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Geothermal Energy

GEOHERMAL ENERGY DEVELOPMENT IN THE EASTERN UNITED STATES FINAL REPORT

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under Interagency Agreements EX-76-A-36-1008
and DE-Alo1-79ET27025

THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY
Johns Hopkins Road, Laurel, Maryland 20707
Operating under Contract N00024-81-C-5301 with the Department of the Navy

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PREFACE

This document represents the final report from the Applied Physics Laboratory (APL) of The Johns Hopkins University on its efforts on behalf of the Division of Geothermal Energy (DGE) of the Department of Energy (DOE).

For the past four years, the Laboratory has been fostering development of geothermal energy in the Eastern United States. While the definition of "Eastern" has changed somewhat from time to time, basically it means the area of the continental United States east of the Rocky Mountains, plus Puerto Rico but excluding the geopressed regions of Texas and Louisiana.

During these years, the Laboratory developed a background in geology, hydrology, and reservoir analysis to aid it in establishing the marketability of geothermal energy in the east. Contrary to the situation in the western states, the geothermal resource in the east was clearly understood to be inferior in accessible temperature. On the other hand, there were known to be copious quantities of water in various aquifers to carry the heat energy to the surface. More important still, the east possesses a relatively dense population and numerous commercial and industrial enterprises, so that thermal energy, almost wherever found, would have a market. Thus, very early on it was clear that the primary use for geothermal energy in the east would be for process heat and space conditioning - heating and cooling, and electrical production was out of the question.

The task then shifted to finding users colocated with resources. This task met with modest success on the Atlantic Coastal Plain. A great deal of economic and demographic analysis pinpointed the prospective beneficiaries, and an intensive "outreach" campaign was mounted to persuade the potential users to invest in geothermal energy. The major handicaps were

1. The lack of demonstrated hydrothermal resources with known temperatures and expected longevity; and
2. The lack of a "bellwether" installation for entrepreneurs to see, touch, and emulate.

It is only at the present time that these two issues appear to be on the way to resolution by DGE user-coupled programs in the east.

Despite the understandable reluctance of entrepreneurs to commit resources to the use of geothermal energy in the presence of the preceding handicaps, the most recent Laboratory effort has been in technology transfer. We have devoted engineering effort to preliminary design for geothermal installations and conversions for a score of schools, hospitals, and other enterprises, who can use the designs for cost/benefit analyses that, if favorable, could lead to detailed engineering. By coupling these efforts with those of local architectural/engineering groups, the beginnings of a geothermal industry infrastructure have been accomplished.

While the future of geothermal energy in the east cannot be predicted with any certainty, the steady increase in the cost of oil, coal, gas, and electricity will surely one day persuade some groups to turn to geothermal heat for space-conditioning or industrial processing. As the parade forms, we believe that a small army will join in. We at APL are pleased to have been in at the beginning.

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EXECUTIVE SUMMARY

The Applied Physics Laboratory (APL) began its geothermal work in 1976 as a Regional Center for the Eastern United States, essentially to foster geothermal development by market studies and development prospectuses. The latter comprise a sort of checklist and timetable for development, including institutional, legal, and economic factors. This has led to a few actual developments, notably in South Dakota and Arkansas.

As the detailed characteristics of geothermal energy in the east slowly emerged, the role of APL gradually shifted to a technical assistance role, focusing on preliminary engineering/economic studies for space heating. This effort was accompanied by a conscious attempt to build a geothermal infrastructure by subcontracting selected assistance studies to local engineering firms. Dozens of these technical assistance studies were carried out and documented.

The legal issues were addressed in some detail; considerable interaction took place among the state legislatures of Delaware, Maryland, and Virginia, the National Council of State Legislatures (NCSL), and the Laboratory. Notwithstanding the difficulties of clarifying the issues of ownership, use, regulation, royalties, and environmental factors, there exist today state geothermal laws in Maryland and in Virginia; a bill has been proposed in Delaware, but was vetoed. Until their constitutionality and practicality are tested in court or by regulatory agencies with an actual case, the future of these laws is unclear. However, it is in a sense remarkable that we have any geothermal law on the books of any eastern states at all.

Very early on it became apparent that tools were badly needed for the economic analysis of the fragile low-temperature hydrothermal resource of the east. It became further apparent that the production of electricity from this resource was out of the question; its proper role will be in space heating or air conditioning.

1. ECONOMIC AND INSTITUTIONAL FACTORS

After an early attempt at crude, order-of-magnitude economic calculations, the assistance of The Johns Hopkins University Center for Metropolitan Planning and Research (Metro Center) was

solicited to develop a sophisticated computer model for geothermal space heating. The modeling went through several evolutionary stages, culminating in the Geothermal Resource Interactive Temporal Simulation (GRITS). This model involves costs in many areas: resource development, distribution, conversion equipment, the addition of a fossil-fuel peaking plant, reinjection, drawdown, money and time, the resource assessment period, and the degradation of the resource over time. The model allows a comparison of a geothermal heating system with an alternative fossil-fuel system. Finally, the equipment lifetime is allowed to differ from the debt service period of the equipment. This simulation will be accessible to users as magnetic tape or by a telephone link with the Metro Center.

In exercising the GRITS model, sensitivity analyses were carried out by varying the basecase parameters for a hypothetical geothermal space-heating system at Salisbury, Md. (later compared with ones at Thermopolis, Wyo., and Boise, Idaho). After running the basecase, which showed a discounted average cost (DAC) over 20 years of \$13.69 per million Btu's, the resource temperature and flowrate were varied. Other parameters varied were drawdown, reinjection depth, transport distance, costs of fossil fuel and electricity, percent demand, household density, and percent industrial utilization. For each condition, the sensitivity of the DAC to the parameter is documented in Ref. G.15 in Appendix D.

Since the demand factor is of fundamental importance to the economic viability of geothermal energy, the question of market penetration was addressed by the Metro Center. The existing capital stock of heating systems is the main obstacle to market penetration despite the fact that unit Btu reductions are available with the use of geothermal energy. This was formally modeled in an aggregative model of the residential sector.

The broad result is that the geothermal provider should pursue new developments, since the owners of existing housing stock will be slow to convert unless substantial financial incentives are created. A sliding scale of incentives, depending on the anticipated future life of a conventional heating system, can be devised to achieve any desired penetration rate. Nevertheless, in the practical sense, the developer would be advised to seek new construction as the market for geothermal energy.

Definitions of the size, composition, and location of potential markets for geothermal energy are of vital importance for the formulation of a plan for the commercialization of geothermal resources. A detailed examination of energy usage in the Atlantic Coastal Plain was therefore undertaken in the most promising hydrothermal areas. Resource temperatures were determined using the available geothermal gradient data and U.S. Geologic Survey (USGS)

estimates of depth to basement. Since heat pumps are available, resource temperatures down to 90°F were considered. Temperatures required for various energy end-uses were ascertained. Using census tract data and the heating demand per person, the residential space-heating and hot-water demands were calculated. Commercial demands were similarly calculated from commercial employment figures for each area. The Standard Industrial Classification Code (SIC) information was used to establish direct contacts with over 500 companies.

Final recommendations included first, targeting the industrial sector. In particular, the Delmarva Peninsula seemed to afford the best opportunity, although uncertainties in the resource presented a major obstacle. Pinpointing future DGE prospecting efforts required a systematic quantitative technique for evaluating suggested strategies. Such strategies require information not only on geologic and engineering factors, but also on socio-economic ones. Such data are readily available only at the county levels. Accumulating the information involves ranking geothermal prospects by amalgamating several bases of comparison, using appropriate weighting factors. A computer program utilized temperature, cost, energy use, the number of towns and cities, the number of heating degree days, and the value added in manufacturing to arrive at a tabular rank order. The weights can easily be varied and new data can easily be added.

2. INFORMATION EXCHANGE

There have been five Technical Information Interchange Meetings where people interested in geothermal energy in the Eastern United States have exchanged technical information.

The first information interchange meeting on eastern geothermal programs, the Near-Normal Gradient Workshop, was held in March 1975 under the aegis of the Energy Research and Development Administration. The second, Technical Information Meeting, was held at APL in September 1978 under the auspices of the Division of Geothermal Energy, Department of Energy (DGE/DOE). A symposium on Geothermal Energy and Its Direct Use in the Eastern United States was sponsored by the Geothermal Resources Council in Roanoke, Va., in April 1979. The fourth and fifth meetings were on Geothermal Energy and the Eastern United States. The fourth was sponsored by the Division of Geothermal Resource Management, DOE, in the fall of 1979. The fifth, again sponsored by the Division of Geothermal Energy, DOE, was held at the Coolfont Conference Center, Berkeley Springs, W. Va., in the fall of 1980.

3. SUPPORTING TECHNICAL DEVELOPMENTS

In the course of the four to five years of involvement in promoting moderate-temperature geothermal resources, several innovative technical excursions were made.

The first concerned a new method of prospecting for deep hydrothermal reservoirs by means of a variation of magnetotelluric techniques using the extremely low frequency (ELF) signals broadcast from the Navy's experimental ELF facility in Wisconsin. The details are given in Chapter 10. Despite the interest shown by the geothermal community, financial support for further investigation was not forthcoming.

The other two innovations concerned the use of geothermal energy for air conditioning. The possibility of increased use of a low-temperature resource in this field would dramatically improve the economics. An ammonia absorption cycle was devised whereby an ammonia-water solution could be used either for heating (by absorption of ammonia in water) or for cooling (by adiabatically expanding gaseous ammonia). With the chosen parameters, it was demonstrated that air conditioning could be provided by a resource with a geothermal temperature of about 150°F or higher.

The second air-conditioning scheme was an adaption of an Einstein-Szilard invention where ammonia is used as the "pusher" gas and butane as the refrigerant. This system also can operate properly at 150°F, or perhaps a little less. As in the ELF case, further support for these developments has not been forthcoming.

4. STATE PLANNING

It was early recognized how important it was to provide state and local bodies with a geothermal "road map," including the resource prospects, market prospects, and institutional and governmental hurdles to be addressed. The state scenario was the tool devised for this task, and five such scenarios were issued. Then, to assist the State of Maryland's Department of Natural Resources, as well as other agencies of state or local governments, APL prepared and issued a tutorial narrative that became the prospectus for the Delmarva Peninsula. The essential feature was significant input from state agencies. This led to APL involvement in setting up state geothermal teams in the east to coordinate state efforts. Delaware and Virginia, with APL assistance, obtained DOE funding to establish state teams. Maryland State perception of geothermal energy prevented implementation here. Finally, as of mid-1981, with NCSL and APL assistance, the legislatures of Delaware, Maryland, and Virginia

had passed geothermal acts. Delaware's act was vetoed by the governor, Maryland's act is in the process of amendment, and Virginia's act has yet to be thoroughly scrutinized.

5. REMAINING TASKS AND RECOMMENDATIONS

Of the tasks remaining to complete the first phase of effort in introducing low-temperature geothermal energy to the Eastern United States, the two most important are the reduction of the costs of geothermal wells and the provision of expertise to manage geothermal fields. The first includes the development of reliable and low-cost downhole pumps to raise the water out of the well. The second involves understanding the hydrogeology at geothermal depths by drilling additional deep wells and performing the necessary geophysical and engineering tests to determine the hydrologic characteristics of the resource. Finally, the demonstration of a functional geothermal community heating system will go a long way to convince skeptics or the uninformed of the geothermal reality.

The following recommendations are made in the light of the above:

1. Reservoir modeling and management techniques are needed to support the fragile economic bases of geothermal usage.
2. The government should mount a program to develop geophysical, geologic, and geochemical techniques to discover the hydrologic conditions in deep sedimentary basins.

 

Chapter 1

INTRODUCTION

1.1 THE OBJECTIVES OF THE LABORATORY PROGRAM

In 1976, the U.S. Energy Research and Development Agency Division of Geothermal Energy established regional centers for the following purposes:

1. Assistance in planning the federal geothermal program;
2. Assistance to individual states in identifying their geothermal potential and the steps required to develop the resources and use them to displace fossil fuel;
3. Identification of federal research and development efforts required to stimulate and expedite use of geothermal energy;
4. Assistance in the development of an infrastructure and transfer of technology until a viable industry should be in place to serve all groups seeking technical assistance in assessing the feasibility of geothermal energy;
5. Performance of market surveys in selected areas, identifying and quantifying the users of energy potentially convertible to geothermal energy and their locations relative to potential or known geothermal resources; and
6. Analysis of methods or incentives to aid geothermal penetration of identified markets in order to displace fossil energy.

APL was the regional center assigned all of the states east of the Rocky Mountains, except Texas and Louisiana. At about the same time, a contract was given to Virginia Polytechnic Institute and State University (VPI&SU) to assess and target geothermal resources under the Atlantic Coastal Plain. At a later time, DOE/DGE established Resource Assessment Teams in the west and initiated contracts for resource assessment in selected areas in the Eastern United States. Appendix A lists the efforts in the east.

In 1976, other than the resource assessment effort just beginning by VPI&SU (Ref. 1) and the information in USGS Circular 726 (Ref. 2), little was known about geothermal energy in the east, and there was no recovery of geothermal energy except for the heating of a high school at Midland, S.D. (Ref. 3), the conversion of the administration building at Hot Springs National Park, Ark., to geothermal space heating (Ref. 4), and the development of a number of hot springs for balneology. There was no industry or infrastructure available nor state laws determining ownership or allocation of geothermal resources, nor the permitting of geothermal development. Although geothermal energy was well known in the west and electrical energy was being produced by geothermal energy at The Geysers near San Francisco, little had been done to use the modest-temperature hot water (hydrothermal) resources so abundant in the west.

1.2 THE STATUS OF GEOTHERMAL ENERGY IN THE EAST TODAY

APL and the other regional centers have worked with DOE/DGE, state and local bodies, and individuals on the mechanics of the development and application of geothermal energy and the amelioration of the financial and institutional hurdles that existed. In a similar manner, knowledge of the elements that affect costs and the overall economics of geothermal energy has evolved with time as experience was gained in resource definition and as technical studies of the engineering feasibility of geothermal energy for specific applications were performed. The skeleton of an industry is visible in both the west and the Eastern United States, as is a legal and institutional understanding of geothermal energy. Appendix B lists some elements of the geothermal infrastructure in the east. The status of geothermal energy in the Eastern United States is summarized in the following subsections.

1. South Dakota (Ref. 5) Four space-heating projects have been undertaken:

- a. High School, Midland
- b. St. Maries Hospital, Pierre
- c. School and part of downtown Philip
- d. Farm building; grain drying and warm stock water at Diamond King Ranch near Midland.

All of the above, with the exception of the Midland High School, were subsidized by DOE in the development of geothermal energy.

2. Hot Springs, Arkansas (Ref. 6). The Hot Springs National Park Headquarters Building is heated geothermally, and it is planned to extend the use of the thermal waters to space heat se-

lected bathhouses. The U.S. Park Service has funded these energy developments.

3. Delaware (Refs. 7, 8, and 9). A well will soon be drilled to determine the hydrothermal resource and water chemistry at Lewes, Del. The costs of the well are being paid by DOE. If successful, the hydrothermal energy will be used for industrial process heat and space heating.

4. New York State (Refs. 10 through 17). A well may soon be drilled to determine the hydrothermal resource at the Clinton Corn Projects Plant of Standard Brands at Montezuma, N.Y. The cost of the well will be paid by DOE. If successful, the hydrothermal resource will contribute process heat in the manufacture of fructose - a high density corn syrup. In an alternative plan, a well may be drilled on the grounds of the high school or the community college in the town of Auburn, N.Y., next door to Montezuma. In either case, the geothermal well will confirm whether or not a hydrothermal resource exists in Cayuga County.

5. Texas (Ref. 18). Space heating and an augmented supply of domestic hot water at the Torbett-Hutchings-Smith Memorial Hospital, Marlin, Tex., will be available in 1981. Multiple direct use of geothermal energy at the Navarro College Union Building and the Navarro County Memorial Hospital, Corsicana, will be operational in 1982. The detailed engineering for these two projects, including drilling of geothermal wells, was paid for by DOE.

1.3 LEGAL STATUS OF GEOTHERMAL ENERGY

1.3.1 Geothermal Legislation in the West

Most of the states in the west have enacted geothermal laws that tend to deal with the utilization of resources capable of manufacturing electricity and with the utility aspects attendant on such capability. In the eastern part of the country, the geothermal resources are not the type to generate electricity, and, therefore, some of the legal questions are quite different.

1.3.2 Geothermal Legislation in the East

In 1976, there were no geothermal laws in the east, and the issue was not even under consideration. Since then, some states have, on their own initiative, considered geothermal legislation. Beginning in 1978, under DOE support, the National Conference of State Legislatures (NCSL) has offered assistance to selected state legislatures who wish to look at the need for geo-

thermal legislation. The following states have seriously considered the issue:

- Maryland - The State of Maryland passed the Geothermal Resources Act in 1978 and, in 1981, passed several amendments to this Act, together with amendments to other acts to clarify and aid in the development of geothermal energy (Ref. 19). In this instance, the original act was passed prior to any effort by NCSL.
- Virginia - The State of Virginia passed a Geothermal Resources Act (Ref. 20) in the 1980-1981 Legislative Session. It is now law.
- Delaware - The State of Delaware's Legislature passed a Geothermal Resources Act in 1980, but it was vetoed by the Governor. A revised bill was not reported out of committee in 1981. The issue will be considered at the next legislative session.

Chapter 4 enlarges on the discussion of legislative issues in the east.

1.4 INFRASTRUCTURE DEVELOPMENT

As the detailed characteristics of geothermal resources in the east have developed - for example, shallow gradient wells, the resource confirmation well at Crisfield, Md., and attendant market studies along the Atlantic Coastal Plain - people have become interested in the application of these resources. Feasibility studies of the utilization of this new energy source further stimulated interest, and consulting engineers are now being asked to perform detailed engineering studies. In areas in the east where resource reconnaissance has occurred (i.e., the Atlantic Coastal Plain) and the subject is publicized, an infrastructure is developing. Appendix B lists those engineering organizations and allied groups in the east that are active in geothermal development and engineering.

It should be noted that hydrothermal geothermal engineering does not involve research or development of new engineering disciplines. All that is required is the appropriate interaction of the following engineering disciplines: geothermal resource assessment and targeting; deep water well drilling and completion; logging and testing the well for hot water recovery and reinjection; the detailed design of the distribution system, the peaking plant, and the central and individual heat exchangers; and finally, the treatment of geothermal water, if required to minimize scaling throughout the sys-

tem plumbing, and the plugging of the reinjection well. The state or regulatory body responsible for resource allocation or permitting must have available the disciplines of reservoir engineering, modeling, and resource management.

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  - b. Geothermal Resources, An Act Concerning, House Bill 651.
  - c. Board of Public Works - Geothermal Resources - State Lands, An Act Concerning, House Bill 652.

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Chapter 2

REMAINING TASKS

2.1 REDUCTION OF GEOTHERMAL WELL COSTS

Most geothermal wells drilled to date have been

1. Wells drilled by private developers in anticipation of geothermal fluid capable of producing electrical energy, or
2. Wells subsidized by the government for resource characterization or exploration.

Only a limited number of wells have been drilled in anticipation of modest-temperature geothermal water.

The costs of these wells, both on a per foot basis and completed (including testing and well plumbing), have been very high (Ref. 1), running on the average at least three times those of oil and gas wells of comparable depth drilled in the Appalachian Basin (Ref. 2). A geothermal water well on the Atlantic Coastal Plain is different from a well in the Appalachian Basin because the sediments are not as competent (i.e., composed of well consolidated and unfractured rock). In time, it is expected that they will be drilled and completed by water-well drillers. The costs of the two types of wells should approach each other with experience in drilling and testing geothermal wells.

2.2 DEVELOPMENT OF RELIABLE AND LONG-LIVED GEOTHERMAL PUMPS

Most modest-temperature geothermal resources must be pumped to insure an economic output of hot water. Because the local water table is drawn down during the pumping cycle, the pump must be located below the lowest point reached by the dynamic water table. Vertical line-shaft turbine pumps, where the motor is at the surface and connected to the pumps by a long shaft, have been used in most geothermal installations to date; however, there is a practical limit to the depth at which these pumps may be used - probably 1000 to 1500 feet. Below these depths, the motor must be placed under the series of pumps and the assembly placed in the well. This submersible pump has a modest life expectancy and must be recovered periodically, e.g., every year or two, and substantially reworked. The cost of this rework adds substantially to the annual

operation and maintenance costs. The industry apparently feels that the market potential does not yet warrant the effort required to develop a type of equipment with a longer life expectancy.

A further consideration is the requirement for variable pumping speed. This is no problem for the vertical turbine pump where a variable speed drive is mounted at the surface between the motor and the shaft to the pumps. However, in the case of the submersible motor, the speed must be varied electrically, which adds to the cost of the submersible system installation.

2.3 COMMUNITY HEATING DEMONSTRATION

The greatest potential for displacing fossil fuel in the east is found in the use of geothermal energy for community heating. Although it could be argued that this is a simple and straightforward engineering job, a demonstration is, we feel, necessary to illustrate all of the issues that must be addressed to utilize this new energy source. We recommend that this demonstration should be supported, either in part or wholly, by DOE. Chapter 6 and Paragraph 2.7.1, below discuss in limited detail the differences in the economics of community heating and of industrial process heat with geothermal energy and why it will be much harder for community heating to develop without substantial help from the federal or state government.

2.4 GOVERNMENT ASSISTANCE IN CHARACTERIZING MODEST-TEMPERATURE RESOURCES

The federal government has funded a considerable effort to characterize the modest hydrothermal resources in the east as well as areas of potential hot dry rock when that has been developed to an engineering science. The effort in the east is summarized here and in Appendix A. This section emphasizes the point that the individual developer of hydrothermal energy in the east does not have the economic incentive to conduct on his own geophysical, drilling, pump testing, or chemical analyses of geothermal resources prior to designing a plant and putting the resource to work. This is still a risky business and can be very expensive.

In the sedimentary basins or coastal plains areas with potential for geothermal energy there exists a considerable body of data on the geothermal gradients. These data are from oil and gas production and test wells where bottom-hole temperatures were measured. Reference 3 calls attention to the data compiled and analyzed by a joint program of the American Association of Petroleum Geologists (AAPG) and the USGS. More recently, DOE/DGE-funded state programs have analyzed oil and gas well data in given states

to provide a more detailed thermal gradient map. The data exist for:

1. The lower half of Mississippi (Ref. 4) and
2. Alabama (Ref. 5).

Programs in the following areas have carried the process a step further with geophysical measurements; additional geothermal gradient and rock thermal conductivity measurements; and the drilling of deep test wells.

3. Nebraska (Refs. 6, 7, and 8),
4. Kansas (Ref. 9),
5. The Atlantic Coastal Plain from New Jersey through Georgia (Refs. 10 and 11),
6. A 100 square mile area from Crisfield, Md., to Wallops Flight Test Center, Va. (Ref. 12), and
7. New York State (Refs. 13 through 21).

The measurement of geothermal gradients, together with a reasonable estimate of the type of sedimentary rocks and their thermal conductivities below the strata usually reached by shallow gradient wells, can provide an estimate of the temperature near the bottom of the sedimentary sequence. However, just as important is the deep hydrology, i.e., the productivity of water-saturated sediments. The data concerning this are much harder to come by and, almost without exception, require deep test wells. Such a well was drilled by DOE/DGE at Crisfield, Md. (Refs. 22, 23, and 24). Other such wells have been drilled, one at Norfolk, Va. (Refs. 25, 26, and 27), one in western New York (Ref. 28) to test waste disposal, and a limited number in Ohio, Pennsylvania, Illinois, Kentucky, and West Virginia for the disposal of liquid industrial waste (Ref. 29). However, these do not provide sufficient and adequate data to allow the assessment of the economic or basic practicality of providing geothermal energy other than in areas very proximate to the test wells. We would suggest the following possible approaches, which are, to some extent, patterned after the French and Icelandic approaches (Ref. 30).

