energy is the annual cost of capital plus the operating costs divided by the number of millions of Btu's available annually from the geothermal well. The number of Btu's available varies with the differential temperature available at the wellhead. Table V lists the annual thermal output of the well for a flow of 500 gallons per minute. Figure 11 shows the cost, in dollars per million Btu's, as delivered from the wellhead heat exchanger as a function of utilization.

Table V

Differential Temperature ΔT °F	Total Btu's
110	2.42×10^{11}
90	1.98 " "
70	1.54 " "
50	1.10 " "

3. The Total Cost of One Million Btu's of Geothermal Energy Delivered to an Individual User

The total cost of geothermal space heating as presented here is the sum of the wellhead costs per million Btu's and the cost per million Btu's of the system to deliver the energy to the individual residence, i.e., the hot water distribution system, the peaking plant and the fossil fuel as required. The distribution system and peaking plant are considered capital costs and a capital recovery factor, using a 10% interest and amortization of 25 years, is 11%. The fossil fuel is an added annual operating cost.

Table VI shows the total cost of one million Btu's of energy delivered to an individual user in one of three community heating systems as a function of the design ambient temperature and the differential temperature. All homes were assumed to be of the same size, i.e., 1800 sq ft with reasonable insulation. The costs include the purchase of fuel oil for the peaking plant at 100,000 Btu per gallon net and at a cost of $20 per barrel.

Figure 12 shows the cost as a function of design ambient temperature for the three different density communities and the hottest geothermal well, viz., ΔT = 110° F. The lowest cost is for a design ambient temperature of 5° F; however the curve is so flat that other considerations other than cost will probably decide design point. Figure 13 shows the same curve for the lowest temperature geothermal well, viz., ΔT = 50° F. Here the lowest cost is at a design ambient temperature of 20° F. Figure 14 shows the cost as a function of design ambient temperature for all assumed well temperatures, i.e., ΔT = 110° F to 50° F for the garden-type of high density community.

Table VI

Total cost of geothermal heat per residence Delaware area. Cost in dollars per million Btu

```
DEL.T= 110.0 DEG F
 DESN TEMP     0.0     5.0    10.0    15.0    20.0    25.0    30.0    35.0
 GARDEN APT  3.415   3.385   3.363   3.354   3.360   3.393   3.536   3.827
 TOWNHOUSE   4.228   4.197   4.176   4.167   4.172   4.205   4.348   4.639
 SUBURBAN    5.842   5.811   5.790   5.781   5.787   5.819   5.962   6.254

DEL.T= 100.0 DEG F
 DESN TEMP     0.0     5.0    10.0    15.0    20.0    25.0    30.0    35.0
 GARDEN APT  3.736   3.690   3.653   3.630   3.621   3.640   3.771   4.052
 TOWNHOUSE   4.548   4.502   4.466   4.442   4.434   4.452   4.583   4.865
 SUBURBAN    6.162   6.116   6.080   6.056   6.048   6.066   6.197   6.479

DEL.T=  90.0 DEG F
 DESN TEMP     0.0     5.0    10.0    15.0    20.0    25.0    30.0    35.0
 GARDEN APT  4.127   4.062   4.008   3.966   3.940   3.942   4.058   4.328
 TOWNHOUSE   4.939   4.875   4.820   4.779   4.753   4.754   4.871   5.140
 SUBURBAN    6.553   6.489   6.434   6.393   6.367   6.368   6.485   6.754

DEL.T=  80.0 DEG F
 DESN TEMP     0.0     5.0    10.0    15.0    20.0    25.0    30.0    35.0
 GARDEN APT  4.616   4.528   4.451   4.387   4.339   4.319   4.417   4.672
 TOWNHOUSE   5.428   5.341   5.263   5.200   5.151   5.131   5.230   5.484
 SUBURBAN    7.042   6.955   6.877   6.814   6.765   6.745   6.844   7.099

DEL.T=  70.0 DEG F
 DESN TEMP     0.0     5.0    10.0    15.0    20.0    25.0    30.0    35.0
 GARDEN APT  5.244   5.127   5.021   4.928   4.852   4.804   4.879   5.115
 TOWNHOUSE   6.057   5.939   5.833   5.741   5.664   5.617   5.692   5.927
 SUBURBAN    7.671   7.554   7.447   7.355   7.278   7.231   7.306   7.541

DEL.T=  60.0 DEG F
 DESN TEMP     0.0     5.0    10.0    15.0    20.0    25.0    30.0    35.0
 GARDEN APT  6.083   5.926   5.780   5.649   5.535   5.451   5.495   5.705
 TOWNHOUSE   6.895   6.738   6.593   6.462   6.348   6.264   6.307   6.517
 SUBURBAN    8.509   8.352   8.207   8.076   7.962   7.878   7.921   8.131

DEL.T=  50.0 DEG F
 DESN TEMP     0.0     5.0    10.0    15.0    20.0    25.0    30.0    35.0
 GARDEN APT  7.256   7.044   6.844   6.659   6.493   6.357   6.357   6.531
 TOWNHOUSE   8.069   7.856   7.656   7.472   7.305   7.170   7.169   7.343
 SUBURBAN    9.683   9.470   9.270   9.086   8.919   8.784   8.783   8.958
```

4. Traditional Alternatives

One important method of estimating the economic prospects for geothermal-based space heating is to compare it with other traditional fuels. In Appendix A, using available data, such as the published rate schedules for electricity and gas, we estimate typical per million Btu costs. These are as follows:

Oil	$5.00/million Btu's
Gas	$4.00/million Btu's
Electric space heating	$11.00/million Btu's

Even though we worked with published tariffs, the block structure of the tariff required that we choose typical consumption in order to arrive at per million Btu cost. We did this and our estimates are in agreement with other estimates calculated from national averages.

The conclusion one may reach is that geothermal, under suitable conditions, can match and even beat the prices of traditional fuels.

VIII. CONCLUSION

The role of geothermal energy in accommodating the demands for space heating and cooling water heating, and moderate temperature industrial processes is quite promising for the following reasons. 1) The reliability of supply is relatively high; these are natural processes and all that remains is to find where nature has been especially generous. 2) Since the resource, itself is in many ways somewhat inexhaustable, the future delivered price will depend only on the direct price of recovery. In the case of fossil fuels, the future price will depend on the price of recovery, the rising cost of discovery, and cartel arrangements. 3) The environmental effects can be controlled through reinjection of the geothermal well water. 4) This source of energy will replace some of the need for conventional sources of energy which in turn implies that the environmental dangers associated with these fuels will decrease commensurately. 5) While geothermal energy of the variety we have been discussing is not as convenient in handling and use as some fossil fuels, it is no less convenient when used in stationary processes such as space heating or industrial processes. 6) Perhaps the most compelling argument in support of geothermal applications comes from the cost analysis. Using standard life cycle costing methods, we have shown that under favorable circumstances, which consist of no more than reasonably warm water and medium-to-high density housing, geothermal energy is less expensive than traditional fuels for satisfying moderate temperature energy demands. While the present picture is favorable we do not yet have a complete picture. While the major system design variables have been considered in this paper, there are many more which must be considered in a full system design. In addition, there are several problems which act as barriers to the full development of the geothermal resource. The properties and extent of the geophysical resource must be assessed as well as the detailed cost of recovery. The legal question of resource ownership has not been resolved in most of the eastern states. Finally, a public or private corporation or authority must have an interest, outside its traditional product line or service supply, in developing a geothermal system.

APPENDIX A

THE COST OF ENERGY FROM TRADITIONAL FUELS

Fuel Oil

Fuel oil with a heat capacity of approximately 135,000 Btu per gallon costs approximately $0.50 per gallon today. In residential furnaces used for space heating the net energy delivered is probably less than 100,000 Btu per gallon, leading to a cost of $5.00 per million Btu's.

