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ENGINEERING AND GEOLOGICAL ANALYSES OF THE GEOTHERMAL ENERGY POTENTIAL OF SELECTED SITES IN THE STATE OF ALASKA

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INTRODUCTION

Resource assessment of a variety of locations in Alaska has demonstrated that the State owns significant geothermal sites. Certain reservoirs have already been identified and they could be utilized for either direct space heating or (probably) for power generation. While several of these reservoirs would have been quite attractive elsewhere, extremely high contruction costs, the sparsity of the Alaskan population and the remoteness from urban markets, indicate unfavorable economics in most cases. The State owns some of the largest petroleum, natural gas and coal resources in the U.S.A. There is an enormous potential for hydroelectric power.

Hence, the demonstration of the desirability of geothermal energy utilization in Alaska faces highly adverse odds. The sites where this mode of energy could compare favorably with other available options are *prima facie* few.

For example, the Aleutian volcanic arc represents a favorable setting, due to the existence of possible shallow magma bodies and deep tectonic fractures for a "vapor dominated" geothermal reservoir as defined by White et al. (1971). Three 1500 ft temperature gradient wells, drilled on Unalaska in the Summer of 1982, have revealed extraordinary geothermal temperature gradients. A reservoir yet to be discovered would be of a quality to produce significant amounts of electric power. Yet, its desirability must be demonstrated against the presently used diesel. Obscuring the issue are future (real or projected) uses. The future price of fossil fuels is difficult to assess. New markets may emerge or expand such as a major bottom fish industry or other heavy users of power.

Although "vapor dominated" reservoirs are expected to be rare (or non-existent) in the rest of Alaska, hot water reservoirs are presumed quite common. The State contains an impressive collection of natural hot springs. Limited drilling activity has produced very encouraging results in at least one site (Prilgrim Springs), while geological and geophysical surveys of a large number of sites have indicated good potential.

It is the purpose of this report to produce ideas and/or options on how geothermal resources might be actually developed assuming a given geological data base for several geothermal prospect areas in Alaska. The possibility of geothermal energy utilization could be weighed against existing (or proposed) modes of energy. The economic attractiveness or lack thereof, will be demonstrated using a common means of comparison among the options.

Six geothermal prospect sites have been selected for this study:

a) Tenakee Springs
b) Sitka Region (Goddard Hot Springs)
c) Pilgrim Springs
d) The Klawasi Region of Copper Valley
e) Summer Bay on Unalaska
f) The Makushin Volcanic Region of Unalaska.

Figure 1 positions the six sites on the map of Alaska. All of these have been the target of general geothermal interest in the past few years. They were included in the July 1980 Alaska Geothermal Implementation Plan (Reeder et al., 1980). Their selection provides a geographic diversity spanning the entire State. With the exception of Tenakee Springs, they are in relative proximity with population centers which, by virtue of their remoteness, pay a premium price for diesel. The attractiveness of geothermal energy utlization is more probable in these sites than elsewhere.

TENAKEE SPRINGS

The thermal springs at Tenakee occur in Cretaceous granitic rocks (Brew and Morrell, 1980) which are cut by numerous high-angle joints. The two most prominent orientations are N50E and N40W. Silurian hornblende and biotite synenite are exposed just south of Tenakee, and have been interpreted (Loney et al., 1975) to bound the granodiorite by an east-west fault which would be located just offshore.

The liquid-dominated hydrothermal system at Tenakee may derive its fluids from connate waters associated with extensive sedimentary units located at depth. The prominent joint sets in the granitic rocks provide an avenue for transporting the heated fluids to the surface. The east-west fault likely serves as a lateral boundary on the reservoir.

Subsurface reservoir temperatures, based on silica and Na-K-Ca geothermometry, have been calculated to be between 101 to 110°C (I. Barnes, personal commun.). During the drilling of seven shallow wells in 1981, temperatures of 100°F were measured at a depth of 180 ft (Miller, 1981). Very small flowrates were obtained through these wells.