The government (i.e., the USGS) should obtain the general resource characteristics in each sedimentary basin and other large resource areas through a geophysics heat flow and deep drilling hydrologic program. In addition, the government should continue

its user-coupled resource confirmation program to extend these data to other parts of each resource area or to new unexplored areas.

An alternative to the postulated USGS program is the resource determination program for the Atlantic Coastal Plain. VPI&SU under DOE/DGE sponsorship has conducted a detailed program of geothermal resource assessment and targeting. The effort covered the coastal plain from New Jersey to Georgia. Because of the size of the area and the known differences in geology, several wells were planned to confirm projections of temperature at depth from the shallow gradient measurements and, more significantly, to measure the hydrologic characteristics of deep aquifers and the chemistry of their waters. A resource confirmation well was completed at Crisfield in 1978 - the only well of its type in the east. It is suggested that a second deep confirmation well in the southeastern coastal plain be supported by DOE to provide additional data on reservoir assessment and engineering for the Atlantic Coastal Plain.

France and Iceland have had an insurance program for geothermal developers where 75% of the cost of a well in a new area is loaned to the group wishing to drill a geothermal well. If the well is successful, the 75% is repaid; if the well is not successful, it need not be repaid. Questions asked of the French about their programs and success and the answers can be found in Refs. 31, 32, and 33. The significant points of the answers were:

1. Loans are forgiven (i.e., become grants) if the temperature is too low or the output insufficient. The terms are negotiated prior to the loan; the geothermal committee makes the final determination.
2. All French geothermal efforts to date (a dozen or so) have obtained government loans.
3. At present, only three loans have had to be converted to grants (see item 1 above).
4. The present trend is toward the ownership of all geothermal enterprises by governmental entities, mainly municipalities, new city planning agencies, low-cost housing bureaus, and so on.

2.5 TRANSFER OF TECHNOLOGY

In the resource assessment program just discussed and in other complementary efforts, a considerable amount of information is developed, and it is no simple task to correlate, compile, and simplify the data and make them available to prospective users of geothermal energy. The state prospectus outlined in Ref. 34 was proposed as a method for each state with an exploitable resource to compile all the available information in one place. The State of Delaware is preparing the first state prospectus similar to that outlined in Ref. 35. We hope this will be emulated by appropriate state agencies for other areas.

2.6 STANDARDS FOR GEOTHERMAL DEVELOPMENT UTILIZATION

In October 1979, the American Society for Testing and Materials (ASTM) organized a committee (designated E-45 in ASTM terminology) to promote the development of standard definitions, test methods, specifications, and practices for the exploration, production, and use of geothermal energy. By the spring of 1981, the committee had held four meetings, the proceedings of which are reported in ASTM minutes.

An APL representative attended all four meetings. The committee is naturally western oriented since that is the area where both government and private activity is the greatest, and APL saw its task as representing the public interest in the development of the moderate- and low-temperature hydrothermal resources of the east. To that end, the APL representative served on the task groups for Logging and Surface Geophysics (E45.1004) and for Energy Utilization Systems (E45.2003).

At the request of these task groups, APL submitted two documents for consideration at the committee meeting in May 1981. The first (Ref. 36), for task group E45.2003, summarized the economic models for geothermal feasibility developed by or under the auspices of JHU/APL. This request by ASTM arose from the realization that the economic models in existence used different methods, had different objectives, and used different definitions of economic feasibility. However, a general ruling by the Executive Committee of E.45 has forbidden (for legal reasons) any ASTM discussion of standards for the pricing and billing of geothermal energy, and while this ruling does not forbid the discussion of economic models for feasibility studies, it did put a damper on any such discussions at the May 1981 meeting.

The second submission (Ref. 37), for task group E45.1004, was a procedure for testing the pumping of hydrothermal wells. The

procedure, which is given in Appendix C, was written for the pumping testing of moderate-temperature resources and attempted to prescribe procedures that would assist the assessment of typical eastern hydrothermal resources. At the May 1981 meeting, the task group decided not to consider pump testing procedures further both because of the wide variation in geothermal fluids, temperatures, and flow rates, and because the requirements of reservoir analysis made it impossible to write a concise pump test procedure of general interest to Committee E.45.

The work of the ASTM committee on geothermal energy has proceeded slowly, as is usual with new ASTM committees. To date, the only test procedure that has been written and submitted for voting is one for the proper installation and use of the valve at the well-head of a geothermal steam well. APL participation on this committee ceased as of the end of Fiscal Year 1981. However, the requests that APL has received for assistance in specifying pump test procedures and performing economic evaluations indicate a continuing need on the part of geothermal developers for these services. To what extent this information can be standardized and promulgated by ASTM may be, and is, arguable but the desirability of continuing this effort is substantiated by the APL experience.

2.7 RECOMMENDATIONS

2.7.1 Resource Engineering and Management

A prospective user of geothermal energy in the Eastern United States will find today that there is little known about the engineering details of geothermal resources, with the exception of the Madison aquifer in South Dakota, a limited area around the geothermal test well at Crisfield, and at Cambridge, Md. Further, they will find that there are no plans or procedures for resource management that insure that the economics of their use of the resource is protected against drawdown or thermal pollution by other users. Many people have discounted both of these problems on the bases that the user must do his own resource engineering and that the first one to exploit the resource has legal protection through the rule of capture. In regions where geothermal resources are high in temperature and geothermal wells are productive, it is true that there is enough financial incentive for the potential user to bear the cost of geothermal resource assessment, determining the detailed engineering characteristics adequate for each use. Further, as with the case of the oil and gas developer, there is sufficient financial incentive for the developer to absorb litigation about resource ownership and usage effects by others. However, there are few, if any, resources in the east where the economics are such that they can provide for either of these contingencies.

A further consideration that should be noted is the difference in the economics of the use of geothermal hot water for industrial process heat as opposed to residential or commercial space heating. The industrial process heat is usually the more economical since it is used year-round in contrast to space heating where the utilization factor of the heating system is based on the heating degree days, which results in probably less than 40% utilization annually. By the use of a peaking or storage system, the utilization factor of the geothermal well can be increased; however, in no way can it approach the industrial utilization factor. References 38 and 39 document the analysis, and Table 2.1 illustrates this point.

Table 2.1

Utilization factors of space heating

Town	Degree heating days	Utilization factor* (%)	Discounted average cost per 10^6 Btu
Salisbury, Md.	4300	42.8	\$17.5
Thermopolis, Wyo.	7500	47.4	10.0
Boise, Idaho	5800	36.3	4.5

* A peaking plant is used to increase the utilization of the geothermal well and minimize discounted average costs (see Ref. 40). The utilization factor is defined as the quantity of geothermal well flows divided by the flow if the well is pumped continuously throughout the year.

The cost of industrial process heat for comparison, assuming several utilization factors, is shown in Table 2.2. The resource conditions are the same as assumed in Table 2.1; however, it should be noted that normally a simpler distribution system is required for the industrial heat case.

Table 2.2

Cost of geothermal energy for industrial process heat

Resource area	Discounted average cost per 10^6 Btu Utilization factor		
	30%	50%	70%
Sailsbury, Md.	\$13.1	\$8.5	\$6.5
Thermopolis, Wyo.	7.7	5.1	4.0
Boise, Idaho	1.7	1.1	0.9

The above discussion illustrates the point that the economics of the moderate temperature resources, as found in the east, are fragile, particularly when considered solely for community space heating. It should also be noted, however, that much of the residential and commercial space heating in the Eastern United States is by gas or oil, and, accordingly, if geothermal is to have an appreciable impact in displacing them, it should be considered seriously for community space heating because that is where the substantial usage is.

In regard to reservoir management, Ref. 41 proposed a program for the east. In essence, the program called for the modeling of the resource in one of the eastern states planning to use geothermal energy and for instrumentation of the wells to provide data for use as input to the resource management model. This would be used to illustrate the mechanics of resource dynamics under use and could be used by other state bodies to determine regulation requirements.

2.7.2 Location of Areas of Increased Permeability

Figure 2.1 shows the geothermal regions in the Eastern United States with potential for geothermal energy. The shaded areas indicate sedimentary sequences deep enough (i.e., 4000 feet or more) that, even with geothermal gradients close to or greater than normal (>20 to $25^\circ\text{C}/\text{km}$), temperatures at the bottom of the sequence are useful in direct applications of geothermal energy. Reference 3, on which Fig. 2.1 is based, shows thermal gradients in the northern North American continent compiled from bottom-hole

- Basement depth greater than 4000 ft below surface (based on Ref. 3).
- Approximate areas of investigation by VPI&SU (Ref. 42).
- Limit of coastal plains sediments.

* Contours adapted by APL from basement map of North America (Ref. 3)

** From Gruy Federal report (Ref. 42)

Fig. 2.1 Potential geothermal resource areas in the Eastern United States.

temperature data on oil and gas wells; the same data are available at a greater scale for AAPG regions. Individual maps are available for almost every state with oil and gas activity. Figure 2.2 shows the gradient data for the Eastern United States. Reference 43 is a new map of the United States of America compiled by the Los Alamos Scientific Laboratory.

DOE/DGE has contracted for a number of resource assessment programs in many eastern areas. They are listed in Appendix A and are shown as approximate areas overlying sedimentary basins and coastal plains in Fig. 2.3. The USGS has a program (Ref. 44) intended to revise Circular 790 (Ref. 45) to include lower temperature geothermal resources (down to 50°C) in the United States.

Almost without exception, these resource assessment programs have concentrated on geology, thermal gradients, and heat flow. We suggest a systematic effort to add the data on deep water availability in each of these areas to complete the hydrothermal assessment. It is surprising how much data are available on this subject in many of the areas. They provide a first-order synoptic view. For example, in the five-state region of Ohio, Indiana, Western Pennsylvania, Illinois, and Kentucky, there is an agreement for disposal of industrial waste in deep basal aquifers (Ref. 29). Accordingly, permeability and transmissibility measurements have been made throughout the eight-state region of Illinois, Indiana, Kentucky, New York, Virginia, Ohio, Pennsylvania, and West Virginia; as a result, a first-order definition of hydrothermal resource is available.

In addition, information relating to the occurrence of water is available in the records of deep borings in many of the eastern states. It has been proposed in Ref. 46 to systematically analyze these data together with the general synoptic geologic assessment of potential deep water-bearing sediments.

It should be noted that no reasonable assessment of the utility or cost-effectiveness of a geothermal well is possible without definitive measures of well productivity, water temperature, and chemistry. Reference 47 discusses these factors in greater detail, and Ref. 46, cited above, was informally proposed to USGS as a part of its extramural program, and, at the Survey's suggestion, was proposed to DOE/DGE.

Fig. 2.2 Gradient data for the Eastern United States.

Fig. 2.3 Potential geothermal resource areas in the Eastern United States showing reservoir confirmation areas.

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Chapter 3

TECHNICAL ASSISTANCE

APL's Geothermal Technical Assistance Program for ERDA/DOE was essentially started shortly after APL was asked to promote the use of geothermal energy in the east. The area encompassing the Eastern United States is shown in Fig. 2-1 of Chapter 2. Informational visits were made to state geologists' energy offices and to users or potential users of geothermal energy. It soon became obvious that some sort of handbook or manual was needed for the potential user that would explain the geological, physical, and engineering terms that most frequently occur in the field. In 1976, the first draft of a geothermal handbook was completed. The 86-page handbook (Ref. 1), printed in 1977, consists of three parts:

1. A glossary of approximately 500 terms,
2. A fact sheet section that defines such subjects as geothermal gradients, rock classification, and geological time scales, and
3. A section of conversion tables for the physical quantities of interest for energy research in general and geothermal research in particular.

As of July 1981, over 700 copies have been distributed.

Geothermal technical assistance, in a broad sense, was carried out by APL during 1976, 1977, and the early part of 1978 by the preparation of planning scenarios for major potential resource areas to assist the states and DOE in planning for geothermal development. The scenarios were essentially macroscopic master plans accompanied by a probable timetable. They included methods on how the geothermal resource would be used, the available and potential market/economics for the resource, and the timescale in which the resource could be developed. They are summarized and referenced in Chapter 11.

In 1979, geothermal Technical Assistance (TA) took a more formal stance (Ref. 2). APL was designated a Center for Technical Assistance for individuals, groups, or organizations interested in the applications of geothermal energy. The Laboratory's response to a request for assistance is in the form of limited engineering and/or economic feasibility study and is not a substitute for detailed design - the province of the consulting engineering community.

Laboratory efforts include

1. Counsel on known information concerning geothermal resources in an area and DOE programs in process there,
2. Preliminary estimates of the hydrologic properties of geothermal resources as functions of time and usage,
3. Advice on recovering geothermal energy in a specific case - an engineering feasibility study, for example,
4. The estimated life-cycle cost of applying geothermal energy in a specific case,
5. The legal, institutional, and other requirements for the application of geothermal energy, and
6. Advice on available federal government opportunities or other federal programs that bear on the use of geothermal energy.

TA requests had been coming to APL almost from the first day the Laboratory started working on the eastern geothermal program. The majority of these requests could be dealt with by a visit to the prospective user or by a simple telephone call or letter. Many requests - in the hundreds - were taken care of this way, far too many to mention specifically in this report.

On the other hand, APL has published formal technical assistance reports for serious potential users of geothermal energy. One of the first reports studied the feasibility of space heating the local high school and hospital with the first eastern DOE/DGE geothermal test well at Crisfield, Md. (Refs. 3, 4, and 5). Other requested technical assistance studies, published as formal reports for the potential geothermal user, concerned

1. The utilization of hydrothermal water for space heating at Hot Springs, Ark. (Ref. 6),
2. Geothermal energy utilization for mariculture on the Eastern Shore of Maryland (Refs. 5 and 7),
3. Vaporization of liquefied natural gas at Cove Point, Md., by geothermal energy (Refs. 5 and 8),
4. Space heating the Pittsville, Md., middle/elementary school (Ref. 9),

5. Space heating the Naval Air Rework Facility in Norfolk, Va. (Ref. 10),
6. Space heating and cooling base housing at McGuire Air Force Base, N.J. (Ref. 11).
7. Space-heating evaluation for a community center and apartment complex in Ocean City, Md. (Ref 12) (TA study contracted to D'Appolonia Consulting Engineering Co.),
8. Feasibility study using geothermal energy for the vacuum distillation of ethanol fuel (Ref. 13) (TA study contracted to Carltech Consulting Engineering Co.). Reference 14 is an extension of the data showing required geothermal water flow rate versus vacuum pressure,
9. Feasibility study using geothermal energy for heat at Dover Air Force Base, Del. (Ref 15). (TA study contracted to Solar Energetics Consulting Engineering Co.),
10. TA consultation as to how geothermal energy might be exploited for space heating at the Naval Submarine Support Base, Kings Bay, Ga. (Refs. 16 and 17), and
11. Publication of a desk-top computer program to estimate geothermal well drawdown and cost for assumed water withdrawal rates (Ref. 18) to assist those considering geothermal energy.
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The process of the transfer of technology is exceedingly slow when it concerns new alternate energy forms such as applications of a modest temperature geothermal resource. An energy extension service to bridge this gap is recommended, patterned after the DOE/DGE Technical Assistance Center effort.

Low-temperature geothermal water at times may not meet the direct-use heating requirements of the intended user, such as when 160°F water is required for space heating and the geothermal resource only provides 120°F. The 120°F water may, of course, be raised to 160°F by burning fossil fuels. However, an effective and frequently recommended alternative is the use of a heat pump to raise the temperature of the water. This method is sufficiently applicable to TA programs to warrant further discussion.

A heat pump is a device that extracts heat from a body at one temperature and amplifies it to a higher temperature. It can be used for either heating or cooling, but the term is generally used in the case of a heating operation while a refrigerator or air-conditioner is used in a cooling operation. A heat pump can extract and deliver several times the amount of energy required to drive it and at temperatures appreciably greater than the thermal source from which it draws energy. The ability of the heat pump to amplify temperature increases the number of ways in which a hydrothermal source of moderate temperature can be utilized. A good hydrothermal source in turn enhances the performance of a heat pump.

In instances where the heat load is a few million Btu's per hour or less, a heat pump with a shallow well may be less costly than drilling for a deeper geothermal source to obtain the required temperature. Initial cost in the case of a deep well system probably will be higher than for a heat pump/shallow well system; however, operating costs for the heat pump system are likely to be more than that of a deep well system. As the combinations of conditions and requirements can vary greatly with location and application, each situation needs to be examined to determine the best alternative. In general, where the heating load is relatively small, a deep well will not be justified; where the heating load is relatively high, a heat pump will not be the economical choice.

Most of the inquiries directed to APL about heat pumps have dealt with the feasibility of using a ground-coupled or groundwater source* for space heating. The fact that ground-source temperatures vary little seasonally gives a ground-source heat pump an advantage over an atmospheric-air-source heat pump for space heating and cooling operations. The performance of ground-coupled (closed water loop) heat pump systems has been more difficult to predict than ground-water (open water loop) heat pump systems because of insufficient design data. However, this situation is changing as more data are gathered. Both types of systems have been neglected in the past because of the lack of information on ground and ground-water conditions needed to assure satisfactory performance. Nevertheless, a large number of manufacturers of water-to-water heat pumps are listed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, the National Water Well Association, and the Air Conditioning and Refrigeration Institute. The availability of groundwater and problems related to its use have been addressed by the National Well Water Association in a comprehensive two-volume report (Ref. 20).

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*Normally, the source of ground and groundwater temperature is solar in origin rather than geothermal, but this technical distinction is not made here.

Much of the aforementioned is discussed in an overview of current heat pump technologies, problem areas, and new technologies (Ref. 21) prepared by APL as a suggested position paper for DOE in May 1979. In May 1980, the Laboratory was requested by the National Conference of State Legislatures to review and comment on its proposed "Guidebook to Ground Water Heat Pumps." Use of a chemical absorption type heat pump (ammonia absorption cycle) with a 140°F geothermal heat source for district heating and air conditioning (Ref. 16) was examined early in the program and appears technically feasible. More recently, the Einstein-Szilard refrigerator has been examined with respect to its use with a geothermal heat source.

Industrial process uses have been investigated with varying results. Poultry processing on the Delmarva Peninsula (Ref. 22) was found to be an application particularly suited to the use of a deep well because of load size and temperature. Deep well energy cost for poultry processing ranged from \$2 to \$4 per 10^6 Btu depending on the well conditions, as compared with \$5 per 10^6 Btu for a heat pump/shallow well system. The use of heat pumps was found to be more expedient in the case of ITT Bakeries because of the modest heat load and the fact that none of the company's plants is located in the areas with enough geothermal potential to meet temperature requirements.

In summary, heat pumps can be used to increase the utility of ground and geothermal heat sources of moderate temperature; geothermal sources with temperatures of 140°F or more can be used to power chemical absorption heat pumps for heating or cooling operations; and, when given a choice between a heat pump with shallow well and a deep well, the economical choice will depend on the size of the heat load, with the deep well system being the more economical in the case of a large load.

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Chapter 4

INSTITUTIONAL AND LEGAL ISSUES

4.1 INTRODUCTION

Development of geothermal energy in the Eastern United States requires the evolution at the state level of new statutes, legal precedents, and management practices to deal with the unique aspects of the resource. The states must address four sets of issues:

1. How to establish or determine the rights to use the resource. This issue has been addressed in terms of characterization, ownership, access, and allocation. Basically, however, the question reduces to who can make use of the resource;
2. How to manage the resource to protect it over time and ensure its efficient use;
3. How to prevent or minimize adverse environmental effects as a result of geothermal energy development; and
4. How to encourage, support, and facilitate the development of geothermal energy.

The functions corresponding to these issues may be characterized as:

1. Legal-political
2. Managerial
3. Regulatory
4. Promotional

There are unavoidable links between the different classes of issues. Most important, the questions surrounding access have implications for all the other issues and for future government action. They have for this reason received a good deal of attention in the discussions relating to geothermal energy development on the Delmarva Peninsula and will be discussed in more detail in Section 4.2.

4.2 RIGHTS TO THE RESOURCE (ACCESS)

Much has been written and debated, both nationally and within the states of the Delmarva Peninsula, as to the characterization, ownership, and rights of access to geothermal resources. These rights have been the focus of much of the institutional-legal task of APL over the past several years, as well as of the work of the National Council of State Legislatures and representatives of the states themselves. However, because of the complexity of the issues and the fact that they can only be finally resolved through actual experience (expressed in judicial decisions, agency regulations, and legislation), the issues remain as clouded on the Delmarva Peninsula as they do in much of the rest of the country. Experience on Delmarva points to two major reasons why the answers to the issues remain problematic. First, it is clear that there is no common vocabulary and understanding with which the various parties to the discussion can proceed. It would be difficult to get legal scholars trained in property and water law to agree on basic points of law and semantics. The problem is compounded when the debate is widened to include legislators (many of whom are lawyers and have their own concepts of property law), scientists, resource managers, and government lawyers. (Just to cite one issue - concepts of what constitutes "ownership" vary widely and have not been clarified to any degree. Thus, there has been much discussion of possible assertion of state "ownership" without a common understanding of what this means, both legally and practically.)

Second, there has been a basic conflict of objectives relating to this issue in at least four areas. On the one hand, there is the objective of finding the legal-constitutional formula that would best reduce uncertainty, minimize the chances of legal conflict, and reduce the cost of access to the resource (e.g., preclude royalties). The motivation here is to facilitate development. Competing with this is the incentive to find an approach that is equitable and constitutional for the owners of the resource (assuming that the state is not the sole owner). This is both a moral and a political consideration.

A third objective is to find an approach that allows for sound management of the resource over its lifetime and to put the approach in the hands of the agency best equipped to handle it. Finally, there has been the temptation to adopt an approach that would provide income to the state in the form of royalties.

However, perhaps the most important aspect of any discussion of the legal-institutional issues is its academic nature. It is difficult enough in factual cases to address the complex issues of property and water law. The difficulty is aggravated when there is no concrete case upon which to focus and very little in the form

of technical information on the general nature of the resource. It would be most helpful for furthering the debate in Delmarva, as elsewhere, if participants attempted to focus on a clear hypothetical or potential case of the ownership-access issue. Only then can the kind of airy circularity that has characterized discussion of this set of issues in Delmarva be avoided. The midwives of a geothermal resource need to proceed on the basis of what the baby is going to look like, not on the basis of abstractions.

Notwithstanding difficulties in clarifying these issues, the three Delmarva states have attempted legislative action. In the case of Maryland, a geothermal law has been on the books for three years. In Delaware, a law was vetoed by the Governor in 1980 and reconsidered in 1981; it failed to emerge from the Legislature. In Virginia, a bill was passed by the Legislature and signed by the Governor. The approaches in the three bills present an interesting array of what can be done on the ownership question. In Maryland, the law is silent on ownership; a 1981 attempt to amend the bill to include a provision for asserting state ownership failed in committee. However, it would appear that the rights to resource extraction belong to the surface owner. The state asserts its interest in the resource by regulating the appropriation; in effect, the state "owns" the right to regulate and ensure proper use of the resource, much as it does with groundwater. In its 1981 session, a joint House-Senate resolution of the Maryland Legislature directed the Department of Natural Resources to study and recommend specific regulations for the access and allocation of geothermal resources. These recommendations, which are requested in the calendar year 1981, would, if acceptable to the Legislature, become the operational law for the State. (An interesting side issue is raised by the fact that Maryland defines the resource to include byproducts that might be extracted from the heat-bearing medium (i.e., water). It is easy to imagine a clear conflict with mineral rights, although it remains to be seen whether this is a real issue. It would presumably require the presence of both a marketable mineral plus a situation where the mineral rights owner was different from the surface owner.)

