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# POTENTIAL FOR SUBSTITUTION OF GEOTHERMAL ENERGY AT DOMESTIC DEFENSE INSTALLATIONS AND WHITE SANDS MISSILE RANGE


Charles A. Bakewell
Joel L. Renner


TOPICAL REPORT


Prepared for the
U.S. Department of Energy
Division of Geothermal Energy

Under Contract No. DE-AC08-80NV10072


by


GRUY FEDERAL, INC.
2001 Jefferson Davis Highway, Suite 701
Arlington, Virginia 22202


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## EXECUTIVE SUMMARY


In August 1980, the Department of Defense (DOD) requested that the Department of Energy (DOE) identify and evaluate geothermal resources that might provide substitute energy at any of 76 defense installations. Gruy Federal, Inc. contracted with DOE to estimate the geologic characteristics and related economics of potential geothermal resources located at or near the 76 installations. The geologic assessment identified 18 installations with possible geothermal resources and 4 Atlantic Coastal Plain resource configurations that represented the alternatives available to East Coast bases. (The China Lake Naval Weapons Center, containing the Coso Hot Spring area, and the naval installation at Adak, Alaska, were excluded from consideration because geothermal activities already are under way there.)

These 18 locations and 4 resource configurations, together with 2 possible resources at the White Sands Missile Range and a potential resource at Kings Bay, Georgia, were examined to determine the relative economics of substituting potential geothermal energy for part or all of the existing oil, gas, and electrical energy usage. Four of the military installations--Mountain Home, Norton, Hawthorne, and Sierra--appear to be co-located with possible geothermal resources which, if present, might provide substitute energy at or below current market prices for oil. Six additional locations--Ellsworth, Luke, Williams, Bliss, Fallon, and Twentynine Palms--could become economically attractive under certain conditions. These preliminary economic conclusions are based on central estimates of possible resources by location and do not reflect the consequences of a dry hole or discovery of resources less adequate than the central estimates. Weighted-average estimates of geothermal costs based on a range of potential resources, together with the cost of a total failure, would be important additional elements in any subsequent study of the more promising locations.

No geothermal resource was found to be economically competitive with natural gas at current controlled prices. Generation of electric power at the locations studied is estimated to be uneconomic at present because of two factors in particular: the relatively high cost of the expected geothermal energy, and the large mechanical inefficiencies in conversion of low-temperature, low-pressure geothermal energy into electricity. However, we must emphasize that these conclusions apply only to the locations we have studied and are based on the resource characterizations presented within the study.

# INTRODUCTION

The need to conserve oil became an increasingly important determinant of United States domestic energy policy during the 1970s. Oil embargoes, temporary disruption of oil imports, and curtailments of oil and LNG shipments into the United States repeatedly underscored the nation's vulnerability to interruptions of its energy supply. At times the interruptions were the result of wars involving Arab countries; at other times the supply disruptions were caused by OPEC decisions or the political or economic whims of a single foreign country. Collectively, world events gave rise to energy policy decisions in the United States to decontrol oil prices, assist development of synthetic fuels, encourage production of alternative fuels, and emphasize substitution of renewable energy resources for fossil fuels. As part of the fossil fuel conservation effort, the Energy Security Act (P.L. 96-294) required that geothermal energy be considered as a possible source of energy for new government facilities.

Military installations, both old and new, are attractive prospects for geothermal energy use, since they frequently require large quantities of energy within relatively small geographic areas. Large and areally-concentrated energy use is a critical factor in the economic feasibility of geothermal energy. A larger energy load permits more rapid recovery of the substantial capital outlay for the geothermal wells at a relatively lower cost per Btu to the user. Geographic concentration of the energy load minimizes surface piping and non-process heat losses, further enhancing the economics of geothermal utilization. Many older facilities use heat-extraction systems that can be adapted to an adequate geothermal source. New installations can be designed to accommodate an appropriate geothermal resource if one is present. Thus the geothermal potential at military installations merits examination from the standpoint of fossil fuel conservation and possible economic savings.

The Department of Defense (DOD) provided a list of 76 military installations and their current usages of fuel oil, natural gas, and electrical power (Appendix A) to the Department of Energy for identification of geothermal substitution potential. The list included the China Lake Naval Weapons Center (containing the Coso Hot Spring area) and the naval installation at Adak, Alaska. However, these two locations were excluded from the present study because geothermal activities are already under way there.

# ANALYTIC APPROACH

The identification and evaluation of co-located geothermal resources requires an analytic approach which integrates resource characteristics, appropriate engineering design, financial assumptions, capital requirements, operating costs, and load considerations. This study followed such an approach by designing a geothermal energy system to fit the geologic data and the anticipated energy load. The combined information was processed to yield system costs and a central estimate of geothermal energy economics without reflecting the cost effect of other outcomes, such as a dry hole. Where it appeared that use during the heating season would clearly be insufficient for economic backout of oil (and gas), a larger load was frequently hypothesized in order to help determine what fraction of the resource would have to be utilized to achieve economic substitution.

## Geologic Evaluation

Resource data were gathered primarily from published and unpublished work of state-coupled resource assessment teams in the appropriate states, U.S. Geological Survey Circular 790, and reports prepared by Dr. Carl Austin and his staff at the China Lake Naval Weapons Center (NWC).

The temperatures and depths estimated for the resources in the present study are inferred from measurements in nearby wells or from the geochemistry of nearby warm springs, and do not always agree with NWC's work. The variances are caused by a fundamental difference in definition of the data appropriate to the respective tasks rather than by different geologic interpretations. The NWC reports are written from the explorationist's viewpoint and are projections of what might, and in some cases probably does, occur at depth. Gruy Federal's analysis takes a considerably more conservative approach, reflecting resources that have been found near the installations. Although there is no guarantee that similar resources will be found on an installation, the data do represent actual local conditions, and there is a reasonable probability that resources at the temperature specified will be found at the projected depth. In most cases, our estimates do not preclude the possibility that higher-temperature resources may be found at similar or greater depths than those presented.

The other major variable in the determination of resource energy potential is the productive capacity of geothermal wells. Flow rates were estimated, where possible, using flow rates in nearby wells. However, these data are often poorly measured and may not accurately predict long-term sustainable flow rates. In many instances the recorded flow rates are from wells considerably shallower than projected geothermal production wells. Many of the DOD installations are in the Basin and Range Province or structurally similar areas where geothermal production is closely linked to fracture permeability. In such instances, production rates vary widely and adequate production depends heavily upon penetration of a fracture zone by the wellbore. In other areas, such as the Atlantic Coastal Plain and the Balcones area of Texas, permeability is known to vary laterally within a given formation, and therefore site-specific flow rates are only best estimates.

For many installations, calculations were made using several flow rates so that the reader might judge the economic effect of the uncertainty in flow rate. Only additional geologic-hydrologic studies at specific installations will allow better estimates of flow rate and more precise economic evaluations.

## Economic Evaluation

Previous work in geothermal economics has convinced us that a direct-use process should be characterized as the combination of various engineering functions: production of the geothermal fluid, its transmission to an application site, extraction of the heat for some direct use, transmission of the fluid to a reinjection site, and reinjection into a suitable formation (Fig. 1). This approach facilitates the design of a sound and internally consistent geothermal system on a modular basis. The economics of that system and its component modules can then be developed by costing the equipment and calculating the value that must be assigned to the geothermal energy to cover the costs of running the entire system. Since the economic information is developed for each module and summed to give system totals, it is possible to identify the high-cost modules, which then become prime targets for cost cutting in subsequent refinement of the system. The resulting composite value of geothermal energy can be compared to corresponding values for other energy sources to determine the most economic resource. This conceptual approach was used in the present study.

Gruy Federal's Geodec (geothermal design and economics) model[1] provides engineering design and economics data for each module and for the total system, as described above. Geodec consists of separate models of the various engineering functions in a geothermal extraction system, plus an economics model (Fig. 2). Appendix B, taken from volume I of the study referenced above, describes the model in detail.

Each engineering module in Geodec designs and costs particular pieces of equipment based on certain process information. The economics model calculates the "arm's-length" cost of geothermal energy to a process as a revenue term divided by an energy use term, typically dollars per million Btu. The revenue term includes revenue necessary to cover the cost of installed equipment, operating costs, and debt service (given a debt/equity ratio), plus revenue to provide some specified internal rate of return on equity. The energy-use term is calculated on three bases: (1) utilization in the process of all the energy theoretically available from thermodynamic considerations; (2) actual energy utilization in the process, annualized; and (3) actual energy utilization during the operating hours required by the use. "Energy theoretically available" is calculated as the enthalpy change in the geothermal fluid between wellhead conditions and a theoretical sink temperature (assumed to be 80°F); "actual energy utilization" is taken directly from load data provided by the client, subject to design, resource, and seasonal constraints. Actual utilization may then have been increased, as

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[1]Developed under DOE contract ET-78C-03-2072 for "A Geothermal Direct Use Economic and Engineering Study Integration," report submitted August 1979.

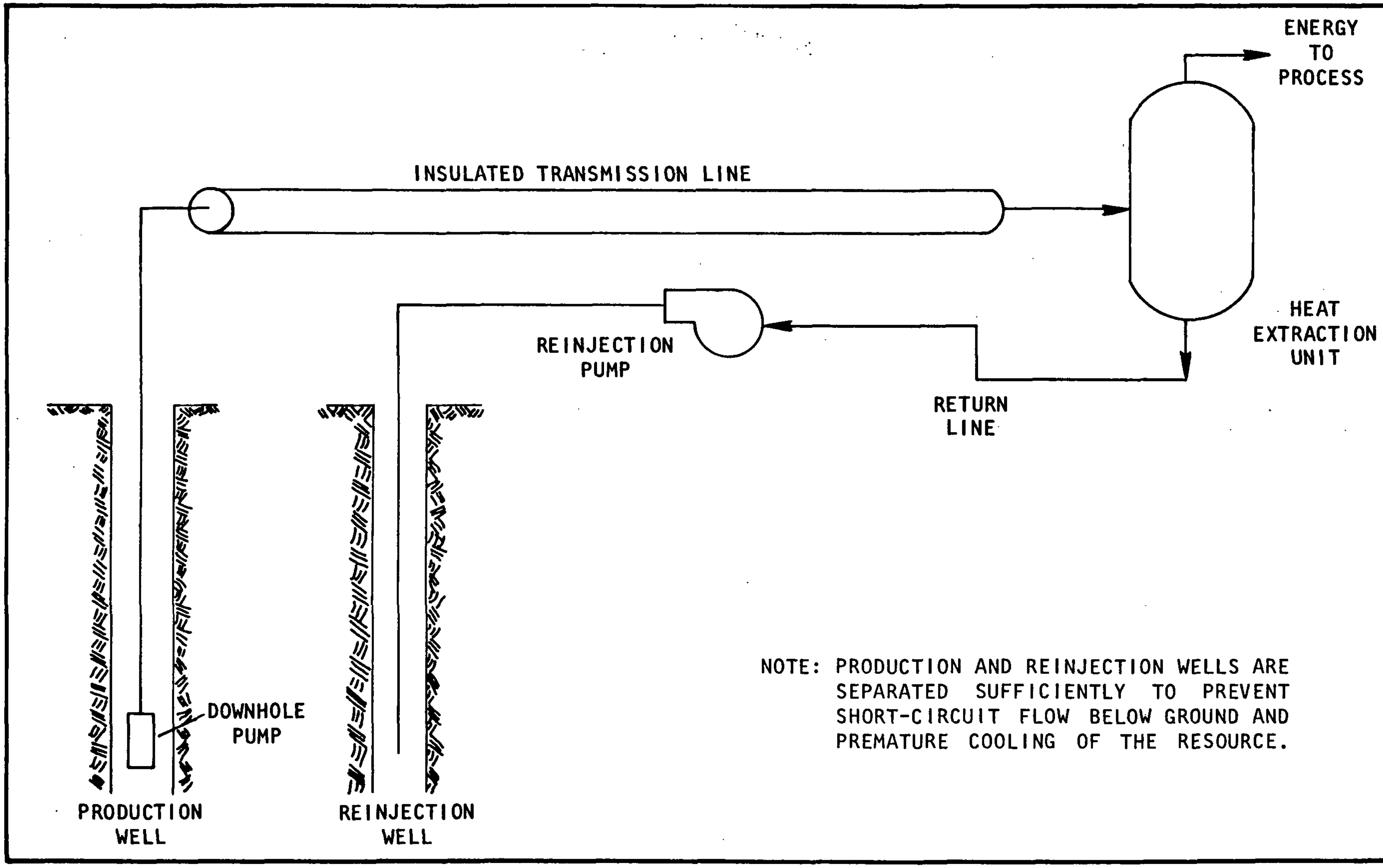


Figure 1.--Geothermal direct use energy system.

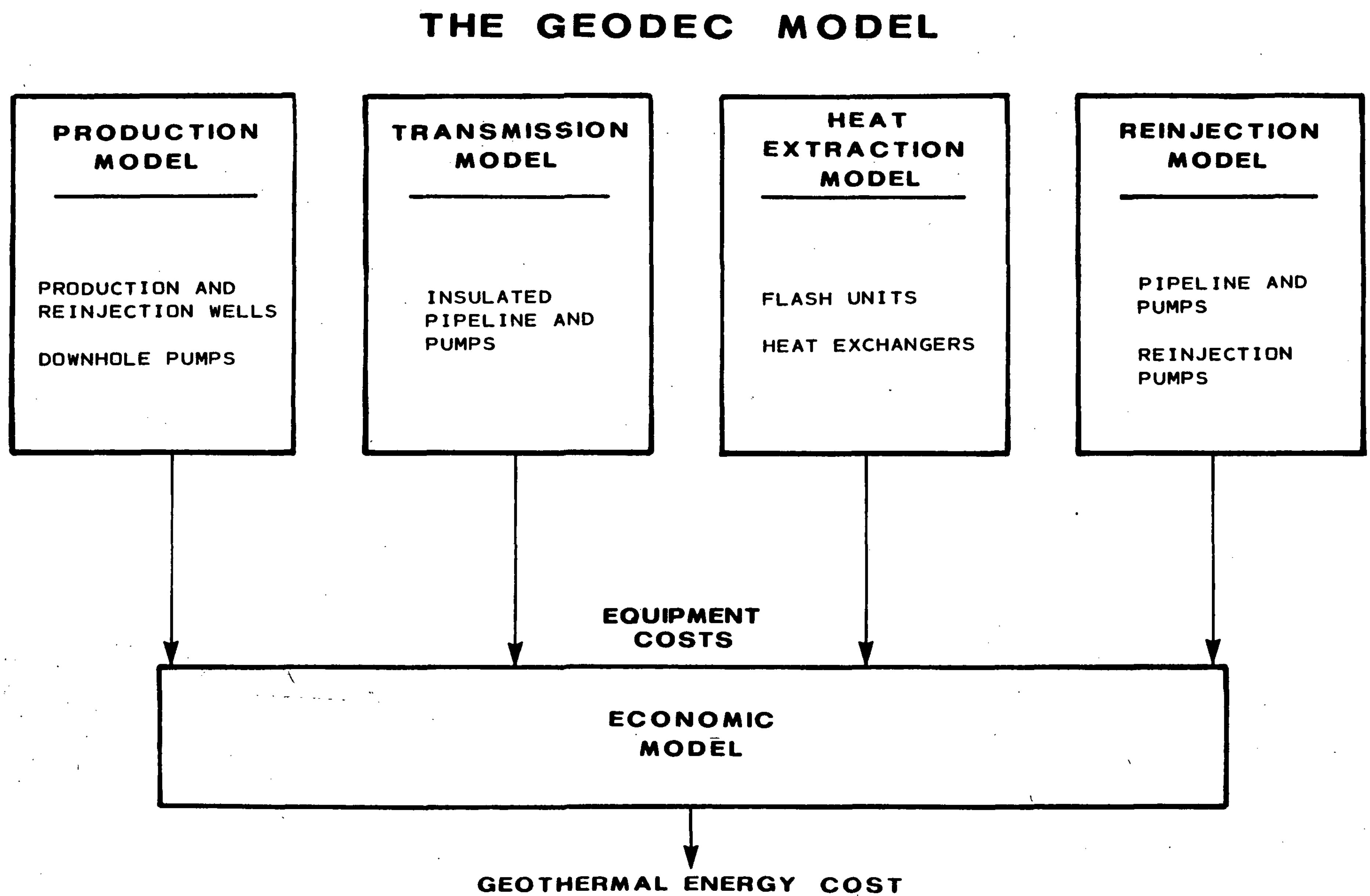


Figure 2.--Block diagram of the Geodec model.

suggested at the beginning of this section, if the DOD load data for the heating season would produce clearly uneconomic geothermal costs.

The Geodec model requires relatively limited geologic, financial, and engineering inputs. The geologic inputs, however, are particularly critical. They include well depth, well flow rate, wellhead temperature, bottomhole pressure, aquifer thickness, and formation permeability. These data, along with the number of production and reinjection wells and various engineering and financial specifications, are the basis for calculating equipment costs and geothermal energy value for the three alternative loads described in the preceding paragraph.

Comparison of the geothermal energy cost for a specific installation with the cost of fuels that could be displaced helps to identify the economically preferable energy source. Other factors, such as total capital or indirect substitition or a policy to conserve natural gas for future, higher-value residential use, could override the more obvious economic conclusion for a particular installation. However, the comparison of present economics governs in this study.

Before proceeding further, a discussion of well costs is necessary. The Geodec well cost model allows manipulation of the percentage of hard rock to be encountered during drilling. However, the percentage to be used for a region--let alone a specific location--is uncertain; therefore Geodec's well cost estimates were compared to those from other models. Many different well-cost models are available; for this study, three were used to develop approximations of well capital costs for preliminary screening economics.

Well costs vary substantially, depending on the difficulty of drilling (e.g., fraction of hard rock, sand cave-in), complexity of well completion (e.g., aquifer isolation, gravel packing, rock fracturing), and mobilization costs. These factors tend to make well costs per foot higher in the eastern United States than in the west, for depths less than 5,000 feet. Eastern drilling experience has confirmed a clear need for separate modeling of costs consistent with greater mobilization costs and drilling and completion conditions unique to the east. The present study approximates well costs in the eastern U.S. according to the following formula, developed by Herron[2] for estimating the cost of a single-production-well/single-disposal-well geothermal system:

$$\text{Cost (1980 dollars)} = \$380{,}000 + (\$110/\text{ft} \times \text{production depth}) + (\$85/\text{ft} \times \text{disposal depth}).$$

Western drilling costs were approximated for various depths using the Geodec model and the well-cost model from EG&G Idaho's geothermal space heating cost-simulation model (Appendix C). Geodec's well costs were consistently below those generated by the EG&G model if Geodec assumed zero percent hard

[2]Herron, E. H., "Estimating Geothermal Energy Costs in the Eastern United States," ASHRAE Transactions, 1981, v. 87, part 1.

rock; however, if Geodec assumed a substantial proportion of hard rock, its well cost estimate approached that of the EG&G model. Since the EG&G cost correlation was developed for western geothermal wells, it obviously reflects an average percentage of hard rock and average completion complexity for that region. Hence for depths of 7,000 feet or less, we used the EG&G model with smoothing at points of discontinuity. For depths greater than 7,000 feet, we decided subjectively to damp the severe cost acceleration in the EG&G model down to the slope of the Geodec estimate.

The different well-cost curves are shown in Fig. 3. Capital costs for eastern wells exceed the EG&G Idaho estimates for western wells to a depth of 5,300 feet. At shallow depths the EG&G capital estimate is close to that given by Geodec; as depth increases, the EG&G estimate rises more sharply, diverging substantially from Geodec's estimate. Our subjective modification of the EG&G cost curve is shown as a dashed line departing from the EG&G curve at 7,000 feet with a slope similar to that given by the Geodec model.

## Alternative Energy Costs

The geothermal economic data output from the study must be compared to non-geothermal energy data as part of the preliminary evaluation of possible geothermal resources. Areas with currently competitive or marginal geothermal possibilities should be ranked for followup study, including resource confirmation and feasibility analysis as appropriate. Those locations with apparently uneconomic geothermal resources would be referred to DOD for final engineering review to ensure that no possibility for geothermal application has been overlooked.

Comparative costs per million Btu for natural gas, oil, and electric power have been approximated.[3] Those energy costs were updated to reflect market prices of oil (FOB New York harbor barge) and natural gas and electricity costs consistent with those reported by DOE in January 1981.[4] The Btu cost data are net of conversion efficiencies of 75 percent for natural gas, 70 percent for fuel oil, and 100 percent for electricity. The cost data are shown below.

Non-Geothermal Energy Costs

| Source | EG&G estimate 9/80 Cost per $10^6$ Btu | EG&G estimate 9/80 Resource cost | January 1981 costs Resource cost | January 1981 costs Cost per $10^6$ Btu |
|---|---|---|---|---|
| Natural gas | $ 4.67 | $0.35/therm | $ 0.24/therm | $ 3.20 |
| Oil | 8.86 | 0.90/gal | 1.03/gal | 10.14 |
| Electricity | 10.25 | 0.035/kwh | 0.040/kwh | 11.71 |

3 EG&G Idaho, "Rules of Thumb for Geothermal Direct Applications," published for U.S. Department of Energy under contract DE-AC07-76ID01570.

4 Monthly Energy Review, January 1981, U.S. Department of Energy, DOE/EIA 0035 (81/01).

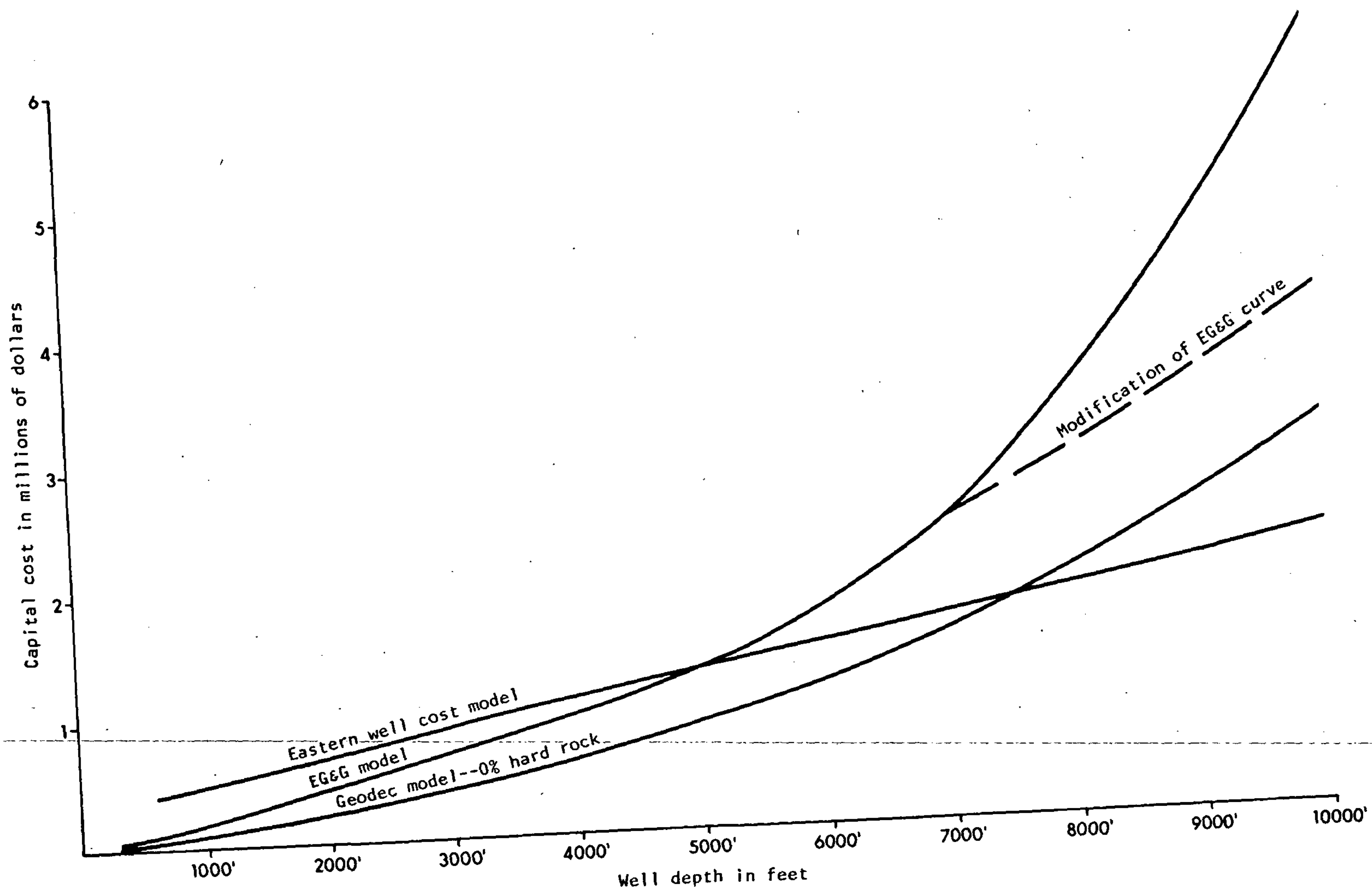


Figure 3.--Capital costs for pairs of wells.

The last column in the table shows the cost per million Btu that was used in the economic screening in this study.

The development of geothermal electric power costs requires three principal elements: a geothermal energy cost per million Btu (such as Geodec calculates), an adjustment factor for the very large process inefficiencies of mechanical conversion from geothermal energy to electricity, and an approximate cost per million Btu of an operating electric-power generation module. The geothermal energy cost calculated by Geodec assumes a 100 percent efficient energy extraction. Division of that cost by the fraction of available energy actually converted into electric power produces a cost value for the geothermal component of the electricity. Addition of the prorated cost of the power plant and its operation to the efficiency-adjusted geothermal component provides a very crude approximation of the total cost of the geothermal-source electricity. The relatively high temperature requirement will exclude most installations in this study from electric-power feasibility analysis.

The rough cost and efficiency data shown in Table 1 for electric generation modules were used to calculate the geothermal-source electric power costs. The module is sized according to binary isobutane cycle efficiency data published by Kestin[5] for geothermal conversion to electricity. The net conversion efficiency is obtained by dividing the net electric energy from the power-generation module by the maximum energy available from the wells; it is shown on the last line of Table 1. The low conversion efficiency (3.6 to 6.9 percent) is characteristic of processes that attempt to convert low-temperature heat to mechanical power. The capital cost per kilowatt capacity and the operating cost per kilowatt-hour are from Milora and Tester.[6] The cost of the power plant and its operation is about $2.72 per million Btu of net output for the alternatives presented, assuming the plant runs all year long with operating costs of $0.0013 per kWh.