Natural Gas

Natural gas with a heat capacity of 1000 Btu per standard cubic foot sells at the following rates in the Delaware area in the winter of 1978-79.

First 300 cu ft = $0.9556/100 cu ft
Next 1200 cu ft = $0.3976/100 cu ft
Next 1500 cu ft = $0.3226/100 cu ft

The conversion of the gas in residential furnaces is probably less than 80% efficient on the average; therefore, the eventual slope of the curve is approximately $4.00 per million Btu.

Electric Resistive Heat

Electric energy is sold to different customers at different rates. In the Delaware area the cost of electric energy for electric heated homes is calculated as follows.

Monthly costs for winter of 1978-79

Cost = $5.85 + 0.04635 (kilowatt hours used during highest month of summer 1978) + 0.02585 (hours in excess of peak 1978 summer month).

For the average all electric home, this represents a cost during the coldest winter months of $10.00 to $11.00 per million Btu's.

Electric Heat Pumps

Heat pumps can be either water- or air-referenced. The seasonal coefficient of performance of these two types of heat pumps is quite different. The water-referenced unit has a substantially better efficiency. The cost of electric energy is reduced directly by this seasonal coefficient of performance.

POTENTIAL HYDROTHERMAL GEOTHERMAL RESOURCES, EASTERN UNITED STATES

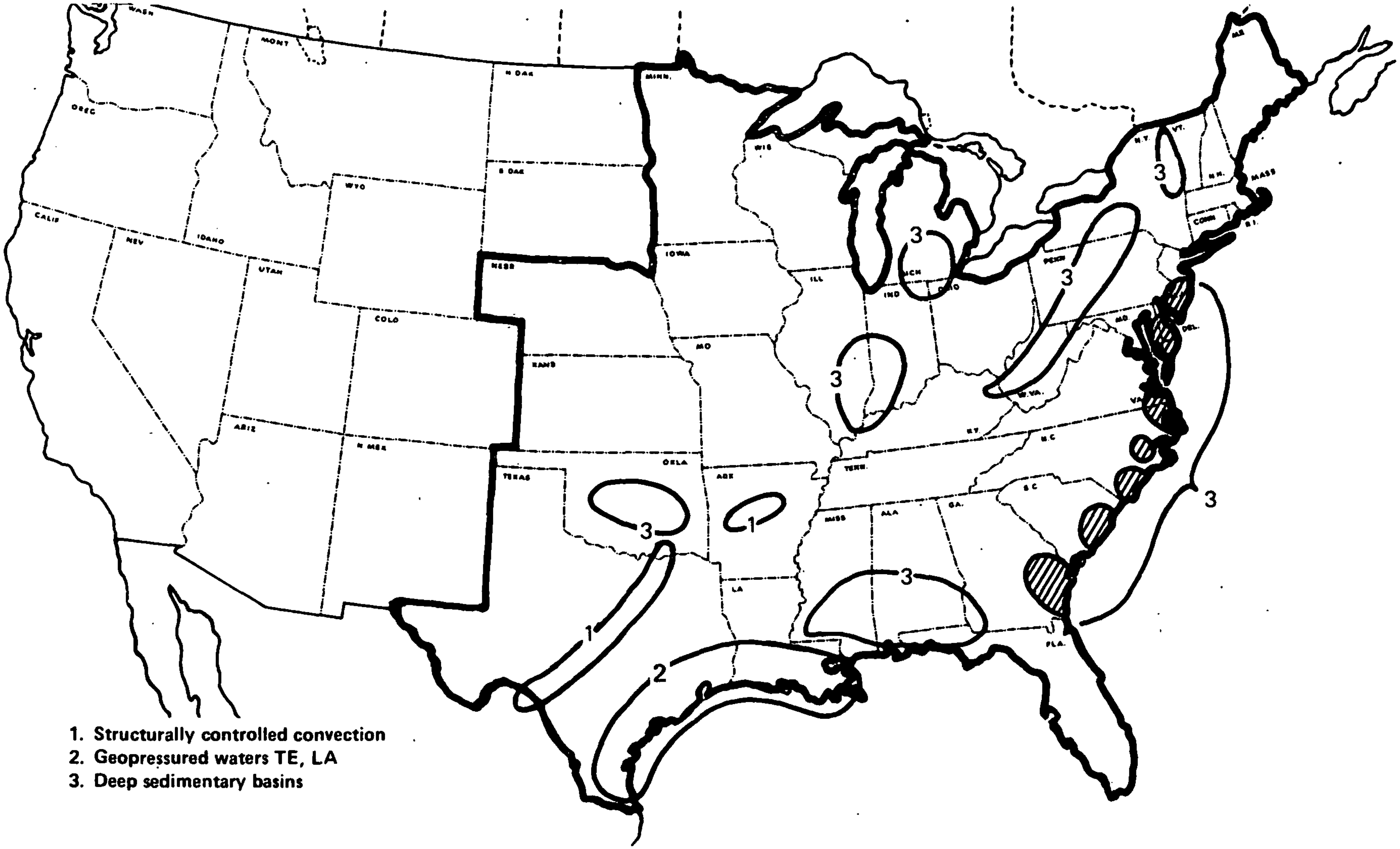


Fig. 1 Potential Hydrothermal Geothermal Resources, Eastern United States

HEAT FLOW IN FAR EASTERN UNITED STATES AND CANADA

Source – Near normal gradient workshop
ERDA–76–11, UC-66A
March 10, 11, 1975

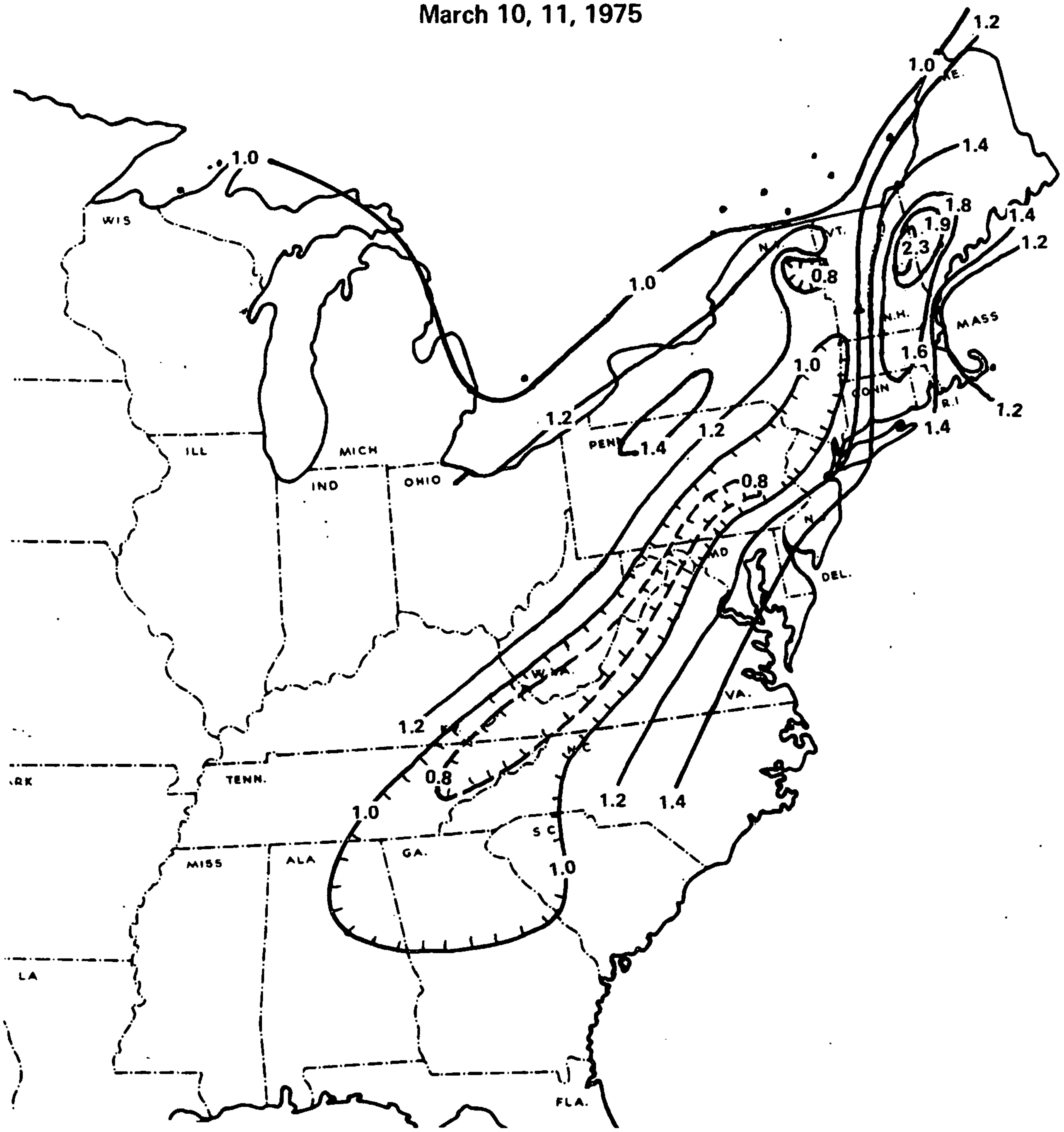
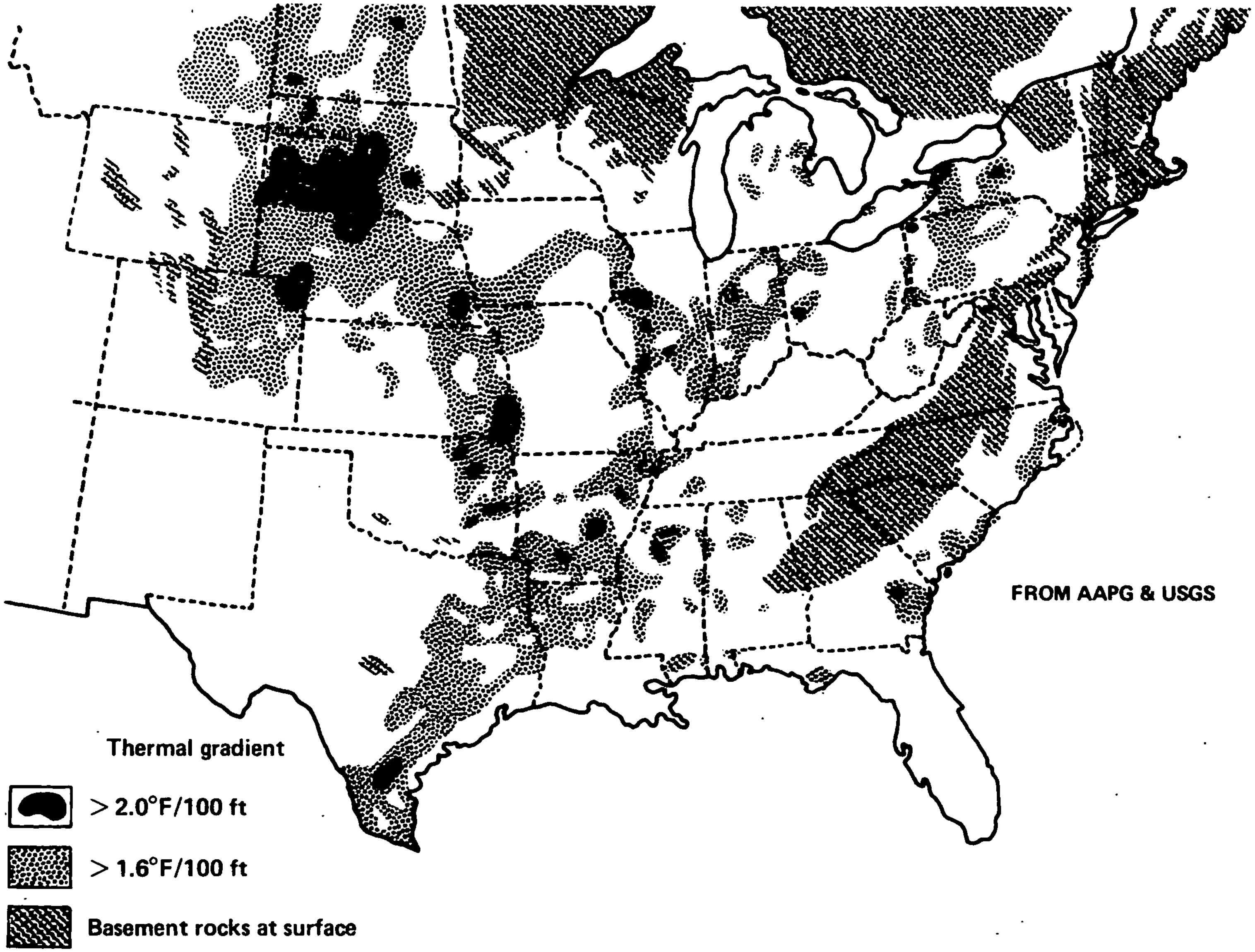