The proposed Delaware law declares the resource to be owned by the state, to be sui generis, and to be accessible only to the surface owner, who may lease the right of extraction to others. It appears that the sole net effect of the ownership by the state is to give it the right to impose a royalty on the extraction of the resource from private land. Virginia defines the resource as sui generis, owned by and available only to the surface owner, and apportioned according to the doctrine of correlative rights.

In reviewing these three approaches, it is difficult to see where any one is superior to the others in meeting the objectives outlined above. It could be argued that the Maryland approach is the most straightforward, the least likely to engender lawsuits, and the least burdensome on the potential developer because it establishes a prior appropriation basis for exploitation. It would allow for a predictable supply unencumbered by concern about correlative rights of others or the necessity of establishing a production unit or some other pool-sharing mechanism.

4.3 MANAGEMENT

The question of the appropriate management of the resource has not been addressed in detail, partly because a useful management plan could only be evolved on the basis of more detailed knowledge of the resource than now exists for the Delmarva region. Technical assistance on this issue to date has stressed the need for the state to acquire adequate information so that it could develop a model of the resource in a given area. Of course, once a physical model is available, it will still be necessary to develop a management program based on some theory of "the public interest." In essence, the state could elect to maintain a sustained yield of the resource, to allow periodic depletion and restoration, or to allow mining (i.e., in a practical sense, permanent depletion at an economically efficient rate). As a practical matter, the evolution of a management plan will depend on a combination of market forces (which will motivate the developer), increased knowledge of the resource, state precedent in the rate of extraction of groundwater or oil and gas (or some other roughly analogous resource), and, finally, a conscious development of a resource management scheme specific to the resource. The three state statutes in their present forms are essentially silent on this issue, allowing broad administrative discretion. (Note that this is a different issue from that of allotment of the resource, which has to do with who extracts. The issues of extraction and use are, of course, joined in most real cases.)

4.4 REGULATION

Consideration of environmental effects of geothermal energy development in Delmarva has ranged from issues of air quality to subsidence. The most clear-cut concern to date is the issue of the impact on potable groundwater of the extraction of the geothermal liquid or the disposal of the energy-depleted fluid. Significant legal and institutional questions do not seem to enter into the picture at this time because there is general agreement that groundwater resources are not to be damaged (i.e., geothermal energy

development would not be allowed if there were significant impact on potable groundwater), and there are in-place mechanisms dealing with the possible disposal of fluids to surface waters. The issue of subsidence is a possible matter of concern, but there has been little incentive to address it in detail because the general technical opinion to date is that it would not be a problem under the kind of geothermal energy development presently envisioned for Delmarva. Although it has been useful to enumerate possible kinds of side effects, the general feeling seems to be that the states and local governments could make the necessary responses to any environmental or land use problems brought on by a proposed or existing geothermal energy development.

4.5 PROMOTION

A wide variety of issues falls into the promotional category, and they have been widely discussed in Delmarva. Among them are the research and development role of the states (a promotional function to the extent that additional knowledge would reduce costs to private developers), the formation of district heating authorities, the relation of tax law and policy on geothermal energy development, and the accessibility of state lands to private exploitation. Probably the most important promotional function at present, however, is the formation and maintenance of some entity at the state level that has a clear mandate to promote progress on geothermal energy issues across the board. In other words, a continued activity at the state level is required to deal with legislative and legal issues, R&D information to potential developers, development of financial incentives, coordination of the regulatory and managerial functions of the state, and liaison with federal and neighboring state programs. It is difficult for any outside group, however effective, to maintain the wide variety of intergovernmental and private sector contacts that are required to move geothermal energy development from promise to reality.

The entity needed (it could be a division of an existing agency, a new group, an interagency committee, or a single person) must be part lobbyist, part interagency coordinator, part educator, and part marketer. Given the reluctance of all governments to involve themselves financially in a major way because of the general cutback of government programs and staffing, it is in the establishment of a visible and competent promotional entity that scarce resources could be best spent. The best promise for the advancement of geothermal energy in Delmarva at present seems to be from the direction of the private sector. The potential developer would be greatly aided by an agent within the state government who has a clear mandate to work for the development of the resource. Mary-

land has created an Energy Supply Financing Administration within the Department of Economic and Community Development. It is to assist developers of any alternative energy source but currently is limited in staff and funds.

4.6 SUMMARY

The institutional and legal issues surrounding geothermal energy development are numerous, complex, and interdependent. They could be debated and analyzed from now until the oceans boil away from geothermal heat. Although there is still a good deal of ambiguity and confusion surrounding the issues in Delmarva and each of the three states is approaching the issues in a different way, the general contours of the issues are now understood in the region as a result of the debate and analysis of these issues over the past several years. It is likely that the most useful institutional analysis for the near future would take the form of evaluation of a concrete development proposal, based on the best technical understanding and the most reasonable assumptions. If such a specific proposal is not forthcoming, it would be useful to develop one of several hypothetical cases and work through the legal, institutional, and managerial aspects of them in each of the states. Officials in the states, aided by available outside technical and legal assistance, could then conduct realistic and worthwhile "geothermal energy games" on the basis of the elevated legal-institutional understanding that has been developed.

4.7 DOCUMENTATION

There has been extensive correspondence with state offices on issues relating to legislation for geothermal energy. The correspondence is too extensive to list here; however, it may be found summarized in chronological order in the Laboratory's Quarterly Reports (Ref. 1).

The geothermal laws and related acts for Virginia and Maryland are the following:

Virginia

Geothermal Energy, State of Virginia House Bill 1663.

Maryland

Bills concerning geothermal energy passed by the Maryland
1981 Legislative Session:

1. Tax Credits - Geothermal Energy Equipment and Energy Conservation Components, An Act Concerning, House Bill 650, Senate Bill 344.
2. Geothermal Resources, An Act Concerning, House Bill 651.
3. Board of Public Works - Geothermal Resources - State Lands, An Act Concerning, House Bill 652.
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Chapter 5

ECONOMIC ANALYSIS TOOLS

The Metro Center and APL worked closely together on the development of economic analysis tools appropriate for the evaluation of low-temperature geothermal resources. Six computer models have been formulated since research began in this area, namely,

1. GTCOST,
2. GREES (Geothermal Resources Economic Evaluation System),
3. GRITS (Geothermal Resource Interactive Temporal Simulation),
4. DSM (Demand Specified Model),
5. BIGMAC (Basic Interactive Geothermal Model with Aquifer Characterization), and
6. CRA (Capital Recovery Assessment).

Of these programs, GRITS is the most sophisticated and has the greatest flexibility. Each of the computer models will be described briefly below to highlight the evolution of the GRITS model. A summary of the sensitivities analysis conducted on the GRITS model will be discussed in the next chapter of this report. Arrangements for the availability of the GRITS computer program when the current JHU geothermal effort ends will be outlined at the end of this chapter.

5.1 THE EVOLUTION OF ECONOMIC ANALYSIS TOOLS

The first geothermal resources examined were those located in South Dakota (Ref. 1). Aquifers studied could provide potable warm water at 141°F (61°C). No pumping costs needed to be included (the wells would be artesian) and the rate of flow could be high, i.e., 1500 gal/min (341 m³/h). Financial analysis was performed to calculate the cost of a rudimentary geothermal heating system, comprised of a well, a hot water distribution subsystem, and a heat exchanger in each building, in order to estimate the town size required for feasible exploitation of geothermal energy for space-heating purposes.

The bulk of the economic research conducted therefore concentrated on the more typical geothermal resources of the Eastern United States. These are located in deep interior sedimentary basins and along the Atlantic and Gulf Coastal Plains. Analyses to estimate the range in the size and cost of district heating systems using geothermal energy that could be competitive with conventional fuels were begun with GTCOST (Ref. 2). Assumptions built into the GTCOST model reflected advances made in understanding geothermal resources in the Eastern United States: the need for a submersible pump, trade-off between pumping water and cost of recovery, and the need for reinjection of geothermal fluids. In addition, a back-up system acting as a peaking plant was found to allow optimization of the cost of the system by increasing the number of residences served by each well, since the geothermal design need not cover the lowest possible ambient temperature.

The need to simulate more complex relationships led to GREES, a detailed computer program (Ref. 3). The GREES computer code incorporated and documented all that was in GTCOST. In addition, it provided the ability to calculate marginal costs, detailed the schedule of life expectancy and replacement cost of system components, expanded the weather catalogue to three areas on the Atlantic Coastal Plain, and provided an adjustable mix of five housing types.

The GREES computer program proved to be very useful and flexible. It showed that, for geothermal resources with temperatures equal to what were expected in the mid-Atlantic Coastal Plain, the cost of energy for community heating was competitive with the cost of fossil fuel; this is based on the model's assumptions that the cost of geothermal wells was similar to oil and gas wells, and that withdrawal rates of geothermal water of 500 gal/min ($114 \text{ m}^3/\text{h}$) per well were obtainable. The program also showed that the distribution system dominated capital costs. Industrial process heat was a bargain because of the higher utilization factor.

As more and more field experience was obtained, however, it became evident that the economic analysis provided by GREES was no longer adequate because of the need to include a resource assessment period and its cost, economic discounting, and the temporal simulation of temperature, flow rate, drawdown, and market penetration.

The GRITS model is the most detailed and advanced of all the models developed by APL and Metro Center (Ref. 4). The program meets all of the needs cited above. Economic consequences of changes in resource characteristics as functions of usage and time can be traced. Costs of resource assessment that cover the engineering design and development of a given geothermal resource are

included. More realistic scheduling of the installation of a community heating system throughout the district heating project life is allowed. Most importantly, the program provides for the use of a discount rate to compare directly streams of costs and revenues incurred through the life of the project. The resultant economic accounting measures calculated by GRITS are the discounted average cost of providing a million Btu of geothermal energy to a household or an industrial user and the net present value of revenues less costs of the project.

During the most recent period of transition for GRITS, new information was used to update the program. A more accurate equation for estimating well costs has been written into the program. Wellhead heat exchanger design parameters were also changed. The capability for the user to specify a wide variety of alternative multiple well transmission line configurations (from production well to distribution system and reinjection well) was added. The model allows a comparison of a geothermal heating system with an alternative fossil fuel system. And, as an interactive program designed for ease of use in exploratory analysis, GRITS was also enhanced by the addition of a variety of features for reporting results and maintaining and changing basecase scenarios. Lastly, to provide for situations where the number of years over which the debt can be repaid is significantly shorter than the project evaluation period, the useful equipment lifetime is allowed to differ from the debt service period of the equipment.

The DSM and BIGMAC models are descendants of the original version of GRITS, developed to alleviate a few potential limitations of GRITS' original form. They have been replaced by the latest version of GRITS. The DSM was created as a simplified version where the demand for geothermal energy is known in advance, and the BIGMAC model was formulated to account for the effect on pumping of aquifer characteristics when they are known. It should be kept in mind that all of the capabilities of DSM and BIGMAC described below are now incorporated in the latest version, Model 9, of GRITS described in Ref. 5.

DSM, a simplified version of the commercial routine of GRITS, was used to analyze a system designed to meet a given heating demand at the design temperature, whereas GRITS assumed that enough demand for the geothermal energy existed to consume whatever geothermal energy the resource could supply (Ref. 6). An example of an application suitable for analysis by DSM is a geothermal well that can be used to heat a limited number of buildings on an isolated university campus or agricultural community.

The BIGMAC model was a modified version of DSM (Ref. 7). It incorporated a series of relationships that take into account

the transmissivity and storage coefficient for an aquifer whose characteristics are known or can be estimated. Also considered is whether the pumping cycle is continuous, varies semiannually or daily, or is of the type resulting from space heating.

At the request of DOE/DGE, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) held a special seminar on the comparison of economic analysis codes for geothermal space heating at its annual meeting in January 1982. At the request of the society, an analysis using the latest version of GRITS (Model 9) was done of selected towns in the east and west (Ref. 8) for comparison with other codes. A narrative description of the GRITS program was presented at the ASHRAE special session (Ref. 9).

5.2 ARRANGEMENTS FOR FUTURE AVAILABILITY OF GRITS

GRITS will be maintained by the Metro Center through FY 1982. However, no funding is anticipated to provide support for the maintenance and dissemination of GRITS or for technical assistance. Procedures to allow access to the model will be arranged.

Potential users requiring assistance in running GRITS should make arrangements with Sally Kane or Peter Kroll for support services. Levels of effort may range from introductory instruction on the use of the model, to the provision of a brief set of computer runs, to a full-scale analysis. Expenses to the user would involve compensation for Kane and/or Kroll's time as well as for that of their assistants, computer costs, and mailing, duplication, telephone, and secretarial expenses. If GRITS is transferred to a machine other than a DEC-10, some conversion will be necessary, requiring Kroll's time and computer expenses. Exact terms and arrangements are currently being discussed and will be made available to interested parties once plans are finalized.

5.3 A PROGRAM FOR CAPITAL RECOVERY ASSESSMENT

The Capital Recovery Assessment (CRA) program is a short program which is frequently useful as a precursor to using GRITS. It may also be used in place of GRITS for simple geothermal applications, where the approximate time to pay back the initial capital investment using the cost of displaced fossil fuel is desired. The program is documented in Ref. 10.

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Chapter 6

SENSITIVITY ANALYSIS

The large number of variables that influence the cost of providing geothermal energy can be handled practically only through computer modeling. Many of the parameters can be expected to vary greatly under actual field operating conditions; therefore, the number of possible combinations of conditions is quite large. To this end, as discussed in detail in the previous section, GRITS was developed with the capability of being run under a wide variety of resource and economic conditions that are specified by the user (Refs. 1 and 2).

This section begins with a discussion of a basecase that was set up to simulate a hypothetical geothermal district heating system in Salisbury, Md. After this scenario is examined, the results from a study of the sensitivity of discounted average cost (DAC) to various resource, demand, and financial factors will be examined.

6.1 DEFAULT VALUES

Values of the parameters in the basecase are shown in Table 6.1. Generally, each parameter was assigned a conservative value selected from the middle range of estimates considered feasible, although the values for maximum flow rate (300 gal/min), market saturation (70%), and wellhead temperature (150°F) represent optimistic estimates.

The set of conditions that make up the basecase values may be described as follows:

1. Housing stock is comprised of dense single-family dwellings, townhouses, and garden apartments in the Salisbury, Md., area, with 70% of the households within the service area hooked up to the district heating system. Two types of commercial buildings, with 4,000 and 10,000 ft² of average floor space, are hooked up to the same district heating system.
2. All space heating demand down to 39°F external temperature is served exclusively by geothermal energy; additional energy demand for colder temperatures (down to -5°F) is served by a fossil-fuel peaking system that

Table 6.1

Salisbury basecase scenario for residential/commercial estimates,
current residential/commercial parameters

RESOURCE CONDITIONS		Parameter
Area under consideration		Salisbury, Md.
Wellhead water temperature (°F)		150
Depth of upwell (ft)		5000
Number of production wells		1
Reinjection temperature (°F)		90
Depth of reinjection well (ft)		5000
Number of reinjection wells		1
Drawdown of upwell (%)		15
Maximum flow per well (gal/min)		300
Transport distance (miles)		0.25
DEMAND CONDITIONS		
Housing types on system	Percentage	Hookup cost per household (\$)
Single family dense	20	1500
Townhouse	40	1500
Garden Apartment	40	400
Market saturation (%)		70
Market penetration (%)		
Initial		15
Annual change		8
Domestic hot water (10^6 Btu/yr/h)		20.10
Number of types of commercial buildings		2
Average floor space (ft^2)		
Type 1		4,000
Type 2		10,000
Average heat demand ($\text{Btu}/\text{ft}^2/\text{deg-day}$)		
Type 1		9
Type 2		9
Number of each type		
Type 1		5
Type 2		2

Table 6.1 (cont'd)

Salisbury basecase scenario for residential/commercial estimates,
current residential/commercial parameters

Rate of commercial market penetration (%)		
Initial		50
Annual change		25
Length of commercial distribution system (miles)		0.2
System design temperature (°F)		39
Minimum ambient temperature (°F)		-5
FINANCIAL CONDITIONS		
System selling price (\$/10 ⁶ Btu) as a multiple of electricity price		70
Study period (years)		20
Storage tank capacity (hours of flow)		2
Capital equipment	Amortization period	Physical life
Wells	30*	30
Piping system	30*	30
Heat exchanger	10*	10
Pumps	10*	10
Hookup	30*	30
Peaking boiler	30*	30
Storage tank	30*	30
* reduced as need to end in study period		
Discount rate (%)		4
Interest rate		15
Inflation rate (%)		8
Real dollar calculations		
Cost of electricity		
Initial price (¢/kWh)		6
Annual change (%)		2
Cost of fossil fuel		
Initial price (\$/10 ⁶ Btu)		9
Annual change (%)		4
Operation and maintenance (% of capital)		1
Boiler cost (\$/10 ⁵ Btu/h)		1500
Distribution system pipe cost (\$ thousand/mile)		250

raises the temperature of the circulating water. All domestic hot water heat is provided by geothermal energy.

3. The resource is tapped by one 5000-ft production well that experiences an average drawdown of 15% (750 ft) at full production as the water is pumped to the surface.
4. The temperature at the wellhead is 150°F and the water is reinjected at 90°F, implying at a logarithmic mean temperature difference across the heat exchanger of 60°F. Maximum flowrate is 300 gal/min.
5. The water is reinjected into the same aquifer at a depth of 5000 ft.
6. The conditions include a 15% charge for borrowed funds, with the system capital components amortized individually over their expected lives or the evaluation period, whichever is shorter.
7. Electricity to operate the pumps is purchased at 6.2¢/KWh, with an annual real increase of 2%. The fossil fuel for the peaking plant is purchased at \$9.00/10⁶ Btu with an annual real price increase of 4%. Selling price is fixed at 70% of the price of fossil fuel.
8. The distribution system costs \$250,000 per mile of installed insulated dual pipe.

The results of running the basecase are shown in Table 6.2. Note that, under these conditions, 90% of all space-heating requirements for the approximately 355 households on the single-well system are served by geothermal energy. The production and reinjection well costs represent the single largest capital cost throughout the evaluation period. Interestingly, the declining real value of the debt service throughout the project evaluation period and the increasing real cost of purchased fossil fuel and electricity are responsible for fossil fuel costs constituting over 30% of the total system costs in the last year of the evaluation period, over 25% greater than well costs. Cost of pumping energy (electricity) nearly equals the well costs in this year. The summary measures for the project that was simulated using the basecase showed a discounted average cost of \$13.69/10⁶ Btu of delivered energy for residential and commercial users and a net present value of revenues less costs of \$691,000. Undiscounted operations costs saved exceed the initial capital cost of \$2,504,000 in year 10.

Table 6.2

Basecase scenario results for
residential/commercial estimates,
last year of the evaluation period

Length of distribution system (miles)	1.28
Number of households	355
Total geothermal Btu's (millions)	30868.07
Total system Btu's (millions)	32766.14
Geothermal utilization (%)	39.19
Service geothermal	90.06
Pumping energy (million kWh)	0.54
Annualized real cost and revenues (\$ thousands)	
Well costs	50
Original pump costs	4
Hook-up costs	24
Pump overhaul costs	6
Pumping costs	49
Distribution system costs	13
Heat exchanger costs	4
Peaking boiler costs	7
Fossil fuel costs	36
Transport costs	6
Storage tank costs	3
Operation and maintenance costs	25
Total annual wellhead costs	123
Total annual system costs	275
Wellhead cost per geothermal million Btu (\$)	3.97
System cost per million Btu (\$)	8.02
Revenue	635
Net revenue	360
Summary measures	
Initial capital cost (\$ thousands)	2504
Net present value of revenues minus costs (\$ thousands)	691
Discounted average cost (\$/10 ⁶ Btu)	13.69
Discounted average wellhead cost (\$/10 ⁶ Btu)	8.26
Break-even point achieved	Year 15
Payback completed	Year 10

Parametric runs were made to check the sensitivity to specific resource, demand, and financial conditions. The values for each parameter tested were varied systematically to capture the effect of the change. The rest of this chapter will outline the results from this analysis. In Tables 6.2 and 6.3 and in the description that follows, any parameter not specifically listed retains its original basecase value.

It should be noted that the DAC can be thought of as the fixed selling price of geothermal energy that, if charged throughout the project life, would just equate the discounted cost and revenue streams. That is, the net present value over the project life equals zero, and the project breaks even at the end. In this analysis, the DAC per million Btu's of geothermal energy can be compared with the selling price of alternate fuels. Geothermal energy can be considered to be competitive with other fuels when the DAC is lower or equal to the selling price of these alternate fuels (taking into account given efficiency differentials).

6.2 EFFECTS OF RESOURCE CONDITIONS ON DAC

Discounted average costs were found to drop exponentially as resource temperature increased, assuming a constant reinjection temperature and flowrate. At resource temperatures of 150°F and higher, delivery costs of geothermal energy to residential/commercial users can be competitive with fuel oil at \$1.25 per gallon. Similarly, an exponential decline in DAC was found to accompany increases in flowrate, assuming moderate drawdown (15%) and constant water and reinjection temperatures. Competitiveness of geothermal energy with current fuel prices dictates flow rates greater than 300 gal/min for residential/commercial district heating systems.

Drawdown in wells is an important resource characteristic, since increased drawdown increases pumping energy costs. In the model, the drawdown is determined as a percentage of well depth. DAC rises linearly with increases in drawdown, with all other values held constant. Thus, DAC can vary by over \$4.00 per million Btu with a change in initial drawdown from 0 to 50%. The effect of changes in annual increase in drawdown is not as pronounced; annual increases ranging from 0.5 to 1% only account for an increase in DAC of \$0.20.

Surface disposal of geothermal fluids is much less costly than reinjection into a subterranean aquifer. The DAC per million Btu's of delivered geothermal energy is reduced by 24% when reinjection of fluids is not required.

For a system of a given length, changes in the cost of installed pipe have a moderate impact on DAC. A 40% (\$100,000) change in pipe cost above the original value of \$250,000 per mile results in a change of 50¢ per million Btu's of delivered energy. However, increases in transport distance are more significant. When transport distance is increased by 0.5 mile, keeping pipe cost constant, DAC per million Btu's of delivered energy increases by approximately \$1.30.

The sensitivity of DAC to increasing prices of purchased conventional fuels was studied based on expected real cost increases for fossil fuel and electricity throughout the remainder of this century. Varying the initial fossil fuel purchase price from \$9.00 to \$14.00 per million Btu (56% over the original basecase value) results in increases in average cost of \$1.10. Varying initial electricity purchase price from a 2¢ to 9.6¢/KWh (56% over the original basecase value) results in a 55¢ increase in the DAC. Increasing the annual change in electricity costs by 1% results in a 15¢ increase in the DAC.