The resulting comparison of economic information from each location with the economic screens will provide guidance regarding the desirability of geothermal development at the locations considered. The use of the words "potential" and "possible" throughout the analysis is intentional; they are intended to be a constant reminder of the uncertainty attending the estimated geologic data. The engineering design and economic analysis tend to convey a certainty regarding the existence of the estimated resource. If the economic data were converted to expected values through application of probabilities to the economic outcomes, the geothermal costs per million Btu identified for each resource in this study probably would rise and thus be less competitive with existing energy sources than is suggested by the comparative data.

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[5]Kestin, Joseph, ed., Sourcebook on the Production of Electricity from Geothermal Energy: Washington, U.S. Department of Energy, 1980, p. 702.

[6]Milora, Stanley L., and Tester, Jefferson W., Geothermal Energy as a Source of Electric Power: Cambridge, Mass., MIT Press, 1976, p. 117.

TABLE 1.--Cost of electric power generation module for various wellhead temperatures and flow rates.

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| <u>Assumed geothermal resource</u>: | | | | | | |
| Wellhead temperature, °F | 257 | 284 | 284 | 302 | 345 | 345 |
| Reinjection temperature, °F | 77 | 77 | 77 | 77 | 77 | 77 |
| Well flow rate, thousand lb/hr | 500 | 500 | 232 | 500 | 500 | 224 |
| Available energy: | | | | | | |
| Maximum, MBtu/hr | 90 | 103.5 | 48 | 112.5 | 134 | 59.9 |
| MW(t) | 26.5 | 30.3 | 14.1 | 33.2 | 39.3 | 17.6 |
| Conversion efficiency, percent | 4.5 | 5.7 | 5.7 | 6.5 | 8.3 | 8.3 |
| Electric energy, gross, MW(e) | 1.20 | 1.74 | 0.81 | 2.16 | 3.27 | 1.46 |
| <u>Power generation module</u>: | | | | | | |
| Gross electric energy, MW(e) | 1.2 | 1.74 | 0.81 | 2.16 | 3.27 | 1.46 |
| Net electric energy, MW(e) | 0.96 | 1.44 | 0.67 | 1.80 | 2.70 | 1.21 |
| MBtu/hr | 3.3 | 4.9 | 2.3 | 6.2 | 9.2 | 4.1 |
| Gross capacity, MW(e) | 1.2 | 1.74 | 0.81 | 2.16 | 3.27 | 1.46 |
| Plant cost (@ $500/kW), thousands | $600 | $870 | $405 | $1080 | $1635 | $730 |
| Capital recovery factor (20 yr @ 10%) | 0.11195 | 0.11195 | 0.11195 | 0.11195 | 0.11195 | 0.11195 |
| Electric energy value | | | | | | |
| Annual capital recovery, thousands | $67.2 | $ 97.4 | $45.3 | $120.9 | $183.0 | $81.7 |
| Operating & maintenance @ $0.0013/kWh, thousands | $13.7 | $ 19.8 | $ 9.2 | $ 24.6 | $ 37.3 | $16.6 |
| Total value, thousands | $80.9 | $117.2 | $54.5 | $145.5 | $220.3 | $98.3 |
| Value per MWh(e) (net) | $9.61 | $9.28 | $9.28 | $9.22 | $9.31 | $9.27 |
| Value per million Btu | $2.82 | $2.72 | $2.72 | $2.70 | $2.73 | $2.72 |
| <u>Geothermal conversion efficiency, percent</u> | 3.6 | 4.8 | 4.8 | 5.4 | 6.9 | 6.9 |

# GEOTHERMAL POTENTIAL

## Geothermal Systems Assumptions

The economic assessment of the potential geothermal sites required that the general geothermal system discussed in the preceding section be made specific. The geologic estimates were processed through a relatively constant geothermal system which was designed for the estimated geologic values and thus was sized to the flow rate and required temperature drop. The flow rate was not adjusted to provide a more economic fluid flow and geothermal system; instead it was assumed that the estimated resource was produced and then used to the extent feasible.

For the sites considered in this study, the following geothermal system was assumed:

a) Production well and downhole pump

One well (20-year life)
Pump (10-year life) delivers flow at 14.7 psia or higher

b) Insulated transmission line and pumps

Insulated pipe sized to mass flow (20-year life)
Pumps (10-year life) to maintain pressure and 10 ft/sec velocity

c) Heat extraction

Heat exchanger (20-year life) for space heating and/or domestic hot water

d) Return pipeline and pumps

Pipeline (20-year life) sized to mass flow, usually not insulated
Pumps (10-year life) to maintain pressure and 10 ft/sec velocity

e) Reinjection well and pump

One well (20-year life)
Pump (10-year life) sized to required reinjection pressure.

Other design assumptions that apply to the geothermal energy systems modeled in this study are:

a) Transmission of fluid

Supply pipeline is buried and has 2-in. insulation. The buried return line usually has no insulation. Supply and return lines are level and are fabricated of cast steel. Each line is usually one mile long.

b) Heat extraction

Heat exchange is either water-to-water (carbon steel shell-and-tube) or water-to-air (air heater). Capacity is usually determined by the temperature of the brine inflow and the assumed reinjection temperature (usually 80° to 90°F). No brine flashing is assumed because of the low temperatures and pressures usually encountered.

c) Reinjection

All geothermal fluid is returned to the aquifer at the depth from which it was produced. Reinjection temperature usually is between 80° and 90°F unless substantial excess heat-exchange capacity results. Reinjection pumps are cast steel.

d) Geologic inputs

Bottomhole static pressure is derived from hydrostatic gradient (0.43 psi/ft).

Drilling difficulty is assumed to be average for the west and for the Atlantic Coastal Plain.

e) Financial parameters

Electricity for pumping costs $0.04/kWh.

Tax and interest rates are zero.

Capital cost is 100 percent "equity" financed with a 10 percent internal rate of return.

Labor and maintenance expense is estimated at 10 percent of capital throughout the system except for the surface pipeline, which is calculated at 4 percent.

## Precision of Estimates

Several geologic and economic factors that are integral to the analysis are subject to substantial variation from the values used. An attempt was made to identify the more likely geologic conditions and related economics. Although the resulting data have been committed to paper, there is a significant probability that the resource conditions may fall short of our estimates, making the economics worse than presented. To provide a feeling for the economic sensitivity to variations in the resource and load for a location, multiple scenarios are presented for each of 18 locations. Only one scenario was prepared for each of the remaining three locations. In each instance the geothermal energy costs are rough estimates, although they do reflect sound engineering principles and the best estimate available for the variables involved.

Other considerations also tend to limit the precision of the estimates and their comparisons to current energy load costs:

a) Concentration of use has been assumed, with a central heat exchanger and limited surface piping.

b) Costs include a heat exchanger (water-to-water or water-to-air) but no other retrofit provisions.

c) Gas prices are assumed to be controlled over the next several years.

d) Geothermal substitution for gas is assumed to occur only if it is directly economic. Gas is not "stored" for later use.

e) Fuel oil was assumed to be used solely for space heating and domestic hot water, whereas natural gas use was assumed to include cooking as well.

These assumptions permitted development of our "ballpark" economics. Locations suggested by this study to have geothermal possibilities would have to be reviewed to refine these and other assumptions in subsequent feasibility work.

Geothermal Economics Summary

For each location possibly co-located with a geothermal resource, the information in this section is presented at two levels of detail. Although the more general summary is presented first, the reader is urged to review and understand the more detailed discussion for a given location before using the information. The detail and related discussion will familiarize the reader with the geothermal system assumed, the energy load reflected, and our evaluation of the geothermal potential for the site.

A general summary of geologic and economic information by installation is presented in Table 2. The last two columns present geothermal energy costs encompassing the resource, engineering design, and two utilization levels. These geothermal costs are then compared to the economic criteria developed above to indentify locations where substitution is potentially economic. The approximate equivalent costs per million Btu for oil and gas are estimated to be $10.14 (at 70 percent efficiency) and $3.20 (at 75 percent efficiency), respectively. The electricity cost comparison is difficult to generalize and will be dealt with in the more detailed discussions by location (no location appears promising for geothermal generation of electricity) as appropriate.

TABLE 2.--Summary of resources and economics.

| Location | Resource | | | Actual energy load, $10^9$ Btu | | | Possible geothermal energy | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Load | | | Theoretical minimum cost per $10^6$ Btu |
| | Temp., °F | Depth, ft | Flow, gal/min | Electric | Fuel oil | Gas | Size, $10^9$ Btu | % of design | Cost per $10^6$ Btu | |
| **AIR FORCE** | | | | | | | | | | |
| Bergstrom AFB, Texas | 95 | 2,100 | 400 | 555 | 1 | 182 | 1 | 5 | $ 490.83 | $ 18.75 |
| Brooks AFB, Texas | | | | | | | | | | |
| (a) | 104 | 1,575 | 400 | 360 | | 230 | 23 | 100 | 24.54 | 11.90 |
| (b) | 104 | 1,575 | 200 | 360 | | 230 | 10 | 95 | 30.14 | 16.73 |
| Davis-Monthan AFB, Arizona | | | | | | | | | | |
| (a) | 194 | 7,000 | 750 | 911 | 3 | 247 | 162 | 67 | 10.96 | 4.91 |
| (b) | 194 | 7,000 | 500 | 911 | 3 | 247 | 108 | 69 | 13.31 | 5.96 |
| (c) | 284 | 10,000 | 750 | 911 | 3 | 247 | 250 | 91 | 7.54 | 2.99 |
| (d) | 284 | 10,000 | 500 | 911 | 3 | 247 | 167 | 96 | 10.06 | 3.99 |
| (e) | 284 | 10,000 | 500 | 911 | 3 | 247 | 246 | 100 | 6.64 | |
| Ellsworth AFB, South Dakota | 120 | 4,400 | 400 | 873 | 56 | 706 | 24 | 40 | 18.72 | 7.82 |
| Kelly AFB, Texas | | | | | | | | | | |
| (a) | 138 | 3,000 | 400 | 1,924 | | 687 | 10 | 12 | 57.01 | 5.91 |
| (b) | 138 | 3,000 | 200 | 1,924 | | 687 | 10 | 25 | 40.31 | 8.35 |
| Lackland AFB, Texas | | | | | | | | | | |
| (a) | 138 | 3,000 | 400 | 1,410 | 3 | 523 | 10 | 12 | 57.01 | 5.91 |
| (b) | 138 | 3,000 | 200 | 1,410 | 3 | 523 | 10 | 25 | 40.31 | 8.35 |
| Luke AFB, Arizona | | | | | | | | | | |
| (a) | 104 | 600 | 1,000 | 838 | 23 | 241 | 59 | 80 | 7.54 | 4.96 |
| (b) | 104 | 600 | 500 | 838 | 23 | 241 | 30 | 81 | 11.08 | 7.41 |
| Mountain Home AFB, Idaho | | | | | | | | | | |
| (a) | 150 | 3,400 | 1,000 | 596 | 126 | 44 | 114 | 40 | 4.57 | 2.07 |
| (b) | 150 | 3,400 | 400 | 596 | 126 | 44 | 45 | 40 | 8.92 | 3.83 |
| Norton AFB, California | | | | | | | | | | |
| (a) | 130 | 400 | 1,100 | 774 | 112 | 193 | 100 | 46 | 3.20 | 1.71 |
| (b) | 130 | 400 | 300 | 774 | 112 | 193 | 27 | 46 | 7.01 | 3.54 |
| Randolph AFB, Texas | | | | | | | | | | |
| (a) | 138 | 3,000 | 400 | 834 | | 244 | 10 | 12 | 57.01 | 5.91 |
| (b) | 138 | 3,000 | 200 | 834 | | 244 | 10 | 25 | 40.31 | 8.35 |
| Williams AFB, Arizona | | | | | | | | | | |
| (a) | 345 | 10,000 | 4,000 | 572 | | 140 | 572 | 26 | 9.16 | 1.24 |
| (b) | 345 | 10,000 | 1,000 | 572 | | 140 | 572 | 100 | 2.96 | 1.60 |
| (c) | 345 | 10,000 | 500 | 572 | | 140 | 269 | 100 | 4.90 | 2.69 |

TABLE 2.--Summary of resources and economics (continued).

| Location | Resource | | | Actual energy load, $10^9$ Btu | | | Possible geothermal energy | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Load | | | Theoretical minimum cost per $10^6$ Btu |
| | Temp., °F | Depth, ft | Flow, gal/min | Elec- tric | Fuel oil | Gas | Size, $10^9$ Btu | % of design | Cost per $10^6$ Btu | |
| **ARMY** | | | | | | | | | | |
| Ft. Bliss, Texas | | | | | | | | | | |
| (a) | 160 | 500 | 100 | 459 | 45 | 1,538 | 8 | 100 | $ 70.20 | $ 16.03 |
| (b) | 160 | 600 | 500 | 459 | 45 | 1,538 | 45 | 33 | 17.66 | 4.71 |
| Ft. Sam Houston, Texas | | | | | | | | | | |
| (a) | 138 | 3,000 | 400 | 365 | 8 | 560 | 10 | 12 | 57.01 | 5.91 |
| (b) | 138 | 3,000 | 200 | 365 | 8 | 560 | 10 | 25 | 40.31 | 8.35 |
| Hawthorne Ammunition Depot, Nevada | | | | | | | | | | |
| (a) | 125 | 1,000 | 700 | 41 | 249 | 31 | 41 | 40 | 7.02 | 2.59 |
| (b) | 125 | 1,000 | 300 | 41 | 249 | 31 | 18 | 41 | 13.00 | 4.72 |
| (c) | 210 | 1,000 | 700 | 41 | 249 | 31 | 137 | 40 | 2.26 | 0.94 |
| (d) | 210 | 1,000 | 300 | 41 | 249 | 31 | 59 | 41 | 4.10 | 1.69 |
| Sierra Army Depot, California | 240 | 4,000 | 500 | 32 | 65 | 20 | 65 | 22 | 8.45 | 1.92 |
| **NAVY** | | | | | | | | | | |
| Dallas NAS, Texas | | | | | | | | | | |
| (a) | 100 | 1,950 | 200 | 60 | | 71 | 13 | 100 | 23.09 | 17.32 |
| (b) | 90 | 1,050 | 200 | 60 | | 71 | 7 | 100 | 35.51 | 26.99 |
| Fallon NAS, Nevada | | | | | | | | | | |
| (a) | 131 | 1,700 | 300 | 45 | 100 | 30 | 23 | 46 | 16.14 | 6.90 |
| (b) | 160 | 1,700 | 300 | 45 | 100 | 30 | 17 | 46 | 51.86 | 9.90 |
| Twentynine Palms Marine Base, Calif. | | | | | | | | | | |
| (a) | 145 | 300 | 1,000 | 153 | 120 | 174 | 194 | 100 | 5.67 | 4.06 |
| (b) | 145 | 300 | 200 | 153 | 120 | 174 | 39 | 100 | 18.51 | 12.63 |
| **ATLANTIC COASTAL PLAIN** | | | | | | | | | | |
| (a) | 125 | 4,300 | 300 | 2 to 1000+ | none to 1000+ | none to 300 | 17 | 40 | 26.78 | 8.99 |
| (b) | 125 | 4,300 | 500 | | | | 28 | 40 | 19.01 | 6.62 |
| (c) | 115 | 3,750 | 300 | | | | 12 | 40 | 36.11 | 11.26 |
| (d) | 115 | 3,750 | 500 | | | | 21 | 40 | 24.67 | 8.34 |
| **WHITE SANDS, NEW MEXICO** | | | | | | | | | | |
| (a) | 198 | 6,000 | 500 | | | 152 | 152 | 100 | 7.21 | 4.39 |
| (b) | 194 | 1,500 | 500 | | | 152 | 59 | 100 | 59.43 | 14.65 |
| **KINGS BAY, GEORGIA** | | | | | | | | | | |
| (a) | 126 | 4,600 | 500 | | | | 11 | 13 | 49.49 | 6.99 |
| (b) | 126 | 4,600 | 500 | | | | 11 | 13 | 46.55 | 6.39 |

Table 2 suggests the following division of the locations according to the attractiveness of geothermal economics:

| Location | Geothermal economic potential | | | Potential backout | Size basis |
| --- | --- | --- | --- | --- | --- |
| | Good | Marginal | None | | |
| Mountain Home | X | | | oil | Heating season |
| Norton | X | | | oil | Heating season |
| Hawthorne | X | | | oil | See discussion |
| Sierra | X | | | oil | Shallower wells? or added uses? |
| Luke | | X | | oil/gas | Oil & some gas |
| Williams | | ? | | electric? | See discussion |
| Ft. Bliss | | ? | | oil/gas | See discussion |
| Ellsworth | | X | | oil | Use all year |
| Fallon | | X | | oil | Use all year? |
| Twentynine Palms | | X | | oil/gas | Use all year? |
| Bergstrom | | | X | | |
| Brooks | | | X | | |
| Davis Monthan | | | X | | |
| Kelly | | | X | | |
| Lackland | | | X | | |
| Ft. Sam Houston | | | X | | |
| Randolph | | | X | | |
| Dallas | | | X | | |
| Atlantic Coastal Plain | | | X | | |
| White Sands | | | X | | |
| Kings Bay | | | X | | |

## DISCUSSION BY LOCATION

Summaries of the resource, design, capital, load, and economics for each location are provided in this section, together with brief discussions of geothermal substitution potential. The discussions focus on the cost of potential geothermal energy per million Btu compared to the cost of current energy use.

The summary page for each location (see Table 3) is in three sections. The first section summarizes the estimated resource; assumptions of bottomhole pressure, permeability, and aquifer thickness are noted. Since thickness and permeability are multiplied together to calculate transmissivity, the data shown represents only one of numerous possible data pairs.

The geothermal system design, capital costs, and energy load are sketched in the second block of information. Capital costs are shown separately for wells, downhole pump, surface pipelines and related pumps, heat exchanger, and reinjection pump. The temperature drop assumed for the brine at the heat exchanger is identified; it usually is intended to result in reinjection at 80° to 90°F. The energy use is presented as an operating load, usually constrained by current oil or gas fuel use or seasonal operating hours. In some instances a year-round load on low-temperature resources was assumed as a possible domestic hot water application. For one location the geothermal energy load is double and quadruple the natural gas usage in an attempt to measure electric generation possibilities, given the apparent uncompetitiveness with natural gas.

The third block of information contains economic data broken down to facilitate further engineering manipulation of the design and economics.

The total capital is the sum of the capital identified within the geothermal system summary. The matrix of energy cost per million Btu identifies the costs of producing the energy from the aquifer, piping the brine above ground and extracting the heat, and reinjecting the brine at its original depth, as well as the total of these costs. (Cost is defined earlier, in the section on economic analytic approach, pp. 4-8.) The three energy-use levels for which these geothermal costs are calculated are (1) the estimated actual load for the operating period specified, (2) the energy available from annualized well flow for the identified heat-exchanger temperature drop, and (3) the energy available from this annualized well flow for the temperature drop between the wellhead and an 80°F sink with no heat losses in transmission. This last condition is attainable only where the resource is almost directly under the application site.

# Table 3

## Geothermal Characteristics and Economics

**Resource Characteristics:**

| | |
|---|---|
| Temperature | Flow Rate |
| Depth | Aquifer Thickness |
| Percent Hard Rock | Permeability |
| | Static Downhole Pressure (psia) |

**Geothermal System**

*Wells:*

| | | |
|---|---|---|
| Production Wells | 1 | Well Diameter |
| Reinjection Wells | 1 | Well Capital ($000s) |

*Downhole Pump:*

| | |
|---|---|
| Surface Delivery Pressure (psia) | Pump Capital ($000s) |

*Surface Transmission:*

| | |
|---|---|
| Supply Pipe Length | Return Pipe Length |
| Supply Pipe Capital ($000s) | Return Pipe Capital ($000s) |
| Supply Pump Capital ($000s) | Return Pump Capital ($000s) |

*Heat Exchanger:*

| | |
|---|---|
| Supply Temperature | Exchanger Capital ($000s) |
| Return Temperature | |

*Reinjection Pump:*

| | |
|---|---|
| Reinjection Temperature | Bottomhole Dynamic Pressure (psia) |
| Reinjection Pressure (psia) | Pump Capital ($000s) |

*Energy Use:*

| | |
|---|---|
| Load ($10^9$ BTUs) | Load % of Available BTUs |
| Operating Hours (% of year) | Load % of Design BTUs |

**Economics:**

Total Capital ($000s)

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | | | | |
| Design | | | | |
| Actual | | | | |

## Bergstrom AFB, Brooks AFB, Ft. Sam Houston, Kelly AFB, Lackland AFB, Randolph AFB, and Dallas NAS, Texas

### Geology

These DOD installations are located near Austin, San Antonio, and Dallas, Texas, along a zone of thermal water associated with the Balcones and Luling-Mexia-Talco Fault Zones. Some use of the geothermal fluids is already being made at Corsicana and Marlin, Texas.

The geothermal resources in this region of Texas and at several of the military installations are under investigation by a group headed by Dr. Charles Woodruff, Jr., at the Bureau of Economic Geology of the University of Texas at Austin. Temperatures and depths used in this economic evaluation are taken directly from that study. The flow rates used here are estimates based on limited data available to Woodruff and his coworkers; the extrapolation of those data to this study is entirely the responsibility of the present authors. Local variations of flow rate in the area under investigation are such that the flow rates used in this study are only educated guesses.

The temperatures and depths of assumed geothermal fluids and the formations in which they occur for these installations are:

| Base | Temp. | Depth | Formation |
|---|---|---|---|
| Bergstrom AFB | 95°F | 2,100 ft | Hosston-Trinity |
| Brooks AFB | 104 | 1,575 | Edwards |
| | *138 | 3,000 | Hosston-Trinity |
| Ft. Sam Houston | 80 | 500 | Edwards |
| | *138 | 3,000 | Hosston-Trinity |
| Kelly AFB | 80 | 1,200 | Edwards |
| | *138 | 3,000 | Hosston-Trinity |
| Lackland AFB | 80 | 1,100 | Edwards |
| | *138 | 3,000 | Hosston-Trinity |
| Randolph AFB | 80 | 500 | Edwards |
| | *138 | 3,000 | Hosston-Trinity |
| Dallas NAS | 90 | 1,050 | Paluxy |
| | 100 | 1,950 | Hosston-Trinity |

Fluid temperatures in the Edwards are generally too low for utilization, and economic evaluations were not conducted except at Brooks AFB. Temperatures in and depths to the Hosston-Trinity at Brooks, Ft. Sam Houston, Kelly, and Randolph are estimated to be the same as those predicted for Lackland (denoted in the table by an asterisk). Thus the Lackland economic evaluation provides an estimate of the economics of geothermal utilization at all five San Antonio bases.

Only limited data are available on which to base estimates of the flow rate at any of these installations; therefore flow rates of 200 and 400 gal/min were used as appropriate in the economic evaluations. Brooks and Lackland economics were calculated for both flow rates to identify the financial sensitivity to flow rate.

## Economic Evaluation

Bergstrom (Table 4) has a relatively low-temperature resource which is not very deep and likely is a short distance from the potential use. However, despite the low capital cost, insufficient geothermal energy is available to generate competitive economics. Even if the resource were used down to a sink temperature of 80°F, the economics would remain unattractive ($18.75 per million Btu) by comparison with foreseeable energy costs.

Groundwater heat pumps may merit consideration.

Brooks (Tables 5 and 6) may have a 104°F resource at relatively shallow depth, but the flow rate is small. Although the resource is assumed to be large and the capital cost is low, utilization to a sink temperature of 80°F would result in a geothermal cost of $16.73 to $11.90 per million Btu, which is clearly uncompetitive with natural gas (no significant oil use).

Lackland (Tables 7 and 8) uses large amounts of gas and electrical energy but little oil. Thus, even if all the resource were used from 138°F down to 80°F, the economics do not favor substitution.

Ft. Sam Houston, Kelly AFB, and Randolph AFB (Tables 7 and 8) offer fuel-oil backout targets that are too small to permit economic substitution of geothermal energy. The potential resource would have to be utilized down to a sink temperature of 80°F almost all year to be competitive with oil. Full utilization for only six months (November through April) would result in geothermal costs in the range of $12.25 to $21 per million Btu compared to $10.14 for oil.

Dallas NAS (Tables 9 and 10) clearly does not offer backout potential since it uses only natural gas and electric power. The Dallas geothermal potential, assuming year-round use, is not competitive with oil, let alone gas and electricity.

## Reference

Woodruff, C. M., Jr., and McBride, N. W., 1979, Regional assessment of geothermal potential along the Balcones and Luling-Mexia-Talco Fault Zones, central Texas: Austin, Bureau of Economic Geology, The University of Texas, 145 p. and appendix, 91 p.