Fig. 2 Heat Flow in Far Eastern United States and Canada



FROM AAPG & USGS

Fig. 3 Thermal Gradients Eastern United States

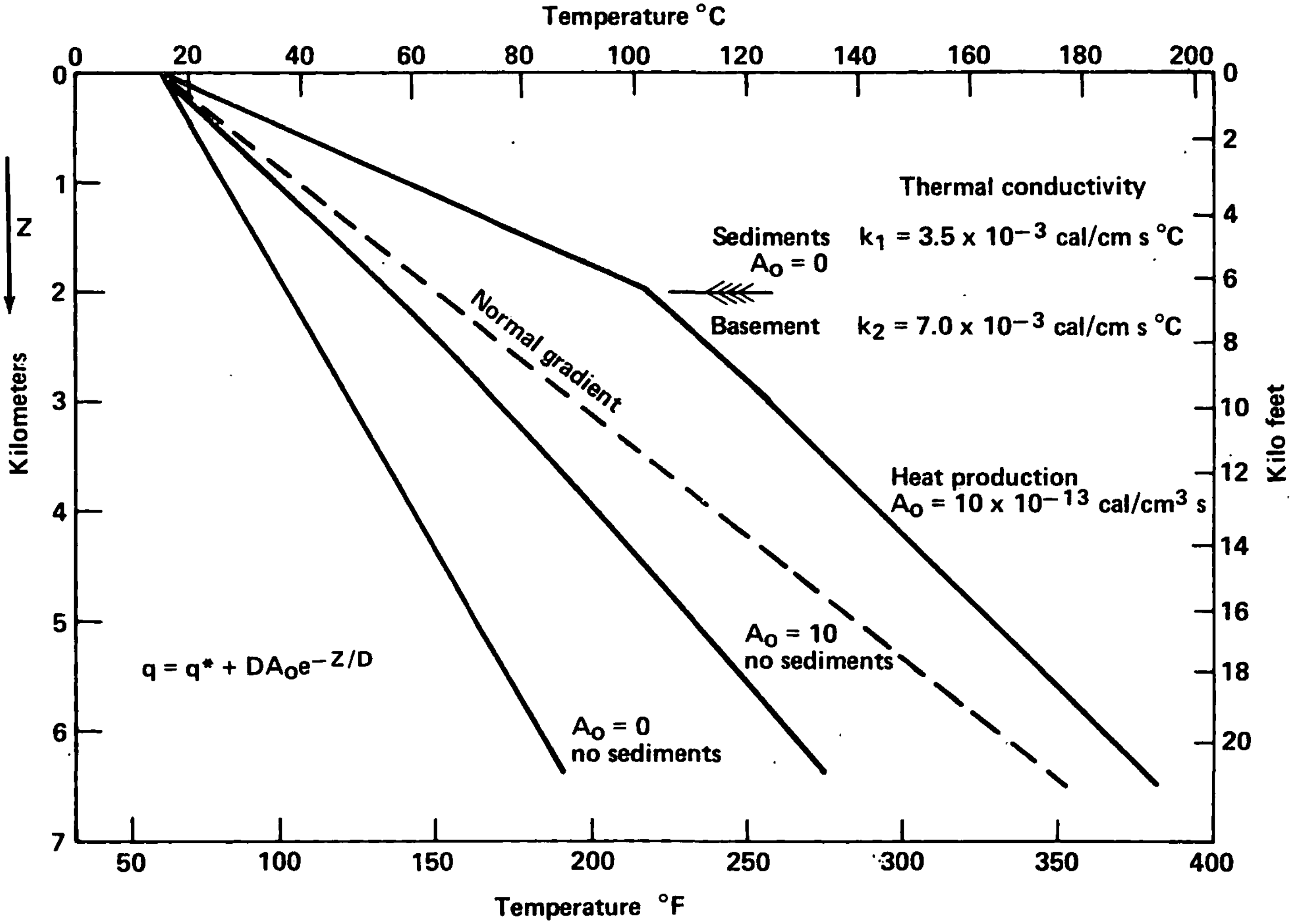


Fig. 4 Calculated Temperature versus Depth

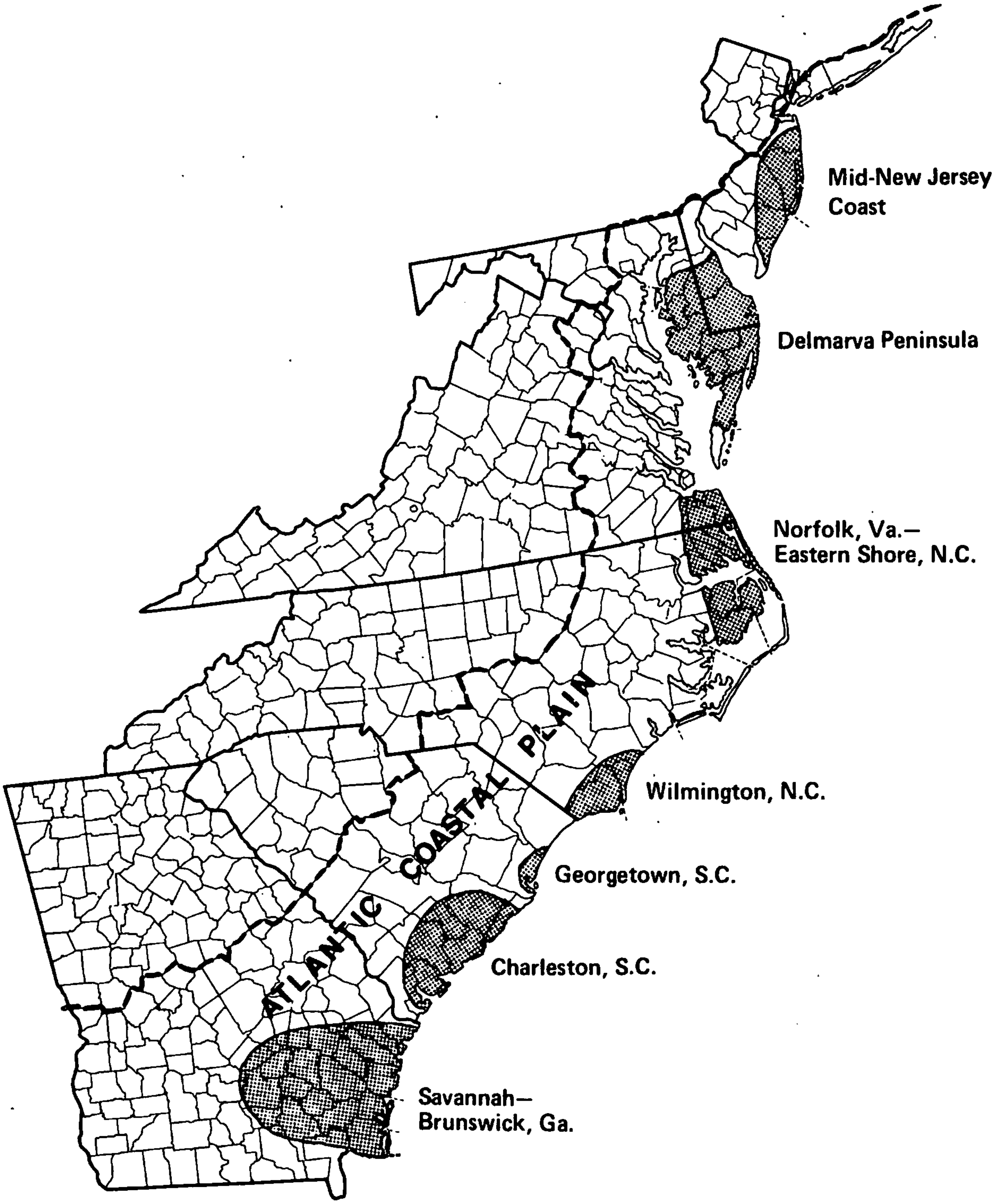