6.3 EFFECT OF DEMAND AND FINANCIAL CONDITIONS ON DAC

The demand for space heating in a particular locale depends on the prevailing climatic conditions. To ascertain the effects of climate, a series of runs was made with uniform resource conditions and similar market conditions. Each run used the optimal design temperature for a specific city (the temperature above which geothermal handles 100% of the heat demand and below which additional heat demands are supplied by a peaking boiler system). In order of increasingly warmer climates, the cities tested were Syracuse, N.Y.; Salisbury, Md.; and Savannah, Ga. Generally, colder climates have lower design temperatures and greater utilization of the geothermal production system. Thus, of the three cities considered, Syracuse had the lowest DAC, at \$6.80. DAC of delivered energy for the Salisbury was \$8.40, \$1.60 above that of Syracuse. DAC of delivered energy for Savannah was \$13.60, or \$5.20 above that of Salisbury.

The density of consumers within a service area is a crucial factor for any district heating system. The GRITS model addresses this consideration through changes in the market saturation level. The length of the distribution system is determined by the number of households of a specific type and the density levels for each type. For systems containing only one housing type, DAC declines exponentially as market saturation levels are increased. A change in saturation from 100 to 60% for townhouses increases DAC from about \$14.00 to \$14.50. With a saturation of 20%, costs rise to approximately \$17.50.

The sensitivity of DAC to industrial utilization of geothermal productive capacity was tested. Increasing the utilization of an industrial geothermal system dramatically lowers the DAC of delivered energy, since fixed capital costs are spread over larger amounts of thermal energy. If the industrial process operates 80% of the year, the DAC is 70% greater than when an industrial process operates 40% of the year.

6.4 COMPARISON OF RESOURCE QUALITY

Lastly, differences in resource quality were tested using an east/west comparison. Table 6.3 lists the selected resource and demand conditions for one representative site in the east (Salisbury) and two in the west (Thermopolis, Wyo., and Boise, Idaho). Note that the values for Salisbury differ from those of the original basecase given in Table 6.1 and from climate tests. The Salisbury scenario resulted in a DAC of \$17.55. The Thermopolis and Boise scenarios, which simulate hotter resources with correspondingly higher flow rates, shallow production wells, and longer transport distances, gave DAC's of \$9.85 and \$4.37, respectively.

Table 6.3

Sensitivity analysis:
Comparison of eastern and western resources,
selected values for resource and demand conditions

	East	West	
	Salisbury, Md.	Thermopolis, Wyo.	Boise, Idaho
Production well depth	5000 ft	3000 ft	1200 ft
Reinjection well depth	5000 ft	3000 ft	1200 ft
Wellhead temperature	140°F	170°F	170°F
Reinjection temperature	90°F	110°F	110°F
Flow	225 gal/min	500 gal/min	1000 gal/min
Drawdown	15%	10%	10%
Transportation distance to users	0.250 mile	3 miles	1 mile
Weather statistics for:	Richmond, Va.	Casper, Wyo.	Boise, Idaho
System design temperature	45°F	24°F	17°F
Minimum ambient temperature	-5°F	-28°F	-13°F

In conclusion, the economic viability of any direct-use application of low- to moderate-temperature resources depends on many factors. The GRITS economic model provides a powerful tool for studying the effects of each of these variables. When specific resource, demand, or financial conditions are uncertain, GRITS allows studies of the sensitivity range of DAC for these parameters.

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Chapter 7

AIDS TO MARKET PENETRATION

The Metro Center's research on the market penetration potential for space heating in the residential sector is summarized in this chapter. The work was begun early in 1979 and has continued to the present. It has concentrated particularly on the capital stock obstacle to residential market penetration; i.e., the fact that consumers with economically viable conventional furnaces may require additional incentives beyond the unit cost advantage of geothermal heating to convert geothermal units. This obstacle was first modeled formally in aggregative models of the residential sector, to predict market penetration by a given date. Further work examined more closely the individual's decision among heating fuels and considered incentive schemes designed to overcome obstacles to conversion.

7.1 AGGREGATIVE MODELS

The early modeling efforts were designed to provide estimates of the percentage of a particular housing stock that might be converted to geothermal usage, given the type of aggregate data that are normally available. The research identified several factors that would influence both initial and subsequent market penetration, as noted in Equation 7.1:

$$M = \beta_{\eta} V + \beta_{\epsilon} \alpha \frac{Ve^{-\Psi V}}{1 - e^{-\Psi V}}, \quad (7.1)$$

where

M = Market share of the housing stock,

V = New housing as a fraction of current stock,

Ψ = Furnace life in years,

$\beta_{\epsilon}, \beta_{\eta}$ = Fraction of existing (ϵ) and new (η) housing that converts to geothermal heating, and

α = Fraction of housing needing new furnaces that is adaptable to geothermal energy.

This equation describes the manner in which the rate of market penetration is positively related to the rate of growth of the housing stock, the attractiveness (with respect to price and risk) of geothermal energy relative to other energy forms, and the ability to convert existing furnaces to geothermal energy. It is inversely related to the productive life of current furnaces based on the fact that owners of operating furnaces will be less susceptible to change.

For example, let us consider a large area in which a geothermal gridwork has been put down. Let us also assume (a) that the source is so viable that all new housing uses geothermal energy ($\beta_n = 1$) and all retrofitted furnaces use it ($\beta_e = 1$, $\alpha = 1$), and (b) that the average furnace life is 20 years ($\Psi = 20$). The first year's market penetration is calculated as about 7.5%, given a value for V of 0.05 (a generally high estimate). This suggests that it is important for the geothermal provider to pursue new developments in which geothermal energy can be included at the time of construction of all units. The developer's decision process for choosing among alternative energy sources in the Baltimore metropolitan area was examined along with the potential market penetration in the Delmarva peninsula, based on the parameters developed for the housing stock for several small towns and on the characteristics of the test well drilled at Crisfield. Geothermal space heating was found to be viable for some of these towns, based on these parameters and on the prices for alternative fuel sources.

7.2 THE CONSUMER'S DECISION

Given the high capital costs of putting down a geothermal grid, it is important for the energy provider to achieve a high rate of market penetration quickly. The next step in our research was to model the consumer's decision more specifically. The particular problem is, given the new availability of a geothermal system, to determine who would buy the new furnaces or, alternatively, how much more efficient the new furnaces must be to induce homeowners to switch types.

On the assumption that geothermal furnaces are more efficient (i.e., have a lower cost per MBtu), homeowners would replace conventional furnaces when the latter are ready for scrap. However, if the present conventional furnace is less than a certain age, it still has a useful life. By way of analogy, consider the purchase of a new car. When this occurs, the old one is sold to someone else for its value in use. A furnace cannot generally be

resold for this value (rather, only for scrap) even though it is still operational. In terms of market acceptance, it is likely that, if purchasing a new car meant that the old one had to be left in the driveway without being driven, the rate of market acceptance of any new car would be substantially lower than it is. The newer the current furnace, then, the more efficient its geothermal replacement must be in order to induce a change in types, since conversion implies a capital loss on the current model.

Algebraically, the formulation is:

$$F_G(s, \infty) - M_C(z) - H > F_C(s, \infty) \quad (7.2)$$

where

$F_G(s, \infty)$ = Present value of consumer surplus from a geothermal unit lasting s years and replaced by ∞ similar units,

$F_C(s, \infty)$ = Present value of consumer surplus from a conventional unit lasting s years and replaced by ∞ similar units,

$M_C(z)$ = Difference between the discounted surplus and scrap value for a conventional unit of age z ($0 \leq z \leq s$), and

H = Cost of converting from a conventional to an alternative unit (hook-up cost).

This condition states that in order to choose a geothermal unit, the present value of its surplus must be large enough to cover the hook-up cost plus the capital loss on the current conventional unit, as well as the surplus of the conventional unit. The results show that consumers are more likely to convert (a) the more efficient the geothermal system is, (b) the older the current furnace, and (c) the lower the conversion (or hook-up) costs.

Moreover, given these parameters, a sliding schedule of incentives can be developed for furnace owners, based on the ages, efficiencies, and hook-up costs for their units. The geothermal energy provider can calculate the net present value of alternative rates of market penetration based on the premise that additional revenue from the increased penetration can be "bought" only with additional incentive payments.

This theoretical model has been incorporated into the GRITS framework to calculate optimum rates of market penetration for known geothermal resources. Very often, the calculation has been that an optimizing utility would benefit most from providing incentives for all of the potential customers to convert immediately - in essence to buy back the customers' capital stocks of furnaces. Under these circumstances, development of a geothermal resource may be economically desirable. Calculations of these decisions and of their sensitivities to changes in market parameters are discussed in several presently available papers (see Refs. 1, 2, and 3).

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Chapter 8

GEOHERMAL MARKET SURVEY - ATLANTIC COASTAL PLAIN

8.1 INTRODUCTION

The definition of the size, composition, and location of potential markets for geothermal energy is of vital importance in formulating plans to commercialize geothermal resources. By the summer of 1977, after working on a scenario for the Atlantic Coastal Plain (Ref. 1), APL began a detailed study of energy usage in the temperature ranges below 250°F for the regions covered by the scenario that seemed to offer promising geothermal resources. Using available information from the USGS maps for the depth to basement and the results of a resource targeting study (Ref. 2) by Virginia Polytechnic Institute and State University (VPI&SU), it was possible to locate the most promising regions for hydrothermal resources along the Atlantic Coastal Plain. Information gathered since that time has not significantly changed the location of the potential resource areas.

The Geothermal Energy Market Survey (designated GEMS in APL terminology) was limited to hydrothermal resources; hot dry rock was ignored because of the expensive technical problems involved in its utilization. The specific objectives of GEMS were to (a) identify existing thermal energy requirements at temperatures below 250°F for each potential resource area; (b) determine the technical feasibility of applying geothermal energy to meet these requirements; (c) estimate the costs of satisfying these markets for thermal energy; and (d) estimate the extent to which geothermal energy can penetrate these markets. The first two objectives may be termed "market identification" and are the subject of this chapter; the latter two, insofar as they have been addressed, are discussed in Chapters 5, 6, and 7.

8.2 THE ATLANTIC COASTAL PLAIN

The Atlantic Coastal Plain, as defined here, consists of the coastal regions of Georgia, South Carolina, North Carolina, Virginia, Maryland, Delaware, New Jersey, and Long Island that lie

to the east of the Piedmont Plateau. This area is composed of sedimentary deposits overlying the granitic basement rock of the North American Continental Plate in depths as great as 10,000 ft (Ref. 3). The sedimentary deposits are layered, each layer slanting to depth in the seaward direction. Basement outcrops at the fall line separate the coastal plain from the Piedmont; therefore, the sedimentary layers, if permeable, will carry absorbed surface water to greater depths below the surface as this water moves seaward. It is this water, heated by the movement through aquifers at depth, that constitutes the viable geothermal resource of the Atlantic Coastal Plain.

If the geothermal gradient and the depth to basement are known, then (on the assumption that the gradient is a constant) the temperature at the bottom of the sedimentary sequences can be calculated. Because relatively few deep wells have been drilled on the Atlantic Coastal Plain, geothermal temperature gradient data are sparse. In 1977, VPI&SU began evaluating and targeting East Coast geothermal resources for DOE. The VPI&SU theory indicated that some areas could show anomalously high gradients because of igneous intrusions into the sedimentary sequences. If these intrusions were slightly enriched in radioactive elements and covered with thermally insulating sedimentary sequences, then the higher-than-normal heat production and lower thermal conductivity would produce an abnormally high geothermal temperature gradient. The VPI&SU field program involved surface gravity, magnetic, and seismic measurements, and the measurement of thermal gradients in relatively shallow test wells (about 1,000 ft deep). In the APL market survey studies, the available geothermal gradient information and the VPI&SU estimates were combined with the estimated basement contours to produce a map of the expected temperatures at basement. This time-consuming procedure is described in Ref. 4. The basement temperature contours, as used in the market survey studies, are shown on Fig. 8.1.

In general, there is no reason to expect that geothermal markets and a useful resource will be located in the same area; as a matter of fact, much of the Atlantic Coastal Plain is thinly populated and lightly industrialized. It is possible to eliminate some of the favorable resource areas offhand as having little potential market; however, this was not done in the APL market survey. Rather, it was decided that any area possessing an estimated resource at basement in excess of 90°F should be studied, and the market survey areas were chosen as shown on Fig. 8.2. Since demographic data are available by political subdivisions, Fig. 8.2 is a repeat of the 90°F contour line of Fig. 8.1, adjusted for county boundaries. The market survey itself will then serve to rank the areas as potential regions for geothermal development.

Fig. 8.1 Estimated maximum temperature at the bottom of the sedimentary pile of the Atlantic Coastal Plain.

Fig. 8.2 Market study areas, Atlantic Coastal Plain.

8.3 MARKET STUDY PROCEDURE

While Fig. 8.1 shows that there is little prospect of finding geothermal temperatures in excess of 212°F on the Atlantic Coastal Plain, the concept of heat pumping made possible the consideration of all energy usage in the temperature range of from 90°F to 250°F for the market survey. The temperatures required for various energy end-uses on the Atlantic Coastal Plain are listed in Table 8.1. Since each consuming sector of the economy places its own constraints on a geothermal distribution system and since each sector will present different problems in data collection, it is convenient to separate energy requirements into the sectors shown in Table 8.2.

Reference 4 presents the results of a market survey for the four northern resource areas shown on Fig. 8.2, namely, southeastern New Jersey, the Delmarva Peninsula, the Norfolk, Va., area, and eastern North Carolina. The residential space and hot water heating demands were calculated using census tract data and the heating demand per person for each resource area. The commercial demands were calculated in a similar manner from the commercial employment figures for each area. In Ref. 4, for the residential-commercial sectors, these calculations are summed county by county. The four resource areas contain 16 military installations. Energy consumption for these installations is available from the Defense Energy Information System reports, and the space and hot water heating loads are estimated from these reports. Agricultural energy demands that can be satisfied by the geothermal resources in these areas are limited to crop drying and heating greenhouses, poultry hatcheries, and broiler houses. Possible uses in dairy or livestock farming have been omitted because of the low density of these operations.

The industrial sector is even more complicated than the agricultural in that it is difficult to separate out the fraction of total energy consumption that can be satisfied by geothermal energy. There are over 3,000 industries in the resource areas covered in Ref. 4. As the survey proceeded, it became evident that the Standard Industrial Classification Codes (SIC's), corresponding to the sectors listed in Table 8.2, would provide the industries of interest. Eight hundred and fifty-seven companies were initially selected for the survey; of these, 674 were in areas of some geothermal promise for the energy needs peculiar to that industry; and 533 companies were actually contacted in the survey. The contacts were personal interviews, which resulted in a reasonable estimate of what contribution geothermal energy could make to that particular company. It was estimated that 317 companies in the four resource areas had potential applications for geothermal energy.

Table 8.1

Temperatures required for various processes
encountered on the Atlantic Coastal Plain.

Temperature (°F)	Process	Temperature (°F)	Process
250	- In-the-can cooking of vegetables - Soybean oil distillation - Most multiple effect evaporations	150	- Clean-up water for food processing plants - Hardwood lumber drying - Bottle washing for soft drinks - Wet capsule formation in pharmaceuticals - Hot water for oyster gapping - Domestic hot water
225	- Rendering of animal fats and oils - Protein denaturization in soybeans - Distillation of pure water - Blanching clams - Soybean drying	125	- Poultry plant scalding water - Metal plating solutions - Caustic peeling of tomatoes
200	- Fruit juice pasteurization - Corn drying - Tobacco redrying - Preheat boiler feed water for steam production - Hydronic space heating - Softwood lumber drying - Soap manufacturing	100	- Forced air space heating - Aluminum and magnesium hydroxide production - Egg incubation - Bottle warming for soft drinks - Poultry house space heating for chicks - Soil warming and greenhouses - Rinse water for soft drink bottling and canning - Poultry house space heating for mature chickens - Aquaculture
175	- Vegetable blanching - Lower limit of absorption air-conditioning - Milk pasteurization		

Table 8.2

Energy-consuming sectors included in
the market survey

Sector	Energy requirement
Residential and commercial	Space heating Water heating
Military	Space heating Water heating
Agriculture	Crop drying (corn, soy beans, tobacco, peanuts) Space heating (poultry) Water heating
Industrial	Food processing Tobacco redrying Textile processing Lumber drying Chemical processing Miscellaneous hot water uses

Table 8.3 summarizes the current energy demands as given in Ref. 4 for the four energy-consuming sectors and for the four resource areas. As the table shows, the total energy demand for these four resource areas that could be supplied from a geothermal resource is 966.1×10^{11} Btu/yr, or the equivalent of 17.26×10^6 barrels of oil. The results of Table 8.3 represent the completion of the first objective of the GEMS programs, that is, to determine the existing market for thermal energy at temperatures below 250°F. From the manner in which the survey was taken and from the information available from a few Technical Assistance studies (discussed in Chap. 3), there are no serious technical barriers to the development of geothermal energy on the Atlantic Coastal Plain. The problems of the final two objectives of GEMS, economic feasibility and market penetration, are also discussed elsewhere in this report. Because of uncertainties in the geothermal resource and the great effort involved, no attempt has been made to systematically determine the "real" geothermal market under these restraints.

Table 8.3

Current demands for space, water, and process heat
in four resource areas
(10^{11} Btu/yr)

	Residential/ commercial	Military	Agricultural	Industrial
Southeastern New Jersey	307.8	25.0	6.0	9.3
Delmarva Peninsula	135.2	8.2	17.8	18.4
Norfolk, Va., area	207.9	96.5	1.0	9.5
Eastern North Carolina	83.8	15.1	10.8	13.8
Total	734.7	144.8	35.6	51.0
Equivalent of 10^6 barrels of oil	13.11	2.59	0.64	0.92

The final recommendations of Ref. 4 are briefly (and incom-
pletely) summarized as follows:

1. Initial efforts at the commercialization of geothermal energy should be directed primarily at the industrial sector because of economic factors resulting from the expense of distribution systems and the economics of a high utilization factor for the resource.
2. Uncertainties in the resource present the major obstacle for potential developers of geothermal resources on the Atlantic Coastal Plain.
3. The Delmarva Peninsula is the most attractive resource area for future development of those considered in Ref. 4.

Following the publication of Ref. 4, APL extended the geo-
thermal market survey to the coastal plain of Georgia (Ref. 5).
The study covered the 32 counties of Georgia along the coastal
plain with the highest expected temperature (greater than 90°F) at
basement, as shown in Fig. 8.3. Because the climatic conditions
and population density in this area are even less favorable for

Fig. 8.3 Geothermal market survey area in Georgia; estimated temperature contours at basement overlaid on county boundaries.

residential and commercial heating than in the areas covered by Ref. 4, only industrial users were contacted. In the counties selected, there were 778 companies in the 20 SIC's. Of these, 163 were selected, and 114 responses containing useful information were obtained from a letter and telephone survey.

In Georgia, as elsewhere, a market survey is complicated by the facts that many companies, particularly the smaller ones, do not possess precise knowledge of how much energy they use or for what purposes, and their aggregate consumption is expressed in a variety of energy units. The results of the Georgia survey, insofar as they have been completed, are given in Ref. 5.

8.4 POTENTIAL COLOCATED HYDROTHERMAL RESOURCES AND ENERGY MARKETS

In order to support the DOE effort to stimulate the commercialization of direct-use geothermal resources, a method for comparing resource areas was developed and illustrated by application to the prospects in 260 counties in the 12 states of the Eastern United States listed in Table 8.4. The methodology is described in

Table 8.4

Geologic, geothermal, demographic, and industrial data
(States and counties where thermal gradient exceeds
1.6°F/100 ft.)

States/Counties	Depth (thousand ft)	Gradient (°F/100 ft)	Population (thousands)	Towns	Cities	Heating degree days (hundreds)	Value added in manufacture	Well depth (assumed)	Temperature (°F)	Extractable heat (Btu/gal)	Cost (\$ per ft)	Residential use (trillion Btu)	Commercial use (trillion Btu)	Industrial use (trillion Btu)
ALABAMA														
BALDWIN	14.0	1.8	70.8	9	0	17	23.30	10.0	190	751	61	1.50	1.27	1.82
BLOUNT	10.0	1.6	32.1	2	0	32	10.50	7.5	175	626	43	.68	.58	.82
CULLMAN	8.0	1.6	58.9	5	0	34	27.00	6.0	151	426	35	1.24	1.06	2.10
LAMAR	8.0	1.6	15.6	3	0	29	7.10	6.0	151	426	35	.33	.28	.55
LAWRENCE	6.0	1.6	28.6	2	0	32	2.90	4.5	127	225	29	.60	.51	.23
LIMESTONE	7.0	1.6	43.5	2	0	32	4.40	5.3	139	325	32	.92	.78	.34
LOWNDES	6.0	1.6	13.3	1	0	21	6.00	4.5	127	225	29	.28	.24	.47
MARENGO	10.0	1.6	23.7	3	0	21	33.70	7.5	175	626	43	.50	.43	2.63
MORGAN	7.5	1.6	83.9	3	1	33	206.00	5.6	145	376	34	1.77	1.51	16.05
PIKE	5.0	1.6	24.3	2	0	26	15.50	3.8	115	125	26	.51	.44	1.21
WALKER	7.0	1.6	64.5	9	0	29	22.80	5.3	139	325	32	1.36	1.16	1.78
WINSTON	8.0	1.6	19.7	3	0	33	18.80	6.0	151	426	35	.42	.35	1.46
ARKANSAS														
CALHOUN	5.0	1.8	5.6	2	0	27	5.00	3.8	123	188	26	.20	.14	.60
CLARK	7.0	1.8	22.2	3	0	29	22.20	5.3	150	413	32	.80	.55	2.67
CLEBURNE	6.0	1.8	14.7	1	0	36	9.00	4.5	136	300	29	.53	.36	1.08
CROSS	8.0	1.9	20.7	3	0	32	12.50	6.0	169	576	35	.75	.51	1.50
DREW	5.0	1.8	16.1	2	0	27	17.20	3.8	123	188	26	.58	.40	2.07
FRANKLIN	10.0	1.8	13.0	2	0	32	3.80	7.5	190	751	43	.47	.32	.46
HOWARD	7.0	1.8	13.3	3	0	30	13.90	5.3	150	413	32	.48	.33	1.67
JACKSON	7.0	1.9	21.2	4	0	32	10.80	5.3	155	457	32	.77	.52	1.30
JEFFERSON	7.0	1.9	84.2	3	1	26	92.40	5.3	155	457	32	3.04	2.08	11.11
LINCOLN	7.0	1.8	13.1	3	0	27	7.49	5.3	150	413	32	.47	.32	.90
LITTLE RIVER	5.0	1.9	11.7	2	0	28	12.20	3.8	126	219	26	.42	.29	1.47
LONOKE	8.0	1.8	26.2	3	0	34	9.10	6.0	163	526	35	.95	.65	1.09
OUCHITA	5.0	1.7	29.4	4	0	27	38.50	3.8	119	156	26	1.06	.73	4.63
PIKE	8.0	1.8	9.4	2	0	33	3.40	6.0	163	526	35	.34	.23	.41
POINSETT	7.0	1.8	27.5	5	0	35	17.10	5.3	150	413	32	.99	.68	2.06
SEVIER	6.0	1.8	12.2	3	0	29	5.90	4.5	136	300	29	.44	.30	.71
VANBUREN	6.0	1.7	10.3	1	0	36	4.82	4.5	131	263	29	.37	.25	.58
ILLINOIS														
BOND	7.0	1.6	14.7	4	0	49	13.20	5.3	139	325	32	.82	.47	.35
CASS	3.5	1.7	14.0	4	0	55	5.50	2.6	100	0	23	.78	.44	.15
CHAMPAIGN	6.0	1.6	164.4	12	3	56	60.60	4.5	127	225	29	9.20	5.21	1.61
CLARK	7.0	1.8	16.2	4	0	53	.00	5.3	150	413	32	.91	.51	.46
CLAY	11.0	1.5	14.9	3	0	48	7.70	8.3	168	563	48	.83	.47	.20
COLES	7.0	2.0	49.9	5	0	53	59.00	5.3	160	501	32	2.79	1.58	1.57
CRAWFORD	9.0	1.9	19.9	4	0	49	48.40	6.8	103	695	39	1.11	.63	1.29
CUMBERLAND	9.0	1.8	10.3	3	0	53	2.50	6.8	177	638	39	.58	.33	.07
DE WITT	6.0	1.7	16.9	5	0	56	18.80	4.5	131	263	29	.95	.54	.50
DOUGLAS	6.0	1.6	19.5	6	0	55	50.60	4.5	127	225	29	1.09	.62	1.35
EDGAR	7.0	1.8	21.6	3	0	53	20.80	5.3	150	413	32	1.21	.68	.55
EDWARDS	13.0	1.8	7.5	3	0	46	.00	9.8	190	751	59	.42	.24	.32
EFFINGHAM	9.0	1.8	28.2	4	0	52	14.70	6.8	177	638	39	1.58	.89	.39
FAYETTE	7.0	1.6	20.8	5	0	51	7.70	5.3	139	325	32	1.16	.66	.20
GREENE	3.5	1.5	16.7	4	0	51	4.40	2.6	94	0	23	.93	.53	.12
LAWRENCE	10.0	1.9	17.5	4	0	47	.00	7.5	197	814	43	.98	.55	.60
LOGAN	5.0	1.8	31.1	4	0	56	65.00	3.8	123	188	26	1.74	.99	1.73
MACOUPIN	4.3	1.8	46.1	11	0	51	8.70	3.2	113	109	24	2.58	1.46	.23
MADISON	4.0	1.8	247.8	20	2	49	645.20	3.0	109	0	24	13.87	7.85	17.17
MASON	4.5	1.8	18.8	3	0	56	4.30	3.4	116	131	25	1.05	.60	.11
MEHARD	4.5	2.0	10.9	4	0	56	.00	3.4	123	188	25	.61	.35	.26
MONROE	3.0	1.8	18.9	3	0	44	.90	2.3	96	.0	21	1.06	.60	.02
MONTGOMERY	6.0	1.6	30.6	9	0	50	15.00	4.5	127	225	29	1.71	.97	.40