Table 4

Geothermal Characteristics and Economics Bergstrom

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 95°F | Flow Rate | 199,130 #/hr. |
| Depth | 2100 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 903. |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $532. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $156. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $348. | Return Pipe Capital ($000s) | $164. |
| Supply Pump Capital ($000s) | $70. | Return Pump Capital ($000s) | $71. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 94°F | Exchanger Capital ($000s) | $78. |
| Return Temperature | 83°F | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 81°F | Bottomhole Dynamic Pressure (psia) | 1576. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $115. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 1.00 | Load % of Available BTUs | 3.8% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 5.2%* |

Economics:

Total Capital ($000s) $1534.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 5.71 | $ 7.15 | $ 5.89 | $ 18.75 |
| Design | 7.77 | 9.71 | 7.99 | 25.47 |
| Actual | 149.52 | 187.12 | 154.19 | 490.83 |

* (1.0/19.189)x 100% = 5.2%

## Table 5

Geothermal Characteristics and Economics Brooks- (a)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 104°F | Flow Rate | 198,761 #/hr. |
| Depth | 1575 ft. | Aquifer Thickness | 125 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 677. |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $378. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $107. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $345. | Return Pipe Capital ($000s) | $347. |
| Supply Pump Capital ($000s) | $70. | Return Pump Capital ($000s) | $71. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 103°F | Exchanger Capital ($000s) | $55. |
| Return Temperature | 90°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 89°F | Bottomhole Dynamic Pressure (psia) | 1156. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $94. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 22.7 | Load % of Available BTUs | 62.9% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

**Economics:**

Total Capital ($000s) $1466.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 2.89 | $ 5.83 | $ 3.18 | $ 11.90 |
| Design | 5.97 | 12.00 | 6.57 | 24.54 |
| Actual | 5.97 | 12.00 | 6.57 | 24.54 |

## Table 6

Geothermal Characteristics and Economics     Brooks- (b)

### Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 104°F | Flow Rate | 99,381 # /hr. |
| Depth | 1575 ft. | Aquifer Thickness | 125 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 677. |

### Geothermal System

#### Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $378. |

#### Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $30 |

#### Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $283. | Return Pipe Capital ($000s) | $285. |
| Supply Pump Capital ($000s) | $69. | Return Pump Capital ($000s) | $69. |

#### Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 102°F | Exchanger Capital ($000s) | $33 |
| Return Temperature | 90°F | Geothermal/Water | |

#### Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 89°F | Bottomhole Dynamic Pressure (psia) | 918. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $43 |

#### Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 10.0 | Load % of Available BTUs | 55.6% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 94.9%* |

### Economics:

Total Capital ($000s)     $1189.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 3.23 | $ 9.78 | $ 3.72 | $ 16.73 |
| Design | 5.53 | 16.74 | 6.36 | 28.63 |
| Actual | 5.82 | 17.62 | 6.70 | 30.14 |

* (10.0/10.535) x 100% = 94.9%

## Table 7

Geothermal Characteristics and Economics    Lackland -(a)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 138°F | Flow Rate | 197,050 #/hr. |
| Depth | 3000 ft. | Aquifer Thickness | 125 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 1290. |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $846. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $167. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $346. | Return Pipe Capital ($000s) | $163. |
| Supply Pump Capital ($000s) | $68. | Return Pump Capital ($000s) | $70. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 136°F | Exchanger Capital ($000s) | $83. |
| Return Temperature | 88°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 84°F | Bottomhole Dynamic Pressure (psia) | 2078. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $122. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 10.00 | Load % of Available BTUs | 10.4% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 12.1%* |

**Economics:**

Total Capital ($000s) $1864.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 1.96 | $ 1.91 | $2.04 | $5.91 |
| Design | 2.20 | 2.15 | 2.29 | 6.64 |
| Actual | 18.93 | 18.43 | 19.65 | 57.01 |

* (10.0/82.912) x 100% = 12.1%

## Table 8

Geothermal Characteristics and Economics — Lackland – (b)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 138°F | Flow Rate | 98,526 #/hr. |
| Depth | 3000 ft. | Aquifer Thickness | 125 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 1290. |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $846. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $46. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $284. | Return Pipe Capital ($000s) | $139 |
| Supply Pump Capital ($000s) | $67. | Return Pump Capital ($000s) | $69. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 134°F | Exchanger Capital ($000s) | $51. |
| Return Temperature | 87°F | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 80°F | Bottomhole Dynamic Pressure (psia) | 1701. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $56 |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 10.0 | Load % of Available BTUs | 20.7% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 24.6%* |

**Economics:**

Total Capital ($000s) $1557.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $2.45 | $3.21 | $2.69 | $8.35 |
| Design | 3.09 | 4.04 | 3.39 | 10.52 |
| Actual | 11.83 | 15.48 | 13.00 | 40.31 |

* (10.0/40.593) x 100% = 24.6%

Table 9

Dallas - (a)

Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 100°F | Flow Rate | 99,460 #/hr. |
| Depth | 1,950 ft. | Aquifer Thickness | 200 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 838. |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $485. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $11. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $285. | Return Pipe Capital ($000s) | $140. |
| Supply Pump Capital ($000s) | $ 68. | Return Pump Capital ($000s) | $ 70. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 98°F | Exchanger Capital ($000s) | $95. |
| Return Temperature | 83°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 80°F | Bottomhole Dynamic Pressure (psia) | 1009. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $39. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 13.1 | Load % of Available BTUs | 75% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

**Economics:**

Total Capital ($000s) $1,193

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 3.38 | $ 9.60 | $ 4.34 | $ 17.32 |
| Design | 4.51 | 12.80 | 5.78 | 23.09 |
| Actual | 4.51 | 12.80 | 5.78 | 23.09 |

## Table 10

Dallas (b)

### Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 90°F | Flow Rate | 99,460 #/hr. |
| Depth | 1,050 ft. | Aquifer Thickness | 200 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 451. |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $201. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $14 |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $285. | Return Pipe Capital ($000s) | $140. |
| Supply Pump Capital ($000s) | $ 69. | Return Pump Capital ($000s) | $ 70. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 89°F | Exchanger Capital ($000s) | $58. |
| Return Temperature | 81°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 78°F | Bottomhole Dynamic Pressure (psia) | 626. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $40. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 6.6 | Load % of Available BTUs | 76% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

**Economics:**

Total Capital ($000s) $877.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 3.44 | $ 18.37 | $ 5.18 | $ 26.99 |
| Design | 4.53 | 24.17 | 6.81 | 35.51 |
| Actual | 4.53 | 24.17 | 6.81 | 35.51 |

# Davis-Monthan Air Force Base

## Geology

Davis-Monthan Air Force Base is located on alluvial valley fill southeast of Tucson, Ariz. There are no surface manifestations of geothermal resources in the area. Sammel (1979) reports that wells in the depth range 160 to 800 feet have temperatures of 86° to 106°F. The geothermal resources map of Arizona shows the base to be within a region where the heat flow is greater than 2.5 heat flow units and near an area where water wells exhibit gradients of 3° to 9°F/100 feet (Hahman and others, 1978). Wells between 7,000 and 10,000 feet in the area have bottomhole temperatures between about 194° and 284°F (W. R. Hahman, personal communication, 1980).

The shallow warm waters are in the same temperature and depth range as those possible at Luke Air Force Base; hence the shallow-resource economics are approximated by the Luke data (see pp. 37-39).

Data on flow rates of potential geothermal wells are not available. Irrigation wells in the area produce from 500 to 12,000 gal/min. Geothermal wells would likely be closer to the lower flow rates. A rate of 750 gal/min was assumed for the deep geothermal systems, and two temperature-depth points, 194°F at 7,000 feet and 284°F at 10,000 feet, were used in economic estimates.

## Economic Evaluation

Four alternative resources were considered for Davis-Monthan (Tables 11 through 14), reflecting flow rates of 750 gal/min and 500 gal/min for a pair of temperature-depth combinations (above). A large amount of natural gas is used at Davis-Monthan, but total replacement with geothermal energy at \$7.54 to \$6.64 per million Btu would be uneconomic even if natural gas prices almost doubled. Little oil is used. The possibility of a shallower resource closer to the base should be examined before Davis-Monthan is rejected as a possibly economic co-located site. However, even full use of a low-temperature resource such as the possibility identified for Luke could not economically replace the current gas and electric loads.

If the geothermal energy could be captured from 284°F down to 80°F for a 750-gal/min flow, the geothermal cost would fall to \$2.99 per million Btu (see Table 9). However, this is not low enough to permit consideration of electric generation. At a conversion efficiency of about 6 percent (see Table 1, above) the \$2.99 is equivalent to about \$52.55 per million electric Btu, or \$0.179/kWh.

## References

Hahman, W. R., Stone, C., and Witcher, J. C., 1978, Preliminary map, geothermal energy resources of Arizona: Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, Geothermal Map No. 1, scale 1:1,000,000.

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

## Table 11

Davis Monthan (a)

### Geothermal Characteristics and Economics

**Resource Characteristics:**

Temperature 194°F

Depth 7000 ft.

Percent Hard Rock N.A.

Flow Rate 362,480 #/hr.

Aquifer Thickness 100 ft.

Permeability 100 mD.

Static Downhole Pressure (psia) 3010

**Geothermal System**

**Wells:**

Production Wells 1

Reinjection Wells 1

Well Diameter 9 in.

Well Capital ($000s) $2401.

**Downhole Pump:**

Surface Delivery Pressure (psia) 17.2

Pump Capital ($000s) $380.

**Surface Transmission:**

Supply Pipe Length 3 mi.

Supply Pipe Capital ($000s) $1267

Supply Pump Capital ($000s) $ 171

Return Pipe Length 3 mi.

Return Pipe Capital ($000s) $1246

Return Pump Capital ($000s) $ 199.

**Heat Exchanger:**

Supply Temperature 186°F

Return Temperature 110°F

Exchanger Capital ($000s) $183.

Geothermal/Water

**Reinjection Pump:**

Reinjection Temperature 107°F

Reinjection Pressure (psia) 17.2

Bottomhole Dynamic Pressure (psia) 4640.

Pump Capital ($000s) $299

**Energy Use:**

Load ($10^9$ BTUs) 162.0

Operating Hours (% of year) 100%

Load % of Available BTUs 44.7%

Load % of Design BTUs 67.1%*

**Economics:**

Total Capital ($000s) $6147

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 1.35 | $ 1.95 | $ 1.61 | $ 4.91 |
| Design | 1.96 | 2.82 | 2.33 | 7.11 |
| Actual | 3.02 | 4.34 | 3.60 | 10.96 |

* (162.0/241.49) x 100% = 67.1%

## Table 12

Davis Monthan (b)

### Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 194°F | Flow Rate | 241,650 #/hr. |
| Depth | 7000 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 3010 |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6" |
| Reinjection Wells | 1 | Well Capital ($000s) | $2401 |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 17.2 | Pump Capital ($000s) | $202. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 3 mi. | Return Pipe Length | 3 mi. |
| Supply Pipe Capital ($000s) | $1115. | Return Pipe Capital ($000s) | $1098. |
| Supply Pump Capital ($000s) | $169. | Return Pump Capital ($000s) | $ 195. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 184°F | Exchanger Capital ($000s) | $138. |
| Return Temperature | 110°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 106°F | Bottomhole Dynamic Pressure (psia) | 4166. |
| Reinjection Pressure (psia) | 17.2 | Pump Capital ($000s) | $179. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 108.0 | Load % of Available BTUs | 44.7% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 68.9%* |

**Economics:**

Total Capital ($000s) $5498.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $1.57 | $2.60 | $1.79 | $ 5.96 |
| Design | 2.34 | 3.86 | 2.66 | 8.86 |
| Actual | 3.52 | 5.79 | 4.00 | 13.31 |

* (108.0/156.754) x 100% = 68.9%

# Table 13

Davis Monthan (c)

## Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 284° F | Flow Rate | 347,775 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 9 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350 |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 63.7 | Pump Capital ($000s) | $126. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 3 mi. | Return Pipe Length | 3 mi. |
| Supply Pipe Capital ($000s) | $1272. | Return Pipe Capital ($000s) | $1247. |
| Supply Pump Capital ($000s) | $145. | Return Pump Capital ($000s) | $172. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 270°F | Exchanger Capital ($000s) | $114. |
| Return Temperature | 180°F | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 173°F | Bottomhole Dynamic Pressure (psia) | 5249. |
| Reinjection Pressure (psia) | 63.7 | Pump Capital ($000s) | $211. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 250.0 | Load % of Available BTUs | 40.2% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 91.1%* |

**Economics:**

Total Capital ($000s) $7636.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .87 | $ 1.04 | $ 1.08 | $ 2.99 |
| Design | 1.92 | 2.29 | 2.39 | 6.60 |
| Actual | 2.19 | 2.63 | 2.72 | 7.54 |

* (250.0/274.374) x 100% = 91.1%

## Table 14

Davis Monthan (d)

Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 284°F | Flow Rate | 231,850 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 63.7 | Pump Capital ($000s) | $53. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 3 mi. | Return Pipe Length | 3 mi. |
| Supply Pipe Capital ($000s) | $1120. | Return Pipe Capital ($000s) | $1098. |
| Supply Pump Capital ($000s) | $ 146. | Return Pump Capital ($000s) | $ 170. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 266°F | Exchanger Capital ($000s) | $85. |
| Return Temperature | 180°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 170°F | Bottomhole Dynamic Pressure (psia) | 4978. |
| Reinjection Pressure (psia) | 63.7 | Pump Capital ($000s) | $135. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 167.0 | Load % of Available BTUs | 40.3% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 95.5%* |

**Economics:**

Total Capital ($000s) $7156

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 1.20 | $ 1.38 | $ 1.41 | $ 3.99 |
| Design | 2.80 | 3.25 | 3.28 | 9.33 |
| Actual | 3.02 | 3.50 | 3.54 | 10.06 |

* (167.0/174.786) x 100% = 95.5%

# Ellsworth Air Force Base

## Geology

Ellsworth Air Force Base in South Dakota is underlain by the Madison (Pahasapa) Formation, a source of geothermal resources elsewhere in the state. At Ellsworth, Gries (1977) estimates the Madison to be about 4,000 feet below the surface and about 400 feet thick and to have a temperature of about 120° to 130°F. Wells in the Madison have flow rates ranging from 80 to 1,000 gal/min; on the average, 300 to 500 gal/min is expected. A 4,645-foot well drilled in 1942 on or near the air base (Sec. 12, T. 2 N., R. 9 E.) reportedly had a specific capacity of 10.6 gal/min/ft drawdown at a pumping rate of 426.5 gal/min. A second well (Sec. 13, T. 2 N., R. 8 E.) drilled to 4,436 feet had a specific capacity of 3.0 gal/min/ft drawdown at an unspecified pumping rate. Temperatures measured in the wells were 129° and 121°F, respectively. Both wells have been plugged and abandoned.

## Economic Evaluation

Ellsworth (Table 15) has marginal economic potential assuming year-round use of the resource down to a sink temperature of 80°F. However, the heating-season economic potential might become good if reinjection were not required. Full utilization with reinjection could cost $7.82 per million Btu; without reinjection, the cost of year-round use could approach $4.98, compared to $10.14 for oil.

## Reference

Gries, J. P, 1977, Geothermal applications on the Madison (Pahasapa) aquifer system in South Dakota: South Dakota School of Mines and Technology, Rapid City, final report for U.S. Department of Energy, IDO/1625/2, 102 p., 2 appendices.

# Table 15

Geothermal Characteristics and Economics — Ellsworth

**Resource Characteristics:**

Temperature 120° F

Depth 4400 ft.

Percent Hard Rock N.A.

Flow Rate 198,000 #/hr.

Aquifer Thickness 400 ft.

Permeability 100 mD

Static Downhole Pressure (psia) 1892

**Geothermal System**

Wells:

Production Wells 1

Reinjection Wells 1

Well Diameter 6 in.

Well Capital ($000s) $1065

Downhole Pump:

Surface Delivery Pressure (psia) 14.7

Pump Capital ($000s) $34

Surface Transmission:

Supply Pipe Length 1 mile

Supply Pipe Capital ($000s) $345

Supply Pump Capital ($000s) $ 69

Return Pipe Length 1 mile

Return Pipe Capital ($000s) $164

Return Pump Capital ($000s) $ 70

Heat Exchanger:

Supply Temperature 118° F

Return Temperature 83°F

Exchanger Capital ($000s) $82

Geothermal/Air

Reinjection Pump:

Reinjection Temperature 80°F

Reinjection Pressure (psia) 14.7

Bottomhole Dynamic Pressure (psia) 2198.

Pump Capital ($000s) $88

Energy Use:

Load ($10^9$ BTUs) 24.1

Operating Hours (% of year) 49.6%

Load % of Available BTUs 37.3%

Load % of Design BTUs 39.7%*

**Economics:**

Total Capital ($000s) $1918

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $2.10 | $ 2.88 | $2.84 | $ 7.82 |
| Design | 2.46 | 3.38 | 3.34 | 9.18 |
| Actual | 5.40 | 6.64 | 6.68 | 18.72 |

* 49.6% x 80% = 39.7%

## Luke Air Force Base

### Geology

Luke Air Force Base is located in the Basin and Range portion of Arizona, in the broad alluvial valley extending to the southeast in which Phoenix and Williams Air Force Base are also located. There are no surface manifestations of geothermal resources in the vicinity of the air base. The geothermal resources map of Arizona (Hahman and others, 1978) indicates, however, that the base is within a region of heat flow greater than 2.5 heat flow units and that water wells in the area have temperature gradients of 3° to 9°F/100 ft.

Irrigation wells 500 to 1,000 feet deep in the vicinity of Luke AFB show temperatures of 85° to 125°F. These large-diameter wells have pumped flow rates as high as several thousand gallons per minute (W. R. Hahmen, personal communication, 1980). Accordingly, a well with a temperature of 104°F at 600 feet and a flow rate of 1,000 gal/min was assumed as representative of possible reservoir conditions in the area of Luke Air Force Base.

### Economic Evaluation

Luke may have a low-temperature resource that is marginally attractive for replacement of oil or oil plus some gas (Tables 16 and 17). Although the temperature is low (104°F), the resource is estimated to have a good flow rate from a relatively shallow depth. Thus the energy available is substantial for the relatively low capital cost projected. If the 1,000-gal/min resource could be utilized almost completely, replacement of oil (and possibly some gas) could be economic, with a cost in the range of $7.54 to $5 per million Btu.

### References


Danielson, Casey, 1977, Report on the geothermal potential of Yuma Proving Ground, Luke Air Force Range, Luke Air Force Base, Williams Air Force Base, and Navajo Ordnance Depot--Arizona: China Lake, California, Naval Weapons Center, unpublished report, 34 p.

Hahman, W. R., Stone, C., and Witcher, J. C., 1978, Preliminary map, geothermal energy resources of Arizona: Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, Geothermal Map No. 1, scale 1:1,000,000.

# Table 16

Luke -(a)

## Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 104°F | Flow Rate | 494,800 #/hr. |
| Depth | 600 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 1000 mD. |
| | | Static Downhole Pressure (psia) | 258 |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 10 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $108. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $122. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $459. | Return Pipe Capital ($000s) | $203. |
| Supply Pump Capital ($000s) | $ 72. | Return Pump Capital ($000s) | $ 73. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 103°F | Exchanger Capital ($000s) | $161. |
| Return Temperature | 86°F | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 85°F | Bottomhole Dynamic Pressure (psia) | 554. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $121. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 59.0 | Load % of Available BTUs | 56.7% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 80.0%* |

**Economics:**

Total Capital ($000s) $1318.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .97 | $ 2.74 | $ 1.25 | $ 4.96 |
| Design | 1.41 | 4.00 | 1.82 | 7.23 |
| Actual | 1.47 | 4.17 | 1.90 | 7.54 |

* (59.0/73.736) x 100% = 80.0%

Table 17

Luke -(b)

Geothermal Characteristics and Economics

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | $104^{o}F$ | Flow Rate | 247,400 #/hr. |
| Depth | 600 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 500 mD. |
| | | Static Downhole Pressure (psia) | 258 |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $108. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $77. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $368. | Return Pipe Capital ($000s) | $173. |
| Supply Pump Capital ($000s) | $ 73 | Return Pump Capital ($000s) | $ 74. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | $103^{o}F$ | Exchanger Capital ($000s) | $100. |
| Return Temperature | $86^{o}F$ | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | $84^{o}F$ | Bottomhole Dynamic Pressure (psia) | 578. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $83 |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 30.0 | Load % of Available BTUs | 57.6% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 81.4%* |

Economics:

Total Capital ($000s) $1056.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 1.28 | $ 4.49 | $ 1.64 | $ 7.41 |
| Design | 1.87 | 6.56 | 2.40 | 10.83 |
| Actual | 1.91 | 6.71 | 2.46 | 11.08 |

* (30.0/36.868) x 100% = 81.4%

## Mountain Home Air Force Base

### Geology

Mountain Home Air Force Base and the associated Saylor Creek Air Force Range are located near Mountain Home, Idaho, in the Snake River Plain, an area of above-normal temperature gradients and elevated heat flow. The air base appears to be somewhat to the north of the Bruneau-Grandview geothermal area. Brook and others (1979) estimate the mean reservoir temperature for the Bruneau-Grandview area to be about 217°F. Water wells between 1,000 and 3,000 feet in depth have maximum wellhead temperatures of about 180°F.

Relatively shallow (200 to 600 feet) wells in the area of the base have water temperatures up to about 75°F. Geochemical data suggest reservoir temperatures of about 150°F. Temperature gradients on the base are about 2.8°F/100 feet; hence 150°F water should be reached at 3,400 feet if the gradients are conductive to that depth.

Flow rates are highly variable and dependent on the geologic unit encountered at depth. Some highly fractured volcanics are prolific producers, but some volcanics and sedimentary units are very poor producers. An estimated production rate of 1,000 gal/min was used for this study.

### Economic Evaluation

Mountain Home AFB has good potential for economic replacement of oil (Tables 18 and 19). The attractiveness depends on the brine flow rate and the ability to use the geothermal energy down to 80°F for more than 40 percent of the year. The base uses a large amount of oil, which provides a good target for substitution of geothermal energy. Oil currently is around $10.14 per million Btu, whereas geothermal energy at the base could range from about $8.92 down to perhaps $4 or less.

### References

Hyde, Joy, and Whelan, J. A., 1977, Geothermal potential of Mountain Home Air Force Base and Saylor Creek Air Force Range, Idaho--Final Report: China Lake, California, Naval Weapons Center, 24 p.

Mitchell, J. C., Johnson, L. L., and Anderson, J. E., 1980, Geothermal investigations in Idaho, part 9, Potential for direct heat applications of geothermal resources: Idaho Department of Water Resources Information Bulletin No. 30.

---------- 1980, Geothermal resources of Idaho: Idaho Department of Water Resources map, scale 1:500,000 (also available as Idaho Department of Water Resources Water Information Bulletin No. 30, part 9, plate 1).

Young, W. H., and Mitchell, J. C., 1973, Geothermal investigations in Idaho, part 1, Geochemistry and geologic setting of selected thermal waters: Idaho Department of Water Administration Water Information Bulletin No. 30, 43 p.

Young, W. H., and Whitehead, R. C., 1974, Geothermal investigations in Idaho, part 2, An evaluation of thermal water in the Bruneau-Grandview area, southwestern Idaho: Idaho Department of Water Resources Water Information Bulletin No. 30.

## Table 18

Geothermal Characteristics and Economics — Mt. Home -(a)

### Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | $150^{o}F$ | Flow Rate | 490,850#/hr. |
| Depth | 3400 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 1000 mD. |
| | | Static Downhole Pressure (psia) | 1462. |

### Geothermal System

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 10 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $813. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $91. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $462. | Return Pipe Capital ($000s) | $203 |
| Supply Pump Capital ($000s) | $69. | Return Pump Capital ($000s) | $ 73 |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | $148^{o}F$ | Exchanger Capital ($000s) | $ 292 |
| Return Temperature | $81^{o}F$ | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | $80^{o}F$ | Bottomhole Dynamic Pressure (psia) | 1687. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $126 |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 114.4 | Load % of Available BTUs | 38.0% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 39.7%* |

### Economics:

Total Capital ($000s) $2129

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .49 | $ .92 | $ .66 | $ 2.07 |
| Design | .51 | .96 | .69 | 2.16 |
| Actual | 1.11 | 2.09 | 1.37 | 4.57 |

* 49.6% x 80% = 39.7%

Table 19

Geothermal Characteristics and Economics Mt. Home -(b)

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 150°F | Flow Rate | 196,340 #/hr. |
| Depth | 3400 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 400 mD. |
| | | Static Downhole Pressure (psia) | 1462 |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 10 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $813. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $40. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $346 | Return Pipe Capital ($000s) | $164. |
| Supply Pump Capital ($000s) | $ 67 | Return Pump Capital ($000s) | $ 71. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 147° | Exchanger Capital ($000s) | $149. |
| Return Temperature | 81°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 80°F | Bottomhole Dynamic Pressure (psia) | 1691. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $ 71 |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 45.1 | Load % of Available BTUs | 37.4% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 39.7%* |

Economics:

Total Capital ($000s) $1721

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .95 | $ 1.70 | $ 1.18 | $ 3.83 |
| Design | 1.01 | 1.80 | 1.25 | 4.06 |
| Actual | 2.33 | 3.86 | 2.73 | 8.92 |

* (49.6% x 80% = 39.7%)

# Norton Air Force Base

## Geology

Norton Air Force Base is situated between two major fault zones, the San Andreas to the northeast and the San Jacinto to the southwest. Between the base and the San Jacinto fault is the Loma Linda fault. No faults or inferred faults are shown on the air base, either on the San Bernardino sheet of the geologic map of California (Olaf Jenkins edition) or in U.S. Geological Survey Water Supply Paper 1419.

Wells along the San Jacinto fault zone near San Bernardino have water temperatures of 106° to 124°F at depths of about 1,000 feet. Wells closer to the San Andreas fault zone have temperatures as high as 129°F at 195 feet. The elevated temperatures are probably caused by upward movement of water along fault zones and possible lateral spreading of the water into near-surface aquifers. If similar conditions are present at the air base, temperatures of about 130°F at 400 feet could be expected.

Flow rates from these wells are quite variable. A 10-inch artesian well drilled several miles west of the air base by the city of San Bernardino produces 1,100 gal/min from 350 feet at 131°F. Flows of at least 200 to 300 gal/min seem reasonable to expect.

## Economic Evaluation

Norton AFB appears to be a very good target for substitution of geothermal energy for oil (Tables 20 and 21). The base uses a large amount of fuel oil and has a relatively shallow, moderately hot resource nearby. The temperature to which Norton's air or water must be heated may be the only limitation on the economic feasibility of oil backout. If the quantity of heat extracted were all that mattered, substitution at brine flows of 300 to 1100 gal/min would seem likely to be competitive with oil and possibly even with natural gas, depending on the heat specifications of the applications. Norton merits further investigation at an early date, and the investigation should include an engineering evaluation of the suitability of 130°F air or water.

## References


Dutcher, L. C., and Garrett, A. A., 1963, Geologic and hydrologic features of the San Bernardino area, California, with special reference to underground flow across the San Jacinto fault: U.S. Geologic Survey Water Supply Paper 1419, 114 pp.

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Table 20 Norton (a)

## Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 130°F | Flow Rate | 543,128 #/hr |
| Depth | 400 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 2000 mD. |
| | | Static Downhole Pressure (psia) | 250. |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 10 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $72. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 17.7 | Pump Capital ($000s) | Free flowing |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $476. | Return Pipe Capital ($000s) | $208. |
| Supply Pump Capital ($000s) | $71. | Return Pump Capital ($000s) | $ 75. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 129°F | Exchanger Capital ($000s) | $288. |
| Return Temperature | 83°F | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 82°F | Bottomhole Dynamic Pressure (psia) | 419. |
| Reinjection Pressure (psia) | 17.7 | Pump Capital ($000s) | $114. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 100.0 ** | Load % of Available BTUs | 42.0% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 45.7%* |

**Economics:**

Total Capital ($000s) $1304.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | .04 | 1.23 | .44 | 1.71 |
| Design | .04 | 1.37 | .49 | 1.90 |
| Actual | .08 | 2.43 | .69 | 3.20 ** |

* (100/219.009) x 100% = 45.7%

** Must adjust to base load level (e.g., 50 x $10^9$ BTUs and about $6.40).

# Table 21

## Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 130°F | Flow Rate | 148,126 #/hr. |
| Depth | 400 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 1000 mD. |
| | | Static Downhole Pressure (psia) | 250. |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 10 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $72. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 64.2 | Pump Capital ($000s) | Free flowing |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $318 | Return Pipe Capital ($000s) | $153. |
| Supply Pump Capital ($000s) | $ 64 | Return Pump Capital ($000s) | $ 67. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 128°F | Exchanger Capital ($000s) | $121 |
| Return Temperature | 83°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 80°F | Bottomhole Dynamic Pressure (psia) | 344. |
| Reinjection Pressure (psia) | 64.2 | Pump Capital ($000s) | $37. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 27.0 | Load % of Available BTUs | 41.6% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 46.2%* |

**Economics:**

Total Capital ($000s) $832.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | .13 | 2.95 | .46 | 3.54 |
| Design | .14 | 3.30 | .52 | 3.96 |
| Actual | .29 | 5.86 | .86 | 7.01 |

* (27./58.432) x 100% = 46.2%

## Williams Air Force Base

### Geology

Williams Air Force Base is located southeast of Phoenix, within the Basin and Range physiographic province of Arizona, on a thick sequence of Quaternary alluvium and Tertiary evaporites (Danielson, 1977). There are no geothermal manifestations at the surface; however, water wells and two deep geothermal wells in the area indicate abnormally warm temperatures at depth. At Mesa, eight miles north-northwest of Williams, water temperatures of about 125°F are reported in wells 1,100 feet deep (Tellier, 1973). Two deep wells drilled by Geothermal Kinetics, Inc. only a mile southwest of the base have reported bottomhole temperatures of 325° and 365°F at 10,000 feet. Although preliminary flow tests were encouraging, the wells did not flow at commercial rates; published estimates of the flow rates are 3,000 to 6,000 gal/min (Danielson, 1977; Renner and others, 1975). The wells and the Air Force base are in an area of anomalously high temperature gradients (Hohman and others, 1978).