Fig. 5 Areas of Study Atlantic Coastal Plain

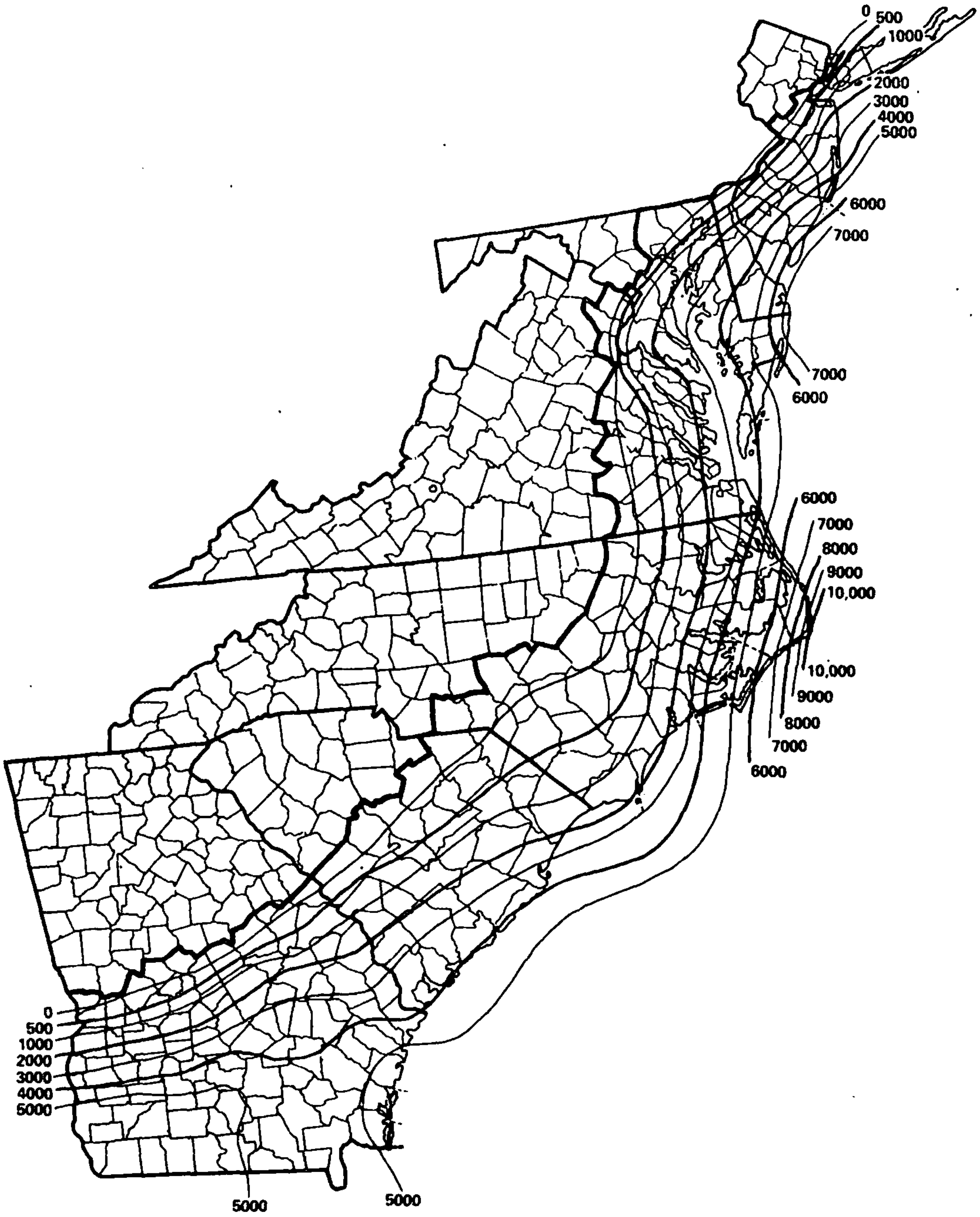


Fig. 6 Structural Surface of Basement Rock in Feet Below Sea Level

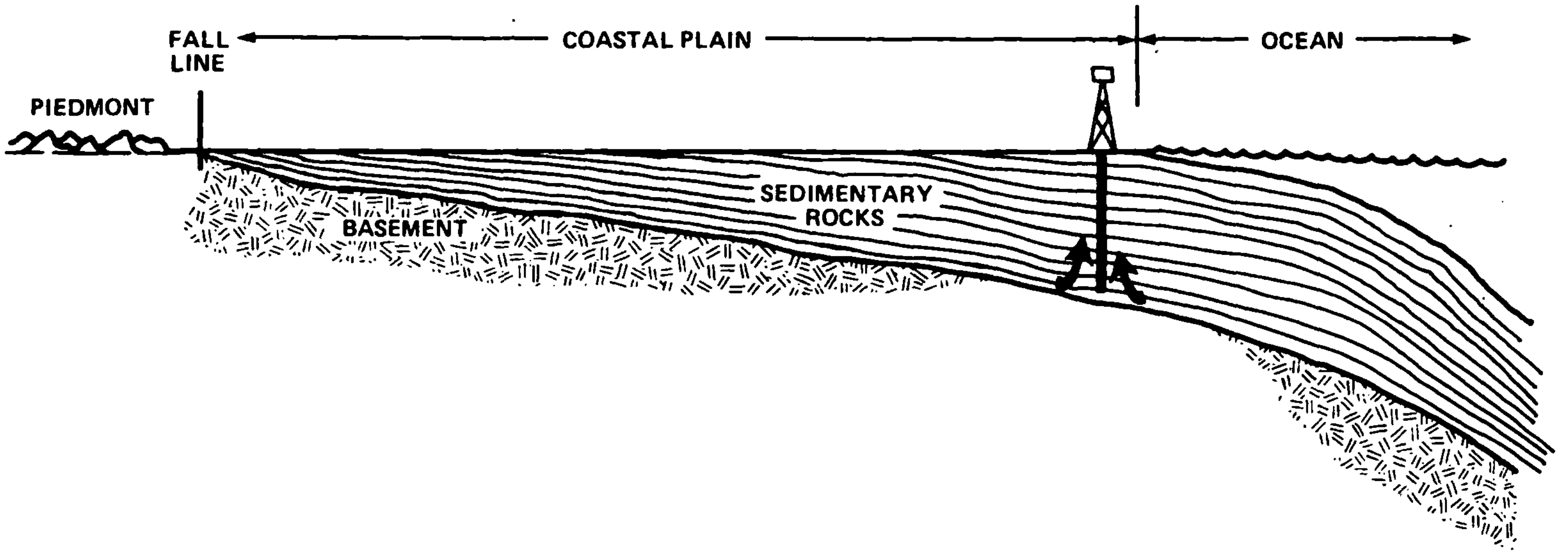


Fig. 7 Cross Sectional View Coastal Plain