Table 8.4 (cont'd)

States/Counties	Depth (thousand ft)	Gradient (° F/100 ft)	Population (thousands)	Towns	Cities	Heating degree days (hundreds)	Value added in manufacture	Well depth (assumed)	Temperature (° F)	Extractable heat (Btu/gal)	Cost (\$ per ft)	Residential use (trillion Btu)	Commercial use (trillion Btu)	Industrial use (trillion Btu)
MORGAN	3.5	1.7	35.6	7	0	53	55.10	2.6	100	0	23	1.99	1.13	1.47
MOULTRIE	7.0	1.7	13.2	4	0	54	10.10	5.3	144	369	32	.74	.42	.27
PIATT	6.0	1.7	16.0	5	0	55	.00	4.5	131	263	29	.90	.51	.52
RICHLAND	11.0	1.8	17.2	2	0	47	15.20	8.3	190	751	48	.96	.55	.40
SA CLAIR	3.7	1.6	280.7	20	3	46	267.30	2.8	99	0	23	15.71	8.90	7.12
SANGAMON	4.5	1.8	172.9	19	1	56	159.60	3.4	116	131	25	9.68	5.48	4.25
SHELBY	7.0	1.9	23.2	7	0	53	5.90	5.3	155	457	32	1.30	.74	.16
VERMILLION	6.0	1.8	98.7	13	1	55	195.60	4.5	136	300	29	5.53	3.13	5.21
WABASH	13.0	1.9	13.5	1	0	46	18.40	9.8	197	814	59	.76	.43	.49
WAYNE	13.0	1.6	17.3	3	0	46	.00	9.8	175	626	59	.97	.55	.40
WHITE	14.0	1.7	16.8	4	0	44	4.50	10.0	182	688	61	.94	.53	.12
INDIANA														
BOONE	4.0	1.8	32.9	5	0	58	29.50	3.0	109	0	24	1.70	.89	1.22
CARROLL	3.5	1.9	17.8	4	0	56	8.70	2.6	105	0	23	.92	.48	.36
CASS	3.5	1.8	39.6	4	0	59	46.20	2.6	102	0	23	2.05	1.07	1.91
CLAY	7.0	2.0	24.5	5	0	54	6.70	5.3	160	501	32	1.27	.66	.28
CLINTON	3.7	1.8	30.6	5	0	60	30.30	2.8	105	0	23	1.58	.83	1.25
DAVISS	8.0	1.8	26.0	3	0	46	17.60	6.0	163	526	35	1.35	.70	.73
DELAWARE	2.7	1.7	128.9	5	1	59	263.50	2.0	89	0	21	6.67	3.49	10.87
DUBOIS	8.0	1.7	32.3	4	0	47	57.60	6.0	157	476	35	1.67	.87	2.38
GIBSON	13.5	1.8	31.2	7	0	46	23.40	10.0	190	751	61	1.62	.84	.97
GREENE	7.0	2.0	28.1	5	0	53	10.40	5.3	160	501	32	1.45	.76	.43
HAMILTON	3.0	1.8	70.9	8	0	57	35.90	2.3	96	0	21	3.67	1.92	1.48
HANCOCK	3.0	1.8	41.0	6	0	56	9.70	2.3	96	0	21	2.12	1.11	.40
HENDRICKS	5.0	1.8	62.2	6	0	56	3.50	3.8	123	188	26	3.22	1.68	.14
HENRY	3.0	1.7	53.5	3	1	58	87.80	2.3	93	0	21	2.77	1.45	3.62
HOWARD	3.0	1.8	87.2	2	1	56	313.80	2.3	96	0	21	4.52	2.36	12.95
JOHNSON	5.0	1.8	70.6	7	0	53	41.50	3.8	123	188	26	3.66	1.91	1.71
KNOX	9.0	1.9	40.2	6	0	49	30.10	6.8	183	695	39	2.08	1.09	1.24
MADISON	2.9	1.8	138.4	10	1	56	453.50	2.2	94	0	21	7.17	3.74	18.72
MARION	4.0	1.8	775.8	10	2	56	679.60	3.0	109	0	24	40.17	20.99	69.32
MARTIN	7.0	1.7	11.0	4	0	48	17.20	5.3	144	369	32	.57	.30	.71
MONROE	7.0	1.8	91.2	1	1	49	197.10	5.3	150	413	32	4.72	2.47	8.13
MONTGOMERY	5.0	1.8	34.1	6	0	58	63.10	3.8	123	188	26	1.77	.92	2.60
MORGAN	6.0	1.8	48.7	5	0	54	10.80	4.5	136	300	29	2.52	1.32	.45
OWEN	6.0	1.8	13.2	2	0	54	2.50	4.5	136	300	29	.68	.36	.10
PARKE	6.0	1.9	15.7	3	0	53	1.30	4.5	140	338	29	.81	.42	.05
PIKE	9.0	1.7	12.2	2	0	46	.30	6.8	170	582	39	.63	.33	.01
POSEY	13.5	1.7	22.8	4	0	46	31.40	10.0	182	688	61	1.18	.62	1.30
PULASKI	3.8	1.8	12.7	3	0	62	8.30	2.8	106	0	23	.66	.34	.34
PUTNAM	6.0	1.9	27.9	4	0	55	29.40	4.5	140	338	29	1.44	.75	1.21
RUSH	3.0	1.6	20.3	2	0	56	12.30	2.3	91	0	21	1.05	.55	.51
SHELBY	4.0	1.6	38.7	2	0	54	45.10	3.0	103	0	24	2.00	1.05	1.86
SULLIVAN	8.0	2.0	19.7	6	0	52	5.50	6.0	175	626	35	1.02	.53	.23
TIPPECANOE	4.5	1.8	114.1	3	2	58	171.60	3.4	116	131	25	5.91	3.09	7.08
TIPTON	3.0	1.8	16.0	7	0	56	11.30	2.3	96	0	21	.83	.43	.47
VANDERBURGH	13.5	1.7	161.6	1	1	46	.00	10.0	182	688	61	8.37	4.37	14.69
VIGO	8.0	2.0	110.6	2	1	54	158.80	6.0	175	626	35	5.73	2.99	6.55
WARRICK	12.0	1.7	34.7	5	0	46	.00	9.0	182	688	53	1.80	.94	1.78
WHITE	4.0	1.9	22.0	6	0	57	.00	3.0	112	100	24	1.14	.60	2.09
KANSAS														
ALLEN	1.0	1.8	15.4	2	0	44	10.30	1.0	69	0	18	4.20	2.38	2.60
ANDERSON	1.5	1.8	8.5	1	0	50	1.20	1.1	75	0	18	2.32	1.31	.30
BOURBON	1.0	2.0	15.7	1	0	42	5.80	1.0	70	0	18	4.28	2.42	1.46
CHEROKEE	1.0	2.0	21.4	4	0	41	29.80	1.0	70	0	18	5.83	3.30	7.52

Table 8.4 (cont'd)

States/Countries	Depth (thousand ft)	Gradient (°F/100 ft)	Population (thousands)	Towns	Cities	Heating degree days (hundreds)	Value added in manufacture	Well depth (assumed)	Temperature (°F)	Extractable heat (Btu/gal)	Cost (\$ per ft)	Residential use (trillion Btu)	Commercial use (trillion Btu)	Industrial use (trillion Btu)
CRAWFORD	1.0	2.0	36.8	6	0	41	24.40	1.0	70	0	18	10.03	5.68	6.15
DOUGLAS	2.0	1.6	64.4	1	1	47	46.10	1.5	79	0	19	17.55	9.94	11.63
FRANKLIN	1.5	1.8	20.2	3	0	47	7.20	1.1	75	0	18	5.50	3.12	1.82
JEFFERSON	2.0	1.6	13.4	5	0	51	.60	1.5	79	0	19	3.65	2.07	.15
LABETTE	1.0	1.8	24.8	4	0	40	11.90	1.0	69	0	18	6.76	3.83	3.00
LEAVENWORTH	2.0	1.6	56.7	3	1	50	10.30	1.5	79	0	19	15.45	8.75	2.60
LINN	1.0	1.9	8.3	3	0	47	.80	1.0	69	0	18	2.26	1.28	.20
MIAMI	1.5	1.7	20.9	3	0	50	8.00	1.1	74	0	18	5.70	3.22	2.02
NEOSHO	1.0	1.8	18.5	3	0	46	13.10	1.0	69	0	18	5.04	2.85	3.30
MICHIGAN														
ALCOMA	7.5	1.6	8.9	1	0	81	1.50	5.6	145	376	34	.46	.26	.04
BAY	12.0	1.6	119.6	2	0	68	189.70	9.0	175	626	53	6.23	3.50	5.35
CLARE	18.0	1.6	22.3	3	0	76	11.20	10.0	175	626	61	1.16	.65	.32
IOSCO	8.0	1.6	28.9	3	0	75	6.70	6.0	151	426	35	1.50	.85	.19
MISSAUKEE	10.0	1.6	9.1	2	0	81	.50	7.5	175	626	43	.47	.27	.01
NEWAYGO	8.0	1.6	31.7	4	0	75	35.10	6.0	151	426	35	1.65	.93	.99
OCEMAN	11.0	1.6	15.1	2	0	81	7.10	8.3	175	626	48	.79	.44	.20
OSCEOLA	10.0	1.6	17.8	3	0	76	19.40	7.5	175	626	43	.93	.52	.55
ROSCOMMON	12.0	1.8	15.2	1	0	81	1.40	9.0	190	751	53	.79	.45	.04
TUSCOLA	8.0	1.7	54.1	9	0	70	31.40	6.0	157	476	35	2.82	1.59	.88
WEXFORD	1.6	1.6	22.1	2	1	84	24.70	1.2	74	0	19	1.15	.65	.70
MISSISSIPPI														
*ADAMS	5.2	.0	37.3	0	1	19	57.20	3.9	158	860	27	.90	.68	5.24
*AMITE	5.4	.0	13.7	2	0	19	5.50	4.0	158	860	27	.33	.25	.50
*CLAIBORNE	5.2	.0	10.1	1	0	24	4.10	3.9	158	860	27	.24	.18	.38
*CLARKE	6.4	.0	15.0	4	0	23	9.30	4.8	158	860	30	.36	.27	.85
*COPIAH	5.2	.0	24.7	3	0	20	17.30	3.9	158	860	27	.60	.45	1.58
*COVINGTON	6.0	.0	14.0	2	0	19	4.30	4.5	158	860	29	.34	.26	.39
*FORREST	5.2	.0	57.8	1	1	19	41.70	3.9	158	860	27	1.40	1.05	3.82
*FRANKLIN	5.2	.0	8.0	3	0	20	1.40	3.9	158	860	27	.19	.15	.13
*GEORGE	5.2	.0	12.5	1	0	17	2.40	3.9	158	860	27	.30	.23	.22
*GREENE	5.6	.0	8.5	2	0	19	.00	4.2	158	860	28	.21	.15	1.14
*GRENADA	11.5	1.9	20.0	1	0	26	31.70	8.6	197	814	50	.48	.36	2.90
*HANCOCK	5.2	.0	17.4	2	0	16	.00	3.9	158	860	27	.42	.32	.81
*HARRISON	5.2	.0	134.6	2	2	16	42.70	3.9	158	860	27	3.26	2.45	3.91
*HINDS	4.8	.0	215.0	6	1	22	154.80	3.6	158	860	26	5.21	3.92	14.18
*HOLMES	10.5	1.8	22.6	4	0	26	5.40	7.9	190	751	46	.55	.41	.49
*HUMPHREYS	4.8	.0	14.6	2	0	26	4.00	3.6	158	860	26	.35	.27	.37
*ISSAQUENA	4.9	.0	2.7	0	0	23	.00	3.7	158	860	26	.07	.05	.00
*JACKSON	5.0	.0	88.0	1	2	16	169.90	3.8	158	860	26	2.13	1.60	15.56
*JASPER	6.0	.0	16.0	2	0	23	6.00	4.5	158	860	29	.39	.29	.55
*JEFFERSON	5.2	.0	9.3	1	0	21	1.10	3.9	158	860	27	.23	.17	.10
*JEFFERSON DAVIS	5.4	.0	12.9	1	0	20	2.10	4.0	158	860	27	.31	.24	.19
*JONES	6.0	.0	56.4	2	1	21	41.80	4.5	158	860	29	1.37	1.03	3.83
*LAFAYETTE	9.5	1.9	24.0	1	0	31	3.60	7.1	190	754	41	.58	.44	.33
*LAMAR	5.6	.0	15.2	3	0	19	12.60	4.2	158	860	28	.37	.28	1.15
*LAWRENCE	6.0	.0	11.1	2	0	20	.00	4.5	158	860	29	.27	.20	.81
*LINCOLN	5.6	.0	26.2	1	0	20	16.90	4.2	158	860	28	.63	.48	1.55
*MADISON	4.5	.0	29.7	4	0	24	22.70	3.4	158	860	25	.72	.54	2.08
*MARION	5.4	.0	22.9	1	0	18	11.10	4.0	158	860	27	.55	.42	1.02
*MONROE	8.0	1.8	13.2	2	0	26	9.00	6.0	163	526	35	.32	.24	.82
*MONTGOMERY	11.5	1.9	34.5	4	0	27	52.30	8.6	197	814	50	.84	.63	4.79
*NOXUBEE	12.0	2.0	14.3	2	0	26	4.60	9.0	205	870	53	.35	.26	.42
*PEARL RIVER	4.8	.0	27.8	2	0	16	7.10	3.6	158	860	26	.67	.51	.65
*PERRY	5.2	.0	9.1	3	0	19	2.60	3.9	158	860	27	.22	.17	.24

Table 8.4 (cont'd)

States/Countries	Depth (thousand ft)	Gradient (°F/100 ft)	Population (thousands)	Towns	Cities	Heating degree days (hundreds)	Value added in manufacture	Well depth (assumed)	Temperature (°F)	Extractable heat (Btu/gal)	Cost (\$ per ft)	Residential use (trillion Btu)	Commercial use (trillion Btu)	Industrial use (trillion Btu)
*PIKE	5.2	.0	31.8	4	0	19	22.10	3.9	158	860	27	.77	.58	2.02
PONTOTOC	9.5	1.9	17.4	1	0	29	6.30	7.1	190	754	41	.42	.32	.58
*SCOTT	5.2	.0	21.4	2	0	25	30.50	3.9	158	860	27	.52	.39	2.79
*SHARKEY	5.0	.0	8.9	2	0	24	.00	3.8	158	860	26	.22	.16	.33
*SMITH	6.0	.0	13.6	2	0	23	3.70	4.5	158	860	29	.33	.25	.34
*STONE	5.2	.0	8.1	1	0	17	4.20	3.9	158	860	27	.20	.15	.38
*WALTHALL	5.6	.0	12.5	1	0	19	2.30	4.2	158	860	28	.30	.23	.21
*WARREN	4.8	.0	45.0	0	1	21	53.00	3.6	158	860	26	1.09	.82	4.86
*WASHINGTON	4.7	.0	70.6	4	1	26	48.40	3.5	158	860	25	1.71	1.29	4.43
*WAYNE	6.0	.0	16.7	1	0	21	5.80	4.5	158	860	29	.40	.30	.53
*WILKINSON	5.4	.0	11.1	2	0	19	2.90	4.0	158	860	27	.27	.20	.27
*YAZOO	5.1	.0	27.3	2	0	24	65.20	3.8	158	860	26	.66	.50	5.97
MISSOURI														
BARTON	1.0	1.9	10.9	2	0	48	3.30	1.0	69	0	18	.13	.10	.08
BATES	1.0	1.6	16.2	3	0	46	1.30	1.0	67	0	18	.19	.15	.03
BOLLINGER	2.0	1.8	10.0	2	0	44	2.90	1.5	82	0	19	.12	.09	.07
CAPE GIRARDE	3.0	1.7	52.6	1	1	42	35.70	2.3	93	0	21	.63	.47	.91
DUNKLIN	4.8	1.6	36.3	8	0	36	16.00	3.6	113	105	26	.43	.33	.41
JASPER	1.0	1.9	82.6	8	1	41	121.90	1.0	69	0	18	.99	.74	3.10
JEFFERSON	1.0	1.7	124.6	7	1	47	66.40	1.0	68	0	18	1.49	1.12	1.69
MCDONALD	1.0	1.7	15.2	3	0	44	6.20	1.0	68	0	18	.18	.14	.16
MADISON	2.0	1.8	9.4	1	0	45	4.50	1.5	82	0	19	.11	.08	.11
NEW MADRID	4.5	1.6	24.1	7	0	41	3.30	3.4	109	0	25	.29	.22	.08
NEWTON	1.0	1.7	36.4	5	0	40	22.80	1.0	68	0	18	.44	.33	.58
PENISCOT	4.8	1.6	24.7	4	0	36	9.40	3.6	113	105	26	.30	.22	.24
PERRY	2.0	1.8	15.5	1	0	46	7.70	1.5	82	0	19	.19	.14	.20
ST FRANCOIS	2.0	1.8	39.5	8	0	46	10.80	1.5	82	0	19	.47	.36	.27
STE GENEVIEVE	2.0	1.8	14.2	2	0	46	21.50	1.5	82	0	19	.17	.13	.55
STODDARD	3.0	1.7	28.2	5	0	41	12.20	2.3	93	0	21	.34	.25	.31
VERNON	1.0	1.9	20.0	1	0	43	3.10	1.0	69	0	18	.24	.18	.08
NEW YORK														
ALLEGANY	7.5	1.6	50.9	10	0	74	43.00	5.6	145	376	34	2.33	1.46	.44
CATTARAUGUS	7.5	1.6	85.7	13	0	74	130.70	5.6	145	376	34	3.92	2.45	1.32
CAYUGA	5.0	2.0	77.6	7	1	69	79.00	3.8	130	250	26	3.55	2.22	.80
CHEMUNG	11.0	1.8	99.8	3	1	66	226.00	8.3	186	720	48	4.56	2.85	2.29
ERIE	3.0	2.0	1089.4	16	3	71	1896.50	2.3	100	0	21	49.79	31.15	19.21
NIAGRA	3.0	2.0	238.6	2	11	67	756.90	2.3	100	0	21	10.90	6.82	7.67
ONONDAGA	4.0	1.8	475.2	14	1	67	792.80	3.0	109	0	24	21.72	13.59	8.03
SCHUYLER	8.0	1.7	17.7	3	0	68	17.40	6.0	157	476	35	.81	.51	.18
SENECA	6.0	1.8	34.0	4	0	68	66.10	4.5	136	300	29	1.55	.97	.67
STEUBEN	10.0	1.7	101.2	15	0	67	181.70	7.5	182	688	43	4.63	2.89	1.84
TIOGA	11.0	1.7	49.1	6	0	73	45.20	8.3	182	688	48	2.24	1.40	.46
WYOMING	5.0	1.8	38.6	7	0	68	41.80	3.8	123	188	26	1.76	1.10	.42
YATES	6.0	1.7	20.7	2	0	64	8.50	4.5	131	263	29	.95	.59	.09
OHIO														
BELMONT	12.0	1.7	82.2	11	0	54	46.20	9.0	182	688	53	4.16	1.82	1.53
CARROLL	10.0	1.6	26.0	3	0	63	12.70	7.5	175	626	43	1.32	.58	.42
CHAMPAIGN	2.2	1.6	31.7	5	0	60	50.60	1.6	81	0	20	1.61	.70	1.68
DARKE	2.5	1.8	53.6	7	0	61	34.10	1.9	89	0	20	2.71	1.19	1.13
DEFIANCE	3.0	1.6	37.2	3	0	61	107.20	2.3	91	0	21	1.88	.82	3.56
ERIE	3.0	1.6	77.4	6	1	59	160.70	2.3	91	0	21	3.92	1.71	5.33
FULTON	3.0	1.6	35.6	7	0	65	55.60	2.3	91	0	21	1.80	.79	1.84
HARDIN	2.0	1.7	31.7	7	0	60	58.80	1.5	80	0	19	1.61	.70	1.95
HARRISON	11.0	1.8	17.9	4	0	57	6.10	8.3	190	751	48	.91	.40	.20
HENRY	3.0	1.6	27.8	6	0	60	83.70	2.3	91	0	21	1.41	.62	2.78

Table 8.4 (cont'd)