The most obvious consumer of the geothermal resource would be the village of Tenakee. Since the springs are located within the community, direct utilization for purposes other than power generation could be easily accomplished. If a deeper high-temperature reservoir were to be discovered, the closest significant population center would be Sitka. A power line route from Tenakee under Tenakee Inlet to Kadashan Bay, over the Moore Mountains (elevation 200 ft), under Peril Strait and onto Baranof Island at Duffield Peninsula is the most direct path. This distance is roughly 50 miles.

Tenakee could be a target for direct utilization. The heating needs of its 50 houses and other structures can be estimated at 1.5 X 10^6 BTU/hrs. on an average year-round basis. The 1981 drilling produced a geothermal gradient of 13°C/100 ft. and with a surface temperature of 16°C. The predicted source temperature of approximately 100°C can be expected at a depth of about 700 ft. If a well, drilled at this depth were to encounter a reservoir, it would need a flowrate of 37500 lbs/hour (for a 40°F useful temperature drop in th heat system). This flowrate can be translated to 70 GPM. The drilling costs are estimated at one million dollars while the distribution system would need another $1.5 million (including pumps). With operating costs of $80,000 ($40,000 for a technician plus $40,000 for pumping costs) and if no taxes or rates of return infringe on the scheme, a 20 year useful life of the system would result in a cost of $15.6/million BTU or an average monthly bill of $340 per household, significantly higher than the present rates. Electric power generation would prove even more costly, compared to diesel generation, since drilling and power plan costs would be very large. Tenakee, with its small market, does not appear to be an attractive target for geothermal utilization even in the most favorable scenario.

SITKA (GODDARD SPRINGS)

One of the more common rock types in this portion of Southeast Alaska is the Sitka Graywacke, a steeply dipping or overturned series of inner submarine fan turbidites. The Sitka Graywacke is prominently jointed and has been regionally metamorphosed to prehnite-pumpellyite facies. Tonalites and granodiorites are exposed south and west of Redoubt Lake, and potassium-argon ages on biotite range from 42 to 46 m.y. This indicates a middle Eocene age of intrusion (Loney and others, 1975). Numerous alkali-olivine diabase dikes are exposed near the hot springs, and range in thickness from centimeters to meters.

Structurally, southeast Alaska is a complex area, cut by numerous high-angle faults. One of the more prominent is the Fairweather-Queen Charlotte system, 190 km in length. This right-lateral, steeply dipping fault is the boundary between the North American and Pacific lithospheric plates. Also of notable size is the Chatam Strait Fault, 400 km long, which has experienced 190 meters of right-lateral movement since the Cretaceous (Loney and others, 1975).

Goddard and Baranof Hot Springs occur in Lower Cenozoic granodiorite

(Brew and Morrell, 1980). High-angle joint sets are common at orientations of N50E and N40W. Goddard Hot Springs are located very near the northwest-trending Redoubt Lake Fault, and Baranof Hot Springs fall on the trace of the Medvejie Lake Fault (Loney and others, 1975).

The shallow liquid-dominated system at Goddard Hot Springs is interpreted to be of very limited extent, based on EM-31 surveys (R. Reifenstuhl, personal commun.) This hydrothermal system is probably quite similar to the Tenakee system, with connate waters associated with sedimentary rocks acting as the fluid source. Extensive exposures of Cretaceous argillite and graywacke are common throughout the Sitka region, but these units are not likely to act as reservoir rocks due to their low permeability and discontinuous jointing.

Subsurface reservoir temperatures for Goddard and Baranof Hot Springs have been calculated at 147°C and 118°C, respectively, based on silica and alkali geothermometry (I. Barnes, personal commun.). If a power plant were constructed near the Goddard Springs, the nearest population center is Sitka. In this case, a possible route for powerlines would be northeastward (parallel to Redoubt Lake) for several miles, then northwest around Mt. Granishinikof, and finally underwater across the Eastern Channel of Sitka Sound (a distance of about 5 miles) to Sitka. The total distance would be approximatley 21 miles.