Primarily on the basis of the Geothermal Kinetics test wells, it is estimated that aquifers capable of production rates of about 4,000 gal/min at a temperature of 345°F can be found about 10,000 feet beneath the base.

Cooler waters might be found at shallower depths. If so, the economic evaluation would be similar to that for Luke Air Force Base.

### Economic Evaluation

Williams definitely has potential (Tables 23 and 24) but will require more analysis and evaluation. The identified resource (345°F at 10,000 feet), at flow rates ranging from 4,000 down to 500 gal/min out of a single well, is capable of producing more energy than is required to replace the entire natural gas load. Utilization at that level of natural gas usage does not result in a competitive geothermal energy cost, but it is possible that a lower temperature from a shallower aquifer could produce geothermal energy at a more competitive rate. DOE and DOD should undertake additional analysis before drilling to 10,000 feet in search of a 345°F resource.

Williams also appears to have potential for electric power, especially if it were allowed to feed its excess power into a regional grid for use by other installations. On the basis of our assumptions, electric power generation at Williams is not economic ($20.69 per million Btu or $0.070 per kWh). However, our assumptions are for an isobutane binary system powered by a saturated geothermal brine. Should the geothermal resource contain a greater proportion of steam than we have assumed, the economics of power generation could improve significantly; and we may have assumed a redundant heat-exchange capability in adding our geothermal design to the Milora and Tester binary power plant module. A feasibility analysis would sharpen the estimates substantially, although the uncertainties regarding the resource can be eliminated only through a drilling and testing program.

A supplementary sensitivity analysis has been developed (see Appendix D) in order to determine how changes in aquifer thickness and permeability affect the downhole and reinjection pump capital and the resulting geothermal energy costs. The analysis was necessary because of the very high pump capital in Table 22; the 4,000 gal/min flow rate assumed apparently is too much for the estimated resource characteristics.

## References


Danielson, Casey, 1977, Report on the geothermal potential of Yuma Proving Ground, Luke Air Force Range, Luke Air Force Base, Williams Air Force Base, and Navajo Ordnance Depot, Arizona: China Lake, California, Naval Weapons Center unpublished report, 34 p.

Hahman, W. R., Stone, C., and Witcher, J. C., 1978, Preliminary map, geothermal energy resources of Arizona: Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, Geothermal Map. No. 1, scale 1:1,000,000.

Renner, J. L., White, D. E., and Williams, D. L., 1975, Hydrothermal convection systems, _in_ White, D. E., and Williams, D. L., Assessment of geothermal resources of the United States--1975: U.S. Geological Survey Circular 726, p. 5-57.

Tellier, A. H., 1973, Geothermal waters of Arizona: Tempe, Arizona State University, M.S. thesis, 30 p.

Table 22

Williams (a)

Geothermal Characteristics and Economics

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 345°F | Flow Rate | 1,789,626 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 12 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 141.9 | Pump Capital ($000s) | $2192. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $760. | Return Pipe Capital ($000s) | $498. |
| Supply Pump Capital ($000s) | $62. | Return Pump Capital ($000s) | $ 68. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 343°F | Exchanger Capital ($000s) | $619. |
| Return Temperature | 200°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 198°F | Bottomhole Dynamic Pressure (psia) | 6945. |
| Reinjection Pressure (psia) | 141.9 | Pump Capital ($000s) | $1715. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 572.4 | Load % of Available BTUs | 13.8% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 25.5%* |

Economics:

Total Capital ($000s) $10,263

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .45 | $ .11 | $ .68 | $ 1.24 |
| Design | .83 | .20 | 1.23 | 2.26 |
| Actual | 3.37 | .79 | 5.00 | 9.16 |

* (572.4/2243.364) x 100% = 25.5%

Table 23

Williams -(b)

Geothermal Characteristics and Economics

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 345°F | Flow Rate | 447,410 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 50 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 10 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 141.9 | Pump Capital ($000s) | $233. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $466. | Return Pipe Capital ($000s) | $318. |
| Supply Pump Capital ($000s) | $ 44. | Return Pump Capital ($000s) | $ 64. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 340°F | Exchanger Capital ($000s) | $183 |
| Return Temperature | 194°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 190°F | Bottomhole Dynamic Pressure (psia) | 5675. |
| Reinjection Pressure (psia) | 141.9 | Pump Capital ($000s) | $332. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 572.4 | Load % of Available BTUs | 55.1% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

Economics:

Total Capital ($000s) $5990.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .58 | $ .23 | $ .79 | $ 1.60 |
| Design | 1.07 | .43 | 1.46 | 2.96 |
| Actual | 1.07 | .43 | 1.46 | 2.96 |

Table 24

Williams - (c)

Geothermal Characteristics and Economics

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 345°F | Flow Rate | 223,700 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 25 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 9 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 141.9 | Pump Capital ($000s) | $132. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $373. | Return Pipe Capital ($000s) | $259. |
| Supply Pump Capital ($000s) | $51. | Return Pump Capital ($000s) | $ 55. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 337°F | Exchanger Capital ($000s) | $100 |
| Return Temperature | 200°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 194°F | Bottomhole Dynamic Pressure (psia) | 5713. |
| Reinjection Pressure (psia) | 141.9 | Pump Capital ($000s) | $207. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 268.6 | Load % of Available BTUs | 51.7% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

Economics:

Total Capital ($000s) $5527.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 1.04 | $ .37 | $ 1.28 | $ 2.69 |
| Design | 1.90 | .65 | 2.35 | 4.90 |
| Actual | 1.90 | .65 | 2.35 | 4.90 |

## Fort Bliss

### Geology

Fort Bliss is northwest of El Paso, Texas. The military reservation extends northeast from El Paso to the southern boundary of the White Sands Missile Range. Much of the base and reservation are in the southern portion of the Tularosa basin in New Mexico and its southernmost extension in Texas, the Hueco Bolson. Geothermal resources have been investigated by Henry (1979) and by Taylor and Roy (1979, 1980, 1981).

The work of Taylor and Roy suggests that the greatest geothermal potential near Fort Bliss is in the Hueco Tanks area of Texas, extending northward into New Mexico slightly to the west of the Hueco Mountains. Stock-watering wells in this area show temperatures as high as 160°F at depths of about 500 feet.

Flow rates have been measured in only a few wells in the vicinity of the thermal area. Wells pumped by windmills produce 10 to 50 gal/min. Knowles and Kennedy (1958) suggest that wells in the near-surface fresh-water zones west of the Hueco Tanks can produce 500 gal/min on spacings of about one-half mile without creating bothersome interference. Thermal wells 50 to 1,000 feet deep in the Hueco Tanks area should be able to achieve flow rates of 100 to 500 gal/min.

### Economic Evaluation

Fort Bliss probably has a better resource than many locations (Tables 25 and 26), but flow rates may be low (100 gal/min) and geothermal energy production might be insufficient to make it economically competitive. Even at 100 percent use of the resource down to an 80°F sink, geothermal costs would exceed the equivalent cost of fuel oil by 60 percent ($16.03 versus $10.14).

Even a 500-gal/min resource replacing fuel oil during the heating season would not be competitive with oil ($17.66 versus $10.14). However, full year-round use ($5.80) might be competitive with a combination backout of both oil and gas. A substantially closer resource could also make Ft. Bliss an attractive prospect.

### References

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---------- 1980, Hueco Tanks: an initial evaluation at a potential geothermal area near El Paso, Texas: Geothermal Resources Council, Transactions, v. 4, p. 253-256.

---------- 1981, An assessment of geothermal resources in Trans-Pecos Texas: El Paso, University of Texas at El Paso, progress report to U.S. Department of Energy, Division of Geothermal Energy, 82 p. and appendix.

## Table 25

Geothermal Characteristics and Economics — Bliss (a)

### Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 160°F | Flow Rate | 48,930 #/hr. |
| Depth | 500 ft. | Aquifer Thickness | 50 ft. |
| Percent Hard Rock | N.A. | Permeability | 500 mD |
| | | Static Downhole Pressure (psia) | 215 |

### Geothermal System

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 5 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $90. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $6. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 4 miles | Return Pipe Length | 4 miles |
| Supply Pipe Capital ($000s) | $951. | Return Pipe Capital ($000s) | $473. |
| Supply Pump Capital ($000s) | $252. | Return Pump Capital ($000s) | $274. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 133°F | Exchanger Capital ($000s) | $24. |
| Return Temperature | 115°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 77°F | Bottomhole Dynamic Pressure (psia) | 358. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $21 |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 7.7 | Load % of Available BTUs | 22.9% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

### Economics:

Total Capital ($000s) $2090.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .39 | $ 15.05 | $ .59 | $16.03 |
| Design | 1.71 | 65.92 | 2.57 | 70.20 |
| Actual | 1.71 | 65.92 | 2.57 | 70.20 |

Table 26

Bliss (b)

Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 160°F | Flow Rate | 244,650 #/hr. |
| Depth | 600 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 1000 mD. |
| | | Static Downhole Pressure (psia) | 258 |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $108. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $4. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 4 mi. | Return Pipe Length | 4 mi. |
| Supply Pipe Capital ($000s) | $1483 | Return Pipe Capital ($000s) | $690. |
| Supply Pump Capital ($000s) | $ 233 | Return Pump Capital ($000s) | $262 |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 150°F | Exchanger Capital ($000s) | $246. |
| Return Temperature | 85°F | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 78°F | Bottomhole Dynamic Pressure (psia) | 372. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $52 |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 45.0 | Load % of Available BTUs | 26.7% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 32.8% |

**Economics:**

Total Capital ($000s) $3078

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .08 | $ 4.37 | $ .26 | $ 4.71 |
| Design | .10 | 5.38 | .32 | 5.80 |
| Actual | .31 | 16.38 | .97 | 17.66 |

## Hawthorne Ammunition Depot

### Geology

Hawthorne Ammunition Depot is in the southern portion of Walker Lake Valley in Nevada, between the Wassuk Range to the west, the Gillis Range to the northeast, and the Garfield hills to the southeast. Surface manifestations of geothermal resources do not occur in the area; however, warm-water wells have been drilled on the depot and near the town of Hawthorne.

The highest temperature found in a well at the depot is 125°F in NAD-1. A 1,000-foot well recently drilled just southwest of the town of Hawthorne reportedly has a water temperature of 210°F and a flow rate of 750 gal/min. It is the highest temperature reported in the southern portion of Walker Lake Valley. Owners of the El Capitan casino plan to use the water for space heating.

Geothermal resources in Walker Lake Valley are probably related to upwelling of thermal waters along fault zones or deep fractures in the bedrock and then lateral spreading in the valley alluvium. Recent faulting has occurred along the eastern front of the Wassuk Range. Whether other faults are present beneath the alluvium that underlies most of the ammunition depot is not known. Additional work on the geothermal resources of the area is currently being conducted by members of the geothermal group of the Nevada Bureau of Mines and Geology.

Currently available information indicates that waters at 125°F are present under part of the depot, and waters as warm as 210°F are known near the base at a depth of about 1,000 feet. Warmer waters are possible, but it is not likely that waters hot enough for electricity generation will be found.

### Economic Evaluation

Hawthorne offers a good potential combination of use and co-located resource (Tables 27 through 30). Temperatures of 125° to 210°F are considered possible at 1,000 feet. Flow rates could range from 300 to 700 gal/min. Seasonal use of the higher temperatures at either flow rate could be competitive with oil ($2.26 to $4.10 per million Btu versus $10.14) and apparently would justify more than one production well. At the lower temperature and a flow rate below 700 gal/min, substantial use beyond the normal heating season would be required for geothermal to be competitive with oil.

Hawthorne's large fuel-oil consumption makes it a good target, given the possible resources.

## References

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Trexler, D. T., Koenig, B. A., and Flynn, Thomas, compilers, 1979, Geothermal resources of Nevada and their potential for direct utilization: Nevada Bureau of Mines and Geology map, scale 1:500,000.

Whelan, J. A., 1977, Geothermal potential of the Naval Ammunition Depot, Hawthorne, Nevada: China Lake, California, Naval Weapons Center unpublished report, 34 p.

## Table 27

Hawthorne- (a)

Geothermal Characteristics and Economics

**Resource Characteristics:**

Temperature 125°F

Depth 1000 ft.

Percent Hard Rock N.A.

Flow Rate 346,200 #/hr.

Aquifer Thickness 100 ft.

Permeability 1000 mD.

Static Downhole Pressure (psia) 430.

**Geothermal System**

Wells:

Production Wells 1

Reinjection Wells 1

Well Diameter 6 in.

Well Capital ($000s) $210.

Downhole Pump:

Surface Delivery Pressure (psia) 14.7

Pump Capital ($000s) $63

Surface Transmission:

Supply Pipe Length 1 mile

Supply Pipe Capital ($000s) $411

Supply Pump Capital ($000s) $ 65

Return Pipe Length 1 mile

Return Pipe Capital ($000s) $187

Return Pump Capital ($000s) $ 67

Heat Exchanger:

Supply Temperature 124°F

Return Temperature 90°F

Exchanger Capital ($000s) $142.

Geothermal/Air

Reinjection Pump:

Reinjection Temperature 88°F

Reinjection Pressure (psia) 14.7

Bottomhole Dynamic Pressure (psia) 641.

Pump Capital ($000s) $82

Energy Use:

Load ($10^9$ BTUs) 41.1

Operating Hours (% of year) 49.6%

Load % of Available BTUs 30.1%

Load % of Design BTUs 39.7% *

**Economics:**

Total Capital ($000s) $1227.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .47 | $ 1.47 | $ .65 | $ 2.59 |
| Design | .63 | 2.00 | .88 | 3.51 |
| Actual | 1.22 | 4.25 | 1.55 | 7.02 |

* 49.6% x 80% = 39.7%

# Table 28

## Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 125°F | Flow Rate | 148,370 #/hr. |
| Depth | 1000 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 300 mD. |
| | | Static Downhole Pressure (psia) | 430 |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $210. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $44. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $318. | Return Pipe Capital ($000s) | $154. |
| Supply Pump Capital ($000s) | $ 64. | Return Pump Capital ($000s) | $ 66. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 123°F | Exchanger Capital ($000s) | $75. |
| Return Temperature | 90°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 87°F | Bottomhole Dynamic Pressure (psia) | 739. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $60. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 17.6 | Load % of Available BTUs | 30.1% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 41.0%* |

**Economics:**

Total Capital ($000s) $991.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .87 | $ 2.70 | $1.15 | $ 4.72 |
| Design | 1.15 | 3.52 | 1.52 | 6.19 |
| Actual | 2.34 | 7.77 | 2.89 | 13.00 |

* (17.6/42.920) x 100% = 41.0%

## Table 29

Geothermal Characteristics and Economics

Hawthorne-(c)

### Resource Characteristics:

Temperature 210°F

Depth 1,000 ft

Percent Hard Rock N.A.

Flow Rate 336,250 #/hr.

Aquifer Thickness 100 ft.

Permeability 1,000 mD.

Static Downhole Pressure (psia) 430.

### Geothermal System

**Wells:**

Production Wells 1

Reinjection Wells 1

Well Diameter 6 in.

Well Capital ($000s) $210.

**Downhole Pump:**

Surface Delivery Pressure (psia) 22.0

Pump Capital ($000s) $30.

**Surface Transmission:**

Supply Pipe Length 1 mile

Supply Pipe Capital ($000s) $414.

Supply Pump Capital ($000s) $ 60.

Return Pipe Length 1 mile

Return Pipe Capital ($000s) $186

Return Pump Capital ($000s) $ 66

**Heat Exchanger:**

Supply Temperature 207° F

Return Temperature 90° F

Exchanger Capital ($000s) $268.

Geothermal/Air

**Reinjection Pump:**

Reinjection Temperature 88 °F

Reinjection Pressure (psia) 22.0

Bottomhole Dynamic Pressure (psia) 635.

Pump Capital ($000s) $78.

**Energy Use:**

Load ($10^9$ BTUs) 136.9

Operating Hours (% of year) 49.6%

Load % of Available BTUs 35.7%

Load % of Design BTUs 39.7%*

### Economics:

Total Capital ($000s) $1311.

| Energy Use Level | Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| | Energy Cost per million BTUs | | | |
| Available | $ .10 | $ .63 | $ .21 | $ .94 |
| Design | .11 | .71 | .23 | 1.05 |
| Actual | .26 | 1.55 | .45 | 2.26 |

* 49.6% x 80% = 39.7%

## Sierra Army Depot

### Geology

The Sierra Army Depot is near the Wendel-Amedee group of hot springs, which discharge about 950 gal/min of water at temperatures up to 205°F. Geochemical data and deep wells in the area suggest reservoir temperatures of about 240°F at about 5,000 feet. Production of geothermal resources may be limited to fracture zones. The faults near the warm springs are not known to continue beneath the Army depot. Information on potential flow rates from geothermal wells is not available, but since the natural flow of the springs is about 950 gal/min, an estimate of 500 gal/min for a well does not appear too unreasonable.

### Economic Evaluation

The estimated Susanville (Sierra) resource (Table 31) far exceeds the needs of the military installation, as indicated by fuel-oil consumption. Full replacement of fuel oil would require only about 20 percent of the annual resource capacity, resulting in a geothermal energy cost of $8.45 per million Btu. This competitive cost might be improved substantially if much more use were found for the resource or if a shallower resource (which could be somewhat cooler) were found at the base.

### References


Brook, C. A., Mariner, R. H., Mabey, D. R., Swanson, J. R., Guffanti, M., and Muffler, L. J. P., 1979, Hydrothermal convection systems with reservoir temperatures ≥90°C, in Muffler, L. J. P., ed., Assessment of geothermal resources of the United States--1978: U.S. Geological Survey Circular 790, p. 18-85.

Higgins, C. T., 1980, Geothermal resources of California: California Division of Mines and Geology, California Geologic Data Map Series, Map No. 4, scale 1:750,000.

Lydon, P. A., Gay, T. E., Jr., and Jennings, C. W., compilers, 1960, Westwood sheet: California Division of Mines and Geology, Geologic Map of California, Olaf P. Jenkins edition, scale 1:250,000.

## Table 31

Susanville (Sierra)

### Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | $240^{\circ}F$ | Flow Rate | 237,000 #/hr. |
| Depth | 4000 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 1720 |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $1017. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 34.3 | Pump Capital ($000s) | $79. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $373. | Return Pipe Capital ($000s) | $171. |
| Supply Pump Capital ($000s) | $ 54. | Return Pump Capital ($000s) | $ 73. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | $235^{\circ}F$ | Exchanger Capital ($000s) | $233. |
| Return Temperature | $90^{\circ}F$ | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | $88^{\circ}F$ | Bottomhole Dynamic Pressure (psia) | 2692. |
| Reinjection Pressure (psia) | 34.3 | Pump Capital ($000s) | $166. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 64.8 | Load % of Available BTUs | 19.5% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 21.5%* |

**Economics:**

Total Capital ($000s) $2166.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .47 | $ .66 | $ .79 | $ 1.92 |
| Design | .51 | .72 | .87 | 2.10 |
| Actual | 2.23 | 2.99 | 3.23 | 8.45 |

* (64.8/301.244) x 100% = 21.5%

## Fallon Naval Air Station

### Geology

The Fallon Naval Air Station and associated target ranges are in or near the southern portion of the Carson Sink in Nevada. The air station itself is in the Lohantan Valley portion of the sink. Surface manifestations of geothermal resources are not found within the limits of the station, but geothermal exploration is being actively conducted in the surrounding area. Geothermal tests have been drilled in both the Soda Lakes (290°F at 500 feet) and Stillwater (312°F at 1,300 feet) areas, about 10 miles northwest and northeast, respectively, of the air station. Lee Hot Springs, about 15 miles to the south, is estimated to have a mean reservoir temperature of 331°F (Brook and others, 1979). The geothermal industry is also investigating the Salt Wells Basin southeast of the air station.

The Navy has made preliminary investigations of the geothermal potential at the Fallon site; the most recent report is by Bruce (1979). The highest subsurface temperature reported at the air station is 131°F at 1,700 feet. Temperatures of 170°F at 165 feet and 158°F at 1,700 feet are reported as near as five miles to the southeast; higher temperatures are possible at greater depths. Temperatures as high as 320°F are suggested by geochemical data at several locations within 12 to 14 miles of the base.

Although none of the available data suggest that high temperatures will <u>not</u> be found beneath the Fallon air station, any evaluation of the economics of a high-temperature resource would be entirely speculative. Hence this study is limited to the better-known low-temperature waters. Relatively shallow warm reservoirs are likely to be found within fracture zones or in aquifers fed by leakage of upflowing waters from fracture zones.

Since groundwater at 131°F is known to be present on the station and 160°F water is known nearby, those temperatures were used in the study. Potential flow rates are not established; a minimum rate would be about 100 gal/min. Flows as high as 1,000 gal/min are also possible. For the economic evaluation a likely average value (300 gal/min) was used.

### Economic Evaluation

The two possible Fallon resources appear to be marginal or uneconomic (Tables 32 and 33). Fallon provides a large fuel-oil target for substitution, but the estimated geothermal resources appear to be inadequate. The hotter resource (160°F) may be as much as five miles away, while the 131°F resource is closer. Greater heat losses and the greater capital required for the surface pipeline to the 160°F resource actually result in a higher cost per million Btu for the hotter source.

If the cooler, nearer resource (131°F) could be used all year, geothermal energy might be marginally economic versus oil (approaching $6.90 per million Btu compared to $10.14 for oil).

## References

Brook, C. A., Mariner, R. H., Mabey, D. R., Swanson, J. R., Guffanti, M., and Muffler, L. J. P., 1979, Hydrothermal convection systems with reservoir temperatures ≥90°C, in Muffler, L. J. P., ed., Assessment of geothermal resources of the United States--1978: U.S. Geologic Survey Circular 790, p. 18-85.

Bruce, J. L., 1979, Fallon exploration project, Naval Air Station, Fallon, Nevada: China Lake, California, Naval Weapons Center Technical Publication No. 6914.

Trexler, D. T., Koenig, B. A., and Flynn, Thomas, compilers, 1979, Geothermal resources of Nevada and their potential for direct utilization: Nevada Bureau of Mines and Geology, map, scale 1:500,000.

## Table 32

Geothermal Characteristics and Economics — Fallon - (a)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 131°F | Flow Rate | 148,080 #/hr. |
| Depth | 1700 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 731. |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $408 |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $129. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $318. | Return Pipe Capital ($000s) | $154. |
| Supply Pump Capital ($000s) | $64. | Return Pump Capital ($000s) | $66. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 128°F | Exchanger Capital ($000s) | $76. |
| Return Temperature | 90°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 87°F | Bottomhole Dynamic Pressure (psia) | 1655. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $117. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 22.9 | Load % of Available BTUs | 40.2% |
| Operating Hours (% of year) | 58.1% | Load % of Design BTUs | 46.5%* |

**Economics:**

Total Capital ($000s) $1332.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $1.89 | $ 2.73 | $2.28 | $ 6.90 |
| Design | 2.54 | 3.92 | 3.06 | 9.52 |
| Actual | 4.47 | 6.65 | 5.02 | 16.14 |

* 58.1% x 80% = 46.5%

## Table 33

Geothermal Characteristics and Economics — Fallon - (b)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 160°F | Flow Rate | 148,080 #/hr. |
| Depth | 1700 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N. A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 731. |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $408. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $102. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 5 miles | Return Pipe Length | 5 miles |
| Supply Pipe Capital ($000s) | $1597. | Return Pipe Capital ($000s) | $764. |
| Supply Pump Capital ($000s) | $293 | Return Pump Capital ($000s) | $315. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 143°F | Exchanger Capital ($000s) | $57. |
| Return Temperature | 115°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 90°F | Bottomhole Dynamic Pressure (psia) | 1605. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $112. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 16.89 | Load % of Available BTUs | 16.5% |
| Operating Hours (% of year) | 58.1% | Load % of Design BTUs | 46.5%* |

**Economics:**

Total Capital ($000s) $3648.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 1.02 | $ 7.52 | $ 1.36 | $ 9.90 |
| Design | 2.92 | 21.68 | 3.93 | 28.53 |
| Actual | 5.33 | 39.91 | 6.62 | 51.86 |

*58.1% x 80% = 46.5%

## Twentynine Palms Marine Corps Base

### Geology

*The administrative area of the Marine Corps base is about six miles north of* the town of Twentynine Palms, California. At least half a dozen small domestic hot-water wells with temperatures from 118° to 148°F are located near the town. Flow rates and depths are not available.

The warm water in these wells is probably related to upflow along fault zones. However, the wells have no apparent relationship to the Mesquite Fault, the only fault shown in the area on the 1:250,000 geologic map of California. The Mesquite Fault is about one mile west of the base administrative area.

Warm water is not known to occur on the base. An area surrounding the town of Twentynine Palms is designated as an area known or inferred to be underlain by thermal water, but the Marine base administrative area is outside it. It appears possible that resources similar to those at Twentynine Palms could be found on the base, however, and this study infers the presence of 145°F water at a depth of about 300 feet near the administrative area. In the absence of information, flow rates of 200 and 1,000 gal/min were assumed.

### Economic Evaluation

The attractiveness of geothermal energy at Twentynine Palms (Tables 34 and 35) depends on the achievable flow rate and the distance of the resource from the base. Since the expected resource is quite shallow, well capital requirements are small. A flow rate of 1,000 gal/min from a 300-foot well is required for geothermal energy to be marginally competitive with oil or with a combination of oil and gas. Pumping at this rate without seriously reducing the flow rate or temperature is technically questionable. If the resource could be found much less than four miles from the base, the competitiveness of geothermal energy might improve drastically and lower flow rates would be more acceptable.

### References


Higgins, C. T., 1980, Geothermal resources of California: California Division of Mines and Geology, California Geologic Data Map Series, Map No. 4, scale 1:750,000.

Rogers, T. H., 1967, San Bernardino sheet: California Division of Mines and Geology, Geologic Map of California, Olaf P. Jenkins edition, scale 1:250,000.