States/Counties	Depth (thousand ft)	Gradient (°F/100 ft)	Population (thousands)	Towns	Cities	Heating degree days (hundreds)	Value added in manufacture	Well depth (assumed)	Temperature (°F)	Extractable heat (Btu/gal)	Cost (\$ per ft)	Residential use (trillion Btu)	Commercial use (trillion Btu)	Industrial use (trillion Btu)
LOGAN	2.3	1.7	37.3	9	0	59	34.80	1.7	84	0	20	1.89	.83	1.15
MIAMI	2.5	1.9	87.3	6	1	56	177.90	1.9	90	0	20	4.42	1.93	5.90
MONTOE	12.0	1.7	15.6	1	0	56	29.14	9.0	182	688	53	.79	.35	.97
SHELBY	2.4	1.8	40.1	5	0	60	90.10	1.8	87	0	20	2.03	.89	2.99
WOOD	2.5	1.8	101.3	18	1	59	137.80	1.9	89	0	20	5.13	2.24	4.57
PENNSYLVANIA														
BEDFORD	20.0	1.6	42.4	4	0	58	19.50	10.0	175	626	61	1.66	.94	.59
BLAIR	17.0	1.6	133.8	7	1	59	173.50	10.0	175	626	61	5.24	2.98	5.23
*BRADFORD	14.0	1.6	60.6	8	0	64	87.00	10.0	175	626	61	2.38	1.35	2.62
*BUTLER	11.0	1.8	138.8	12	1	60	203.30	8.2	190	751	48	5.44	3.09	6.13
CAMBRIA	17.0	1.6	188.4	26	1	57	239.00	10.0	175	626	61	7.38	4.20	7.21
CAMERON	12.0	1.6	6.8	1	0	66	.00	9.0	175	626	53	.27	.15	.00
*CARBON	27.0	2.1	52.2	12	0	64	54.70	10.0	213	939	61	2.05	1.16	1.65
CENTRE	17.0	1.6	108.3	8	1	61	75.10	10.0	175	626	61	4.24	2.41	2.26
CLEARFIELD	13.0	1.6	78.5	8	0	66	60.90	9.8	175	626	59	3.08	1.75	1.84
*COLUMBIA	17.0	1.8	59.5	7	0	60	105.90	10.0	190	751	61	2.33	1.33	3.19
CRAWFORD	13.0	1.8	85.5	10	0	68	132.30	9.8	186	720	59	3.35	1.91	3.99
ELK	12.0	1.6	37.1	3	0	71	48.60	9.0	175	626	53	1.45	.83	1.47
FOREST	10.0	1.6	5.2	1	0	71	6.20	7.5	175	626	43	.20	.12	.19
GREENE	14.0	1.6	38.3	2	0	57	4.40	10.0	175	626	61	1.50	.85	.13
HUNTINGDON	22.0	1.6	39.8	4	0	59	34.70	10.0	175	626	61	1.56	.89	1.05
INDIANA	14.0	1.6	85.5	5	0	60	61.00	10.0	175	626	61	3.35	1.91	1.84
JEFFERSON	12.0	1.7	46.0	8	0	65	40.20	9.0	182	688	53	1.80	1.03	1.21
*LACKAWANA	17.0	1.9	234.0	18	1	61	293.60	10.0	197	814	61	9.17	5.21	8.85
LAWRENCE	11.0	1.6	105.2	8	0	58	156.30	8.3	175	626	48	4.12	2.34	4.71
*LUZERNE	20.0	1.8	342.2	33	2	64	462.70	10.0	190	751	61	13.41	7.63	13.95
LYCOMING	15.0	1.6	115.1	8	1	60	244.00	10.0	175	626	61	4.51	2.56	7.36
MCKEAN	11.0	1.7	51.5	7	0	74	121.80	8.3	182	688	48	2.02	1.15	3.67
MIFFLIN	20.0	1.6	44.2	3	0	57	85.50	10.0	175	626	61	1.73	.98	2.58
*MONROE	25.0	2.2	55.7	4	0	62	55.40	10.0	220	1001	61	2.18	1.24	1.67
*MONTGOMERY	18.0	1.9	17.1	1	0	60	52.10	10.0	197	814	61	.67	.38	1.57
*NORTHAMPTON	18.0	2.2	224.8	19	2	58	513.90	10.0	220	1001	61	8.81	5.01	15.49
*NORTHUMBERLAND	21.0	1.9	100.2	11	0	60	171.30	10.0	197	814	61	3.93	2.23	5.16
*PIKE	17.0	2.2	14.5	2	0	67	.00	10.0	220	1001	61	.57	.32	2.36
POTTER	12.0	1.6	16.9	5	0	71	5.60	9.0	179	657	53	.66	.38	.17
*SCHUYLKILL	30.0	1.8	158.7	26	1	63	177.80	10.0	190	751	61	6.22	3.54	5.36
SNYDER	20.0	1.6	31.3	6	0	60	19.00	10.0	175	626	61	1.23	.70	.57
SOMERSET	17.0	1.6	78.8	13	0	57	27.10	10.0	175	626	61	3.09	1.76	.82
UNION	17.0	1.6	31.3	3	0	60	22.10	10.0	175	626	61	1.23	.70	.67
WARREN	8.0	1.6	47.2	5	0	65	82.70	6.0	151	426	35	1.85	1.05	2.49
WASHINGTON	13.0	1.8	213.5	26	0	59	295.20	9.8	190	751	59	8.37	4.76	8.90
*WAYNE	15.0	1.8	34.3	3	0	73	25.60	10.0	190	751	61	1.34	.76	.77
WESTMORELAND	15.0	1.6	380.9	36	0	57	566.60	10.0	175	626	61	14.93	8.49	17.08
WEST VIRGINIA														
BARBOUR	19.0	1.8	16.1	3	0	53	1.80	10.0	190	751	61	.55	.28	.15
BRAXTON	17.0	1.6	13.1	3	0	49	1.70	10.0	175	626	61	.45	.23	.14
MARSHALL	12.0	1.6	39.4	5	0	56	86.00	9.0	175	626	53	1.35	.68	7.10
NICHOLAS	25.0	1.6	25.7	2	0	51	3.80	10.0	175	626	61	.88	.44	.31
PRESTON	18.0	1.6	27.6	4	0	59	7.60	10.0	175	626	61	.94	.47	.63
RANDOLPH	25.0	1.7	26.4	3	0	60	10.80	10.0	182	688	61	.90	.45	.89
TAYLOR	17.0	1.6	15.5	1	0	53	4.30	10.0	175	626	61	.53	.27	.35
UPSHUR	18.0	1.6	21.7	1	0	53	11.40	10.0	175	626	61	.74	.37	.94

Ref. 6. To give suggestions for future prospecting efforts required a systematic technique for examining the geothermal potential of the areas. Also needed was a quantitative technique to evaluate alternative future federal resource allocation strategies in support of DOE/DGE and DOE/RA (Resource Applications) programs intended to stimulate the commercialization of low- to moderate-temperature geothermal resources.

Comparative evaluations of geothermal prospects must consider not only geologic and engineering data, but also socio-economic information. Because the data are most readily available at the county level, the prospects were evaluated at that level.

This method for comparing prospects is an outgrowth of work during the 1940's arising from the von Neumann-Morgenstern axiomatization of utility (Ref. 7) and is related to the work of Arrow and Goodman at the Cowles Commission in the 1950's. Goodman's review (Ref. 8) of the work is the basic reference for this application. Keeney and Raifa (Ref. 9) present a thorough modern discussion of methods that might be used to extend this procedure.

The method is based on the definite opinion that there will never be adequate data or a clear policy that will determine, once and for all, the strategy to be followed in the commercialization of geothermal energy. From this point of view, it is clear that the available data must be assessed according to criteria and policies that are given as much visibility as possible so that new data or a change in the purpose for which the evaluation of a strategy is undertaken can be accommodated.

This method evaluates alternative strategies by ranking the geothermal prospects. The ranking is carried out by amalgamating the assessments of the prospects according to several bases of comparison. The process of amalgamation requires that the different bases of comparison be assigned weights to indicate the importance of each basis to the overall purpose of the evaluation.

To state the problem more formally, consider a matrix in which the prospects to be ranked are presented as rows and the bases of comparison as columns. The problem is to devise rules for selecting the "best" row. If the elements of the matrix can be interpreted as "utilities" in the von Neumann-Morgenstern sense, a number of methods of amalgamation might be considered (Refs. 7 and 8). However, the natural bases of comparison for ranking geothermal prospects are as disparate as temperature and population.

To improve the comparability, each basis can be scaled to the unit interval, or ranks can be assigned to each basis separately. Where a natural scaling exists (e.g., the boiling point of

water), the scaling method has some advantages, but for the present problem natural scalings are not immediately apparent. The method of ranking each basis separately has therefore been adopted, with 1 the highest rank, 2 the next highest, and so on. Tied ranks are replaced with their averages. Observe that, in a given column, functions of the data that preserve order (in particular, linear functions) do not change the assigned ranks.

The bases of comparison are selected from the available data in order to satisfy in part the purpose of the evaluation. Another way to reflect the policy or purpose is to recognize that the elements of the bases do not enter equally into consideration. Each column must be weighted in accordance with its importance. The final score is obtained by taking the weighted average of the ranks in each row and then ranking the weighted averages at the columns.

The proposed ranking scheme can be carried out by hand or on a pocket calculator for small data bases. As the data bases become larger, the work becomes tedious. We therefore coded a small set of computer routines to handle them.

Table 8.5 is a sample page of the data used in the applications. The table lists 39 counties in seven states that rank among the first 25 under at least one criterion. The data were all obtained from published sources or derived by simple manipulation of published data.

The examples given below may make the proposed method seem less abstract and may provide insight into the way ranks change under different criteria. It should be understood that what is proposed is a method of ranking a given set of prospects; it is not a selection of prospects. The particular set of counties used in the example was chosen because the data were readily available. Other prospects might be selected as being especially pertinent for exploration, for example, or other data may be used as the bases of comparison. In any case, the additional prospects or the different criteria can be accommodated easily.

Examples of ranking are given for four categories of development. The first overall ranking gives equal weight to temperature, cost, energy use (residential, commercial, or industrial), the number of towns and cities, the number of heating degree days, and value added in manufacturing. The second ranking emphasizes residential use and selects as the bases of comparison temperature, well cost, current residential use of energy, the number of towns and cities, and the number of heating degree days. The third emphasizes commercial applications and uses the same bases of comparison as the second except that the current commercial use of energy

Table 8.5

Selected prospects under different criteria

States/Countries	Overall	Residential	Commercial	Industrial
ALABAMA				
ARKANSAS				
ILLINOIS				
CHAMPAIGN	19	27	27	44
SANGAMON	9	13	13	11
VERMILLION	13	30	29	21
INDIANA				
KNOX	38	34	36	25
TIPPECANOE	28	25	26	23
KANSAS				
MICHIGAN				
TUSCOLA	31	22	24	70
MISSISSIPPI				
*HARRISON	60	77	74	20
*HINDS	18	36	32	1
*JACKSON	79	95	88	16
*MADISON	84	89	80	15
MONTGOMERY	72	94	82	17
*WASHINGTON	42	45	44	6
MISSOURI				
NEW YORK				
ALLEGANY	36	26	25	97
CATTARAUGUS	20	17	16	59
CAYUGA	26	10	9	52
CHEMUNG	30	15	15	33
STEUBEN	7	1	1	10
TIOGA	33	12	11	64
WYOMING	43	24	22	84
OHIO				
BELMONT	23	19	21	26
PENNSYLVANIA				
BLAIR	21	32	33	34
*BUTLER	5	2	2	2
CAMBRIA	12	23	23	19
*CARBON	17	14	14	22
CENTRE	22	29	30	45
CLEARFIELD	24	21	20	39
*COLUMBIA	25	28	28	24
CRAWFORD	10	8	8	12
JEFFERSON	29	16	17	35
*LACKAWANA	2	4	4	5
LAWRENCE	14	20	19	18
*LUZERNE	1	3	3	7
LYCOMING	15	31	31	27
MCKEAN	16	9	10	14
*NORTHAMPTON	4	6	6	3
*NORTHUMBERLAND	11	11	12	9
*SCHUYKILL	6	7	7	8
WASHINGTON	3	5	5	4
WESTMORELAND	8	18	18	13
WEST VIRGINIA				

is substituted for residential use. The fourth emphasizes industrial development and selects temperature, well cost, current industrial use, the number of towns and cities, and value added in manufacturing. In these examples, the weightings are always taken as equal although it is obvious that a particular criterion (e.g., the number of towns and cities) should have a greater importance under the residential criterion than under the industrial one.

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9. R. L. Keeney and H. Raiffa, Decisions with Multiple Objectives: Preferences and Value Tradeoffs, J. Wiley and Sons, New York, 1976.

Chapter 9

TECHNICAL INFORMATION INTERCHANGE MEETINGS

There have been five Technical Information Interchange Meetings where people interested in geothermal energy in the Eastern United States have met to exchange technical information.

The first such meeting on Eastern geothermal programs, the Near-Normal Gradient Workshop, was held in March 1975 under the aegis of the Energy Research and Development Administration. The second, Technical Information Meeting, was held at the Applied Physics Laboratory in September 1978 under the auspices of DOE/DGE. A symposium on Geothermal Energy and Its Direct Use in the Eastern United States was sponsored by the Geothermal Resources Council in Roanoke, Va., in April 1979. The fourth meeting was sponsored by the Division of Resource Management/DOE in the fall of 1979. The fifth, again sponsored by the Division of Geothermal Energy/DOE, was held at the Coolfont Conference Center, Berkeley Springs, W.Va., in the fall of 1980.

In general, attendees represented DOE/RA, the USGS, NOAA, state geologic and energy offices, DOE Regional Offices, Program Research and Development Announcement (PRDA) recipients, industry, the national laboratories, financial analysis firms, and interested county offices. Virtually all attendees participated in the programs, summarizing their efforts in promoting the use of geothermal energy in the Eastern United States.

The Applied Physics Laboratory organized the second, fourth, and fifth meetings, taking responsibility for the agenda, the amenities, and the publication of the minutes. The minutes, taken as a whole, provide a retrospective record of what has been learned and what has been done about geothermal energy in the east. They consist of

1. Near-Normal Gradient Workshop, ERDA, 10-11 Mar 1975.
2. Technical Information Meeting, JHU/APL QM-78-124, Nov 1978.
3. Geothermal Energy and Its Direct Use in the Eastern United States, Geothermal Resources Council Special Report No. 5, Apr 1979.

4. Geothermal Energy and the Eastern United States -
Fourth Technical Information Interchange Meeting
(4th TIIM), JHU/APL QM-79-261, Dec 1979.
5. Geothermal Energy and the Eastern United States -
Fifth Technical Information Interchange Meeting (5th
TIIM), JHU/APL QM-80-185, Dec 1980.

A number of the articles from the fourth and fifth meetings have been cited where relevant in the present document. The remaining articles, not otherwise cited herein, are of sufficient interest to the geothermal energy community to warrant listing them.

FOURTH TIIM

Section	Title	Author
I	Summary of Department of Energy Geothermal Programs	R. A. Black
II	Federal/State Geothermal Planning and Project Implementation	B. B. Barnes
III	Summary Description of the DOE/DGE State Coupled Program	G. P. Brophy
IV	Future Directions in the Direct Heat Applications Program	M. Skalka
V	Status of Federal Legislation of Interest to Geothermal Energy Development	R. C. Stephens
VI	Preliminary Definition of Selected Geothermal Resources, Eastern USA	J. L. Renner
VII	Mid-Atlantic and Southeastern Moderate Temperature Program - Geologic Set- ting and Targeting Process	R. Gleason and J. Lambiase
VIII	The Hot Dry Rock Eastern Program	J. C. Maxwell
IX	Geothermal Application Assessment for the TVA Region	C. E. Whittle
X	The MITRE Programs in Support of Geo- thermal Development	D. Entingh

Section	Title	Author
XI	The U.S. Geologic Survey Eastern Geothermal Programs	A. Kover
XV	Geothermal Heating for the Crisfield, Maryland High School	F. C. Paddison
XVI	Status Report: Engineering and Economic Studies, Direct Application of East Coast Geothermal Resources in the Frozen Food Industry	R. Costello and M. Knebel
XVII	LNG Vaporization at Cove Point, Maryland using Geothermal Energy	A. B. Litchfield
XVIII	Department of Defense Geothermal Development Program	T. A. Ladd and C. F. Austin
XIX	Geothermal Energy Market Assessment, Atlantic Coastal Plain	W. J. Toth
XX	Comparison of Potential Geothermal Resources, Eastern United States	R. F. Meier
XXI	Geothermal Studies, West Virginia	H. Reike
XXVII	Mississippi State Geologic Survey, DOE State Coupled Program	E. Luper
XXVIII	Kansas State Geologic Survey, DOE State Coupled Program	D. Steeples
XXIX	The Regional Aquifer System Analysis Program	G. Bennett

FIFTH TIIM

I	Keynote Address	D. Lombard
II	NOAA's Geothermal Mapping Program	D. Clark
III	Gruy Federal Work Plans for FY 1981	J. Renner
IV	Atlantic Coastal Plain: Geological Targeting and Evaluation Progress Report	J. Lambiase

Section	Title	Author
VI	Ohio Geothermal Resources (HDR Program)	Y. Eckstein
VII	Heat Generation and Heat Flow in Western Pennsylvania	Y. Eckstein
VIII	Mid-Continent HDR Program	R. R. B. von Frese et al.
IX	Southeastern Gulf Coast Heat Flow Program	D. L. Smith
XIV	Overview: Northeastern Geothermal Program	J. Maxwell
XV	A Preliminary Geothermal Resource Appraisal of the Tennessee Valley Region	W. P. Staub
XVI	User Coupled Resource Confirmation	S. Prestwich
XVII	The DOE/DGE State Coupled Program	M. Wright
XVIII	Utilization of Geothermal Energy at the Cove Point (Md.) LNG Receiving Terminal	A. Litchfield
XXI	Department of Defense East Coast Geothermal Program	T. A. Ladd
XXII	Geothermal Energy - Naval Air Re-work Facility	F. K. Hill
XXIV	Review of Technical Assistance in the Eastern United States	F. C. Paddison
XXVI	Recent Federal District Heating Initiatives	E. Peterson
XXVII	Geothermal Awareness Program	T. J. Duesterberg and J. C. Engle
XXVIII	Status of Geothermal Legislation	R. Stephens
XXIX	National Conference of State Legislatures, Geothermal Project Overview	K. Wonstolen
XXX	Brookhaven Geothermal District Heating Model	R. Leigh and A. Reisman

Section	Title	Author
XXXI	The Geothermal Progress Monitor Project	D. J. Entingh and B. Walker
XXXII	USGS Low-Temperature Geothermal Resource Assessment of the United States	M. Reed and C. Bufe
XXXIII	U.S. Geological Survey Regional Aquifer Program	G. Bennett
XXXIV	National Geothermal District Heat Market Penetration Estimate	D. J. Entingh
XXXV	Market Penetration of Geothermal Community Heating Systems	R. Dubin
XXXVI	Market Penetration of Geothermal Energy for Industrial and Residential Applications	R. J. Thomas and R. A. Nelson
XXXVII	Geothermal Industrial Utilization Plan Overview	J. Markiewicz and M. Iriarte
XXXVIII	Market Penetration of Hydrothermal Energy for Non-Electric Uses	T. A. V. Cassel, P. D. Blair, and W. F. Finan

Chapter 10

SUPPORTIVE INNOVATIVE TECHNICAL DEVELOPMENTS

In the course of four to five years involvement in promoting moderate-temperature geothermal resources, several innovative technical excursions were made by APL. One was a new methodology of prospecting for deep hydrothermal reservoirs by means of a variation of the magnetotelluric technique. This involved using the extremely low frequency (ELF) signals broadcast from the Navy's experimental ELF facility at Clamslake, Wis. The other two were attempts to extend the use of moderate-temperature geothermal sources to air conditioning as well as heating. These two methods were the ammonia absorption heating/refrigeration system and the Einstein-Szilard refrigerator. The former can also permit the long-distance transfer of energy. In a large number of cases, the capital costs of geothermal energy will be repaid with profit only if well usage can be extended beyond the limited heating season.

10.1 PROSPECTING FOR HYDROTHERMAL RESOURCES WITH ELF SIGNALS

APL has examined the use of the coherent ELF transmissions from the Sanguine transmitter at the Navy's Wisconsin Test Facility in prospecting for geothermal brines and other anomalous conductivity regions in the earth (Ref. 1). The advantage of using these signals is that they come from a powerful transmitter and antenna system and that the coherent transmissions afford signal integration times that last for hours, if necessary. While the skin depth of these signals (45 and 75Hz) restricts accurate measurements to depths of 2 to 5 km, the precision with which they may be made provides significant information about subsurface geology. It is likewise important to process VLF signals (12 to 18 kHz) to help separate the effects of surface terrain features as well as magnetotelluric signals to probe deeper into the earth to obtain the full story of the structure of the anomalies being measured. In addition to the use of coherent integration with signals at each antenna location, it is possible to obtain coherent information from a set of antenna locations. These may be used to fit the spatial pattern of signal scattering from deep anomalies to obtain further improvement in signal processing and anomaly identifications. These features make the method valuable in geological prospecting.

An example of the scattered signature on the surface above a local high-conductivity volume of spherical or paraboloidal shape is shown in Fig. 10.1 for several traverses near an anomaly. This coherent pattern should be compared with the pattern in Fig. 10.2 of a high-conductivity dike anomaly to show the possibilities of anomaly identification.

The dominant background noise is the magnetotelluric background at the Sanguine frequencies. It consists of two parts: the first is from distant thunderstorms and magnetospheric disturbances; the second is from additional pulse-type interference that may be generated by nearby thunderstorms. These interfering pulses must be edited from the measured data before integration to obtain the best possible signal-to-noise ratio. The mean noise amplitude E of the vertical electric field is expected to be -76 dB referred to one volt per meter per root Hertz (Ref. 2). For

$$\sigma = 10^{-2} \text{ mho/m and } \epsilon = \epsilon_0,$$

the corresponding E parallel field is

$$E_{\parallel} = -144 \text{ dB}$$

or

$$6 \times 10^{-8} \text{ V/M } \sqrt{\text{Hz}} .$$

The incident $E_{\perp}$ is expected to be

$$2 \times 10^{-8} \text{ V/M } \sqrt{\text{Hz}} .$$

Figure 10.3 is a plot of the signal-to-noise ratio anticipated for typical anomalies at various depths, showing that integration times of 30 min to 1 h are adequate. The incident $E_{\parallel}$ amplitude was estimated from the measurements by Bannister (Ref. 2); the noise background used is based upon the measurements by Maxwell (Ref. 3).

In all geological prospecting, it is necessary to use to the utmost the very few data points that are available to decipher the complexity of the various geological structures. It is desirable, for example, to make gravity and magnetic anomaly measurements at each of the antenna locations in the electromagnetic survey to get additional structure-dependent information for later data processing on the computer to obtain a self-consistent determination of the geothermal source. Our studies show that the ELF measurements can make a significant contribution to the understanding of the subsurface structure.

Fig. 10.1 Scattered wave signature caused by an underground high-conductivity anomaly.

Fig. 10.2 Scattered signature caused by a high-conductivity dike.

Fig. 10.3 Signal-to-noise ratios (in 1-Hz band) for several traverses near a high-conductivity anomaly.

Although several people at the Energy Research and Development Administration and the USGS had expressed interest in the basic ELF technique, USGS was not able to support the program as it was proposed. The major objection given by the USGS was the fact that the Navy's Wisconsin Test Facility transmitter (or other transmitters) would probably not be operating in the future, and in view of that risk, it would not be worth spending any significant effort to develop the technique. Instead, the USGS suggested that a brief, simple demonstration experiment be conducted. Although there is considerable room for belief that the United States will possess an ELF experimental facility in Wisconsin for years to come, APL was amenable to pursuing the USGS suggestion. Nevertheless, although APL proposed an experimental verification program using an ELF receiver available at APL (Ref. 4), the USGS felt unable to support this activity.