The distance between the Goddard Springs and Sitka precludes direct utilization even if a reservoir of sufficient proportions were found. A deep water reservoir at 150°C could produce enough power either in a flash or a binary system plant. Transmission of power would be feasible.

Figure 2 presents an economic comparison between diesel and geothermal generated electrical costs. An economic model was written that used a rate of return as a comparing yardstick between geothermal and diesel generation. The high investment costs of geothermal development are eventually offset by the high operating costs associated with diesel fuel. The calculation of the rate of return did not take into account the in-town standard administrative and maintenance costs associated with either option. Hence, the R.O.R. should be used for what is intended, i.e., comparison. The market size and the demand for eventual payoff is of course important. As can be seen, the two curves intersect at a plant capacity (or market demand) of 27 MW. If the electrical demand for Sitka is above this level, geothermal becomes more attractive. Yet, the uncertainty of the existence of the geothermal reservoir and the recent committment towards hydroelectric power cast a doubtful light over geothermal energy development.

PILGRIM SPRINGS

The thermal activity at Pilgrim Springs is located in the Pilgrim River Valley, a fault-bounded tectonic depression (graben). Precambrian amphibolites and Mesozoic plutons are the common rock types in the area, with local exposures of conformable and unconformable (overthrust) Paleozoic carbonates. Potassium-argon dating by Turner and Swanson (1981) indicates a cooling age of 84 m.y., which suggests intrusive igneous activity in the Upper Cretaceous.

Gravity surveys conducted in the region by Kienle et al. (1980) indicate that Pilgrim Springs is located near the intersection of two possible fault zones which form the corner of a downdropped basement block. Other faults in the area have been verified by seismic data and geologic mapping, and one or more of these faults could provide deep conduits for the geothermal anomaly.

It has been suggested (Wescott and Turner, 1982) that the Pilgrim River Valley graben may represent an incipient rift extending 250 kilometers across the central Seward Peninsula and offshore into the Bering Sea. Based on this hypothesis, the anomalous heat flow in the Pilgrim Springs area is due to tensional tectonics and active rifting.

The possible existence of a major rift system is significant for the regional geothermal potential. A helium survey was conducted to test this rift model, and nine out of eleven helium anomalies occur near the proposed rift segments and suggest abnormally high heat flow in these areas. Futhermore, extensive basaltic fields north of the Pilgrim Springs area have been interpreted as resulting from eruption in a zone of crustal weakness produced by the general north-south extension (Turner and Swanson, 1982).

The amount of separation along this proposed rift is less than the widths of the Quaternary depressions which have probably been enlarged by normal faulting and marginal subsidence, along with rifting. Potassium-argon dating indicates that extrusive volcanism which was associated with rifting began in the Upper Miocene (Turner and Swanson, 1981).

Finally, a permafrost boundary has been identified which encloses an area of 1 to 1.5 km^2. The thickness of this permafrost is over 350 ft.

Temperature data at Pilgrim Springs was previously limited to shallow depth (4.5 meters) temperature readings (Turner and Forbes, 1980), Helium soil surveys (Wescott and Turner, 1981), and geothermometry (Motyka and others, 1980). The temperature data for this study were taken from temperature versus depth curves recorded in six exploration wells. These curves showed a trend toward a maximum temperature at depths from 40 to 100 ft, followed by a rapid temperature decrease at depths from 100 to 250 ft, and finally by a constant geothermal gradient ranging from 1.8°C to 2.1°C per 100 ft, down to a depth of 900 ft. Two deep wells (PS4 and PS5) show temperature trends that would intersect at 155°C at a depth of 4875 ft, suggesting that all the wells overlay the source reservoir at a depth of 4875 ft.

The shallow temperature anomaly observed in all the wells suggests that, somewhere in the immediate vicinity, hot water is flowing upward through a fault or fissure system which extends vertically from a depth of about 50 ft to the deep source reservoir at a depth of 4875 ft.