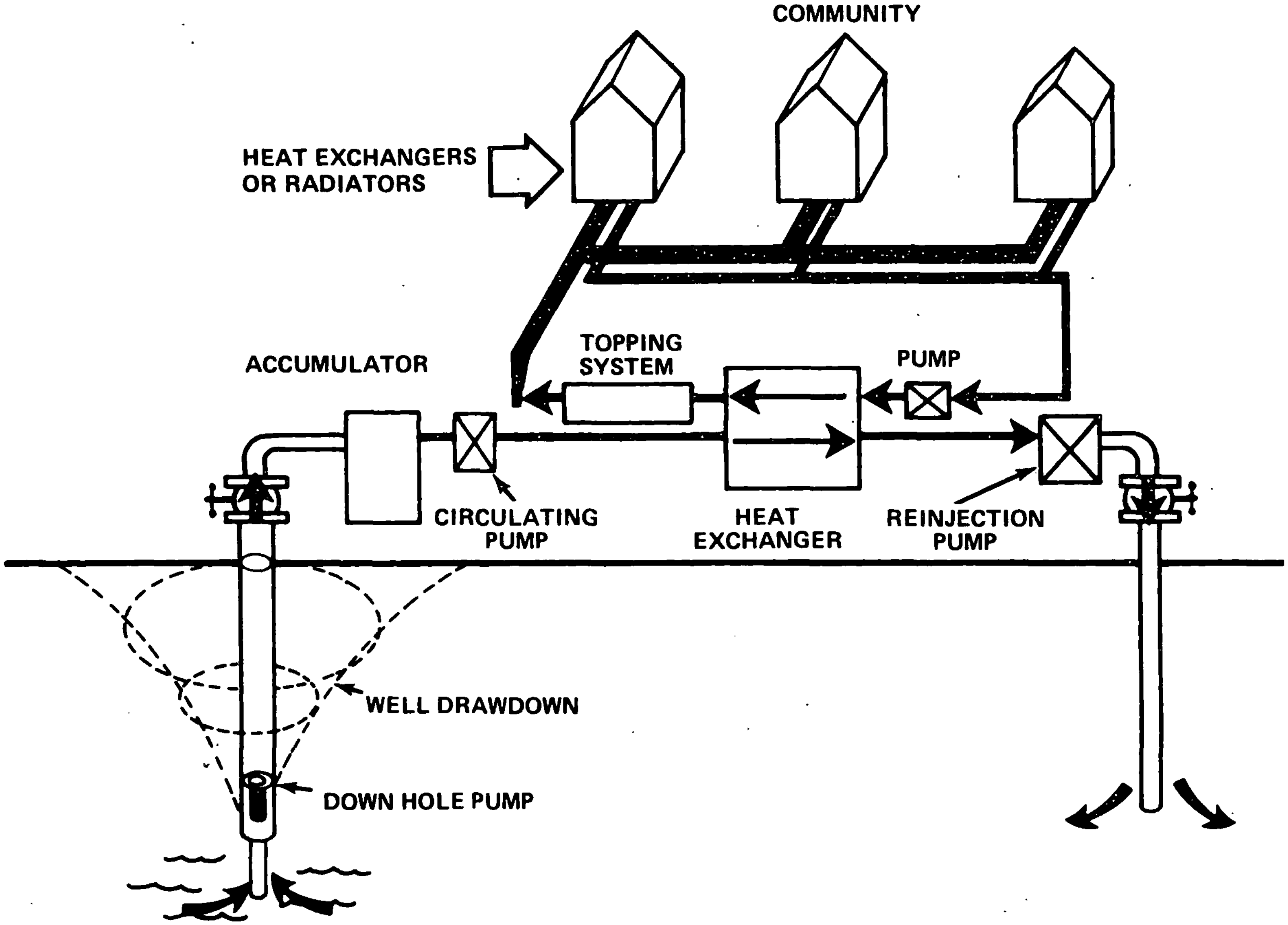


Fig. 8 Illustration of Community Heating — Hydrothermal resource

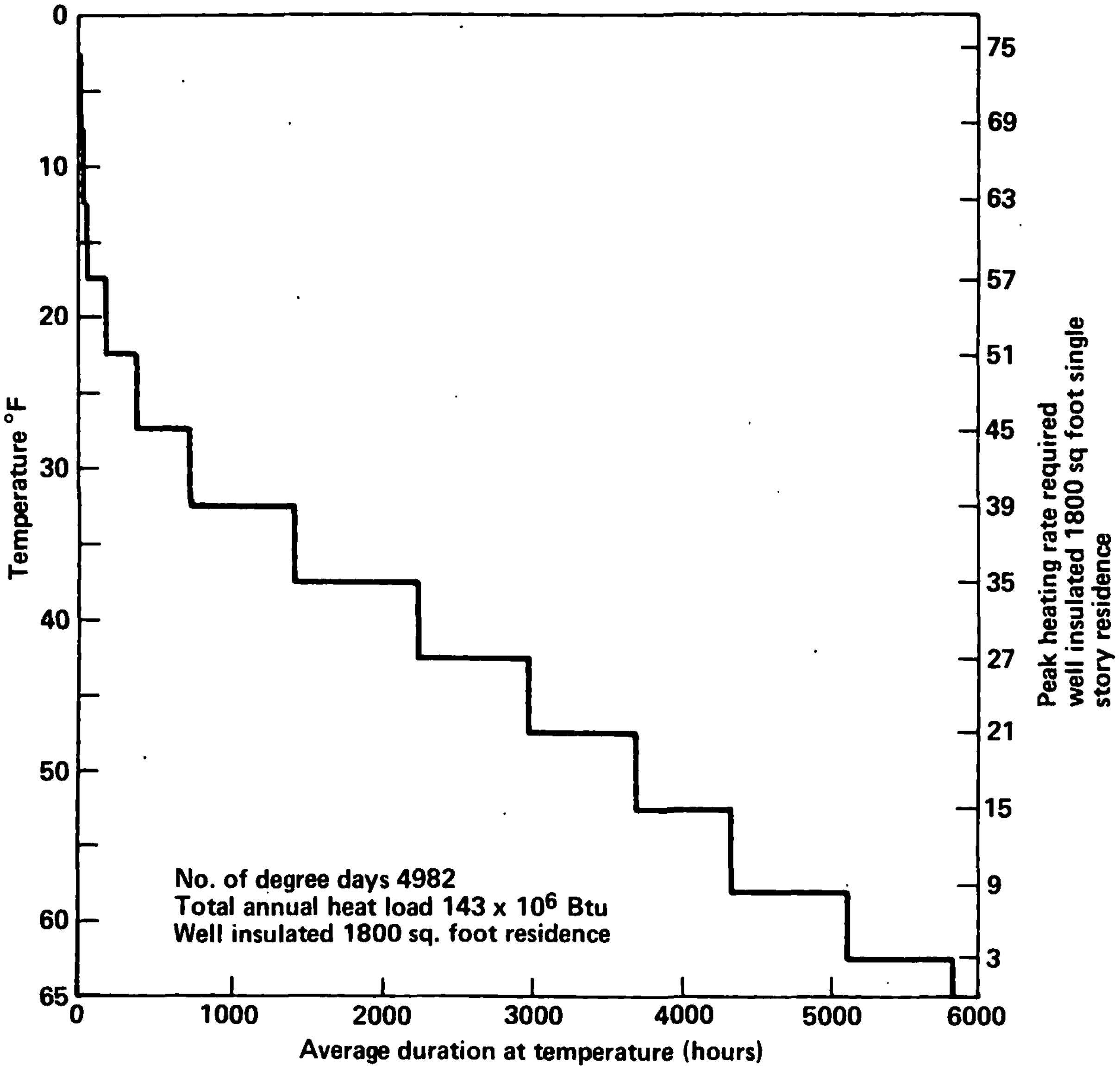


Fig. 9 Annualized Frequency of Hourly Temperatures Delaware Area, 1951 – 1960 Period