10.2 AMMONIA ABSORPTION REFRIGERATOR

The use of low-temperature (100 to 200°F) thermal energy from geothermal resources and power plants has been limited primarily to non-electric applications, such as space heating, and even then to buildings within a few miles of the thermal source. The ammonia absorption system described here (Refs. 5 and 6) offers a means of providing space heating and air conditioning to communities hundreds of miles from a thermal source. Low-grade thermal energy is converted into a chemical intermediate that can be pumped long distances without large thermal losses.

A generalized diagram of an ammonia absorption cycle is shown in Fig. 10.4. The ammonia is separated by distillation from the aqua ammonia by means of the thermal energy from the geothermal source or waste heat from a power plant. Thus, the thermal energy is stored chemically in the separated ammonia. The ammonia is piped to the user to provide air conditioning by the evaporation of liquid ammonia or to provide space heating by the absorption of ammonia vapor by water in the well-known ammonia absorption process. The absorption of ammonia by water is very exothermic, yielding about 620 Btu/lb of ammonia vapor for the system design given here. The heat of vaporization of liquid ammonia in this system is about 490 Btu/lb.

A point design was done for a system to supply the heating and cooling for 1,000 homes. However, the design was not optimized, its main function being to illustrate system operation. The following assumptions and parameters were used:

Fig. 10.4 The basic ammonia absorption cycle.

1. A low-temperature geothermal source at 150°F or higher provides a peak distillation temperature of 140°F at the generator. Many hot-water aquifer systems have water warmer than this temperature.
2. The geothermal source is assumed to be at a considerable distance from the residential area. The example assumes a separation of about 100 miles.
3. The average heating load per home is assumed to be 4×10^5 Btu/day. Further, the temperature of the air delivered to the home is assumed to be between 100 and 120°F, which is comparable to that of conventional forced-air systems.

4. The average cooling load per home is taken to be 2×10^5 Btu/day. The delivered air temperature is assumed to be 50 to 55°F.
5. For pipe sizing and system scaling, a distribution system serving 1,000 homes is assumed.

The heating mode of the point system design is shown in Fig. 10.5. A geothermal source or a power plant supplies low-grade thermal energy as hot water to the generator to permit the distillation of ammonia from a concentrated 54% (by weight) solution. Nearly pure (99.6%) ammonia vapor and dilute 34% aqua ammonia are produced. In the process, thermal energy is converted and stored as latent heat of vaporization in the ammonia water vapor and as potential heat of solution. The ammonia vapor and dilute solution are pumped to the user where the latent heat of vaporization and potential heat of solution are reconverted in the absorber into thermal energy for use in space heating. The cooled concentrated solution from the absorber/heat exchanger is then piped back to the generator for redistillation and recycling.

When this system is used for district heating, the absorber in Fig. 10.5 may be subdivided and placed at the homes and buildings that are to be heated. Alternatively, a central community facility may be used for the absorption process. The heat of absorption can be used for producing hot water or a hot brine solution that can be pumped to nearby buildings for space heating. Thus, the low-grade thermal energy from the source may be chemically stored, transported many miles to the consumers without large thermal losses, and regenerated locally for heating.

In the cooling mode shown in Fig. 10.6, the ammonia vapor from the generator must be liquefied. Pressures in excess of 150 psia are required to liquefy the ammonia at 80°F; they are achieved by modifying the concentrations of the two aqua ammonia solutions. The concentrated solution is 57.3%, and the dilute solution is 53% ammonia. In the generator, the latter solution has a vapor pressure of about 150 psia at 140°F, which is sufficient to liquefy the vapor when it is cooled below 80°F in a condenser.

For air conditioning, only liquid ammonia is pumped to the users for evaporation and cooling. In the evaporator, the pressure is reduced to below 75 psia and cold water is produced to cool the buildings. As in the heating mode, the evaporator may be subdivided and placed at the individual buildings, or a central facility can be used to produce cold brine solutions. In the cooling mode, absorption takes place at the geothermal source with the 53% solution from the generator, producing the 57.3% solution that is sent back to the

Fig. 10.5 Heating system.

Fig. 10.6 Cooling system.

generator. Since only liquid ammonia is pumped to the user in the cooling mode, a large savings in pumping energy is achieved, but much of the energy savings is required for the operation of a cooling tower. Nevertheless, efficiencies are much greater in this system than for heat pumps and conventional air conditioners. The following summarizes the mass flow rates of the point design:

	Heating mode	Cooling mode
Fluids pumped to 1000 homes		
Ammonia vapor (60 psia)	490 lb/min (2590 ft ³ /min)	
Ammonia liquid		310 lb/min (62 gal/min)
34% aqua ammonia	1150 lb/min (155 gal/min)	
Fluids returned to thermal source		
Ammonia vapor (75 psia)		310 lb/min (1310 ft ³ /min)
54% aqua ammonia	1640 lb/min (238 gal/min)	

Seasonal switchover of the system can be accomplished at the user end with only two valves: one to change the direction of flow in the vapor pipe and the other to allow liquid ammonia to enter the evaporator from one of the other two pipes of the system. Thus, in the heating mode, only the absorber is used; in the summer cooling mode, only the evaporator is used. The changes are slightly more complex at the thermal source. In the winter heating mode, the absorber at the source is not used, and the concentrated solution returning from the users is sent directly to the generator. In the summer cooling mode, the absorber and cooling tower are put on-line and, after a short start-up period at the proper pressures, the concentrations of the aqua ammonia are modified to the levels required. Also, only two of the three pipes in the distribution system are required in the summer.

10.3 THE EINSTEIN-SZILARD REFRIGERATOR

A recent commentary (Ref. 7) briefly reviewed the Einstein-Szilard absorption refrigerator (Ref. 8) with three working fluids, NH_3 , H_2O , and butane (Fig. 10.7).

As the discussion below shows, it appears that the Einstein-Szilard refrigerator can be operated with the modest source temperatures (say, 150°F or below) that are readily available from eastern geothermal resources, solar energy, or cogeneration systems. Unlike the better known Electrolux Servel system (based on the von Platen and Munters patent), which uses hydrogen as an inert gas to equalize the internal pressure and $\text{NH}_3/\text{H}_2\text{O}$ as the working and absorbing

Fig. 10.7 Einstein-Szilard absorption refrigerator.

fluid, the Einstein-Szilard absorption refrigerator uses a condensable gas (butane) to equalize the pressure. Butane was chosen because in the liquid state it does not mix with the $\text{NH}_3/\text{H}_2\text{O}$ solution. Further, in the Einstein refrigerator, the NH_3 vapor is used mainly as the "pump" for the butane vapor from the evaporator (1 on Fig. 10.7) to the absorber (6). Thus, cooling in the evaporator comes mainly from the latent heat of butane. A feature common to the Einstein and the Servel systems is that there is no mechanical, moving component such as mechanical pumps or valves. In the Einstein refrigerator, the fluid is circulated through the bubble pump (36); in the Servel system, the circulation is accomplished by boiling off the $\text{NH}_3/\text{H}_2\text{O}$. As the heat is put into the solution in the generator tank (29), the NH_3 vapor (nearly dry saturated vapor) is evolved with water that remains mostly in liquid state. This avoids wasting the large latent heat of water. More important, the use of saturated "equilibrium" vapor allows the system to be driven at a source temperature much lower than is possible with any other known refrigeration system.

The performance of the Einstein-Szilard refrigerator was estimated through a simplified analysis (Ref. 9) in order to assess its possible application to the low-temperature (i.e., lower than 160°F) geothermal resources of the Eastern United States. For simplicity, it was assumed that the two internal heat exchangers are perfect and that the gases are ideal. For this analysis, the effects of the continuous temperature distributions in the generator, absorber, and evaporator, as well as the effect of the presence of water vapor, were ignored.

Figure 10.8 is a plot of cooling temperature versus heat load for four operating conditions for a fixed flux of gaseous NH_3 . The exponential shape of the curves is controlled by the vapor pressure curve of butane. The change in the ratio of the butane to the NH_3 flux and the butane enthalpy changes are reflected in these curves.

The theoretical performance estimate is quite encouraging. The heat fluxes are 588 Btu/min for the geothermal source and 148 Btu/min for the evaporator load with the following conditions: temperatures of 80°F (condensor), 140°F (generator), and 50°F (evaporator), an NH_3 weight fraction of 0.52 in the strong solution (in the condensor), and an NH_3 vapor flux of 1 lb/min. An estimated efficiency is obtained of 0.252, where the additional contribution arising from the isobaric expansion of NH_3 vapor in the evaporator

Symbol	$T_{\text{cond}} (^{\circ}\text{F})$	X_{cond}	Btu cooling at 50°F per pound of water
■	70	0.6	10.9
▲	80	0.6	6.2
◆	80	0.52	6.7
●	90	0.52	4.5

Fig. 10.8 Theoretical cooling capability of Einstein refrigerator per pound of NH_3 gas.

has been ignored. It is expected to contribute about a 10% increase in the cooling Btu. This performance is extremely interesting, particularly because no other refrigeration system can provide a comparable capability with a source temperature of, say, 145°F without requiring a significant amount of high-grade (electrical) energy.

The status of the Einstein refrigerator was outlined in a letter to the Director of the Energy Research Office of DOE and was discussed briefly with him in person. Although the Carnot efficiency is necessarily poor, nevertheless the Btu's of cold per Btu of (geothermal) heat is high. The latter is basically wasted during the air-conditioning season, so the Einstein-Szilard air conditioner seems to be economically sound.

At this time it is not clear what, if any, future is in store for this intriguing idea.

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Chapter 11

STATE TEAMS AND STATE PROSPECTUSES

Early in the organization of the geothermal program, it was recognized that it was a substantial task to inform state and local governments, and individuals, of the prospects for local geothermal energy; the prospective energy markets to which they could apply; how to assess the magnitude and characteristics of geothermal energy; and how to develop a resource, put it to use, and understand its economics. Furthermore, feedback was desired to assist the DOE in organizing its program of supporting research, resource assessment, and commercialization. In 1976, the standard references for potential geothermal resources on the national level were Refs. 1 and 2. As these references were western-oriented, APL visited 26 states in 1976-78 to gather whatever additional information was available for the eastern part of the country (as defined by what was then Geothermal Region 5). These visits had several purposes: to obtain geological information relating to potential geothermal resources, to inform the concerned state office of the national geothermal program, and to become familiar with states' organizations for the development of alternative energy forms. One result of these visits was the long-range planning scenarios prepared in 1977-78 for the Division of Geothermal Energy, which are summarized here; another was the Technical Assistance studies, which continued until the completion of the APL effort and which are described in Chapter 3 of this report.

The scenario was the tool used to accomplish the tasks outlined in Chapter 3. The Laboratory wrote five scenarios, concerning

1. Arkansas (Ref. 3),
2. The Madison aquifer in South Dakota (Ref. 4),
3. The Eastern Gulf Coastal Plain (Ref. 5),
4. The Atlantic Coastal Plain (Ref. 6), and
5. Hot Dry Rock in the East (Ref. 7).

It was soon realized that these documents had to be narrative in nature and had to have the early participation of state and local governments and of individuals. Two South Dakota scenarios

(Refs. 8 and 9) were the first of these narrative reports. Unfortunately, the interaction or iteration required among the state and local governments, and individuals, and the Laboratory never occurred because of the change of responsibility for that area decided by DOE/DGE.

In time, the state prospectus concept evolved, where a state body develops a road map or "how-to-do-it" description of geothermal assessment, permitting, engineering, economics, legal, and taxation requirements and operation of a facility using geothermal energy (Refs. 10 and 11). If these state prospectuses are developed by enough states, and aggregated, they will fulfill the functions of the original scenarios, namely, to guide the federal government in planning for geothermal development.

As the APL effort developed in time, intensive efforts to affect state legislative actions and the organization of the state governmental structure to assist in the development of geothermal energy were limited to the eastern seaboard, in particular, the states of Delaware, Maryland, and Virginia. In July and September 1977 (Ref. 12), meetings of East Coast state geologists were briefed by ERDA, APL, and VPI&SU on the federal geothermal program for the eastern coastal plain. These meetings were concerned not only with geological aspects of geothermal energy but also with the general nature of future state contributions to the development effort.

In the spring of 1978, the State of Maryland enacted a Geothermal Resource Act (Ref. 13). The Act was written with the assistance of APL and supported by APL in testimony before the Economic Affairs and Environmental Affairs Committees of the Maryland legislature. While the Maryland Geothermal Act, as passed by the legislature, differed in several respects from the draft as prepared by APL, it did define a geothermal resource and gave the authority for the management and regulation of the resource to the state's Department of Natural Resources. The promulgation of the rules and regulations for the utilization of geothermal energy was left to the department.

To assist the state's Department of Natural Resources, as well as other agencies of the state or local governments and interested private parties, APL prepared and issued a tutorial narrative. Since the eastern shores of Delaware, Maryland, and Virginia were similar as to resource and possible utilization, this narrative was prepared as a "prospectus" for the Delmarva Peninsula (Ref. 11).

The Delmarva Prospectus, as published in June 1979, was designed to supply the reader with the information required to begin planning for a geothermal installation. A list of its chapter headings provides an idea of the scope of the document.

- I. Introduction
- II. Description of Resource (for Delmarva)
- III. Potential Hydrothermal Energy beneath Delmarva
- IV. Reservoir Parameters for Geothermal Energy Retrieval
- V. Geothermal Wells and Well-Pumping Systems
- VI. Applications Engineering and Economics
- VII. Technical and Regulatory Steps for Development
- VIII. Discussion of Current Environmental, Financial, and Legal Infrastructures
- IX. Initiatives Required for Geothermal Development
- X. Lists of Contacts for Assistance in Geothermal Development

This prospectus was written with significant input from state agencies, particularly those of Maryland. Since the legal and institutional factors are state-specific, the prospectus makes no attempt to be complete at the state level. It was intended as a framework to be completed in a state-specific manner by the individual states.

At the time the prospectus was issued and distributed to DOE and interested parties in the three states, a possibility existed that DOE would support the formation of state teams to complete the state-specific prospectuses and to coordinate geothermal development. Therefore, in 1979 and 1980, APL urged the three states to form an infrastructure that could complete the prospectus and submit plausible proposals to DOE for support of their efforts (e.g., see Refs. 14 and 15). These efforts met with a slow response because state energy agencies were relatively new, they were faced with urgent problems in conventional energy uses, and they lacked expertise in alternative forms of energy. However, by late 1979, Delaware had submitted a proposal to DOE and, in fiscal 1981, the State Energy Office was partially funded to complete the Delaware Geothermal Energy Prospectus.

In Virginia, after several presentations by APL, the Coal and Energy Commission established a Geothermal Subcommittee, which

included VPI&SU, and submitted a proposal to DOE for the completion of a State Prospectus and Geothermal Map (Ref. 16). The Maryland State Energy Office of the Department of Natural Resources, in a meeting with DOE and APL in April 1980, offered to attempt to complete the prospectus if DOE support could be obtained (Ref. 17). However, staff problems in the State Energy Office prevented implementation of Maryland's plan in 1980 and new legislation proposed by the Legislature in 1981 changed the direction of the state's effort.

Following the passage of the Maryland Geothermal Act in 1978, APL in conjunction with the National Conference of State Legislatures (NCSL) held a series of meetings in Delaware and Virginia to offer guidance in writing geothermal resource acts. The Legislature of Delaware passed a Geothermal Act in 1980 that provided for the legal and regulatory framework to guide geothermal development and state ownership of geothermal resources. The act was vetoed by the Governor in July 1980 on the grounds that it imposed a "new regulatory maze and layer of red tape" and "jeopardized the legitimate property rights of Delaware landowners." The act was modified but did not emerge from the House Committee of the legislature in the 1981 session. In Virginia, a geothermal act was passed by the 1981 legislature and has been signed by the Governor (Ref. 18).

Several modifications to the Maryland Geothermal Act were introduced into the 1981 session of the Maryland Legislature. At the request of the Energy Administration of the Department of Natural Resources, APL testified in support of these bills before legislative committees on February 9 and 11 and March 12 and 13, 1981 (Ref. 19). The most important of these bills were Joint House Resolution 26 and Senate Bill 832. The former directed the Department of Natural Resources to review the issues of access and allocation of geothermal resources. Since the question of ownership is not clarified in the Maryland Geothermal Act, this review and the resulting allocation recommendation will be the operational law of the State. Senate Bill 832 creates an Energy Supply Financing Administration within the Department of Economic and Community Development. This administration is to provide technical and financial assistance to developers of alternative energy supplies (including geothermal) and is empowered to issue bonds to raise money in support of feasibility studies, demonstration projects, and energy-supply projects. In effect, the administration becomes the advocate for alternative energy forms. As the bill was passed and signed into law, it only provides for one staff position — a reflection of the reluctance of the 1981 Legislature to create a new bureaucracy.

In summary, as of mid-1981, the states of Maryland and Virginia had passed Geothermal Acts; all three states had created in

principle an infrastructure to promote geothermal energy; and at least one state (Delaware) was working to complete a geothermal prospectus. The future of activity at the state level in the face of decreased DOE support and the absence of the assistance and encouragement of DOE contractors, such as APL, is uncertain.

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Appendix A

RESOURCE ASSESSMENT AND RESERVOIR CONFIRMATION PROGRAMS FEDERALLY FUNDED IN THE EAST

This appendix contains a list, Table A.1, of Resource Assessment Programs in the east sponsored by USGS and Reservoir Confirmation Programs sponsored by DOE. Some of the programs listed were sponsored by both agencies. Within the DOE-sponsored tasks, programs were either in support of the hydrothermal program or the hot dry rock program; the individual sponsor is listed. Figure A.1 shows the deep sedimentary basins and plains with potential for hydrothermal and later perhaps hot dry rock geothermal developments. Also indicated are the approximate areas where resource confirmation studies have occurred. Table A.2 lists these efforts and cites the appropriate references.

Table A.1

Resource assessment and reservoir confirmation programs
in the east

	Organization/Contact	Resource	Remarks
RESOURCE ASSESSMENT, USGS Low temperature geothermal assessment nationwide	Working Group/Marshall Reed, USGS		In process; Ref. 1.
RESERVOIR CONFIRMATION, DOE/DGE Lewes, Del.	State Energy Office, Delaware/ Dan Anstine		In process; Refs. 2 and 3.
Cayuga County, N.Y. (Montezuma)	Standard Brands/NYSERDA, B. Krakow SUNY/Buffalo, D. S. Hodge		In process; Refs. 4, 5, and 6.
User-coupled reservoirs confirmation program	Taylor Instruments/NYSERDA, B. Krakow		Withdrawn; Ref. 4.
RESERVOIR CONFIRMATION, DOE Atlantic Coastal Plain	VPI&SU, J. Costain	Hydrothermal and hot dry rock.	In process of documentation; Refs. 7, 8, 9, 10, and 33.
Southern Mississippi	Mississippi State Univ., Edwin Luper	Hydrothermal	Complete; Ref. 11.

Table A.1 (cont'd)

Resource assessment and reservoir confirmation programs
in the east

	Organization/Contact	Resource	Remarks
Alabama	Geological Survey of Alabama, T. L. Neathery	Hydrothermal	Complete; Ref. 12.
Nebraska	Univ. of Nebraska at Omaha, W. D. Gosnold, Jr.	Hydrothermal	In process; Refs. 13, 14, and 15.
Kansas	Kansas Geological Survey, Donald Steeples	Hydrothermal	In process; Ref. 16.
Delaware	Delaware Geologic Survey, K. Woodruff	Hydrothermal	Refs. 2, 3, and 17.
New York			
The Capitol area	Dunn-Geoscience Corp., M. R. Sneeringer/ NYSERDA	Hydrothermal	Refs. 18 through 23.
The mid and western area	SUNY/Buffalo, D. S. Hodge/ NYSERDA	Hot dry rock	Complete; Refs. 5 and 6.

- * Contours adapted by APL from basement map of North America (Ref. 3)
** From Gruy Federal report (Ref. 42)

Fig. A.1 Potential geothermal resource areas in the Eastern United States showing reservoir confirmation areas.

Table A.2

Areas of resource confirmation studies

Area	Organization, Contact	Resource	Remarks
New Hampshire and other areas	MIT, G. Simmons	Hot dry rock	Complete; Ref. 24.
New England	Amherst College, J. Brophy	Hydrothermal	Complete.
New Hampshire	State Geologist	Hydrothermal	Complete; Ref. 24.
TVA region	Orau, W. P. Staub	Hydrothermal	Ref. 25.
Southeastern Gulf Coastal Plain	Univ. Florida, Gainesville, D. L. Smith	Hot dry rock	Complete; Ref. 26.
Ohio and western Pennsylvania	Kent State Univ., Y. Eckstein	Hydrothermal	Complete; Refs. 27 and 28.
Mid-continent	Purdue Univ., R. R. P. vonFrese	Hot dry rock	Complete; Ref. 29.
North Dakota	Geologic Survey, Killams	Hydrothermal	Complete; Ref. 30.
East in general	Gruy Federal, J. Renner		Complete; Ref. 31.
West Virginia	Univ. West Virginia, H. Heike	Hot dry rock	Complete; Ref. 32

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6. K. Hilfiker, "Geothermal Studies, Western New York," Sect. XXIII, 4th TIIM.
7. R. Gleason and J. Lambiase, "Mid-Atlantic Southeastern Moderate Temperature Program - Geologic Setting and Targeting Process," Sect. VII, 4th TIIM.
8. J. Lambiase, "Atlantic Coastal Plain Geological Targeting and Evaluation Progress Report," Sect. IV, 5th TIIM.
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17. S. M. Kane, "Industrial Application of Geothermal Energy in Lewes, Delaware: An Economic Analysis," Geothermal Resources Council (to be published, Transactions, 1981).
18. J. R. Dunn, "Analysis of Potential Geothermal Resources and Their Use, Lebanon Springs Area, New York" (to be published by New York State Energy Research and Development Authority, 1981).
19. M. R. Sneeringer and J. R. Dunn, "Exploration for Geothermal Resources in the Capital District of New York" (to be published by New York State Energy Research and Development Authority, 1981).
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23. J. R. Young, "Geothermal Studies, Saratoga Spring, New York," Sect. XXII, 4th TIIM.

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26. D. L. Smith, "Southeastern Gulf Coast Heat Flow Program," Sect. IX, 5th TIIM.
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29. R. R. P. VonFrese et al., "Mid-Continent HDR Program," Sect. VIII, 5th TIIM.
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33. C. E. Schubert, "The Eastern Hot Dry Rock Target Prospect Evaluation," Sect. X, 5th TIIM.

Appendix B

GEOHERMAL INFRASTRUCTURE IN THE EASTERN UNITED STATES

In this appendix are listed those organizations that have had experience or claim to have capability in developing hydrothermal or hot dry rock. Their listing here should not be construed as an endorsement, nor do we claim these lists are complete. It is reasonable to state, however, that there does exist an infrastructure, which we predict will continue to grow and gain in capability. Table B.1 lists consulting engineering organizations, and Table B.2 lists discipline-related organizations.