## Table 34

Geothermal Characteristics and Economics 29 Palms-(a)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 145°F | Flow Rate | 491,634 #/hr. |
| Depth | 300 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 1000 mD. |
| | | Static Downhole Pressure (psia) | 129. |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 10 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $54. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $39. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 4 miles | Return Pipe Length | 4 miles |
| Supply Pipe Capital ($000s) | $1848. | Return Pipe Capital ($000s) | $1833. |
| Supply Pump Capital ($000s) | $244 | Return Pump Capital ($000s) | $254 |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 140°F | Exchanger Capital ($000s) | $160. |
| Return Temperature | 95°F | Geothermal/Water | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 92°F | Bottomhole Dynamic Pressure (psia) | 280. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $86. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 194.1 | Load % of Available BTUs | 70.9% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

**Economics:**

Total Capital ($000s) $4519.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .11 | $ 3.70 | $ .25 | $ 4.06 |
| Design | .15 | 5.17 | .35 | 5.67 |
| Actual | .15 | 5.17 | .35 | 5.67 |

## Table 35

Geothermal Characteristics and Economics 29 Palms- (b)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 145°F | Flow Rate | 98,327 #/hr. |
| Depth | 300 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 1000 mD. |
| | | Static Downhole Pressure (psia) | 129. |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $54. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | Free flow | Pump Capital ($000s) | - |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 4 miles | Return Pipe Length | 4 miles |
| Supply Pipe Capital ($000s) | $1136. | Return Pipe Capital ($000s) | $1129. |
| Supply Pump Capital ($000s) | $249. | Return Pump Capital ($000s) | $266. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 130°F | Exchanger Capital ($000s) | $48. |
| Return Temperature | 85°F | Geothermal/Water | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 77°F | Bottomhole Dynamic Pressure (psia) | 164. |
| Reinjection Pressure (psia) | 40.7 | Pump Capital ($000s) | $18. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 38.8 | Load % of Available BTUs | 71.5% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

**Economics:**

Total Capital ($000s) $2900

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .11 | $ 12.27 | $ .25 | $ 12.63 |
| Design | .16 | 17.98 | .37 | 18.51 |
| Actual | .16 | 17.98 | .37 | 18.51 |

## Atlantic Coastal Installations

### Geology

Many military installations are located near the Atlantic coast. An intensive study of the geothermal potential of this region is being conducted by the Virginia Polytechnic Institute and State University (VPI&SU). Estimated temperatures and depths of geothermal potential in the Atlantic Coastal Plain were provided by that study.

Unlike many others in the United States, the potential geothermal resources of the Atlantic Coastal Plain are conductive in nature and do not involve convective movement of water. Hence knowledge of regional geophysics and geology enables VPI&SU scientists to make reasonable estimates of subsurface temperatures and depths to basement at the military installations on the Atlantic coast (see Table 36).

Only one deep well has been tested for geothermal fluid production in the Atlantic Coastal Plain. The test, though not conclusive, showed that flow rates of 150 to 300 gal/min appear to be possible. Extrapolation of this single test to the remainder of the Atlantic Coastal Plain is risky, however. To increase the utility of the present study, flow rates of 300 and 500 gal/min were used with two depth-temperature pairs (115°F at 3,750 feet and 125°F at 4,300 feet). The flow rates chosen represent a reasonable average and maximum flow rate to be expected in the Coastal Plain. The temperature-depth combinations are representative of the temperatures and depths for geothermal projects in the region.

### Economic Evaluation

The Atlantic Coastal Plain appears to offer little opportunity for economic substitution of geothermal for fossil fuels in space heating applications (Tables 37 through 40). The hypothetical geothermal resources do not provide enough heat during the heating season to be competitive. If the entire resource could be used down to an 80°F sink throughout the year, geothermal energy would be marginally competitive with oil. Perhaps heat pumps on much shallower wells would offer better economics than the deeper wells.

Kings Bay (Tables 41 and 42) appears to be even poorer than the prototypical Atlantic Coastal Plain resource because of its limited space-heating season. If the resource could be used completely for the entire year, it could compete with oil and coal; however, year-round use of such a low temperature apparently is not required. At present, geothermal energy is not an economically viable option for Kings Bay.

### References

Costain, J. K., 1979, Geothermal exploration methods and results--Atlantic Coastal Plain, in A symposium of geothermal energy and its direct uses in the eastern United States: Geothermal Resources Council Special Report No. 5, p. 13-22.

Costain, J. K., Glover, Lynn III, and Sinha, A., 1976 and continuing, Evaluation and targeting of geothermal energy resources in the southeastern United States: Virginia Polytechnic Institute and State University, Blacksburg, quarterly progress reports to the U.S. Department of Energy, Division of Geothermal Energy.

Glover, Lynn III, 1979, General geology of the east coast with emphasis on potential geothermal energy regions: A detailed summary, in A symposium of geothermal energy and its direct uses in the eastern United States: Geothermal Resources Council Special Report No. 5, p. 9-11.

TABLE 36.--Estimated depth to basement and basement temperatures at Atlantic Coast Defense installations.

| State and installation | Service | Depth to basement, ft | Temp. at basement, °F |
|---|---|---|---|
| **Delaware** | | | |
| Dover Air Force Base | AF | 3,020 | 113 |
| Facility, Lewes | N | 6,135 | 131 |
| **Georgia** | | | |
| Hunter Army Airfield | A | 4,035 | 124 |
| Fort Stewart | A | 4,000 | 122 |
| Moody Air Force Base | AF | 4,265 | 113 |
| Submarine Support Base, Kings Bay | N | 4,530 | 113 |
| **Maryland** | | | |
| Naval Academy | N | 1,705 | 88 |
| Ordnance Station, Indian Head | N | 1,445 | 86 |
| Communication Unit, Washington | N | 1,445 | 86 |
| Air Station, Patuxent River | N | 2,955 | 102 |
| **New Jersey** | | | |
| McGuire Air Force Base | AF | 1,085 | 72 |
| Ft. Monmouth | A | 675 | 63 |
| Weapons Station, Earle | N | 920 | 66 |
| Fort Dix | A | 820 | 68 |
| Air Engineering Center, Lakehurst | N | 1,475 | 73 |
| **North Carolina** | | | |
| Marine Corps Air Station, Cherry Point | N | 3,020 | 99 |
| Camp Lejeune | N | 1,770 | 90 |
| Sunny Point Military Ocean Terminal | A | 1,410 | 86 |
| Facility, Cape Hatteras | N | 8,725 | 176 |
| Hospital, Cherry Point | N | 3,545 | 104 |
| Regional Medical Center, Camp Lejeune | N | 1,770 | 90 |
| Marine Corps Air Station, Jacksonville | N | 1,640 | 88 |
| **South Carolina** | | | |
| Marine Corps Recruit Depot, Parris Island | N | 3,410 | 122 |
| Charleston Air Force Base | AF | 2,495 | 100 |
| Facilities Engineering Command, Charleston | N | 2,495 | 100 |
| Marine Corps Air Station, Beaufort | N | 3,020 | 118 |
| Fleet Ballistic Missile Submarine Training Center, Charleston | N | 2,495 | 100 |
| Hospital, Beaufort | N | 3,215 | 118 |
| Shaw Air Force Base | AF | 655 | 73 |
| Myrtle Beach Air Force Base | AF | 2,165 | 88 |
| **Virginia** | | | |
| Fort Belvoir | A | 1,445 | 86 |
| Fort A. P. Hill | A | 145 | 86 |
| Marine Corps Air Facility, Quantico | N | 1,510 | 84 |
| Surface Weapons Center, Dahlgren Lab | N | 1,510 | 84 |
| Regional Medical Center, Portsmouth | N | 2,295 | 102 |
| Norfolk Shipyard | N | 2,295 | 102 |
| Oceana Air Station | N | 3,020 | 104 |
| Security Group Activity NW, Chesapeake | N | 2,725 | 104 |
| Fleet Combat Training Center, Virginia Beach | N | 3,315 | 104 |
| Hospital, Quantico | N | 1,510 | 84 |
| Supply Annex Cheatham, Williamsburg | N | 1,345 | 77 |
| Weapons Station, Yorktown | N | 1,740 | 79 |
| Fort Eustis | A | 1,410 | 75 |
| Langley Air Force Base | AF | 2,130 | 93 |
| Fort Monroe | A | 2,265 | 95 |
| Air Rework Facility, Norfolk | N | 2,330 | 95 |
| Amphibious Base, Little Creek, Norfolk | N | 2,590 | 99 |
| Fort Story | A | 2,985 | 104 |

## Table 37

Geothermal Characteristics and Economics — Atlantic Coastal Plain-(a)

### Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 125°F | Flow Rate | 148,520 #/hr. |
| Depth | 4,300 ft. | Aquifer Thickness | 200 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 1640. |

### Geothermal System

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $1218. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $78. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $318. | Return Pipe Capital ($000s) | $154. |
| Supply Pump Capital ($000s) | $ 64 | Return Pump Capital ($000s) | $ 66. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 123°F | Exchanger Capital ($000s) | $72. |
| Return Temperature | 90°F | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 87°F | Bottomhole Dynamic Pressure (psia) | 1872. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $29. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 17.05 | Load % of Available BTUs | 30.9% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 39.7%* |

### Economics:

Total Capital ($000s) $2000.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 3.22 | $ 3.10 | $ 2.67 | $ 8.99 |
| Design | 4.40 | 4.23 | 3.65 | 12.28 |
| Actual | 9.69 | 8.65 | 8.44 | 26.78 |

*49.6% x 80% = 39.7%

## Table 38

Geothermal Characteristics and Economics Atlantic Coastal Plain-(b)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 125°F | Flow Rate | 247,530 #/hr. |
| Depth | 4300 ft. | Aquifer Thickness | 200 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 1640. |

**Geothermal System**

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $1218. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $72 |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $370. | Return Pipe Capital ($000s) | $173. |
| Supply Pump Capital ($000s) | $72. | Return Pump Capital ($000s) | $74. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 123°F | Exchanger Capital ($000s) | $105. |
| Return Temperature | 90°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 88°F | Bottomhole Dynamic Pressure (psia) | 2020. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $71. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 28.42 | Load % of Available BTUs | 30.9% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 39.7%* |

**Economics:**

Total Capital ($000s) $2241.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 2.46 | $ 2.18 | $ 1.98 | $ 6.62 |
| Design | 3.38 | 2.99 | 2.71 | 9.08 |
| Actual | 7.04 | 6.11 | 5.86 | 19.01 |

* 49.6% x 80% = 39.7%

Table 39

Geothermal Characteristics and Economics Atlantic Coastal Plain-(c)

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 115°F | Flow Rate | 148,520 #/hr. |
| Depth | 3750 ft. | Aquifer Thickness | 200 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 1538. |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $1111. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $51. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $317 | Return Pipe Capital ($000s) | $154. |
| Supply Pump Capital ($000s) | $ 65 | Return Pump Capital ($000s) | $66. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 113°F | Exchanger Capital ($000s) | $60. |
| Return Temperature | 90°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 87° F | Bottomhole Dynamic Pressure (psia) | 1770. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $48. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 11.89 | Load % of Available BTUs | 28.5% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 39.7%* |

Economics:

Total Capital ($000s) $1872.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 3.60 | $ 4.05 | $ 3.61 | $ 11.26 |
| Design | 5.53 | 6.23 | 5.54 | 17.29 |
| Actual | 11.96 | 12.21 | 11.94 | 36.11 |



* 49.6% x 80% = 39.7%

## Table 40

Geothermal Characteristics and Economics Atlantic Coastal Plain - (d)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 115°F | Flow Rate | 247,530 #/hr. |
| Depth | 3750 ft. | Aquifer Thickness | 200 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 1538. |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $ 1111 |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $121 |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $369. | Return Pipe Capital ($000s) | $173. |
| Supply Pump Capital ($000s) | $72. | Return Pump Capital ($000s) | $74. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 114° F | Exchanger Capital ($000s) | $88 |
| Return Temperature | 90°F | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 88°F | Bottomhole Dynamic Pressure (psia) | 1918. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $90. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 20.67 | Load % of Available BTUs | 29.7% |
| Operating Hours (% of year) | 49.6% | Load % of Design BTUs | 39.7%* |

**Economics:**

Total Capital ($000s) $2099.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 2.76 | $ 2.84 | $ 2.74 | $ 8.34 |
| Design | 4.10 | 4.21 | 4.06 | 12.37 |
| Actual | 8.33 | 8.24 | 8.10 | 24.67 |

* 49.6% x 80% = 39.7%

## Table 41

**Geothermal Characteristics and Economics** — Kings Bay (a)

### Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 126°F | Flow Rate | 247,530 #/hr. |
| Depth | 4600 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 300 mD. |
| | | Static Downhole Pressure (psia) | 1754. |

### Geothermal System

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $1197 |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $211. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $370. | Return Pipe Capital ($000s) | $173. |
| Supply Pump Capital ($000s) | $ 72. | Return Pump Capital ($000s) | $ 74. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 124°F | Exchanger Capital ($000s) | $139 |
| Return Temperature | 85°F | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 83°F | Bottomhole Dynamic Pressure (psia) | 2295. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $87. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 10.8 | Load % of Available BTUs | 10.8% |
| Operating Hours (% of year) | 25.0% | Load % of Design BTUs | 12.8%* |

### Economics:

Total Capital ($000s) $2323

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ 2.70 | $ 2.22 | $ 2.07 | $ 6.99 |
| Design | 3.20 | 2.63 | 2.47 | 8.30 |
| Actual | 18.76 | 15.55 | 15.18 | 49.49 |

* (10.8/84.624) x 100% = 12.8%

## Geothermal Characteristics and Economics

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 126°F | Flow Rate | 247,530 #/hr. |
| Depth | 4600 ft. | Aquifer Thickness | 100 ft. |
| Percent Hard Rock | N.A. | Permeability | 500 mD. |
| | | Static Downhole Pressure (psia) | 1754 |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $1197. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 14.7 | Pump Capital ($000s) | $162. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mile | Return Pipe Length | 1 mile |
| Supply Pipe Capital ($000s) | $370. | Return Pipe Capital ($000s) | $173. |
| Supply Pump Capital ($000s) | $ 72. | Return Pump Capital ($000s) | $ 74. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 124°F | Exchanger Capital ($000s) | $139. |
| Return Temperature | 85°F | | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 83°F | Bottomhole Dynamic Pressure (psia) | 2079. |
| Reinjection Pressure (psia) | 14.7 | Pump Capital ($000s) | $52. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 10.8 | Load % of Available BTUs | 10.8% |
| Operating Hours (% of year) | 25.0% | Load % of Design BTUs | 12.8%* |

**Economics:**

Total Capital ($000s) $2239.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | 2.40 | 2.22 | 1.72 | 6.34 |
| Design | 2.85 | 2.63 | 2.05 | 7.53 |
| Actual | 17.25 | 15.55 | 13.75 | 46.55 |



* (10.8/84.624) x 100% = 12.8%

## White Sands Missile Range

### Geology

White Sands Missile Range is in the Tularosa basin of New Mexico and Texas. Geothermal manifestations are not present at the surface. A recently completed study (Cunniff and others, 1980) of the geothermal potential of the missile range provided the data used in the present study. According to this study, temperatures of about 198°F are possible at depths of 6,000 feet in wells with flow rates of about 500 gal/min. The study also considered the potential for transporting geothermal fluids from the vicinity of Hueco Tanks, Texas, and we have included an analysis of the economics of this scheme, using estimates of 194°F water temperature and 500 gal/min flow rate.

### Economic Evaluation

Two alternative resources were considered for the White Sands Missile Range (Tables 43 and 44), using data from the Cuniff study. The 198°F resource at 6,000 feet is 3.75 miles away, while the 194°F resource at 1,500 feet is assumed to be 20 miles away. The long-distance transportation from the shallower resource adds substantially to capital requirements and heat losses in transit. As a result the more distant resource has a much higher, uncompetitive energy cost. The nearer resource also appears to be uncompetitive with natural gas, not only at current prices but also at foreseeable decontrolled prices ($7.21 per million Btu versus $3.20 or more for current natural gas).

### Reference

Cunniff, R. A., with Swanberg, C. A., Brown, K., Alexander, S., and Rybarczyk, S., 1980, Geothermal potential of White Sands Missile Range, New Mexico: Las Cruces, New Mexico Energy Institute, NMEI-57, 24 p. plus appendix and misc. figures and tables.

Table 43

Geothermal Characteristics and Economics     White Sands - (a)

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 198°F | Flow Rate | 241,278 #/hr. |
| Depth | 6000 ft. | Aquifer Thickness | 400 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 2580 |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $1729. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | Free flowing | Pump Capital ($000s) | - |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 3.75 miles | Return Pipe Length | 3.75 miles |
| Supply Pipe Capital ($000s) | $1394. | Return Pipe Capital ($000s) | $642. |
| Supply Pump Capital ($000s) | $205. | Return Pump Capital ($000s) | $233. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | 185°F | Exchanger Capital ($000s) | $163. |
| Return Temperature | 113°F | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | 99°F | Bottomhole Dynamic Pressure (psia) | 2882. |
| Reinjection Pressure (psia) | 35.6 | Pump Capital ($000s) | $88. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 152.0 | Load % of Available BTUs | 60.9% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 100% |

Economics:

Total Capital ($000s) $4454.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .75 | $ 2.62 | $ 1.02 | $ 4.39 |
| Design | 1.18 | 4.11 | 1.62 | 6.91 |
| Actual | 1.24 | 4.29 | 1.68 | 7.21 |

## Table 44

Geothermal Characteristics and Economics    White Sands - (b)

### Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | 194°F | Flow Rate | 241,656 #/hr. |
| Depth | 1500 ft. | Aquifer Thickness | 200 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 645. |

### Geothermal System

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 6 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $360. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 17.2 | Pump Capital ($000s) | $30. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 20 miles | Return Pipe Length | 20 miles |
| Supply Pipe Capital ($000s) | $7434 | Return Pipe Capital ($000s) | $3422. |
| Supply Pump Capital ($000s) | $1079 | Return Pump Capital ($000s) | $1253. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 138°F | Exchanger Capital ($000s) | $81 |
| Return Temperature | 110°F | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 70°F | Bottomhole Dynamic Pressure (psia) | 1112. |
| Reinjection Pressure (psia) | 17.2 | Pump Capital ($000s) | $109. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 59.4 | Load % of Available BTUs | 24.7% |
| Operating Hours (% of year) | 100.% | Load % of Design BTUs | 100% |

### Economics:

Total Capital ($000s) $13,768

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .24 | $ 13.88 | $ .53 | $ 14.65 |
| Design | .95 | 56.33 | 2.15 | 59.43 |
| Actual | .95 | 56.33 | 2.15 | 59.43 |

## CONCLUSIONS

Opportunities for economic substitution of geothermal energy for existing electrical, oil, and natural gas loads at military installations appear to be relatively limited. Numerous limiting factors eliminate one or another of the installations studied, as mentioned in the individual evaluations.

However, some installations are either good or marginal prospects and merit further study. Mountain Home, Norton, Hawthorne, and Sierra appear to have good geothermal potential, although an effort to match the resource and the geothermal system more closely to the energy use is needed in each case. Ellsworth could be upgraded from marginal to good if its resource could be used for more of the year and if the cost of the geothermal system could be substantially reduced (e.g., no reinjection). Luke, Ft. Bliss, and Fallon might move into the "good" category if they could be used through most of the year. Ft. Bliss, Fallon, and Twentynine Palms could improve if the geothermal resources were found substantially closer to the use location than we currently estimate. Williams' resource potential puts it in the marginal category because of the unexplored alternatives it offers; other configurations for the geothermal system may be more economic than the one we have modeled. However, the base uses only natural gas and electricity, both much tougher economic targets than oil.

We recommend several followup steps based on our analysis:

1. DOD should review and analyze the potential match of geothermal systems to current energy use for the installations we have identified as good or marginal prospects.

2. A final engineering review of the information should be made by each installation for those we have modeled and categorized as uneconomic. This would make sure that no opportunity is overlooked.

3. A program for systematic confirmation of resources and feasibility analysis of the good and marginal sites should be planned and conducted. The plan should be designed with highest priority given to the installation where it appears that the most fuel oil can be replaced economically. Other fuel-oil savers should follow, within limits of the budgets for feasibility studies and capital expenditures. The economic feasibility analyses should include probability distributions of the resource possibilities and the respective economics (e.g., the likelihood of a dry hole at some capital cost) and summary weighted averages (expected value technique).

4. This study should be updated periodically to incorporate the latest geologic information and prices of oil, gas, and electrical power. It will be particularly important to follow the price of natural gas in response to decontrol, since so many installations use so much natural gas.

5. For locations where the geothermal prospects are uneconomic, the possibility of using groundwater heat pumps at shallower depths should be investigated.

# APPENDICES

APPENDIX A

Rec'd GFI
Arlington Office
AUG 11 1980

DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND
200 STOVALL STREET
ALEXANDRIA, VA 22332

IN REPLY REFER TO
1113C/TAL
6 AUG 1980

Mr. John W. Salisbury
Deputy Director
Division of Geothermal Energy
Resource Applications
Department of Energy
Washington, DC 20461

Dear Jack:

This letter provides information on oil and gas backout potential for those Defense installations specified in your letter of May 13, 1980, as possibly being co-located with geothermal resources.

Using this data, it is requested that DOE now provide some indication of resource potential at those installations which represent the greatest targets of opportunity. Defense could then determine the conversion requirements from which cost estimates could be developed.

We have an excellent start on a DOE/DOD geothermal program which I sincerely hope can continue for, as the enclosures show, Defense installations could contribute significantly to geothermal acceptance and development.

Yours truly,

Tom

THOMAS A. LADD
Geothermal Program Coordinator

Enclosures (3)

Copy to:
Deputy Assistant Secretary of Defense (Energy, Environment & Safety)
Special Assistant for Energy, Department of the Navy
Special Assistant for Energy, Department of the Army
Special Assistant for Energy, Department of the Air Force
Special Assistant for Energy, Department of the Marine Corps

SELECTED AF INSTALLATIONS
ENERGY CONSUMPTION-FY 79

| | ELECTRIC (COMMERCIAL) | | Fuel Oil | Natural Gas |
|---|---|---|---|---|
| | MBTUS* | Prime Fuel | MBTUS** | MBTUS** |
| Barksdale AFB LA | 831,639 | Gas | 0 | 310,596 |
| Bergstrom AFB TX | 554,932 | Gas | 772 | 182,886 |
| Brooks AFB TX | 360,459 | Coal/Gas | 154 | 230,013 |
| Charleston AFB SC | 684,087 | Gas/Oil | 199,166 | 83,275 |
| Davis-Monthan AFB AZ | 911,147 | Gas | 3,020 | 246,845 |
| Dover AFB DE | 766,701 | Oil | 543,142 | 0 |
| Ellsworth AFB SD | 873,177 | Hydro | 56,073 | 705,979 |
| England AFB LA | 420,706 | Oil/Gas | 410 | 135,711 |
| Kelly AFB TX | 1,923,826 | Coal/Gas | 207 | 687,339 |
| Lackland AFB TX | 1,409,597 | Coal/Gas | 2,746 | 523,343 |
| Langley AFB VA | 1,160,592 | Oil | 473,887 | 75,445 |
| Luke AFB AZ | 837,809 | Gas | 23,311 | 241,141 |
| McGuire AFB NJ | 755,857 | Gas/Oil | 163,929 | 515,139 |
| Moody AFB GA | 330,182 | Oil | 66,102 | 8,969 |
| Myrtle AFB SC | 564,155 | Oil | 99,364 | 0 |
| Mt. Home AFB ID | 595,521 | Hydro | 126,088 | 43,944 |
| Nellis AFB NV | 941,269 | Gas | 37,675 | 305,807 |
| Norton AFB CA | 774,438 | Gas/Oil | 111,640 | 192,968 |
| Randolph AFB TX | 833,934 | Coal/Gas | 167 | 243,866 |
| Shaw AFB SC | 850,687 | Oil | 141,791 | 103,757 |
| Williams AFB AZ | 572,424 | Hydro/Gas | 217 | 139,693 |

*12-month total
**Nov-Apr FY 79 total

Atch 1

SELECTED NAVY INSTALLATIONS
ENERGY CONSUMPTION - FY 1979

| | Commercial Electric MWH * | Fuel Oil MBTU ** | Natural Gas MBTU * |
|---|---|---|---|
| NAS Barbers Pt., HI | 21,544 | 9,960 | - |
| MCAS Kaneohe Bay, Oahu, HI | 69,697 | 33,854 | - |
| Naval Academy, MD | 56,000 | 137 293 | 282,152 |
| Indian Head, MD | 10,669 | 976,585 | - |
| Communication Unit, Wash, MD | 6,053 | 36,008 | - |
| Patuxent River, MD | 67,359 | 513,631 | - |
| NAVSTA Adak, AK | - | 581,923 | - |
| PG School, Monterey, CA | 24,101 | 1,378 | 153,550 |
| NAVFAC Pt. Sur, CA | 1,132 | 4,060 | - |
| NWC China Lake, CA | 88,365 | 255,247 | - |
| Twenty Nine Palms, CA | 44,978 | 120,008 | 174,002 |
| Parachute Test Range (El Centro, CA) | 13,493 | 697 | 15,180 |
| NAVFAC, Lewes, DE | 1,628 | 9,906 | - |
| Meridian Air Station, MI | 88,839 | 300,077 | 479,497 |
| NAS Fallon, NV | 13,228 | 99,637 | 30,278 |
| NWS Earle, NJ | 13,143 | 125,036 | - |
| NAEC Lakehurst, NJ | 25,325 | 394,381 | - |
| MCAS & MC Hospital, Cherry Pt., NC | 71,550 | 452,720 | - |
| MCB Camp LeJeune, NC | 193,826 | 1,682,775 | - |
| NAVFAC, Cape Hatteras, NC | 2,431 | 11,174 | |
| REGMEDCEN Camp LeJeune, NC | 6,586 | 41,338 | - |
| Parris Island, SC | 26,935 | 176,087 | 303,362 |
| MCAS Beaufort, SC | 53,945 | 70,426 | 88,291 |
| FBMSTC Charleston, SC | 8,935 | 5,663 | - |
| NAVHOSP Beaufort, SC | 9,434 | 21,723 | 30,978 |
| NAS Dallas, TX | 17,576 | - | 71,160 |
| Chase Field, TX | 29,731 | - | 51,351 |
| Quantico, VA | 69,959 | 748,849 | 170,031 |
| Dahlgren, VA | 29,929 | 74,365 | - |
| REGMEDCTR Portsmouth, VA | 20,099 | 152,368 | 13,058 |
| NAVSHIPYD Norfolk, VA | 96,231 | 881,652 | 41,659 |
| NAS Oceana, VA | 72,233 | 391,914 | 44,869 |
| SGA NW Chesapeake, VA | 11,968 | 20,185 | - |
| FCTC Dam Neck, VA | Not separate in FY 1979 | | |
| NWS Yorktown, VA | 27,135 | 302,113 | - |
| NARF Norfolk, VA | 313,342 | 2,400,081 | 203,967 |
| Little Creek, VA | 53,262 | 734,830 | 51,327 |

* 12 month total
** October-April FY 1979 total

SELECTED ARMY INSTALLATIONS
ENERGY CONSUMPTION - FY 1979

| | Commercial Electric MWH/yr | Fuel Oil Gal Oil/yr | Natural Gas Thousand cf/yr |
|---|---|---|---|
| Fort Stewart, GA (incl. Hunter) | 122,776 | 3,186,575 | 399,175 |
| Louisiana Army Ammunition Plant | 13,263 | - | 155,375 |
| Fort Polk, LA | 100,539 | - | 721,925 |
| Pine Bluff Arsenal, Arkansas | 10,076 | 532,000 | 251,200 |
| Sierra Army Depot, CA | 9,384 | 469,175 | 19,075 |
| Hawthorne Ammunition Plant, NV | 12,035 | 1,803,375 | 30,000 |
| Fort Mammouth, NJ | 52,003 | 5,396,475 | 100,300 |
| Fort Dix, NJ | 70,440 | 11,138,575 | 218,700 |
| Fort Buss, TX | 134,699 | 323,750 | 1,507,400 |
| Fort Sam Houston, TX | 107,032 | 57,925 | 554,050 |
| Lone Star Ammunition Plant, TX | 16,916 | 2,625,000 | 251,000 |
| Red River Army Depot, TX | 40,895 | 647,150 | 428,400 |
| Longhorn Army Ammunition Plant, TX | 15,026 | - | 521,200 |
| Tooele Army Depot, Utah | 39,129 | 3,676,925 | 51,700 |
| Fort Belvoir, VA | 116,822 | 7,060,725 | 114,025 |
| Fort A. P. Hill, VA | 3,274 | 269,150 | 5,300 |
| Fort Eustis & Ft. Story, VA | 73,629 | 5,273,100 | 5,375 |
| Fort Monroe, VA | 15,749 | 447,975 | 72,500 |

# APPENDIX B

## The Geodec Model

The general configuration of the Geodec model was described in Section 2. This section presents a detailed description of the model, consisting of a separate description of each design module and a description of the economic routine.