If a power plant were constructed at Pilgrim Springs, the closest major consumer of that electricity would be the community of Nome. One possible route for powerlines would be westward from Pilgrim Springs to the Cobblestone River Valley, crossing the Kigluaik Mountains at Mosquito Pass, and then south to Jensens Camp and along the road to Nome. This distance is roughly 55 miles. The next closest significant settlement is at Teller, which would be a distance of 45 miles.

The Pilgrim Springs geothermal site has a proven intermediate temperature and shallow reservoir capable of producing 300 GPM of 90°C (at the wellhead) artesian water. Induced air lifted flowrates may reach 1500 GPM. A much hotter and hence deeper reservoir has been postulated. However, the distance between Pilgrim Springs and Nome prohibits the consideration of a hot water pipeline while power generation is also quite doubtful. The depth of the reservoir, the length of the transmission line, and transmission line losses preclude a reasonable calculation.

The presence, though, of a significant amount of hot water could aid in two areas: a) development of a large resort area on site and, b) use of the water as a mineral leaching or permafrost thawing medium in present or contemplated mining operations. Such speculative uses are beyond the scope of this report.

COPPER VALLEY

The tectonic framework of the Copper River Basin is dominated by east-west trending orogenic arcs which are concave to the south, and by the Wrangell Mountains to the east. The regional aeromagnetic map of the Copper River Basin suggests that the andesitic and basaltic lavas of the Wrangell massif underlie the mud volcanoes of the Klawasi hydrothermal springs at a relatively shallow depth (Andreason and others, 1964). A rapid decrease in the magnetic gradient westward from Mt. Drum probably indicates that the lavas are thinner and more deeply buried under the alluvium of the Copper River.

The Moore Creek exploration well drilled by the Pan American Petroleum Corporation penetrated olivine basalt of the Talkeetna Formation after passing through 7500 ft of Cretaceous sedimentary rocks. These units probably extend underneath the Wrangell volcanic pile. The Moose Creek Well encountered high pressure water in bentonitic shale at a depth of 5430 ft.

The hydrothermal reservoirs in the Klawasi area are probably artesian aquifers lying at depths of up to 7000 ft within the sedimentary sequence. A significant amount of cooling and mixing occurs during the upward migration of these fluids, especially in passing through glacial till and permafrost. Nichols and Yehle (1961) report surface temperatures of 12 to 30°C and flow rates up to 10 GPM for the Klawasi springs.

For a power plant constructed at

Upper Klawasi Spring, the Lower Klawasi and Shrub Springs are at distances of roughly five and seven miles, respectively, so heat loss during piping of the fluids could be significant. Glennallen is about 20 miles west of Upper Klawasi Spring, and the other community in the area is Copper Center, roughly 15 miles southwest of Upper Klawasi Spring. Either of these two communities would be a likely recipient of the geothermal engery.

An economic comparison of diesel versus geothermal utilization is presented in Figure 2. (A description of the model is included in the Sitka section.) The point of intersection is 22 MW, within the range of forecasted needs in the Copper Valley region. A vigorous geothermal exploration and subsequent drilling (if indicated) is recommended for the Copper Valley region.

SUMMER BAY, UNALASKA ISLAND

The rocks of Unalaska Island consist of three main groups. The oldest and most extensive is the lower Tertiary Unalaska Formation, composed of interbedded igneous and sedimentary members. This formation has been extensively folded, faulted and metasomatically altered. Upper Tertiary calc-alkaline plutons comprise the second lithologic category. These plutons have been emplaced by such mechanisms as assimilation, stoping, and forceful intrusion. The third group consists of basalt and andesite flows of the Quaternary Makushin Volcanics (Drewes and others, 1961).