Table B.1

Consulting engineering firms,
engineering and applications

Shore Engineering, Melta, VA	Energy Concepts, Annapolis, MD
Solar Energetics, Wilmington, DE	A. J. Jacques, Albany, NY
D'Appolonia, Pittsburgh, PA	Carltech Associates, Columbia, MD
CH2M Hill, Reston, VA	Fosdick and Hilmer, Inc.,
Burns and Roe, Paramus, NJ	Cincinnati, OH
Stone and Webster Engineering	Ebasco Services, Greensboro, NC
Co., Boston, MA	Caple, Cromwell, Neyland, Triumph,
EBL, Salisbury, MD	Levy, and Gathell, Inc., Little
Gruy Federal, Arlington, VA,	Rock, AR
and Houston, TX	Radian Corp., Austin, TX
Kidde Consultants, Newark, DE	Ham-Mer Consulting Engineers,
Malone and Williams (Architects),	Austin, TX
Salisbury, MD	American Geothermal Energy Asso-
Harold A. Schlenger and Asso-	ciates, Omaha, NE
ciates, Inc., Baltimore, MD	Dunn Geoscience Corp., Latham, NY
Kirkham Michael and Associates,	Delmarva Energy Resources, Inc.
Omaha, NE	Montehanin, DE

Table B.2

Infrastructure in the Eastern United States

Utilities

Delmarva P&L, Wilmington
Georgia Power, Atlanta
Niagara-Mohawk Power Co.,
Albany
Carolina Power and Light Co.
Long Island Lighting
Pennsylvania Power and Light

Financiers

The Armfield Organization,
Winston-Salem, NC
Paul Rodzianko, NY, NY
(Geothermal Energy Corp.)
L. F. Rothschild, Unterberg
Tobin, NY, NY

Hydrologists

Geraghty and Miller, Inc.,
Annapolis, MD
The Berkeley Group,
Berkeley, CA

Universities

VPI&SU (Coastal Plain)
Kent State Univ. (Ohio and
western Pennsylvania)
Univ. of Perdue (Midcontinent)
Univ. of Florida (eastern
Gulf Coastal Plain)
SUNY, Buffalo (western New York)
Orau (TVA region)
SD School of Mines (western SD)
Univ. of West Virginia (W. VA)
Univ. of Syracuse (New York)
MIT (New England)
Johns Hopkins Univ. (eastern
United States)

Drillers

Read Drilling and Development
Corp., Washington, DC
A. C. Schultes and Sons, Inc.

Heat Pumps

Westinghouse Electric,
Staunton, VA
Argonne National Lab., Inc.
Oak Ridge National Lab
Brookhaven National Lab

State Geologic Surveys

Nebraska	Georgia
New York	New Hampshire
Delaware	Mississippi
Maryland	Alabama
New Jersey	North Dakota
Virginia	South Dakota

OTHERS

USGS, Reston, VA
NYSERDA, NY
MITRE, McLean, VA
USGS/WR, Atlanta, GA
Trenton, NJ
Michigan Energy & Resource
Research Assoc., MI
Techmecon Analytic Research
Inc., Philadelphia, PA
International Business Service
Washington, DC
Engineering and Economic
Research, Inc.,
Falls Church, VA
Technical Research Analysis
Co., VA

Appendix C

PROPOSED ASTM STANDARD TEST METHOD FOR PUMP TESTING GEOTHERMAL WELLS*

1. SCOPE

1.1. This test method covers the procedures to be used in the pump-testing of geothermal wells which may possibly yield fluids in sufficient quantities and of sufficient temperature to serve as useful sources of energy.

1.2. The scope of this test method is limited to wells which penetrate formations that naturally contain water in place but no restriction is placed on the chemistry of the water.

1.3. The intent of this test method is to determine the hydrologic properties of water-bearing formations; that is, the amount of fluid that can be pumped from an aquifer with a specified drawdown that depends upon the permeability and the storage coefficient of the aquifer.

1.4. The sequence of procedures for pump testing are prescribed.

1.5. The format and content of data recording are prescribed.

2. APPLICABLE DOCUMENTS

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3. SUMMARY OF METHOD

Selected aquifers are isolated and the drawdown measured for a specified pumping rate. Following a specified period of pumping, the rate of recovery of the fluid level is measured with the pump turned off. Drawdown is next measured for several pumping rates. The measured data are recorded in a prescribed manner.

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*Forwarded by JHU/APL Lett. CQO-3025, to R. K. Traeger, Sandia Lab., "Transmittal of Proposed Pump Tests Procedures for Hydrothermal Wells," 27 Apr 1981.

4. SIGNIFICANCE AND USE

The utility of a hydrothermal resource is determined by the temperature of the geothermal fluid, the chemistry of the fluid, and the quantity that can be pumped to the surface. The rate at which the well can be pumped is the property most difficult to determine. Since the aquifer properties that determine an economical flow rate and the lifetime of the hydrothermal reservoir are not directly observable, it is necessary that a pump test of the well be designed and performed in a manner that results in data that can be analyzed to determine aquifer properties. The determination of such aquifer properties as permeability and storage coefficient is performed by matching the measured drawdown data to a type curve derived from a mathematical model of the aquifer. While the type curve (plot of drawdown versus time) depends upon the assumptions made in the model, this dependence may be weak over the time of a reasonable well pump test. Thus, it is necessary that a pump test be designed and carried out with the continuity and accuracy that will suffice for analysis to reveal significant departures, if there be any, from the assumptions made in the derivation of the type curve that is chosen. Even if there is reason to believe that the idealized assumptions made in nonequilibrium Theis theory are applicable, the analysis of the data is tedious and difficult if the pump test is interrupted, if the flow is variable, or if the test is not adequately logged.

5. TERMINOLOGY

In this standard test method, the following definitions are used.

5.1. Geothermal fluid: the fluid consisting of water as the solvent which is of sufficient temperature to provide useful energy at the surface. For the purpose of this test method, the geothermal fluids are assumed to be available only at depth below the surface and to remain substantially in the liquid phase if pumped to the surface.

5.2. Aquifer: a formation of permeable rock, sand, or gravel which contains geothermal fluids.

5.3. Permeability: a measure of the capacity of a geologic stratum to transmit a fluid. As used in petroleum engineering, the amount of permeability is the "darcy" with the dimension of area; it is a property of the stratum alone. The U.S. Geological Survey uses a unit with the dimensions of gallons per day per square foot called the meizner; this unit is defined for the viscosity of pure water at 60°F and is thus a property of the medium and of the fluid.

5.4. Transmissivity: the product of permeability and the thickness of the aquifer. In the U.S. Geological Survey hydraulic unit, the dimensions are gallons per day per foot.

5.5. Storage coefficient: a dimensionless property of an aquifer that measures the volume of fluid released from or taken into storage by a column of the aquifer with unit cross section per unit change in hydraulic head.

5.6. Drawdown: the distance the water level is lowered below the piezometric surface as the well is pumped. Within the confines of the well, drawdown is the linear distance, relative to the static head, that the fluid surface is lowered by the process of pumping.

5.7. Equilibrium well equations: the equations that relate the drawdown of a well to the pumping rate, well diameter, and aquifer properties for those instances where, in a finite time, an effective steady state is reached.

5.8. Nonequilibrium well equations: equations that relate well drawdown, well diameter and well spacing, and aquifer parameters as a function of time. For an ideal confined aquifer, no steady state exists and a nonequilibrium well equation must be used.

5.9. Type curve: a plot of drawdown versus a variable that includes time, well diameter and well spacing, and aquifer properties. The usual type curve is the solution of the well drawdown as a function of time using the aquifer and well assumption introduced by Theis in 1935, and the determination of aquifer properties is usually first attempted by matching the observed drawdown curve against the Theis curve. This does not preclude an attempt to match the experimental data to a type curve based upon different boundary conditions or aquifer properties.

6. PREPUMP TEST PROCEDURES

Prior to the pump test of a geothermal well, the Test Director will have acquired the following information and performed the following procedures.

6.1. Collected such information as is available from well boring materials and corings on the geologic characteristics, depths, and thickness of formations bearing geothermal fluids.

6.2. Attempted to correlate the information from the well boring materials and geophysical logging with such geological knowledge as is available to estimate the flow available from the aquifer or aquifers selected for pump tests.

6.3. Determined the disposition of the pumped geothermal fluids.

6.4. The Director of the Pump Test is responsible for providing the information required for the analysis of the well and aquifer performance. Therefore, the well test report shall include the following information:

6.4.1. Well diameter as function of depth.

6.4.2. Casing dimensions and cementing procedures.

6.4.3. Well screens or perforation dimensions over the formations that will be pump tested.

6.4.4. Well development methods used in the areas that will be pump tested.

6.5.4. Description of apparatus used for the pump test and the specified or tested accuracy thereof.

7. APPARATUS USED FOR PUMP TESTING

7.1. A submersible centrifugal or turbine shaft pump capable of delivering a continuous flow at the volume rate required for the pump test and from a depth within the well that meets the requirements for the possible utilization of the well.

7.2. A throttling valve at the well head to control the flow rate of the pump.

7.3. A flow meter at the well head to measure the flow rate of the pumped geothermal fluid.

7.4. A submersible pressure transducer that will measure the fluid pressure when the transducer is mounted at a position in the well bore at or near the production zone.

7.5. A submersible temperature transducer that is capable of measuring the fluid temperature when placed at the depth of the producing aquifer.

7.6. A temperature transducer placed in the well output at the surface.

7.7. Surface-mounted digital and strip chart recorders for the submerged pressure transducer, temperature transducer, and flow meter.

7.8. Sand traps mounted in the fluid conduit before the flow rate meter or meters.

7.9. Valves and containers to collect samples of the pumped geothermal fluid for the determination of physical and chemical properties of the geothermal fluid.

7.10. Recording current meter or watt meter to measure the electrical power consumed by the down-hole pump.

7.11. Pressure gauge in discharge pipe located before the throttling valve.

8. PUMP TEST PROCEDURES, LOWEST DESIGNATED AQUIFER OR AQUIFERS

The objectives of the pump test of a geothermal well determine the details of certain procedures. In particular, if the well were drilled to obtain precise information on the aquifers bearing the geothermal fluids, a lengthy pump test, of the order of weeks or months, may be required and an observation well would improve the determination of aquifer parameters. This test procedure assumes that the more modest objective of assessing the economic feasibility of the well for a specified user is operative, and that for economic reasons, an ambitious program of characterizing the hydrothermal reservoir is not tenable. The length of time specified for the pump-down procedures may be extended as finances permit or user requirements dictate.

The following procedure assumes that, as the pump test proceeds, the dynamic level of the geothermal fluid can be measured only in the well being pumped, that is, the production well. This limitation limits the accuracy with which aquifer characteristics can be determined, but is believed realistic because of the great expense involved in drilling an observation well penetrating the same deep aquifer as that from which the geothermal fluid is pumped. If an observation well is available, it will be assumed that the instrumentation to measure and record the water level within the well will be installed and used.

8.1. Drop the pressure and temperature transducers to the level of the production zone.

8.2. Install the submersible pump to a depth below the static fluid level of the well that is estimated to exceed by a factor of 2 the drawdown for the prescribed pump test period.

8.3. Install the flow measuring and temperature measuring equipment at the well head. Install the throttling valve on the fluid outlet pipe. Open the throttling valve to its maximum extent.

8.4. Start the pump and recording equipment. Check for operation. Operate pump for 15 minutes and turn off. Record as a function of time the fluid flow rate and pressure transducer output (well drawdown). Observe sand production if any. Record power consumption of pump. Allow well to recover for at least 15 minutes; record pressure transducer reading during recovery period.

8.5. Close the throttling valve an amount sufficient to produce a total dynamic head on the pump equivalent to 10 to 20% of the static head. Repeat step 8.4.

8.6. Repeat step 8.5 until at the beginning of each test the pressure on the gauge before the throttling valve is equivalent to approximately one-half of the static head due to the depth of pump placement below the equilibrium surface of the geothermal fluid in the well bore.

8.7. Start the pump for a continuous pump test of at least 24 hours duration. Adjust the throttling valve to maintain a constant pumping rate as the drawdown proceeds. Record the bottom hole pressure and fluid flow rate at intervals of 1 minute or less for the first hour and at 5-minute intervals thereafter. Record the bottom hole temperature every 5 minutes for the first hour and at 15-minute intervals thereafter. Check geothermal fluids for sand or suspended solids at 15-minute intervals for the first hour and every hour thereafter. Turn off the pump at the end of the designated pump test period (24 hours or longer).

8.8. Record the bottom hole pressure for a period of time equal to the pumping time or until the fluid level in the well has essentially reached equilibrium.

8.9. Start the pump and throttle the flow rate to 0.25 of that maintained in step 8.7. Continue pump test for 1 hour. With pump operating, increase the flow rate to 0.50 of that of step 8.7 and pump for 1 hour; increase pump rate to 0.75 of that of step 8.7 and pump for 1 hour; repeat the process for a flow rate equal to that of step 8.7 and for a flow rate with the throttle valve fully open. Record the bottom hole pressure and the flow rate at 1-minute intervals through the above test. At the end of the above 5-hour test, turn off the pump and measure the bottom hole pressure for a 5-hour recovery period.

9. PUMP TEST PROCEDURES, TWO PRODUCTION ZONES

9.1. Withdraw the pump and pressure and temperature transducers from the well.

9.2. Perforate the well casing covering the next higher aquifer or aquifers of interest. Clean and deburr the well bore. Follow well completion techniques used on lower aquifers.

9.3. Replace the pressure transducer at the bottom of the well and the temperature transducer at the level of the new perforations.

9.4. Repeat steps 8.7 and 8.8 of procedure 8 and step 9.1.

10. PUMP TEST PROCEDURES, HIGHER AQUIFERS

10.1. Isolate the zone of aquifers pump tested in procedure 8 by a drillable cement container or hydraulic packer.

10.2. Pump test the aquifer or aquifers perforated in step 9.2 following procedures 8.4 through 8.9.

10.3. Higher aquifers will be pump tested as required by following procedures 9.1, 9.2, 10.1, and 10.2.

11. REPORT

The pump test report shall include the following information:

11.1. The items covered in procedure 6.4.

11.2. The results of the pump tests of procedures 8 and 9 itemized as follows:

11.2.1. Bottom hole pressure as a function of time.

11.2.2. Pumping rate as a function of time.

11.2.3. Bottom hole temperature as a function of time.

11.2.4. Fluid temperature at the wellhead as a function of time.

11.2.5. Fluid pressure at the wellhead and before the throttling valve as a function of time.

11.2.6. Report of the chemical analysis of the geothermal fluids for each production zone tested.

- 11.2.7. Density of the geothermal fluid for each zone tested measured at the temperature of the fluid during the pump test.

11.3. The pump test procedures shall be logged in time sequence with notation of any deviations from the test plan caused by apparatus failure, sand production, decisions of the Test Director, or unforeseen circumstances.

12. PRECISION AND ACCURACY

The prepump test information that must be provided to the Well Analyst is given in procedure 6.4. This information plus the continuity and accurate logging of the pump test are essential to analysis of well performance. Instrumentation and measurement specifications are as follows.

12.1. Down-hole pump: must be capable of pumping geothermal fluids at the required flow rate against the projected dynamic head and operate continuously at the geothermal temperature encountered.

12.2. Wellhead flow meter: measure flow rate with an accuracy of 1% over a flow rate range of 10:1.

12.3. Down-hole and wellhead temperature transducers: an accuracy of 0.1°F from surface ambient to geothermal temperature.

12.4. Down-hole pressure transducer: full-scale accuracy of 0.1% and sensitivity of 0.05% at geothermal temperatures.

12.5. Digital recorders: 6-digit readout, capable of printout every 10 seconds for each channel.

12.6. Strip chart recorders: accuracy 0.5% of full scale, time accuracy 0.1% of chart time-scale division.

12.7. Density measurement of geothermal fluids: 0.01% accuracy.

12.8. Wellhead pressure meter: accuracy 1.0% of full scale.

Appendix D

JHU/APL EXTERNAL REPORTS AND PAPERS

A. HANDBOOK

1. C. S. Leffel, Jr., and R. A. Eisenberg, "Geothermal Handbook," JHU/APL SR 77-1, Jun 1977.

B. GENERAL

1. J. E. Tillman, "Eastern Geothermal Resources: Should We Pursue Them?" Science, 7 Nov 1980.

C. PLANNING DOCUMENTS (SCENARIOS)

1. W. J. Toth, "The Atlantic Coastal Plain," JHU/APL QM-77-129, Oct 1977.
2. E. L. Fox, "The Coastal Plain in Southern Arkansas," JHU/APL QM-77-129-1, Oct 1977.
3. C. A. Shipley, "The Madison Limestone Aquifer in Western South Dakota," JHU/APL QM-77-129-2, Nov 1977.
4. W. J. Toth, "The Eastern Gulf Coastal Plain," JHU/APL QM-77-129-3, Feb 1978.
5. C. S. Leffel, Jr., "Hot Dry Rock," JHU/APL QM-77-129-4, Mar 1978.
6. R. C. Eberhart and R. Freeman, "Geothermal Energy Development by the Sioux at Kyle, South Dakota," JHU/APL QM-78-226, Apr 1978.
7. R. Freeman and R. Meier, "Potential Application of Madison Formation Waters for Community Heating in South Dakota," JHU/APL QM-78-042R, Sep 1978.

D. EASTERN UNITED STATES GEOTHERMAL TECHNICAL INTERCHANGE MEETINGS

1. "Eastern Hydrothermal Region First Quarterly Information Exchange Meeting, APL, September 19, 1978," JHU/APL CQO-2319 (QM-78-124), 8 Nov 1978.

2. Geothermal Energy and the Eastern United States - Fourth Technical Information Interchange Meeting, Minutes, JHU/APL QM-79-261, Dec 1979.
3. Geothermal Energy and the Eastern United States - Fifth Technical Information Interchange Meeting, Minutes, JHU/APL QM-80-185, Dec 1980.

E. TECHNICAL ASSISTANCE

1. JHU/APL Lett. CQO-2544, to W. R. Rice, "The Crisfield, Maryland Well and Geothermal Energy," F. C. Paddison and A. M. Stone, 12 Nov 1979.
2. F. C. Paddison, "Geothermal Heat as a Supplementary Energy Source in the Eastern United States," College of Industrial Management and Textile Science Conference, Slashing Today and Tomorrow, Nov 1979, Clemson University; JHU/APL QM-79-251, Nov 1979.
3. W. J. Toth, "A Profile of the Delmarva Poultry Industry," JHU/APL QM-80-002, Jan 1980.
4. JHU/APL Lett. CQO-2828, "Technical Assistance - Mariculture Industry on the Eastern Shore of Maryland," F. C. Paddison and A. M. Stone, Feb 1980, forwarding "Application of Geothermal Energy for Mariculture," K. Yu and F. C. Paddison, JHU/APL QM-80-013, Jan 1980.
5. JHU/APL Lett. CQO-2850, to D. B. Lombard, DOE/DGE, "Report on Technical Assistance for Columbia LNG Corp.," F. C. Paddison and A. M. Stone, 28 Mar 1980.
6. JHU/APL Lett. CQO-2862, "Data for Industrialization Plan for Hydrothermal," F. C. Paddison, Apr 1980.
7. R. von Briesen and K. Yu, "Technical Assistance Report No. 4 - Geothermal Space Heating, Pittsville Middle/Elementary School, Pittsville, Maryland," JHU/APL QM-80-101, Jun 1980.
8. F. K. Hill and R. W. Henderson, "Technical Assistance Report No. 5 - Geothermal Space Heating, Naval Air Rework Facility, Norfolk, Virginia," JHU/APL QM-80-102, Jun 1980.
9. K. Yu and F. C. Paddison, "Technical Assistance - Hydrothermal Resource Application in the Eastern United States," Annual Meeting Transactions, Vol. 4, Geothermal Resources Council, 1980. Also JHU/APL QM-80-134, Oct 1980.

10. F. K. Hill and R. von Briesen, "Technical Assistance Report No. 6 - Geothermal Space Heating and Air Conditioning, McGuire Air Force Base, New Jersey," JHU/APL QM-80-190, Dec 1980.
11. F. C. Paddison, "Summary of Interested Parties and Cost Estimates for a Test Well at Kings Bay, Georgia," JHU/APL CQO-2980 to D. B. Lombard, DOE/DGE, Jan 1981.
12. F. C. Paddison, "Forwarding of Report on Economics of Geothermal Energy at Kings Bay, Georgia," JHU/APL Lett. CQO-2994 to D. B. Lombard, DOE/DGE, 13 Feb 1980.
13. "Technical Feasibility of Use of Eastern Geothermal Energy in Vacuum Distillation of Ethanol Fuel," Carltech Associates, JHU/APL QM-81-066, Apr 1981. Also Geothermal Resource Council, 1981 Annual Meeting, Vol. 5.
14. "Technical Feasibility of Use of Eastern Geothermal Energy in Vacuum Distillation of Ethanol Fuel - Extension of Data," Carltech Associates, JHU/APL QM-81-123, Sep 1981.
15. "Ocean City, Maryland, Geothermal Energy Evaluation," JHU/APL QM-81-109, 17 Aug 1981.
16. R. von Briesen, "Dover AFB Geothermal Energy Evaluation," JHU/APL QM-81-144, Nov 1981.
17. C. S. Leffel, Jr., "Geothermal Community Heating for Cape Charles, Virginia," JHU/APL QM-81-133, Oct 1981.
18. "A Program for Single-Phase Moderate Temperature Geothermal Well Drawdown and Pumping Energy for the HP-97 and Other Desk Calculators," QM-81-138, Nov 1981.

F. MARKET ASSESSMENT, PENETRATION, AND RANKING

1. W. Toth, "Geothermal Markets on the Atlantic Coastal Plain," Geothermal Resources Council Special Report No. 5, Apr 1979.
2. F. O. Mitchell, "Evaluation of Potential Geothermal Resource Areas," JHU/APL QM-79-163/GT, Jul 1979.
3. W. J. Toth and F. C. Paddison, "Geothermal Energy Markets on the Atlantic Coastal Plain," Energy Technology VI, Feb 1979.

4. "Geothermal Energy Market Penetration: Development of a Model for the Residential Sector," JHU/APL QM-79-209, Sep 1979.
  5. W. J. Toth, "Definition of Markets for Geothermal Energy in the Northern Atlantic Coastal Plain," JHU/APL QM-80-075, GEMS-002, May 1980.
  6. F. O. Mitchell, "Evaluation of Potential Geothermal Resource Areas," JHU/APL QM-79-163/GT (Revised), Jul 1980.
  7. A. C. Goodman, "Geothermal Market Penetration in the Residential Sector: Capital Stock Impediments and Compensatory Incentives," Annual Meeting Transactions, Vol. 4, Geothermal Resources Council, 1980. Also published in JHU/APL QM-80-134, Oct 1980.
  8. W. F. Barron, "An Analysis of Benefits and Costs of Accelerated Market Penetration by a Geothermal Community Heating System," Annual Meeting Transactions, Vol. 4, Geothermal Resources Council, 1980. Also published in JHU/APL QM-80-134, Oct 1980.
  9. R. Dubin, A. C. Goodman, and S. Kane, "Market Penetration of Innovative Energy Technology," presented at Joint International Meeting of Canadian Operational Research Society/The Institute of Management Science and Operations Research Society of America, Toronto, May 1981.
- G. ECONOMIC ANALYSIS TOOLS, AIDS, AND DATA
1. "A Review of Recent Energy Price Projections for Traditional Space Heating Fuel, 1985-2000," JHU/APL QM-79-016, GEMS-005, Mar 1979.
  2. R. Weissbrod and W. Barron, "Cost Analysis of Hydrothermal Resources Applications in the Atlantic Coastal Plain," Geothermal Resources Council Special Report No. 5, Apr 1979.
  3. K. Yu and F. C. Paddison, "Cost of Geothermal Wells," JHU/APL QM-79-142, Jun 1979.
  4. R. Weissbrod, W. Barron, P. Kroll, and W. J. Toth, "Economic Evaluation Model for the Direct Use of Moderate Temperature (up to 250°F) Geothermal Resources in the Northern Atlantic Coastal Plain," JHU/APL QM-79-124, GEMS-003, Jun 1979.

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