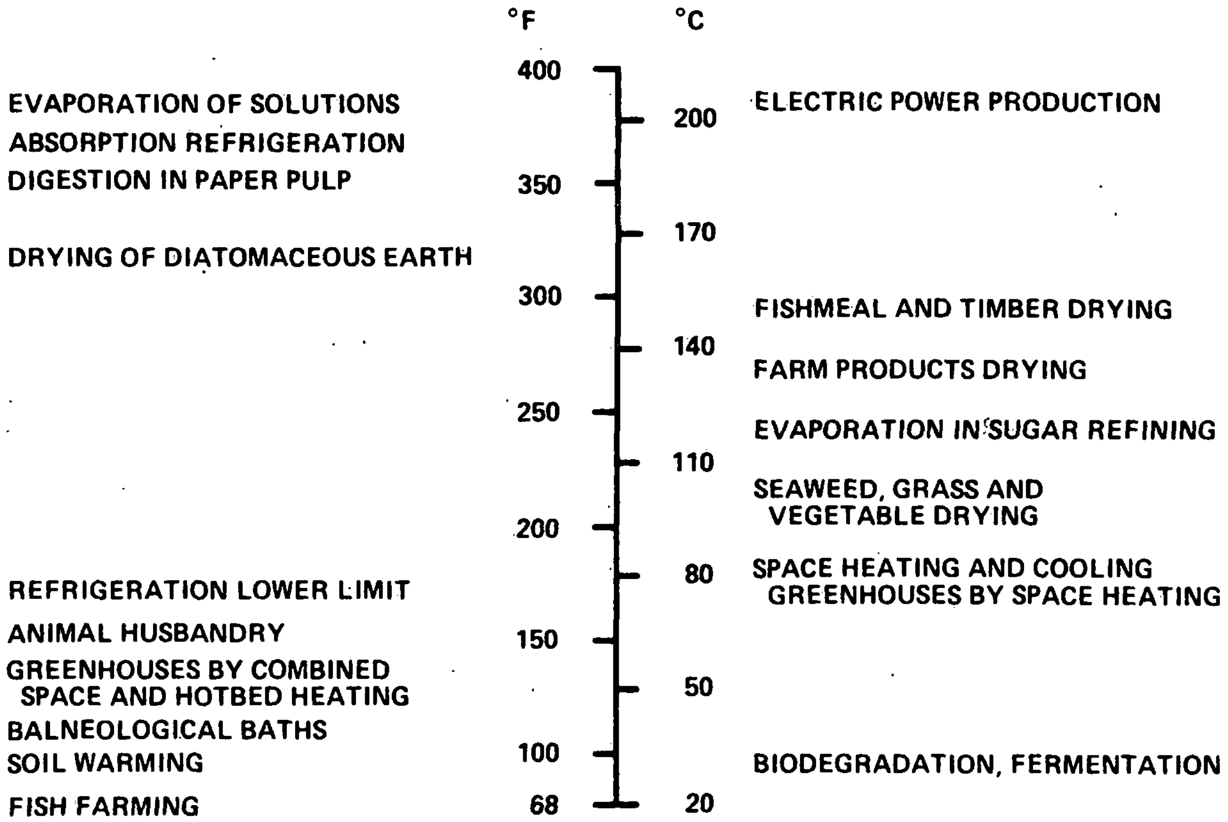


Fig. 10 Required Temperatures for Various Processes

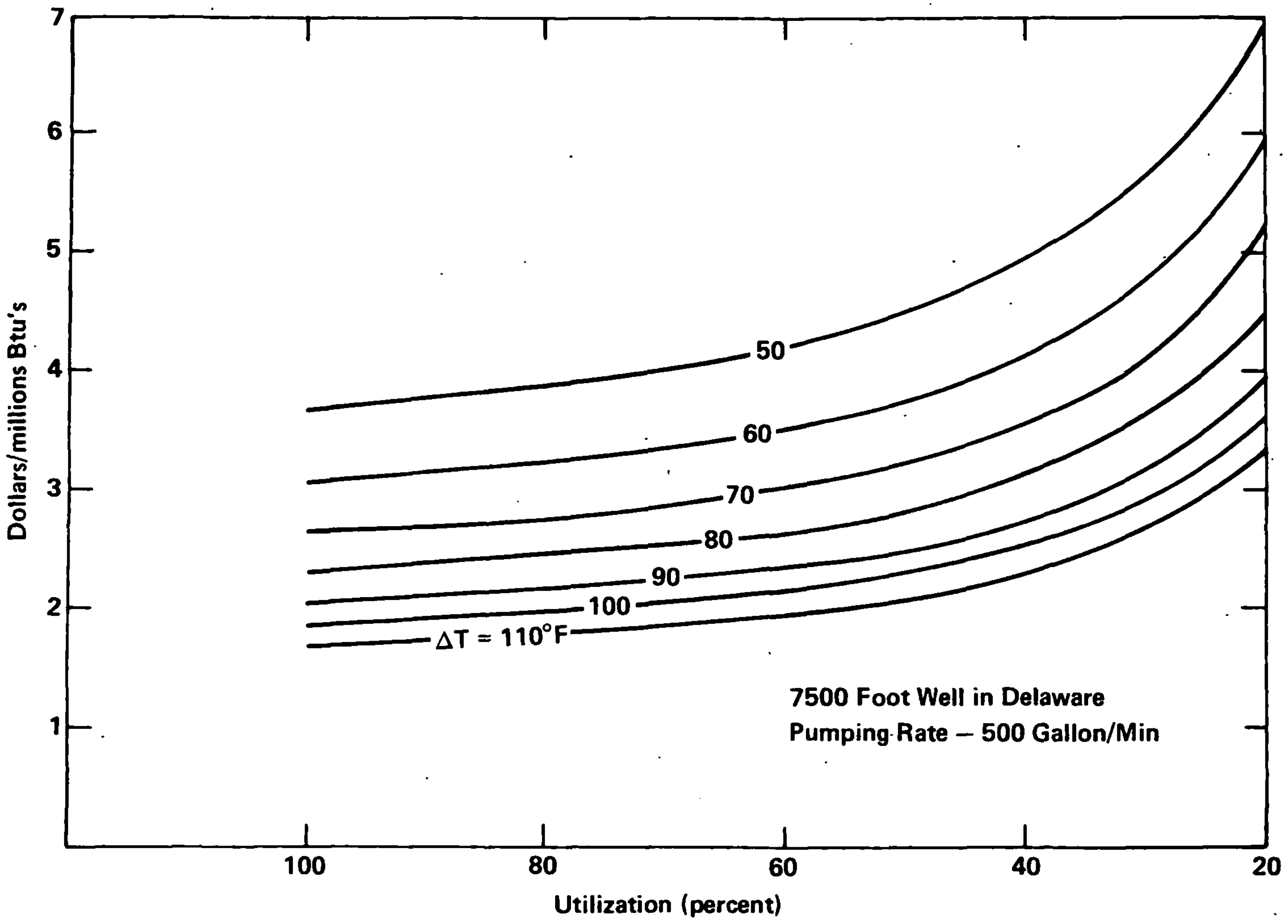


Fig. 11 Well-Head Costs of Geothermal Water

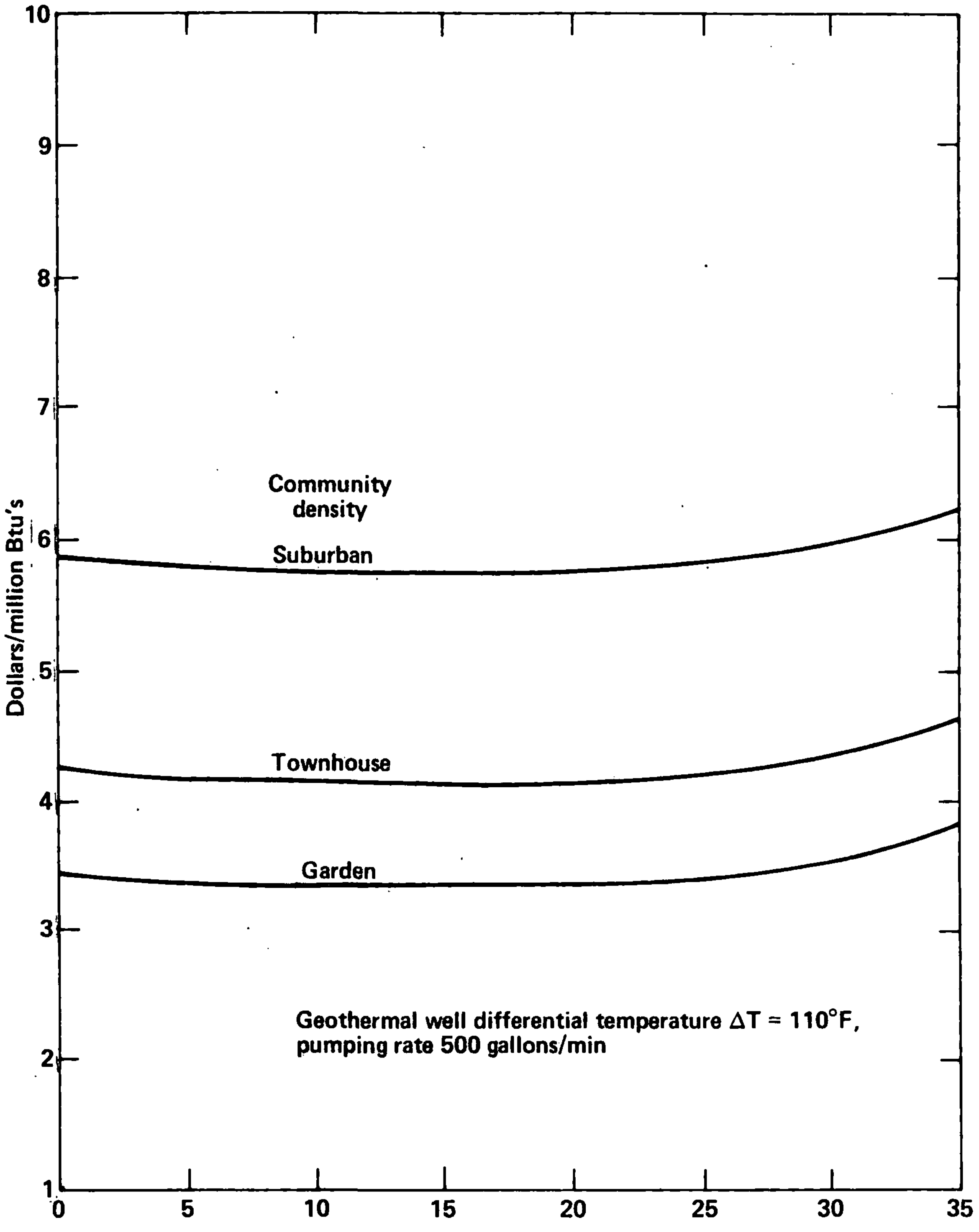


Fig. 12 Cost of geothermal energy – Atlantic Coastal Plain, Delaware.