### Geothermal Well Module

The cost of a developed geothermal field, including production, reinjection, and spare wells, is determined by a geothermal well module using an analysis developed by Milora and Tester* (henceforth, M&T). Land acquisition (leasing costs and legal fees), exploration, surface piping, auxiliary well field equipment, and construction labor are included in the cost estimate.

Input data to the well module are:

- Number of production wells
- Average well depth
- Average well flow rate
- Fraction of hard rock drilling
- Ratio of production to reinjection wells.

*Milora, Stanley L., and Tester, Jefferson W., Geothermal Energy as a Source of Electric Power, MIT Press, Cambridge, Mass. (1976).

From these data the module calculates:

- Mass flow rate from the field
- Total wells in the field
- Total reinjection wells
- Total capital costs
- Annual labor and maintenance costs.

Downhole and reinjection pumps are considered separately in other modules.

M&T use an exponential model of drilling costs versus well depth to correlate data from the literature. Drilling costs were found to be nearly independent of well diameter, so this parameter was removed from further consideration. Since the greater part of the data was for wells 6 to 12 inches in diameter, the cost estimate should be applicable in this range. M&T do not indicate that directionally drilled wells were included in the data base; hence, the cost estimate should not be applied to directional drilling. Wells are assumed to be placed in an equilateral triangular grid with 1000-foot spacing.

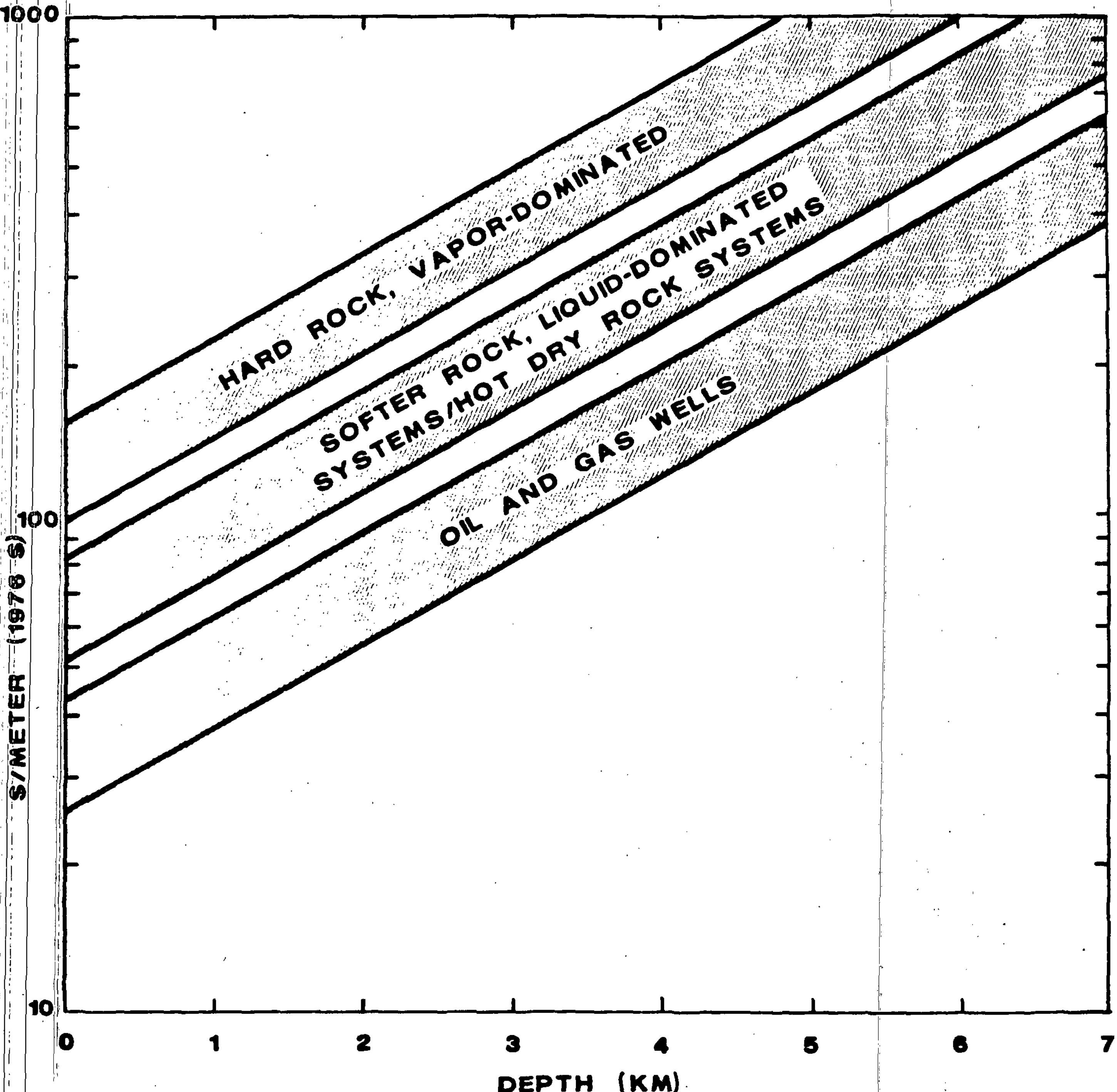
The cost data were segregated into three categories: Hard-rock, vapor-dominated geothermal reservoirs; soft-rock, liquid-dominated and hot dry rock systems; and oil and gas wells. The correlation of these data is shown in Figure 3-1. The curve passing through the center of the soft-rock, liquid-dominated region of this plot is described by the equation:

$$\log \frac{\Phi_{i,s}}{63{,}000D} = 0.172D$$

where D = well depth in kilometers

$\Phi_{i,s}$ = cost in 1976 dollars for drilling and casing a well in soft rock.

# GEOTHERMAL WELL COSTS, INCLUDING DRILLING AND CASING*




* ADAPTED FROM MILORA AND TESTER (1976), P.82

Figure 3-1

The analogous curve for hard-rock, vapor-dominated systems is described by the equation:

$$\log \frac{\Phi_{i,H}}{120{,}000D} = 0.172D$$

where $\Phi_{i,H}$ = cost in 1976 dollars for drilling and casing a well in hard rock.

Since both have the same slope, the models for soft- and hard-rock wells may be linearly combined provided we first define a weighted intercept for the cost-depth plot:

$$\Phi_0 \equiv 63 + 57 f_H$$

where $f_H$ = fraction of well depth that is hard rock

$\Phi_0$ = weighted intercept of the cost-depth plot in dollars per meter.

The combined correlation then becomes

$$\log \frac{\Phi_i}{1000\Phi_0 D} = 0.172D$$

where $\Phi_i$ = cost in 1976 dollars of drilling and casing a well.

When $f_H$ = 0, the soft-rock cost model is obtained. When $f_H$ = 1, the hard-rock cost model is obtained. Although not designed specifically for such use, $f_H$ may be assigned values less than zero for extremely soft drilling conditions and values greater than one to indicate particularly difficult or costly drilling.

The total number of wells in a field is given by:

$$n = n_p(1 + 1/r) + n_{ps} + n_{rs}$$

where $n_p$ = number of active producing wells,

$n_{ps}$ = number of spare producing wells.

$n_{rs}$ = number of spare reinjection wells,

$r$ = ratio of production to reinjection wells

$n$ = total number of wells in the field.

If n is not integral, it must be rounded to the next highest integral value.

The cost for casing and drilling all wells in the field is:

$$\Phi_w = n\Phi_i$$

where $\Phi_w$ = total field cost in 1976 dollars for drilling and casing.

The cost of auxiliary equipment--principally surface piping--is a function of the number of wells in the field. The following correlation of M&T data was developed to calculate this cost.

If $n < 73$,

$$\log f_w = 0.54 \log n - 1.31$$

If $n \geq 73$,

$$f_w = 0.50$$

where $f_w$ = fraction of total well cost due to auxiliary equipment.

The data and correlation are shown in Figure 3-2.

# AUXILIARY EQUIPMENT COST CORRELATION

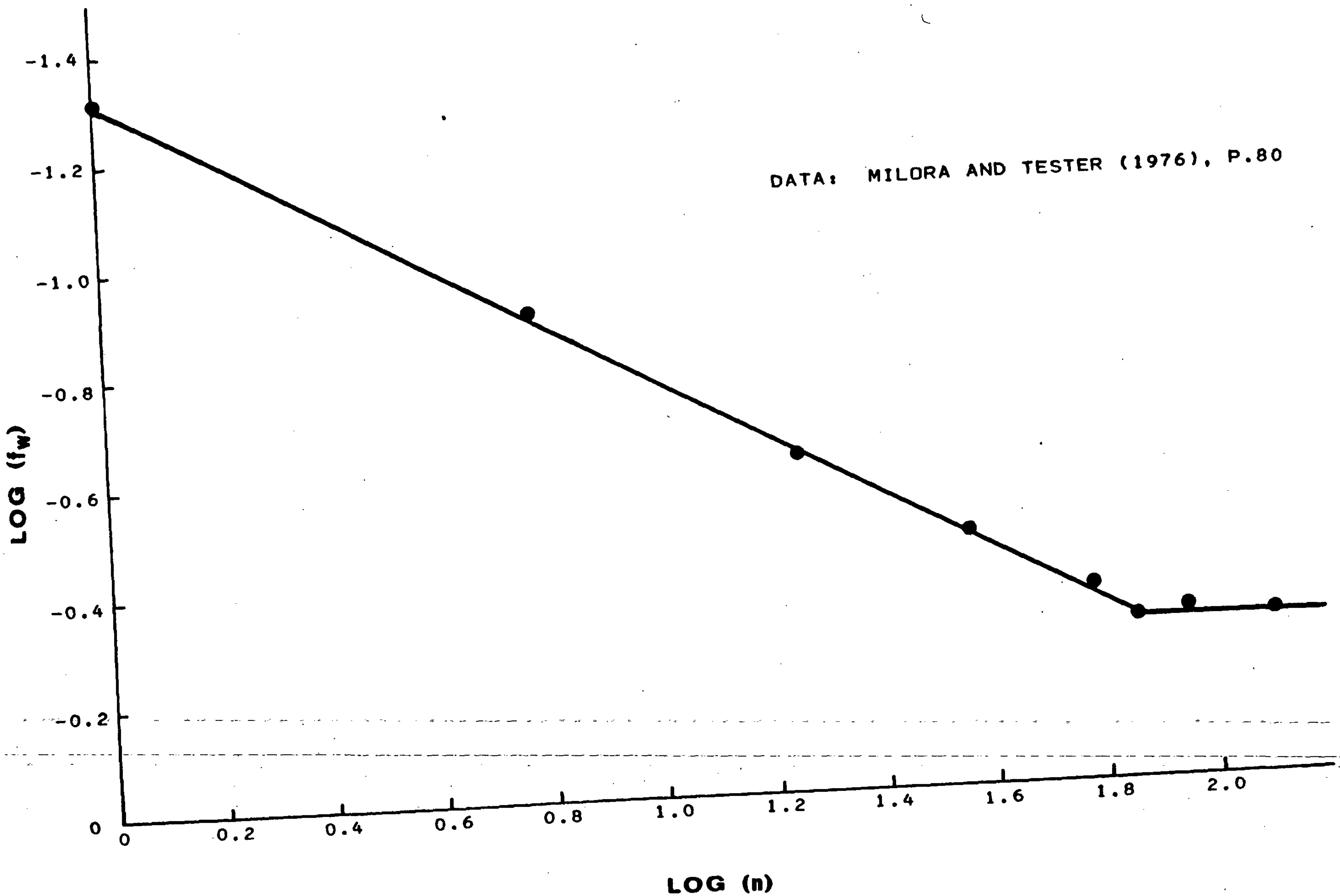



Figure 3-2

Indirect production costs are expressed as a percentage of direct costs. Land acquisition, exploration, and contingency are the major components of indirect costs, which M&T calculate at 56 percent of direct costs.

The total capital cost for a producing geothermal field is:

$$\Phi = (1 + f_i)(\Phi_w + f_w\Phi_w)/1000$$

where $\Phi$ = developed well field cost in thousands of 1976 dollars

$f_i$ = ratio of indirect costs to direct costs.

The annual maintenance and labor costs are estimated as 10 percent of total capital costs:

$$\Phi_{m\ell} = 0.10\Phi$$

where $\Phi_{m\ell}$ = annual maintenance and labor cost in thousands of dollars.

Operating costs for this portion of the geothermal process are negligible, since downhole and reinjection pumps are treated separately outside the well model. Consequently there is no operating cost function in this module.

Downhole Pump Module

Downhole pumps are utilized in geothermal fields where the aquifer is not artesian. Although wells with subsurface temperatures high enough to produce vapor pressures greater than hydrostatic pressure can be made to flow without pumps, two-phase flashing flow will result. Such flow delivers liquid and vapor to the surface at the saturation temperature for the pressure existing at the wellhead. Flashing flow has the advantage of pumpless operation and no operating expenses, but surface delivery temperatures are lower than subsurface temperatures, and surface pipes must be of large diameter to transport the vapor phase of the geothermal fluid.

A downhole pump placed in the wellbore near the bottom of the hole will prevent flashing flow. The pump increases fluid pressure in the wellbore sufficiently to prevent flashing and provide enough head to deliver the geothermal fluid to the wellhead as a liquid. Under these flow conditions the surface temperature is essentially that of the formation, and no vapor phase is present.

Downhole pumps may also be used in artesian aquifers to increase flow rates above those achievable with natural flow alone.

Armstead* indicates that technical difficulties have arisen in the development of downhole pumps for the high-temperature, high-salinity conditions encountered in geothermal reservoirs. The routine use of carbon steel pumps in conventional water wells suggests that these difficulties may be overcome by using corrosion-resistant materials and construction methods and by taking steps to avoid cavitation in the pump assembly.

Input data to the downhole pump module are:

- Average well depth
- Average well flow rate
- Well casing diameter
- Wellhead temperature
- Number of production wells
- Bottomhole static pressure
- Slotted casing height
- Formation permeability
- Annual operating hours
- Electric energy costs.

*Armstead, H. C. H., Geothermal Energy, Halstead Press, New York (1978).

From these data the module calculates:

- Bottomhole dynamic pressure
- Wellhead pressure
- Fluid velocity
- Number of pumping stages
- Hydrostatic head per stage
- Fluid horsepower per pump
- Pump efficiency
- Electric motor efficiency
- Capital cost of installed pumps
- Annual labor and maintenance costs
- Annual operating costs.

To determine the size of the downhole pump required for each well, the geothermal aquifer was modeled as a cylinder of water-bearing rock centered on the wellbore, whose height is the thickness of the producing formation. Since the well module designs wells with 1000-foot spacing, the radius of the cylinder was taken to be 500 feet. This assumes that neighboring wells do not influence the production capacity of a given well. The model further assumes that the pressure 500 feet from the wellbore is constant at the static formation pressure. In the absence of contradictory data from developed fields that have been producing for several years, this assumption appears reasonable, but it would be tenuous for fields not practicing reinjection.

The volumetric flow rate to the wellbore from the cylindrical formation is given by Amyx, Bass, and Whiting* to be:

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*Amyx, J. W., Bass, J. M., Jr., and Whiting, R. L., Petroleum Reservoir Engineering, McGraw-Hill Book Co., New York (1960), p. 77.

$$Q = \frac{2\pi kh(P_e - P_w)}{\mu \ln(r_e/r_w)}$$

where $Q$ = volumetric flow rate, cc/sec

$k$ = rock permeability, darcies

$h$ = thickness of the producing formation, cm

$\mu$ = viscosity of the geothermal fluid, cp

$P_e$ = pressure at the external boundary of the cylinder, atm

$P_w$ = dynamic pressure on the wellbore, atm

$r_e$ = radius of the external boundary, cm

$r_w$ = wellbore radius, cm.

If the volumetric flow is specified, the pressure in the wellbore at depth may be computed by rearranging the equation into the form

$$P_w = P_e - \frac{Q\mu \ln(r_e/r_w)}{2\pi kh}$$

The pressure in the wellbore must of course be greater than zero and, to avoid flashing and cavitation problems, should be greater than the minimum recommended suction head at the inlet to the downhole pump.

Cameron Hydraulic Data* indicates minimum recommended suction heads for pumping hot water (Figure 3-3). At temperatures above 184°F the curve is well correlated by:

$$\ln\left(\frac{P_{min}}{14.7}\right) = 10.16 \ln\left(\frac{T + 460}{644}\right)$$

where $P_{min}$ = minimum recommended suction pressure, psia

$T$ = water temperature at the pump suction, °F.

Below 184°F the equation yields conservative suction pressures.

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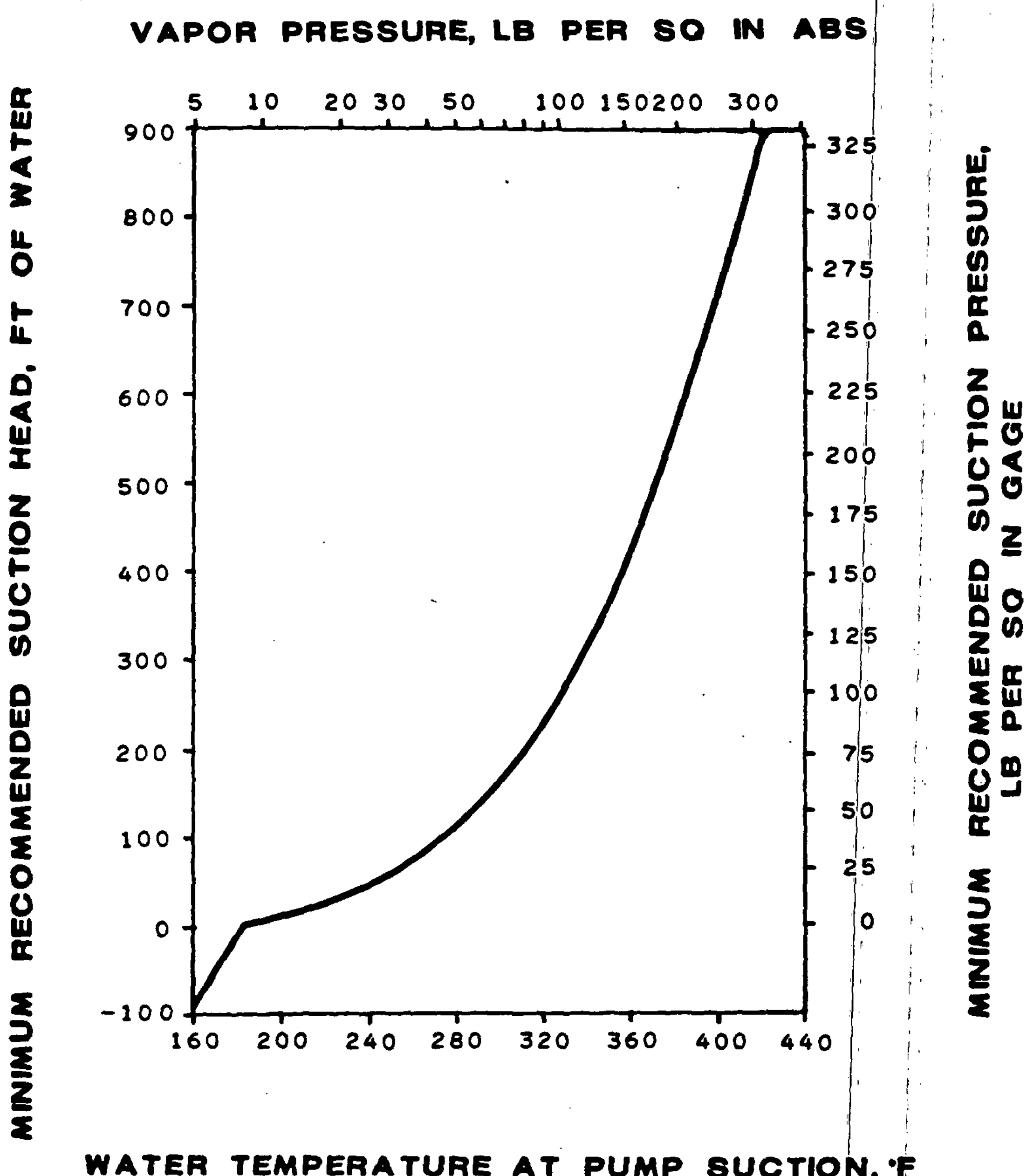
*Shaw, G. V., and Loomis, A. W., eds., Cameron Hydraulic Data, Ingersoll-Rand Co., Woodcliff Lake, N. J. (1970), p. 18.

# SUCTION HEAD REQUIREMENTS FOR PUMPING HOT WATER *




* ADAPTED FROM CAMERON HYDRAULIC DATA (1970).

Figure 3-3

Flow in the production casing is assumed to be isothermal. The wellhead pressure is fixed at the minimum recommended suction pressure unless otherwise specified. Friction losses in the production casing for laminar and turbulent flow are computed using correlations given by Peters and Timmerhaus.*

For $Re \leq 2100$, $f = \frac{16}{Re}$ laminar flow

For $Re > 2100$, $f = \frac{0.04}{Re^{0.16}}$ turbulent flow

where Re = Reynolds number

f = Fanning friction factor

The solution of a mechanical energy balance for the production casing yields the fluid horsepower required from the downhole pump. The pump design is multistage with axial flow. These are high-capacity, low-head pumps with a limit of about 25 feet of head per stage.

Typical efficiencies of axial-flow pumps were not available, so the data for centrifugal pumps given in Peters and Timmerhaus were correlated and used.

$$\ln \frac{1 - \varepsilon_p}{0.7} = -0.291 \ln \left(\frac{Q}{20}\right)$$

where Q = volumetric flow rate, gpm

$\varepsilon_p$ = centrifugal pump efficiency.

*Peters, M. S., and Timmerhaus, K. D., Plant Design and Economics for Chemical Engineers, McGraw-Hill Book Co., New York (1968).

An electric motor driver was assumed, and the efficiency data of Peters and Timmerhaus were again correlated.

$$\ln \frac{1-\varepsilon_m}{0.7} = -0.169 \ln \dot{W}_B$$

where $\dot{W}_B$ = pump brake horsepower
$\varepsilon_m$ = electric motor efficiency.

The cost for downhole pumps was estimated from the data of Guthrie.* The cost of a single-stage, axial-flow pump was deduced by subtracting electric motor driver costs from the curves containing both costs. The cost of the multistage unit was then determined by multiplying the required number of stages by the cost per stage and adding the cost of a single driver for all stages.

Guthrie's pump data are for carbon steel construction, whereas the present study requires stainless steel pumps. However, Guthrie indicates that 70 percent of a pump's capital cost is installation cost, so adjusting for the different construction material should introduce little error. Stainless steel pumps should cost roughly three times as much as those made from carbon steel. Installation costs should be equivalent for the two materials of construction.

$f_i = 0.70$
$f_m = 0$ for carbon steel
$f_m = 2.0$ for stainless steel
$I = 472.1$ Marshall and Swift cost index (1976)
$I_B = 303.3$ Marshall and Swift cost index (1970)

$$\Phi_p = [(1 + f_i)(n_s\Phi_s + \Phi_D) + f_m(n_s\Phi_s + \Phi_D)] \frac{I}{I_B}$$

*Guthrie, K. M., Process Plant Estimating, Evaluation, and Control, Craftman Book Co., Solana Beach, Calif. (1974).

where $\Phi_p$ = cost for an installed downhole pump, thousands of 1976 dollars

$f_i$ = installation cost factor

$n_s$ = number of pump stages required

$\Phi_s$ = cost of each pump stage, thousands of 1970 dollars

$\Phi_D$ = cost of electric motor driver, thousands of 1970 dollars

$f_m$ = material of construction factor

$I_B$ = cost index for the data base year

$I$ = cost index for 1976.

The cost of fitting active production wells and spare production wells is given by:

$$\Phi = \Phi_p(n_p + n_{ps})$$

where $\Phi$ = cost of downhole pumps for the field, thousands of 1976 dollars.

Annual labor and maintenance costs are charged at 10 percent of capital.

$$\Phi_{m\ell} = 0.10\Phi$$

Power requirements are computed for the active production wells by the relation:

$$\Phi_{op} = (0.7475 \times 10^{-5})n\dot{W}_M t_{on} C$$

where $\Phi_{op}$ = annual operating expenses, thousands of 1976 dollars

$\dot{W}_M$ = pump driver horsepower

$t_{on}$ = annual operating time, hours per year

$C$ = electric energy cost, cents per kilowatt hour

Transmission Module

The transmission module designs a carbon steel pipe surrounded by a layer of insulation of any thickness (including zero thickness), laid at a depth of 5 feet and covered with soil. Thermal and mechanical energy losses are determined for this system; those determinations fix temperature drops and pumping requirements.