The first of the two major hydrothermal areas is at Summer Bay. A large normal fault striking N45W and dipping 60 to 75° south is well exposed along the coast just south of Summer Bay. This fault may be projected across Summer Bay Lake and through the Summer Bay warm spring, although exposures are poor. Therefore, joints trending N45W are highly suspected as controlling the source waters of the springs (Reeder, 1981). The largest of the springs has a temperature of 35°C and a dishcarge of 2 GPM. Two shallow exploration wells were drilled in 1980 and encountered temperatures of 43 to 50°C. Silica geothermometry indicates a subsurface reservoir temperature of 86°C (Motyka and others, 1981). It is not clear what lithologic unit is acting as a cap for this aquifer, because no impermeable material was detected during drilling. A very thin layer consisting mainly of mineral precipitates, derived from the warm waters, may exist above the aquifer. Schlumberger electric soundings, EM-31 Geonics surveys, and Dipole-Dipole resistivity surveys indicate that the shallow aquifer is fairly limited in extent. Data from a Helium soil survey suggests that the hydrothermal source is derived from volcanic rocks, and not from acidic igneous or metamorphic rocks found at such places as Tenakee or Goddard Hot Springs. Summer Bay is approximately 5 miles overland to Dutch Harbor or half the distance if an underwater route is employed.

The Summer Bay reservoir at 86°C could be an interesting find. The city of Unalaska presently has 200 customers with an estimated average heat demand of 20,000 BTU/hr per house. Total use on the island is then 4 X 10^6 BTU/hr. The five mile distance will result in a reduction of 25°C from the wellhead temperature. Hence, in the best of cases, a useful temperature drop of 10°F can be contemplated within a proposed system. The flow rate demand will be 400,00 lbs/hr or 800 GPM. At least four (shallow) wells would be needed for such a flowrate, costing $4 million. The pipeline and distribution system would cost another $8 million (using standard engineering economic figures) for a total of $12 million for capital expenditures. The annual operating costs are expected to top $300,000. If a 20 year useful life were to be considered and if no taxes or rates of return were to be imposed, then a cost consideration of $26 per million BTU can be calculated. An average heating bill of $375/month must be assessed on households in order to recover the investment. Such a figure is quite unattractive considering the present (or projected) costs.

MAKUSHIN VOLCANO

The second major hydrothermal area on Unalaska Island is at Makushin Volcano. The rock contacts between the Unalaska Formation and the granitic plutons in the Makushin region are commonly near vertical and irregular, with the intrusive bodies interfingering into the highly altered sediments. Joints are common in these rocks with orientations of N60E and N55W, and the fumarole activity at Fields 2 and 3 appears to follow the N60E joint system. High-angle faults are also common, along with dikes.

Most of the faults appear to be normal faults and strike N55W and N35E. One of these N55W faults trends directly into Fumarole Field 5, and two other faults with N55W orientations bound Fumarole Field 2 (Reeder, 1981).

Large, vapor-dominated hydrothermal systems, are postulated to exist beneath the eastern and southern flanks of Makushin Volcano, where their eastern extent is marked by Field 1 and their western extent delineated by Fields 2 and 3. Such systems are probably driven by dike-like magma bodies located several kilometers beneath the fumaroles. The dominant gases being discharged from most of the fumaroles are CO_2, N_2, SO_2, and H_2S. Motyka and others (1982) estimated reservoir temperatures of between 232 to 278°C, based on gas geothermometry. Three temperature gradient wells drilled during the summer of 1982 encountered maximum bottomhole temperatures of 200°C at a depth of 1500 feet in the plutonic rocks.

Preliminary gravity modeling suggests that the plutonic rocks and the Unalaska Formation extend beneath the Makushin volcanic pile with no major fault displacements. Such lithologies, if highly fractured, could contain large, vapor-dominated, systems at depths greather than about 1 kilometer.

Should a power plant be constructed to utilize the resource, the plant would need to be close to the wells to minimize the loss in quality when transporting steam. Powerlines could follow Makushin Valley for roughly 6 miles to Broad Bay, where underwater cable could transport the electricity to Dutch Harbor, or an overland route around Captains Bay could be constructed. The safest location for power plant construction from a volcanic hazards viewpoint, would be roughly 4 miles east of Field 1 behind the north-trending massif of Vista Ridge (Arce and Economides, 1982).