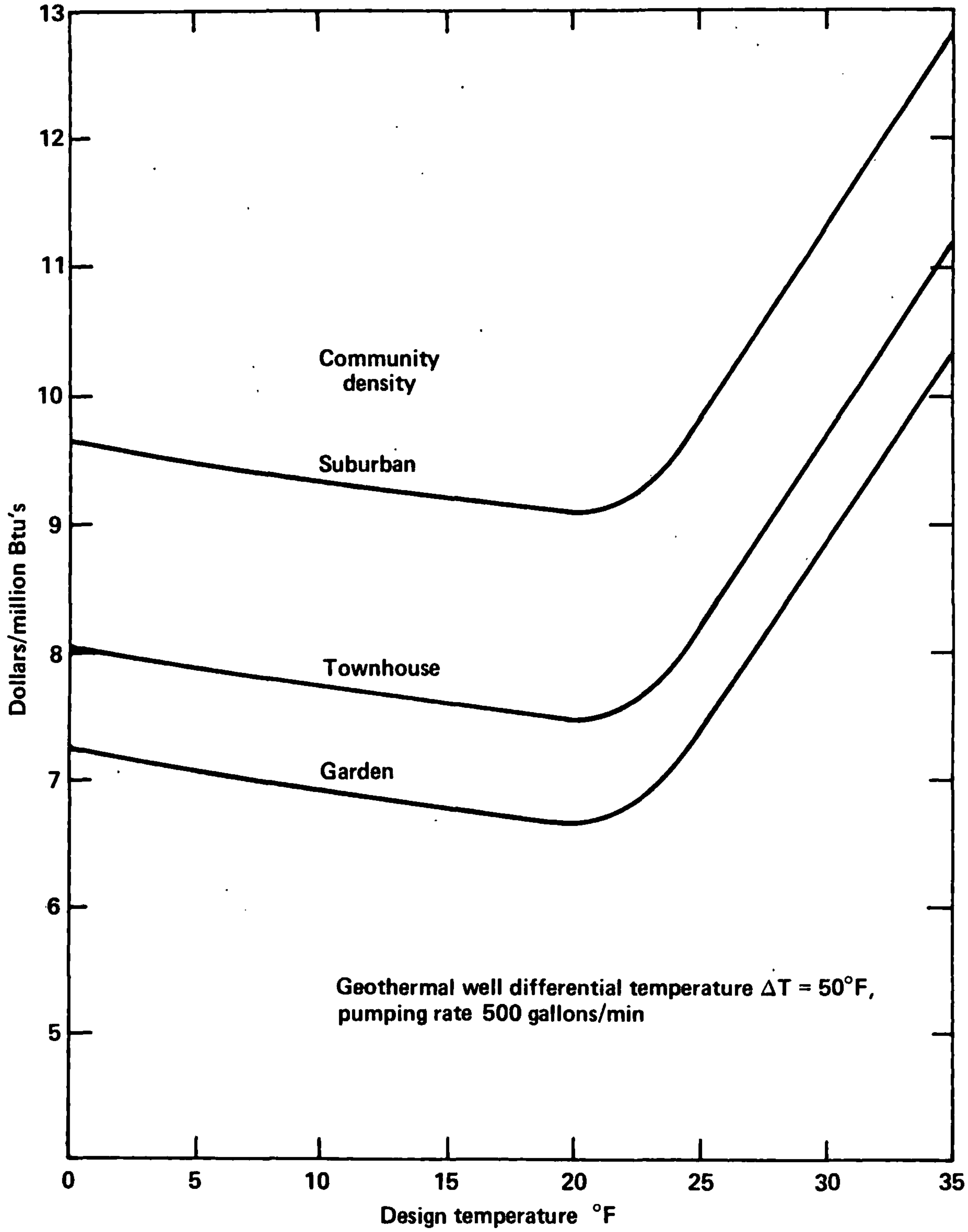


Fig. 13 Cost of geothermal energy – Atlantic Coastal Plain, Delaware.

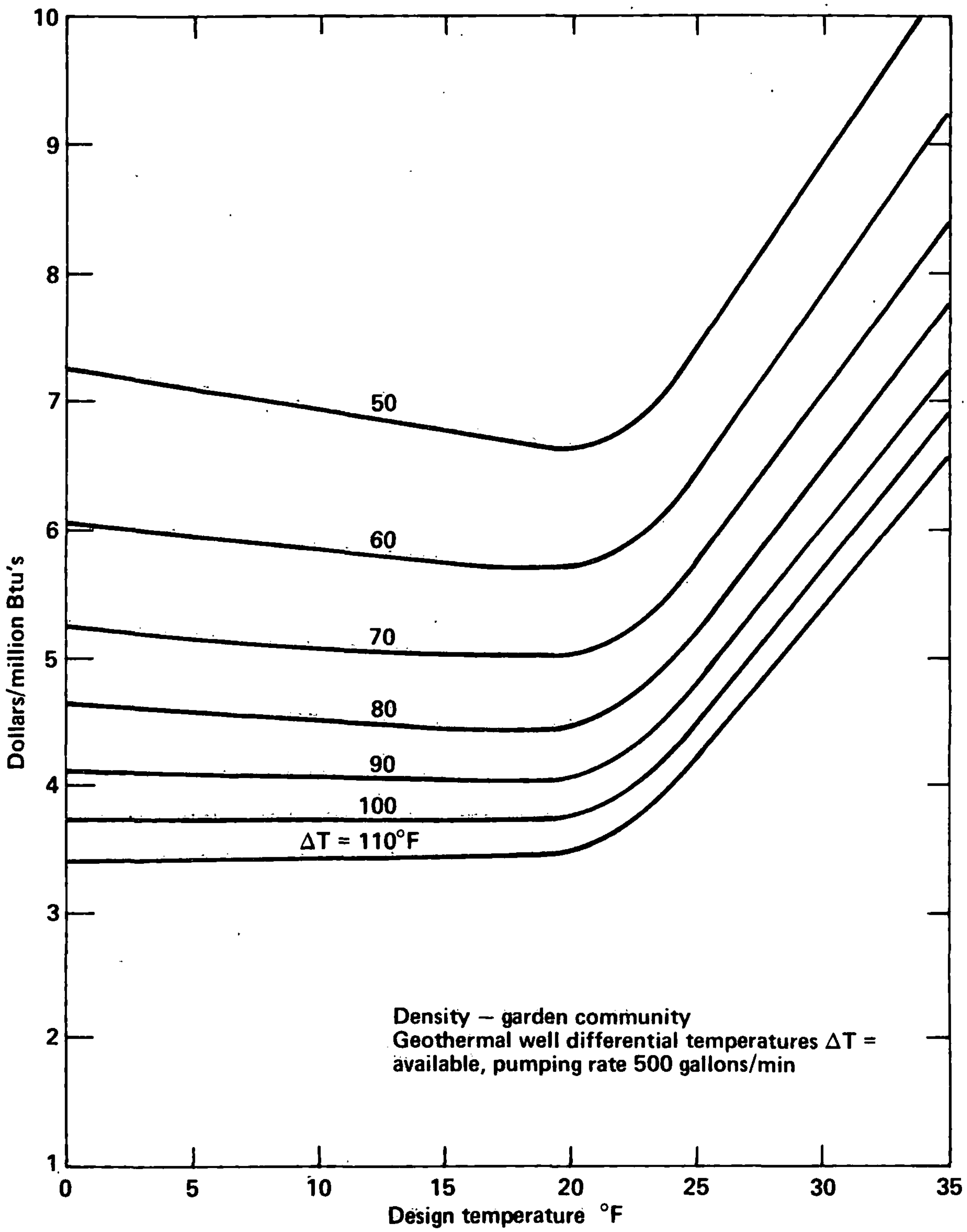


Fig. 14 Cost of geothermal energy — Atlantic Coastal Plain, Delaware.