Pipelines crossing uneven terrain must be divided into segments free of peaks or valleys. Supply pipelines (i.e., pipelines from geothermal source to application site) operate at fluid velocities in the range of 8 to 12 feet per second to minimize residence time and consequent temperature drop. Return pipelines (for reinjection) operate at lower velocities--typically 4 to 8 feet per second--with the prime objective of minimizing pumping costs. The return lines are uninsulated since heat loss is not important.

Input data to the transmission module are:

Pipeline flow rate
Pipeline length
Pipeline inlet temperature
Fluid velocity
Insulation thickness
Inlet elevation
Outlet elevation
Type of pump construction (cast iron, carbon steel, or stainless)
Inlet pressure
Annual operating hours
Electric energy costs.

From these data the module calculates:

Pipeline outlet temperature
Outlet pressure
For each pumping station:
- Number of pumps in parallel
- Number of pump stations in series
- Fluid horsepower of each pump
- Hydrostatic head of each pump
- Pump efficiency
- Electric motor efficiency

Capital cost of installed pipeline
Annual pipeline labor and maintenance costs
Capital cost of installed pumps
Annual pump labor and maintenance costs
Pump operating costs.

If the properties of the fluid in the pipeline are assumed constant throughout the length of the line, the temperature profile is logarithmic:

$$\ln \frac{T_O - T_A}{T_I - T_A} = -\left(\frac{UA}{L}\right)\left(\frac{1}{C_p}\right)\left(\frac{L}{\dot{m}}\right)$$

where $T_O$ = temperature at outlet of pipeline, °F
$T_I$ = temperature at inlet of pipeline, °F
$T_A$ = soil design temperature, °F
$C_p$ = pipeline fluid heat capacity, Btu/lb °F
$L$ = pipeline length, ft
$\dot{m}$ = mass flow rate of fluid in pipeline, lb/hr
$U$ = overall heat transfer coefficient, Btu/hr ft$^2$ °F
$A$ = surface area of pipeline, ft$^2$

The conductance of energy through a unit length of pipe is given by the reciprocal of the sum of the resistances in series.* Resistance of metal pipe and resistance at the earth's surface may be neglected.

$$\frac{UA}{L} = \frac{1}{\frac{1}{\pi D_P h} + \frac{\ln(D_I/D_P)}{2\pi K_I} + \frac{\ln[(D_E - D_I)/D_I]}{2\pi K_E}}$$

*Kreith, Frank, Principles of Heat Transfer, Intext Educational Publishers, New York (1963).

where $D_p$ = diameter of the pipeline, ft

$h$ = heat transfer coefficient for the pipeline fluid, Btu/hr ft$^2$ °F

$D_I$ = outside diameter of the insulation, ft

$k_I$ = thermal conductivity of the insulation, Btu/hr ft °F

$D_E$ = depth of the pipeline trench, ft

$k_E$ = thermal conductivity of the soil, Btu/hr ft °F.

The depth of the pipeline trench is taken to be 5 feet; the heat capacity of the pipeline fluid, 1 Btu/lb °F; the thermal conductivity of the insulation, 0.1 Btu/hr ft °F, which corresponds to that of asbestos; and the soil thermal conductivity, 1.5 Btu/hr ft °F, which is for wet soil. Pipelines designed with this model should be less than 2 to 3 feet in diameter to ensure sufficient soil coverage.

The soil design temperature is not fixed. For locations in the northern United States a value of 32°F is recommended; for warm climates in southern regions of the U.S. values as high as 60°F may be used. The inside heat transfer coefficient is given by the Dittus Boelter equation:*

$$Nu = \frac{hD_p}{k} = 0.023Re^{0.8}Pr^{0.3}$$

where $k$ = thermal conductivity of the pipeline fluid, Btu/hr ft °F

$Pr$ = Prandtl number

$Nu$ = Nusselt number

The equation is valid for cooling fluids in turbulent flow ($Re > 2100$), Prandtl numbers greater than 0.7, and pipelines with length-to-diameter ratios greater than 60.

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*Bennett and Myers, Momentum, Heat and Mass Transfer, McGraw-Hill, New York (1974).

The velocity of the fluid in the pipeline provides a simple design variable for sizing the pipeline and pumps. The economic design velocity for pipe flow that minimizes the sum of pumping costs (which increase with increasing velocity) and pipe costs (which decrease with increasing velocity) is around 6 feet per second. No value is assigned to the thermal energy of the fluid in the pipe when making this calculation.

The loss of geothermal energy in the pipeline is an additional cost which makes the economic velocity for supply pipelines higher than that which would otherwise be calculated. A value of 10 feet per second is recommended.

A mechanical energy balance is calculated to determine pump size. Pump capacity is limited to 10,000 gallons per minute and head to 250 feet of water. These are the limits indicated by Perry* for single-stage centrifugal pumps.

$$-\dot{W}_F = \dot{m}\frac{g}{g_c}(z_O - z_I) + \frac{(P_O - P_I)}{\rho} + F$$

where $\dot{W}_F$ = pump work required, ft $lb_f$/hr
$\dot{m}$ = mass flow rate, lb/hr
$z_O$ = pipeline outlet elevation, ft
$z_I$ = pipeline inlet elevation, ft
$P_O$ = pipeline outlet pressure, $lb_f/ft^2$
$P_I$ = pipeline inlet pressure, $lb_f/ft^2$
$F$ = friction loss, ft $lb_f$/lb
$\rho$ = fluid density, $lb/ft^3$
$g$ = acceleration of gravity, $ft/sec^2$
$g_c$ = gravitational constant, ft-lb/$lb_f$ $sec^2$

*Perry, John H., Chemical Engineers Handbook, McGraw-Hill Book Co., New York (1963).

Friction loss is given in terms of the Fanning friction factor:

$$F = \frac{2f\,V^2 L}{g_c D_p}$$

where $V$ = fluid bulk velocity, ft/sec

$L$ = pipeline length, ft

$D_p$ = pipeline diameter, ft

The computed friction loss is for straight runs of new pipe. An additional 25 percent is added to account for friction losses in pipe fittings and valves and increased pipe roughness due to corrosion and scaling.

A cost estimate for the pipeline is developed from the pipe size and length, insulation thickness, and the number and size of pumps. Costs of pipe and insulation are developed separately from those of the pumps. Data from Guthrie were correlated to give expressions for material and labor for constructing the pipeline. The cost for linear pipe of carbon steel with average fittings is:

$$\ln \frac{\Phi_M}{20L} = 0.520 \ln \frac{D_P}{2}$$

where $\Phi_M$ = pipe cost in 1970 dollars.

Labor costs for pipe handling, aligning, trenching, and backfilling are:

$$\ln \frac{\Phi_L}{11.6L} = 0.390 \ln \frac{D_I}{2}$$

where $\Phi_L$ = pipe installation labor cost in 1970 dollars.

The insulation diameter in the above expression accounts for the larger trench and backfill required for insulated pipe.

Insulation cost is estimated at \$40 per cubic foot, and the installation labor factor is given by Guthrie as 2.25 times capital.

$$\Phi_c = \frac{\pi}{4}(D_I^2 - D_p^2) \times L \times (\$40/\text{cu ft})$$

$$f_\ell = 2.25$$

$$\Phi_I = (1 + f_\ell)\Phi_c$$

where $\Phi_c$ = insulation cost in 1970 dollars
$f_\ell$ = installation labor factor
$\Phi_I$ = installed insulation cost in 1970 dollars.

The total cost of the pipeline is the sum of the pipe, labor, and insulation costs.

$$\Phi = \left(\frac{\Phi_M + \Phi_L + \Phi_I}{1000}\right) \frac{I}{I_B}$$

where $\Phi$ = installed pipeline capital cost in thousands of 1976 dollars.

Annual labor and maintenance costs are taken as 4 percent of capital costs.

$$\Phi_{m\ell} = 0.04\Phi$$

Operating costs are zero.

Pumping station costs are estimated using the correlations for pump and motor efficiency and costs described for reinjection pumps.

$$\Phi = \Phi_p(n_p n_s)$$

$$\Phi_{m\ell} = 0.10\Phi$$

$$\Phi_{op} = (0.7475 \times 10^{-5}) n_p n_s \dot{W}_M t_{on} C$$

where $\Phi_p$ = installed cost of each pump, thousands of 1976 dollars
$n_p$ = number of pumps in parallel at each pumping station
$n_s$ = number of pumping stations in the pipeline
$\dot{W}_M$ = electric motor horsepower for each pump.

## Flash Unit Module

Flash units provide a simple means of producing clean, low-pressure steam from geothermal brines. Uncondensable gases dissolved in the brine, which will also flash into the vapor stream of the flash unit, can pose corrosion or pollution problems. The quantity and type of these gases is brine-dependent, and the design of the geothermal energy system must account for their effects.

Flash units may be designed as vertical or horizontal tanks. Horizontal tanks are recommended for the high liquid flow rates typical of geothermal systems. Further, horizontal vessels are less expensive than vertically fabricated vessels. The design procedure used here is derived from Aerstin and Street.*

All units are assumed to be fitted with wire mesh demister pads.

Input data to the flash unit module are the following:

- Number of units in parallel
- Feed flow rate
- Feed temperature
- Flash steam pressure
- Material of construction (carbon steel, stainless steel lined, or stainless steel shell)
- Vertical or horizontal design
- Length-to-diameter ratio (horizontal vessels only).

From these data the module calculates:

- Flash steam flow rate
- Bottoms flow rate

*Aerstin, F., and Street, G., Applied Chemical Process Design, Plenum Press, New York (1978).

Flash unit diameter
Unit height or length
Liquid residence time
Installed capital cost
Annual labor and maintenance costs.

Material and energy balances for the flash unit describe the steam flow rates:

$$\dot{m}_v = \dot{m}_f \left(\frac{h_f - h_\ell}{h_v - h_\ell}\right)$$

$$\dot{m}_\ell = \dot{m}_f - \dot{m}_v$$

where $\dot{m}_f$ = feed stream mass flow rate, lb/hr
$h_f$ = feed stream enthalpy, Btu/lb
$\dot{m}_v$ = overhead vapor stream flow rate, lb/hr
$h_v$ = vapor stream enthalpy, Btu/lb
$\dot{m}_\ell$ = bottom liquid stream flow rate, lb/hr
$h_\ell$ = liquid stream enthalpy, Btu/lb.

For vertical vessels, the diameter is chosen so that vapor velocity in the vessel above the feed is less than a design velocity which limits entrainment of liquid drops to an acceptable level.

$$V_{load} = V_v \left(\frac{\rho_v}{\rho_\ell - \rho_v}\right)^{\frac{1}{2}}$$

$$D_f = \left(\frac{V_{load}}{(\pi/4)(0.227)R_{dv}}\right)^{\frac{1}{2}}$$

where $V_{load}$ = a measure of the entrained liquid load, $ft^3/sec$
$V_v$ = vapor load in the flash unit, $ft^3/sec$
$\rho_v$ = vapor density, $lb/ft^3$
$\rho_\ell$ = liquid density, $lb/ft^3$
$D_f$ = flash unit diameter, ft
$R_{dv}$ = a design parameter.

A value of 1.15 for the design parameter is recommended for vessels that may experience surges.

Multiple units are designed to limit the vessel diameter to less than 15 feet. The height of the vessel above the feed must be sufficient to allow for liquid drop disengagement; a minimum of 1 foot is required.

$$H_d = 0.75 D_f$$

where $H_d$ = disengagement height, ft.

An additional foot of height is added to allow space for the demister pad, and a vapor space of 1 foot between the feed point and the liquid levels is necessary.

$$H_v = H_d + 2$$

where $H_v$ is the vapor space height in feet.

The tank space below the feed is designed to provide sufficient liquid holdup. Holdup times of 2 to 10 minutes are recommended in the literature. For geothermal designs, the large liquid volumes encountered may allow satisfactory operation at much lower holdup times.

$$H = \frac{\dot{m}_\ell \Theta}{(\pi/4)(60 D_f{}^2 \rho_\ell)}$$

where H = liquid level in the flash unit, ft

$\Theta$ = liquid residence time, min.

The total tank height is the sum of vapor and liquid sections.

$$H = H_\ell + H_v$$

where H = tank height, ft.

The dominant factor in the design of horizontal flash units is the liquid residence time. Recommended values are from 5 to 15 minutes. Geothermal applications may produce satisfactory operation at smaller residence times by virtue of the high liquid flow rates. A conservative value of 2.5 minutes is used in the model.

The vessel length-to-diameter ratio is specified to fix the volume as a function of diameter. Length-to-diameter ratios of 2 to 4 produce vessels of minimum cost per unit volume. Selecting a liquid residence time fixes the volume and the diameter of the vessel. The vessel is then sized by selecting a liquid level for the tank. Typical designs fix the liquid height at 80 percent of the diameter, provided a minimum of 1 foot is available for vapor space. The liquid volume in the tank is given by:

$$f_v = 1 - f_\ell$$

$$d_r = |1 - 2f_v|$$

$$f = \cos^{-1}(d_r) - d_r(1 - d_r^2)^{1/2}$$

$$\text{If } f_v \leq 0.5, \quad f_a = 1 - f/2$$

$$\text{If } f_v > 0.5, \quad f_a = f/2$$

$$V = \frac{\dot{m}_\ell \Theta}{60\rho_\ell} = \frac{\pi}{4}(f_a D_f^2 H)$$

where $V_\ell$ = liquid volume of the tank, cu ft

$f_a$ = fraction of cross-sectional area filled by liquid

$D_f$ = tank diameter, ft

$H$ = tank length, ft

$f_v$ = fraction of the diameter which is vapor filled

$f_\ell$ = fraction of the diameter which is liquid filled.

Incorporating the length-to-diameter ratio fixes the tank diameter:

$$D_f^3 = \frac{\dot{m}_\ell \Theta}{(\pi/4)(60 d_\ell f_a \rho_\ell)}$$

where $d_\ell$ = length-to-diameter ratio.

Sufficient tank length for disengagement is then checked.

$$H_d = \left(\frac{V_{load}}{(\pi/4)(0.22D_f)}\right)\left(\frac{f_v}{f_a R_{dh}}\right)$$

where $H_d$ = disengagement length, ft

$R_{dh}$ = a design parameter for horizontal tanks.

In this case, a value of 0.167 is recommended for the design parameter. If H is greater than $H_d$, sufficient length is available; if H is less than $H_d$, $f_v$ must be increased until sufficient disengagement length is determined.

Data from Guthrie are used to estimate both vertical and horizontal vessel costs.

$$\ell n(Y) = -0.661 + 1.036\,\ell n(H)$$

$$\ell n(X/Y) = 1.348\,\ell n(D/2)$$

$$\ell n\left(\frac{\Phi v}{1000}\right) = 0.801\,\ell n(X/4.0) \quad \text{for vertical vessels}$$

$$\ell n\left(\frac{\Phi_v}{800}\right) = 0.771\,\ell n(X/5.0) \quad \text{horizontal vessels}$$

where $\Phi_v$ = vessel cost in thousands of 1970 dollars.

Factors are then included for material of construction, installation, and design pressure:

$f_i$ = 3.16 vertical vessels

$f_i$ = 2.05 horizontal vessels

$f_m$ = 1.00 carbon steel

$f_m$ = 2.30 stainless-steel clad

$f_m$ = 3.50 solid stainless steel

$$\ell n(f_p) = 0.463\,\ell n(P_v/50)$$

where $f_i$ = installation factor

$f_m$ = material of construction factor

$f_p$ = design pressure correction factor

$P_v$ = design pressure, psig.

The total cost of the installed vessel is given by:

$$\Phi = n_f \Phi_v (f_m f_p + f_i) \frac{I}{I_B}$$

where $n_f$ = number of flash units

$\Phi$ = installed vessel cost, thousands of 1976 dollars.

Maintenance and labor are taken at 5 percent of capital per year.

$$\Phi_{m\ell} = 0.05\Phi$$

Operating costs are assumed to be zero.

## Heat Exchanger Module

Heat exchangers are designed using overall heat transfer coefficients and log mean temperature differences. The overall heat transfer coefficients vary strongly with the phase of the fluids in the heat exchangers. The following values are adequate for estimates of heat exchanger designs in geothermal systems:

| | |
|---|---|
| Brine/Boiling Fluid | 250 Btu/hr $ft^2$ °F |
| Brine/Liquid | 125 Btu/hr $ft^2$ °F |
| Brine/Vapor | 8 Btu/hr $ft^2$ °F |

Estimates for other fluid systems are available in Perry. The estimates for geothermal brines fall in the lower range of suggested values as a result of scaling allowances.

Input data to the heat exchanger module are:

- Number of exchangers in parallel
- Exchanger type (floating head, reboiler, or plate-and-frame)
- Overall heat transfer coefficient
- Hot fluid outlet temperature
- Cold fluid mass flow rate
- Cold fluid inlet temperature
- Cold fluid outlet temperature
- Heat exchanger surface area
- Overall heat transfer coefficient

(last six items: three out of six required)

From these data the module calculates:

- The three factors not specified above
- Log mean temperature difference
- Installed capital cost
- Annual labor and maintenance costs.

The heat exchanger performance is modeled by:

$$\dot{Q} = \dot{m}_H(h_{H,i} - h_{H,o})$$

$$m_c = \frac{\dot{Q}}{h_{c,o} - h_{c,i}}$$

$$\Delta T_{\ell m} = \frac{(T_{H,i} - T_{c,o}) - (T_{H,o} - T_{c,i})}{\ln\left(\frac{T_{H,i} - T_{c,o}}{T_{H,o} - T_{c,i}}\right)}$$

$$A = \frac{\dot{Q}}{U\Delta T_{\ell m}}$$

where $\dot{Q}$ = heat transfer rate, Btu/hr

$\dot{m}_H$ = mass flow rate of the hot-side fluid, lb/hr

$h_{H,i}$ = enthalpy of the hot-side fluid at the exchanger inlet, Btu/lb

$H_{H,o}$ = enthalpy of the hot-side fluid at the exchanger outlet, Btu/lb

$\dot{m}_c$ = mass flow rate of the cold-side fluid, lb/hr

$h_{c,i}$ = enthalpy of the cold-side fluid at the exchanger inlet, Btu/lb

$h_{c,o}$ = enthalpy of the cold-side fluid at the exchanger outlet, Btu/lb

$\Delta T_{\ell m}$ = log mean temperature difference, °F

U = overall heat transfer coefficient, Btu/hr ft$^2$ °F

A = required heat transfer area, ft$^2$.

The cost of floating-head heat exchangers and reboilers are correlated from the data of Guthrie. Factors are applied for exchanger type, materials of construction, design pressures, and installation, as follows:

| | |
|---|---|
| $f_d = 1.0$ | floating head |
| $f_d = 1.35$ | reboiler |
| $f_m = 0$ | carbon steel shell/carbon steel tubes |
| $f_m = 1.7 + 0.217 \ln(A/100)$ | carbon steel shell/stainless steel tubes |
| $f_m = 2.7 + 0.217 \ln(A/100)$ | stainless steel shell/stainless steel tubes |

$$\ln \frac{f_s}{0.05} = 0.650 \ln(P_s/100)$$

$$\ln \frac{f_t}{0.04} = 0.306 \ln(P_t/100)$$

$$f_i = 2.17$$

where $P_s$ = shell side design pressure, psig
$P_t$ = tube side design pressure, psig
$f_d$ = exchanger type factor
$f_m$ = material of construction factor
$f_s$ = shell side pressure correction factor
$f_t$ = tube side pressure correction factor
$f_i$ = installation factor.

The exchanger area is limited to less than 25,000 square feet. Multiple units are placed in parallel to ensure that the areas of individual units are less than the maximum value. The base cost of individual exchangers is given by:

$$\ln(\Phi_x/3000) = 0.671 \ln(A/200)$$

where $\Phi_x$ = base cost of a heat exchanger in thousands of 1976 dollars.

The cost of the installed units is:

$$\Phi = n_x \Phi_x [(f_d + f_t + f_s) f_m + f_i](I/I_B)$$

where $\Phi$ = installed capital cost of the heat exchangers in thousands of 1976 dollars.
$n_x$ = number of exchangers in parallel.

Labor and maintenance costs are charged at 10 percent of capital per year.

$$\Phi_{m\ell} = 0.10\,\Phi$$

Operating costs are zero.

## Reinjection Pump Module

Reinjection pumps are surface pumps and as such are standard units. Large-capacity, high-head pumps are generally required for geothermal reservoir applications. Designs with high reinjection-to-production well ratios trade higher operating costs of reinjection pumps for lower capital costs of additional reinjection wells. At low reinjection flow rates, gravity feed may be sufficient so that pumps are not required.

Input data to the reinjection pump module are:

- Average well depth
- Number of reinjection wells
- Total reinjection flow rate
- Well casing diameter
- Reinjection temperature
- Bottomhole static pressure
- Slotted casing height
- Formation permeability
- Reinjection pressure
- Material of construction (cast iron, carbon steel, or stainless steel)
- Annual operating hours
- Electric energy costs.

From these data the following results are calculated:

- Bottomhole dynamic pressure
- Hydrostatic head
- Fluid horsepower of each pump
- Pump efficiency
- Electric motor efficiency
- Fluid velocity

Capital cost of installed pumps
Annual labor and maintenance
Annual operating costs.

The reinjection model is the same as that for downhole pumps, except that the downhole pump is replaced by a reinjection pump at the wellhead and the flow direction is reversed. A reinjection pump is designed for each active and spare reinjection well. Minor modifications of the routine would allow a single pump to serve multiple wells, if desired.

Isothermal flow in the wellbore and the rock formation is assumed. The volumetric flow rate in each active reinjection well is known, and the static downhole pressure is fixed as a constant at a radius of 500 feet from the wellbore. The dynamic pressure in the wellbore can then be determined from the equation

$$P_w = P_e + \frac{Q \mu \ln(r_e/r_w)}{2\pi kh} .$$

The dynamic downhole pressure will be greater than the static downhole pressure. If the pressure in the wellbore is too high, hydraulic fracturing of the formation rock may occur, increasing the effective permeability of the formation and therefore reducing pumping costs. However, high formation pressures are thought to induce seismic activity and some state statutes limit reinjection pressure to 0.5 psi per foot of well depth. Reinjection for extended periods of time at pressures greatly exceeding this guideline is to be avoided.

The solution of the mechanical energy balance for the production casing yields the fluid horsepower required for the reinjection pumps. The selected design is for single-stage centrifugal pumps which are limited to a head of less than 250-300 feet and a capacity of less than 10,000 gallons per minute.

The centrifugal pump and electric motor efficiency correlations of the Peters and Timmerhaus data were used to determine pump and driver sizes.

The cost estimate is taken from Guthrie:

$$\ln \frac{\Phi_R}{600} = 0.470 \ln \frac{\dot{W}_F}{0.5834}$$

where $\Phi_R$ = cost of reinjection pump in thousands of 1970 dollars

$\dot{W}_F$ = fluid horsepower of each reinjection pump.

$$\frac{\Phi_M}{5000} = \frac{\dot{W}_B}{200}$$

where $\Phi_M$ = cost of an electric motor drive in thousands of 1970 dollars

$\dot{W}_B$ = brake horsepower of the reinjection pump.

Factors for installation, materials of construction, suction pressure, and indexing to 1976 complete the cost estimate:

$f_i$ = 2.30

$f_m$ = 1.0 cast iron

$f_m$ = 1.38 cast steel

$f_m$ = 2.03 stainless steel

$f_p$ = 1.00 for suction pressure <150 psi

$f_p$ = 1.62 for suction pressure 150-500 psi

$f_p$ = 2.12 for suction pressure 500-1000 psi

$$\Phi_p = [(1 + f_i)(\Phi_R + \Phi_M) + f_m f_p \Phi_R + \Phi_m](I/I_B)$$

where $\Phi_p$ = cost of the installed reinjection pump in thousands of 1976 dollars

$f_i$ = installation factor

$f_m$ = material of construction factor

$f_p$ = suction pressure factor.

The cost of fitting each active and spare reinjection well is:

$$\Phi = \Phi_p(n_p/r + n_{rs})$$

where $\Phi$ = installed capital cost of well field reinjection pumps in thousands of 1976 dollars.

The number of active reinjection wells, $n_p/r$, must be rounded to the next highest integer.

Annual labor and maintenance costs are charged at 10 percent of capital.

$$\Phi_{m\ell} = 0.10\,\Phi$$

Power requirements are computed for the active reinjection wells:

$$\Phi_{op} = (0.7475 \times 10^{-5})(np/r)\dot{W}_M t_{on} C$$

Power requirements are assumed to be the only operating costs.

Process Modification Module

All costs incurred in modifying a process to utilize geothermal energy must be charged to the geothermal energy system. Capital or operating costs may be more or less than those of a process using conventional energy sources. These costs are handled in the same manner as those for each piece of equipment in the geothermal system. The annual maintenance and labor costs may be charged as a fraction of capital. Operating costs are those which are functions of production rate.

Input data to the process modification module are:

Additional capital cost of the installed process
Additional annual labor and maintenance costs
(as a percentage of capital costs)
Reduction in annual operating costs
Annual operating hours
Equipment lifetime
Rate of return on equity.

These data are passed to the economic analysis model.

## Economic Model

Two types of economic studies may be performed with the economic analysis model. In the first, costs of production, transmission, energy extraction, and modified process equipment are charged to the price of the geothermal energy utilized by the process, giving the cost of geothermal energy utilized by the modified process at a specified rate of return. If energy demands are equivalent for the modified geothermal process and a conventional process, the cost of utilized geothermal energy may be directly compared with the cost of utilized energy in a conventional system. In making this comparison, process energy utilization efficiencies and the costs of pollution abatement equipment must be charged against the cost of utilized energy in the conventional process, since these factors are included in the geothermal energy cost. This calculation procedure was used in our study integration.

A second type of economic evaluation is required when the energy demands of the geothermal process and the conventional process differ. The value of energy in the conventional process replaced by the geothermal system is considered a revenue (i.e., a negative operating cost) to the geothermal system. The rate of return is adjusted until a zero cost is determined for the utilized geothermal energy. This rate of return is the incremental rate of return for the geothermal process compared to the conventional process.

The economic routine calculates its results on a unit-by-unit basis so that different equipment lifetimes and rates of return can be accommodated. Investments involving borrowed capital may be analyzed as well as total equity investments.

The results of the routine contain two measurements of energy utilization efficiency. The design utilization factor is a ratio of the annual geothermal energy utilized to the quantity of energy that could be extracted from the geothermal fluid at design wellhead and reinjection temperatures. The available energy utilization factor is the ratio of the annual utilized geothermal energy to the maximum energy that could be extracted as heat from the geothermal fluid. The maximum quantity of extracted energy corresponds to reinjection of the geothermal fluid at the thermal sink temperature.