Unalaska is a major site of geothermal exploration activities in the State. Figure 2 indicates a juncture between the diesel and the geothermal curves at 32MW. Present projections suggest an electric power demand of 50 MW by the year 2000. Geothermal development is indicated if the enormous logistical costs associated with the terrain and the weather are kept in check.

CONCLUSIONS

Of the six sites examined, only two (Copper Valley and Unalaska/Makushin Volcano) appear to be attractive candidates for geothermal development. In both cases, sufficient reservoirs must be discovered. While the geothermal anomalies (and temperatures) are there, the fluid is yet to be discovered. The only means of verification is drilling. The attractiveness of geothermal development depends largely on capital expenditures. Significant overruns beyond the estimates used in this study shift the market size requirements upwards. Such an event would prove geothermal economically unattractive. A high escalation of diesel costs would have the opposite effect.

REFERENCES

Andreassen, G.E., Granty, A., Zietz, I. and Barnes, D.F.: "Geologic Interpretation of Magnetic and Gravity Data in the Copper River Basin, Alaska", U.S.G.S. Prof. Paper 316-H, 1964.

Arce, G.N. and Economides, M.J.: "Analysis of Volcanic Hazards from Makushin Volcano, Unalaska Island, Proc. IV New Zealand Geothermal Workshop pp. 93-99, 1982.

Brew, D.A. and Morrell, R.P.: "Intrusive Rocks and Plutonic Belts of Southeastern Alaska, U.S.A.", U.S.G.S. Open-File Report 80-78, pp 34, 1980.

Drews, H. Fraser, G.D., Snyder, G.L. and Barnett, H.F., Jr.: "Geology of Unalaska Island and adjacent insular shelf, Aleutian Islands, Alaska", U.S.G.S. Bull. 102B-S, pp 583-676, 1961.

Kienle, J., Lockhart, A. and Peace, J.: "Seismic refraction survey of the Pilgrim Springs geothermal area, Alaska", in Turner, D.L. and Forbes, R.B. (Eds.) A Geological and Geophysical study of the Geothermal Energy Potential of Pilgrim Springs, Alaska, UAF Geophysical Institute Report, UAG R-271, 1980.

Loney, R.A., Brew, D.A., Muffler, L.J. and Pomeroy, J.S.: "Reconnaissance Geology of Chichagof, Baranof and Kruzof Islands, Southeastern Alaska", U.S.G.S. Prof. Paper 792, pp. 105, 1975.

Miller, D.S.: "Final Completion Report, Tenakee Drilling Project", prepared for the State of Alaska, Division of Energy and Power Development, 1981.

Motyka, R.T., Moorman, M.R. and Forbes, R.B.: in Turner, D.L. and Forbes, R.B.. (Eds.): "A Geological and Geophysical Study of the Geothermal Energy Potential of Pilgrim Springs, Alaska", UAF Geophysical Institute Report UAG R-271, 1980.

Motyka, R.J., Moorman, M.A. and Poreda, R.: "Fluid geochemistry of the Makushin geothermal area, Unalaska Island, Alaska", 1982.

Nichols, D.R. and Yehle, L.A.: "Mud Volcanoes in the Copper River Basin, Alaska", In: Raasch, G.O. (Ed.) Geology of the Arctic, International Symposium, Arctic Geology, Calgary, 1960. Proceedings, v.2, pp. 1063-1087, 1961.

Reeder, J.W., Coonrod, P.L., Bragg, N.J., Denig-Chakroff, D. and Markle, D.R.: "Alaska Geothermal Implementation Plan" Report by the State of Alaska to D.O.E., Contract DE-FGS1-79R000074, pp. 108, 1980.

Reeder, J.W.: "Vapor-dominated hydrothermal manifestations of Unalaska Island and their geologic and tectonic setting, " 1981 IAVCEI Symosium-Arc Volcansm, Volcanological Society of Japan and the IAVCEI, pp. 297-298, 1981.