These two measures of efficiency lead to the calculation of three geothermal energy costs:

1. Utilized energy cost--the cost of geothermal energy utilized by the process.

2. Design capacity energy cost--the cost of geothermal energy that could be extracted from the geothermal fluid at design temperatures. For this calculation, the operating costs are scaled to continuous operation.

3. Available energy cost--the cost of the maximum energy that can be extracted from the geothermal fluid. Again, continuous operating costs are necessary.

An economic summary is displayed on a unit-by-unit basis on the output forms in Appendix B (published under separate cover), accompanied by process totals so that the significant elements of total energy cost are easily identified. The greatest potential for large reductions in total cost lies in those elements of the process which constitute large percentages of the total product cost.

Input data to the economic model are:

- Geothermal supply temperature
- Geothermal return temperature
- Thermal sink temperature
- Total geothermal production
- Total annual energy demand, or
- Annual operating hours
- Debt/equity ratio
- Interest rate
- Tax rate
- For each piece of equipment in the process:
    - Installed capital cost
    - Annual labor and maintenance costs
    - Annual operating costs
    - Annual operating hours
    - Equipment lifetime
    - Return on equity.

The following results are calculated:

- Design utilization factor
- Available energy utilization factor
- For each piece of equipment:
    - Annual operating income before depreciation and taxes
    - Annual taxable income
    - Annual interest and debt amortization
    - Annual depreciation allocation to equity

Total annual revenue
Available energy cost
Design capacity energy cost
Utilized energy cost
Percent of total utilized cost.

The energy that would be supplied by the geothermal system with continuous operation is given by:

$$E_d = \frac{(h_w - h_r)F_T(8766)}{10^6}$$

where $h_w$ = enthalpy of the geothermal fluid at the wellhead, Btu/lb
$h_r$ = enthalpy of the geothermal fluid at the reinjection wells, Btu/lb
$F_T$ = total brine flow rate, lb/hr
$E_d$ = design capacity energy extraction rate, $10^6$ Btu/year.

The energy that would be supplied by the geothermal system with continuous operation and reinjection at the lowest available temperature is:

$$E_{max} = \frac{(h_w - h_{min})F_T(8766)}{10^6}$$

where $h_{min}$ = enthalpy of the geothermal fluid at the thermal sink temperature
$E_{max}$ = maximum energy that can be extracted from the geothermal fluid.

The thermal sink temperature was taken to be 80°F.

Two measures of energy utilization efficiency can be determined.

$$\varepsilon_u = \frac{E_u}{E_d}$$

$$\varepsilon_t = \frac{E_u}{E_{max}}$$

where $E_u$ = total geothermal energy actually utilized by the process, $10^6$ Btu/year

$\varepsilon_u$ = design utilization efficiency

$\varepsilon_t$ = efficiency based on maximum possible energy extraction.

The design utilization efficiency is a measure of the annual operating time of the designed process. The efficiency of the geothermal system based on the maximum possible energy extraction is a measure of both operating time and the extraction efficiency as indicated by the reinjection temperature. High efficiencies indicate operation at design capacity for most of the year and reinjection at temperatures near the thermal sink temperature.

The annual cost of each unit in the geothermal process is divided by the three energy quantities, $E_u$, $E_d$, and $E_{max}$. These costs are computed as follows:

The cash flow on the equity fraction of the capital investment is the sum of the profit on equity plus the depreciation of the equity.

$$C_E = C_D + P_A = f_E \Phi \left( \frac{i_E(1 + i_E)^{n_L}}{(1 + i_E)^{n_L} - 1} \right)$$

where $C_E$ = annual cash flow on equity capital, thousands of dollars

$C_D$ = annual depreciation on equity capital, thousands of dollars

$P_A$ = annual profit after taxes, thousands of dollars

$f_E$ = fraction of the capital that is equity

$\Phi$ = capital cost of each unit, thousands of 1976 dollars

$i_E$ = compound interest rate of return on the equity fraction

$n_L$ = lifetime of the unit, years.

Straight-line depreciation of the equity fraction is used over the lifetime of the unit.

$$C_D = \frac{f_E \Phi}{n_L}$$

The annual taxes are:

$$C_T = \left(\frac{f_T}{1 - f_T}\right) P_A$$

where $C_T$ = annual taxes paid on the income from the unit, thousands of dollars

$f_T$ = effective tax rate for the installation.

The profit before taxes is the sum of profit after taxes and the annual taxes.

$$P_B = P_A + C_T$$

The payment of interest and principal on borrowed capital is deductible. The principal is considered here as the depreciation scheme for the borrowed capital. This results in a sinking fund depreciation scheme.

$$P_D = (1 - f_E)\Phi\left[\frac{i_D(1 + i_D)^{n_L}}{(1 + i_D)^{n_L} - 1}\right]$$

where $P_D$ = annual payment of principal and interest on borrowed capital

$i_D$ = interest on borrowed capital.

The net income after operating expenses is the sum of profit before taxes, debt payment, and equity depreciation.

$$C_N = P_B + P_D + C_D$$

where $C_N$ = annual net income, thousands of dollars.

The total annual income is the sum of the net income, maintenance and labor costs, and operating expenses.

$$C_T = \Phi_{m\ell} + \Phi_{op} + C_N$$

where $C_T$ = total annual income required on the unit, thousands of dollars

$\Phi_{op}$ = annual operating expenses of the unit, thousands of dollars

$\Phi_{m\ell}$ = annual maintenance and labor cost for the unit, thousands of dollars.

The utilized energy cost is the total annual cost divided by the utilized energy.

$$P_u = \frac{1000\, C_T}{E_u}$$

where $P_u$ = utilized energy cost, dollars per million Btu.

If the designed system were utilized year round, the design capacity energy cost would be:

$$P_c = \frac{\left\{\Phi_{m\ell} + C_N + \Phi_{op}\left(\frac{8766}{t_{on}}\right)\right\}1000}{E_d}$$

where $P_c$ = design capacity energy cost, dollars per million Btu

$t_{on}$ = annual operating time for the unit, hours

If the maximum energy could be extracted by the given design, the cost of energy would be a minimum.

$$P_{min} = \frac{\left\{\Phi_{m\ell} + C_N + \Phi_{op}\left(\frac{8766}{t_{on}}\right)\right\}1000}{E_{max}}$$

The values for each unit are summed to determine the costs for the entire geothermal energy system.

APPENDIX C

# GEOTHERMAL SPACE HEATING COST-SIMULATION MODEL DESCRIPTION

EG&G Idaho's user-oriented micro-computer will approximate cost for several types of geothermal space heating applications. Simplifying assumptions, unit cost, and unit heat load information are built into the program, allowing cost calculations based on a minimial user input. Types of applications which can be modeled are (1) single-family home, (2) apartment building, (3) school, (4) hospital, and (5) commercial greenhouse. Required input, acceptable ranges, and user-default values are shown in Table I.

Based on the input data and built-in values, the computer assigns a winter design temperature (see Table II), and computes and displays the design and annual heat loads, capital cost for supply and heating systems, and the total capital cost of the geothermal system. Unit and annual energy costs and total annual cost for the geothermal system are computed by amortizing the appropriate capital cost at 10% interest over 20 years and adding costs for maintenance and power consumption for pumping.

A number of simplifying assumptions are employed in the cost modeling:

1. Heat available from the geothermal fluid is limited to a temperature differential of 25°F; the flow rate F, in gpm, required to heat load, H, in Btu/hr, is F = H/12500.
2. Pumps are assumed to be 80% efficient; pumping is from the depth of the resource or 300 ft, whichever is less; pumps are sized for wellhead pressure of 100 ft, the pumping depth, and required flow rate, with a supply-pipe loss of 7 ft of head per 1000 ft of pipe. Pumps are costed at \$50 + \$350 per horsepower.
3. Heat load is a function of the application type, size, and the design temperature parameter (discussed below).
4. Heating system costs are functions of the application type, size, and geothermal water temperature.
5. Supply pipe and cost is a function of the flow rate.
6. Annual maintenance is 3% of capital cost.
7. Disposal cost and tax credits are not considered.
8. Well cost is a function of well depth and flow rate. An input of 0 for resource depth results in an assigned cost for a collection system.

Equations and data used in the computer model are presented.

1. Design Temperature Difference: $\Delta T$ = 65°F - Winter Design Temperature (Table III)
2. Annual utilization factor: AN = Fahrenheit Degree Days/(365 X $\Delta T$)

3. Design Heat Load: H = Area X $\Delta$T X Unit Heat Load (Table III)

4. Annual Heat Load: AH = H X AN X 8760

5. Heating System Cost: HC = Area X Unit Heating System Cost (Table III)

6. Maximum Geothermal Flow: F = H/12500

7. Pump Horsepower (80% Efficiency): HP = gpm x 3.16 X $10^{-4}$ X [Pump Depth + 100 + (7 x $10^{-3}$) X Distance to Supply]

8. Pump Power Cost: PP = $/Kwh X HP x 0.7457 X 8760 X AN

9. Pump Cost: PC = $50 + 350 X HP

10. Supply Pipe Cost: SP = Distance to Supply X Pipe Unit Cost (Table IV)

11. Well Cost: W = Depth X Well Unit Cost (Table V)

12. Supply Capital Cost: SC = W + PC + SP

13. Total Capital Cost: CC = SC + HC

14. Annual Maintenance: AM = 0.03 X CC

15. Energy Unit Cost: $EC = \frac{10^6}{AH} \frac{SC \times 0.1 (1.1)^{20}}{(1.1)^{20} - 1}$

16. Annual Cost: $AC = \frac{CC \times 0.1 (1.1)^{20}}{(1.1)^{20} - 1} + AM + PP$

TABLE I

DEFAULT VALUES AND ALLOWABLE RANGES FOR USER INPUT

| Parameter | Acceptable Range | |
|---|---|---|
| Type of Application | | |
| 1 = Single-Family Home | 1,000 - 5,000 ($ft^2$) | 1000 |
| 2 = Apartment Building | 5,000 - $10^6$ ($ft^2$) | 5000 |
| 3 = School | 10,000 - ($ft^2$) | 10000 |
| 4 = Hospital | 10,000 - ($ft^2$) | 10000 |
| 5 = Commercial Greenhouse | 10,000 - $10^6$ ($ft^2$) | 10000 |
| Fahrenheit Degree Days | 0 - 10,000 | 5000 |
| Distance to Supply | $\geq$ 0 (ft) | 100 |
| Depth to Resource | 0 - 10,000 | 0 |
| Resource Temperature (°F) | 33 - 600 | 180 |

TABLE II

WINTER DESIGN TEMPERATURE DETERMINED FROM DEGREE DAYS

| Fahrenheit Degree Days | Winter Design Temperature (°F) |
|---|---|
| 1000 | 25 |
| 2000 | 15 |
| 3000 | 5 |
| 4000 | 0 |
| 5000 | -5 |
| 6000 | -10 |
| 7000 | -15 |
| 8000 | -20 |
| 9000 | -25 |
| 10000 | -30 |

TABLE III

UNIT HEAT LOADS AND HEATING SYSTEM COSTS

| Application Type | Unit Heat Load(1) (Btu/hr ft$^2$ °F) | Heating System Unit Cost(2) ($/ft$^2$) |
|---|---|---|
| 1 | 0.5 | 2.00 |
| 2 | 0.4 | 1.20 |
| 3 | 1.0 | 3.50 |
| 4 | 1.0 | 5.50 |
| 5 | 1.25 | 1.30 |

(1) Function of area, design temperature difference
(2) Function of area, geothermal supply temperature; for supply temperatures <180°F unit value is multiplied by the ratio 180/supply temperature.

TABLE IV

SUPPLY PIPE UNIT COSTS

| Maximum Flow Rate (gpm) | Unit Pipe Cost ($/ft) |
|---|---|
| 100 | 10 |
| 100 - 600 | 16 |
| 601 - 1000 | 25 |
| 1001 - 1500 | 33 |
| 1500 | 40 |

TABLE V

WELL UNIT COST

| Depth (ft) | Unit Cost ($/ft) |
|---|---|
| 0 - 1000 | 90 |
| 1001 - 2000 | 120 |
| 2001 - 3000 | 180 |
| >3000 | Depth (189.35 - 0.03751 X depth + 4.994 X $10^{-6}(\text{Depth})^2$) |

NOTE: Domestic type wells (flow <100 gpm, depth $\leq$1000 ft) are costed at $20/ft.

# APPENDIX D

## Cost Sensitivity Analysis of Potential 4,000 gpm Geothermal Energy Resource at Williams AFB

The discussion and data in the main text (pages 47 through 51) describing the geothermal potential at Williams AFB assume an estimated aquifer thickness of 150 feet with permeability ranging from 100 mD down to 25 mD. The producing aquifer thickness seems able to provide 500 gpm and 1,000 gpm, assuming permeabilities of 25 mD and 50 mD, respectively, at a relatively modest cost. However, when the 150-foot thick aquifer with a permeability of 100 mD and a static downhole pressure of 4,300 psia is required to produce 4,000 gpm of geothermal brine, pumping becomes very expensive.

Since a 4,000 gpm flow rate is considered potentially feasible at Williams AFB, a sensitivity analysis is appropriate to ascertain how changes in the estimated geologic characteristics might substantially affect the geothermal economics. If we take the well depth (10,000 feet), temperature (345°F), and static downhole pressure (4,300 psia) as fixed, then aquifer thickness and permeability remain as the geologic variables.

A sensitivity analysis of capital investment and direct-use energy cost to changes in aquifer thickness and permeability has been developed by processing geologic alternatives through the Geodec model. The effect of increasing aquifer thickness or permeability should be a reduction in pumping requirements. In fact, the pump capital and operating costs do fall significantly as thickness and permeability are increased from the initial estimates we used. The results are summarized in Table A.

Case 1 in Table A is our original 4,000 gpm resource estimate, as detailed on page 49, and includes $3.9 million capital investment in downhole and reinjection pumps. Case 2 doubles the original aquifer thickness to 300 feet, resulting in a $2.2 million reduction in pump capital and a 39 percent reduction in direct-use energy cost per million Btu. Further increases in aquifer thickness to 450 feet and 500 feet in Cases 3 and 4, respectively, generate additional, significant reductions in investment capital and energy cost. Case 4, with a 500-foot aquifer thickness, requires only $823,000 of downhole and reinjection pump capital, but produces geothermal energy at a cost that is not competitive with natural gas, partly because of the relatively small natural gas requirements together with a high resource cost.

Case 4 utilization of the entire 4,000 gpm resource down to a sink temperature of 80°F for electric generation might be marginally competitive ($10.98 per million Btu) with commercially available electric power ($11.71 per million Btu). The geothermal electric cost is calculated from the $.57 available geothermal energy cost (Table E) divided by the geothermal-to-electric conversion efficiency of 0.069 plus an electric generation module cost of $2.72 per million electric Btu (see discussion on pages 10 and 11). The estimated geothermal electric cost of $10.98 assumes that all excess power would be fed into the existing system of transmission lines for use elsewhere. However, even if it were possible to use or sell all the power, uncertainty of resource quality and life require a substantial prospective energy cost saving, rather than just a marginal benefit, before such a project is undertaken.

## Table A

### Cost Sensitivity Analysis of Williams AFB Geothermal System at 4,000 gpm Flow

**Sensitivity Variables**

Estimated aquifer thickness (feet)
Estimated permeability (millidarcies)

**Constant Geothermal Characteristics**

| | |
|---|---|
| Wellhead temperature | 345°F |
| Well depth | 10,000 ft. |
| Static downhole pressure | 4,300 psia |

| | Sensitivity Variables | | | Total | Direct use Energy Cost* per million Btu for using: | | |
|---|---|---|---|---|---|---|---|
| Case | Aquifer Thickness (ft.) | Aquifer Permeability (mD.) | Geothermal temp. drop (°F) | Capital Investment ($000s) | Max. Avail.** | Design Capacity*** | Estimated Load**** |
| 1 | 150 | 100 | 143 | $10,264 | $1.24 | $2.26 | $9.16 |
| 2 | 300 | 100 | 143 | 8,113 | .76 | 1.40 | 5.64 |
| 3 | 450 | 100 | 143 | 7,341 | .60 | 1.10 | 4.42 |
| 4 | 500 | 100 | 143 | 7,180 | .57 | 1.04 | 4.18 |
| 5 | 150 | 200 | 143 | 8,180 | .77 | 1.41 | 5.67 |
| 6 | 150 | 300 | 143 | 7,494 | .61 | 1.12 | 4.51 |

* Excludes electric generating costs ($2.72 per million Btu) and geothermal-to-electric conversion efficiency adjustment of .069 (divide direct use cost by .069).

** Resource temperature dropped to 80°F.

*** Full use of geothermal temperature drop to 200°F (fourth column from left).

**** 572.4 billion Btu/year.

Cases 5 and 6 double and triple the Case 1 permeability, with about the same effect generated by doubling and tripling the aquifer thickness.

Thus, our original 4,000 gpm geothermal energy cost (Case 1) could be substantially overstated if a significantly greater permeability or aquifer thickness is present. However, if the original assumptions of 150-foot thickness and 100-millidarcy permeability are appropriate, large pumps will be required to suck 4,000 gpm from the production well and to force it back into the formation after use. The resulting geothermal energy costs will be very high, suggesting the need for further, detailed examination of the likelihood that the thickness and permeability will be as little as 150 feet and 100 millidarcies, respectively. Such a restricted resource probably should not be expected to produce as much as 4,000 gpm.

Detailed data for Cases 1 through 6 are presented in Tables B through G, respectively.

## Table B

### Geothermal Characteristics and Economics

Williams
(Case 1)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | $345^{o}F$ | Flow Rate | 1,789,626 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 12 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 141.9 | Pump Capital ($000s) | $2192. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $760. | Return Pipe Capital ($000s) | $498. |
| Supply Pump Capital ($000s) | $ 62. | Return Pump Capital ($000s) | $ 68. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | $343^{o}F$ | Exchanger Capital ($000s) | $619. |
| Return Temperature | $200^{o}F$ | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | $198^{o}F$ | Bottomhole Dynamic Pressure (psia) | 6945. |
| Reinjection Pressure (psia) | 141.9 | Pump Capital ($000s) | $1715. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^{9}$ BTUs) | 572.4 | Load % of Available BTUs | 13.8% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 25.5%* |

**Economics:**

Total Capital ($000s) $10,264.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .45 | $ .11 | $ .68 | $ 1.24 |
| Design | .83 | .20 | 1.23 | 2.26 |
| Actual | 3.37 | .79 | 5.00 | 9.16 |

* (572.4/2243.364) x 100% = 25.5%

## Table C

**Geothermal Characteristics and Economics**

Williams
(Case 2)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | 345°F | Flow Rate | 1,789,626 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 300 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 12 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 141.9 | Pump Capital ($000s) | $ 738. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $760. | Return Pipe Capital ($000s) | $498. |
| Supply Pump Capital ($000s) | $ 62. | Return Pump Capital ($000s) | $ 68. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | 343°F | Exchanger Capital ($000s) | $619. |
| Return Temperature | 200°F | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | 198°F | Bottomhole Dynamic Pressure (psia) | 5622. |
| Reinjection Pressure (psia) | 141.9 | Pump Capital ($000s) | $1018. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^9$ BTUs) | 572.4 | Load % of Available BTUs | 13.8% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 25.5%* |

**Economics:**

Total Capital ($000s) $ 8,113.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .23 | $ .11 | $ .42 | $ .76 |
| Design | .42 | .20 | .78 | 1.40 |
| Actual | 1.69 | .79 | 3.16 | 5.64 |

* (572.4/2243.364) x 100% = 25.5%

Table D

Geothermal Characteristics and Economics

Williams
(Case 3)

Resource Characteristics:

Temperature 345$^{o}$F

Depth 10,000 ft.

Percent Hard Rock N.A.

Flow Rate 1,789,626 #/hr.

Aquifer Thickness 450 ft.

Permeability 100 mD.

Static Downhole Pressure (psia) 4300

Geothermal System

Wells:

Production Wells 1

Reinjection Wells 1

Well Diameter 12 in.

Well Capital ($000s) $4350.

Downhole Pump:

Surface Delivery Pressure (psia) 141.9

Pump Capital ($000s) $ 184.

Surface Transmission:

Supply Pipe Length 1 mi.

Supply Pipe Capital ($000s) $760.

Supply Pump Capital ($000s) $ 62.

Return Pipe Length 1 mi.

Return Pipe Capital ($000s) $498.

Return Pump Capital ($000s) $ 68.

Heat Exchanger:

Supply Temperature 343$^{o}$F

Return Temperature 200$^{o}$F

Exchanger Capital ($000s) $619.

Geothermal/Air

Reinjection Pump:

Reinjection Temperature 198$^{o}$F

Reinjection Pressure (psia) 141.9

Bottomhole Dynamic Pressure (psia) 5182.

Pump Capital ($000s) $ 800.

Energy Use:

Load ($10^9$ BTUs) 572.4

Operating Hours (% of year) 100%

Load % of Available BTUs 13.8%

Load % of Design BTUs 25.5%*

Economics:

Total Capital ($000s) $ 7,341.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .14 | $ .11 | $ .35 | $ .60 |
| Design | .26 | .20 | .64 | 1.10 |
| Actual | 1.03 | .79 | 2.60 | 4.42 |

* (572.4/2243.364) x 100% = 25.5%

## Table E

**Geothermal Characteristics and Economics**

Williams
(Case 4)

**Resource Characteristics:**

| | | | |
|---|---|---|---|
| Temperature | $345^{o}F$ | Flow Rate | 1,789,626 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 500 ft. |
| Percent Hard Rock | N.A. | Permeability | 100 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

**Geothermal System**

**Wells:**

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 12 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

**Downhole Pump:**

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 141.9 | Pump Capital ($000s) | $ 62. |

**Surface Transmission:**

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $760. | Return Pipe Capital ($000s) | $498. |
| Supply Pump Capital ($000s) | $ 62. | Return Pump Capital ($000s) | $ 68. |

**Heat Exchanger:**

| | | | |
|---|---|---|---|
| Supply Temperature | $343^{o}F$ | Exchanger Capital ($000s) | $619. |
| Return Temperature | $200^{o}F$ | Geothermal/Air | |

**Reinjection Pump:**

| | | | |
|---|---|---|---|
| Reinjection Temperature | $198^{o}F$ | Bottomhole Dynamic Pressure (psia) | 5094. |
| Reinjection Pressure (psia) | 141.9 | Pump Capital ($000s) | $ 761. |

**Energy Use:**

| | | | |
|---|---|---|---|
| Load ($10^{9}$ BTUs) | 572.4 | Load % of Available BTUs | 13.8% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 25.5%* |

**Economics:**

Total Capital ($000s) $ 7,180.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .12 | $ .11 | $ .34 | $ .57 |
| Design | .22 | .20 | .62 | 1.04 |
| Actual | .89 | .79 | 2.50 | 4.18 |

* (572.4/2243.364) x 100% = 25.5%

Table F

Geothermal Characteristics and Economics

Williams
(Case 5)

Resource Characteristics:

| | | | |
|---|---|---|---|
| Temperature | $345^{o}F$ | Flow Rate | 1,789,626 #/hr. |
| Depth | 10,000 ft. | Aquifer Thickness | 150 ft. |
| Percent Hard Rock | N.A. | Permeability | 200 mD. |
| | | Static Downhole Pressure (psia) | 4300 |

Geothermal System

Wells:

| | | | |
|---|---|---|---|
| Production Wells | 1 | Well Diameter | 12 in. |
| Reinjection Wells | 1 | Well Capital ($000s) | $4350. |

Downhole Pump:

| | | | |
|---|---|---|---|
| Surface Delivery Pressure (psia) | 141.9 | Pump Capital ($000s) | $ 840. |

Surface Transmission:

| | | | |
|---|---|---|---|
| Supply Pipe Length | 1 mi. | Return Pipe Length | 1 mi. |
| Supply Pipe Capital ($000s) | $760. | Return Pipe Capital ($000s) | $498. |
| Supply Pump Capital ($000s) | $ 62. | Return Pump Capital ($000s) | $ 68. |

Heat Exchanger:

| | | | |
|---|---|---|---|
| Supply Temperature | $343^{o}F$ | Exchanger Capital ($000s) | $619. |
| Return Temperature | $200^{o}F$ | Geothermal/Air | |

Reinjection Pump:

| | | | |
|---|---|---|---|
| Reinjection Temperature | $198^{o}F$ | Bottomhole Dynamic Pressure (psia) | 5622. |
| Reinjection Pressure (psia) | 141.9 | Pump Capital ($000s) | $ 983. |

Energy Use:

| | | | |
|---|---|---|---|
| Load ($10^{9}$ BTUs) | 572.4 | Load % of Available BTUs | 13.8% |
| Operating Hours (% of year) | 100% | Load % of Design BTUs | 25.5%* |

Economics:

Total Capital ($000s) $ 8,180.

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .25 | $ .11 | $ .41 | $ .77 |
| Design | .45 | .20 | .76 | 1.41 |
| Actual | 1.81 | .79 | 3.07 | 5.67 |

* (572.4/2243.364) x 100% = 25.5%

## Table G

**Geothermal Characteristics and Economics**

Williams
(Case 6)

**Resource Characteristics:**

Temperature 345°F

Depth 10,000 ft.

Percent Hard Rock N.A.

Flow Rate 1,789,626 #/hr.

Aquifer Thickness 150 ft.

Permeability 300 mD.

Static Downhole Pressure (psia) 4300

**Geothermal System**

**Wells:**

Production Wells 1

Reinjection Wells 1

Well Diameter 12 in.

Well Capital ($000s) $4350.

**Downhole Pump:**

Surface Delivery Pressure (psia) 141.9

Pump Capital ($000s) $ 408.

**Surface Transmission:**

Supply Pipe Length 1 mi.

Supply Pipe Capital ($000s) $760.

Supply Pump Capital ($000s) $ 62.

Return Pipe Length 1 mi.

Return Pipe Capital ($000s) $498.

Return Pump Capital ($000s) $ 68.

**Heat Exchanger:**

Supply Temperature 343°F

Return Temperature 200°F

Exchanger Capital ($000s) $619.

Geothermal/Air

**Reinjection Pump:**

Reinjection Temperature 198°F

Reinjection Pressure (psia) 141.9

Bottomhole Dynamic Pressure (psia) 5182.

Pump Capital ($000s) $ 729.

**Energy Use:**

Load ($10^9$ BTUs) 572.4

Operating Hours (% of year) 100%

Load % of Available BTUs 13.8%

Load % of Design BTUs 25.5%*

**Economics:**

Total Capital ($000s) $ 7,494

| Energy Use Level | Energy Cost per million BTUs: Production Well and pumping | Transmission/ Extraction | Reinjection well/pumping | Total System |
|---|---|---|---|---|
| Available | $ .18 | $ .11 | $ .32 | $ .61 |
| Design | .32 | .20 | .60 | 1.12 |
| Actual | 1.30 | .79 | 2.42 | 4.51 |

* (572.4/2243.364) x 100% = 25.5%