Turner, D.L. and Forbes, R.B. (Eds.): "A Geological and Geophysical Study of the Geothermal Energy Potential of Pilgrim Springs, Alaska", UAF Geophysical Institute Report, UAG R-271 1980.

Turner, D.L. and Swanson, S.E.: "Continental rifting - a new tectonic model for the Central Seward Peninsula", in Wescott, E.M., and Turner, D.L. (Eds.), Geothermal Reconnaissance Survey of the Central Seward Peninsula, Alaska, UAF Geophysical Institute Report UAG R-284, 1981.

Wescott, E.M. and Turner, D.L., (Eds.): "Geothermal Reconnaissance Survey of the Central Seward Peninsula, Alaska," UAF Geophysical Institute Report UAG R-284, 1981.

Wescott, E.M. and Turner, D.L.: "Geothermal Energy Resource Assessment of Parts of Alaska, final report to the Division of Geothermal Energy, D.O.E., pp. 69, 1982.

White, D.E., Muffler, L.P.J. and Truesdell, A.H.: "Vapor-dominated hydrothermal systems compared with hot-water systems", Economic Geology, v.66, no.1, pp. 75-97, 1971.

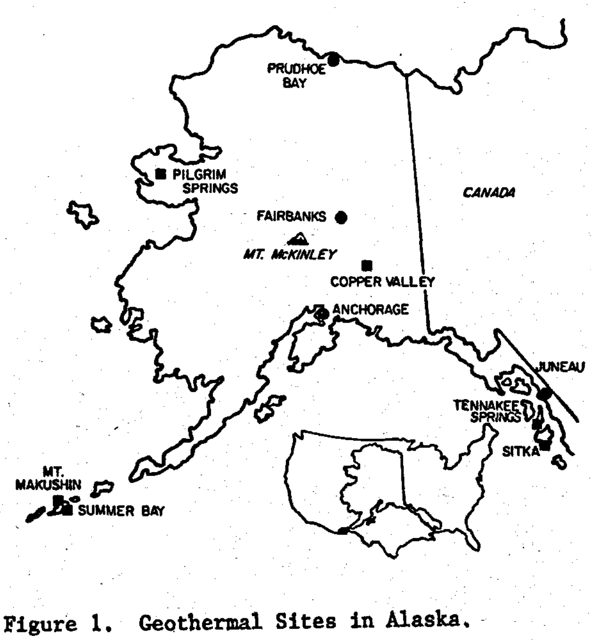

Figure 1. Geothermal Sites in Alaska.

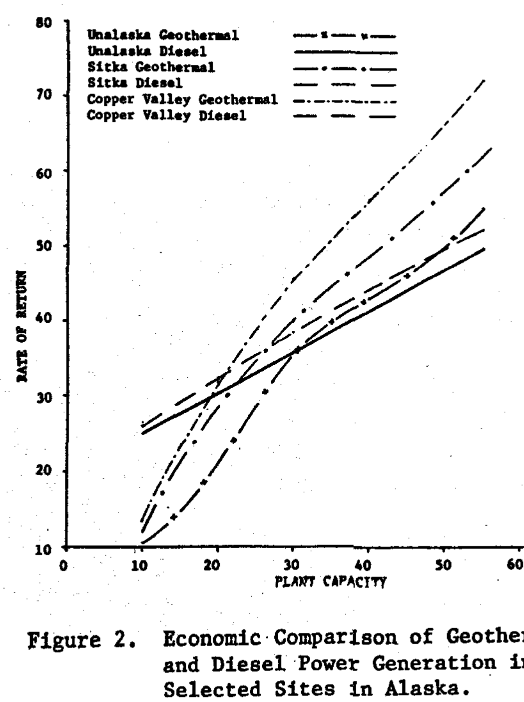

Figure 2. Economic Comparison of Geothermal and Diesel Power Generation in Selected Sites in Alaska.