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SMALL SCALE GEOTHERMAL DEVELOPMENT POTENTIAL FOR ISLAND NATIONS SITUATED ALONG THE PACIFIC "RING OF FIRE"

by

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ABSTRACT

Geothermal energy has a great potential for meeting the electrical and thermal energy requirements of many countries and territories lying along tectonically active zones within and surrounding the Pacific Basin. Energy requirements for many of the small, scattered island nations preclude development of conventional generating facilities large enough to incorporate any economies of scale. However, by attempting to discover and develop shallow, relatively low temperature, geothermal reservoirs associated with recent vulcanism on many of these island nations, exploration expenditures and risks, and problems associated with the development of high temperature resources can be reduced. Exploration and development drilling for these resources can be accomplished with truck mounted rotary drilling rigs that are less costly and more suitable for operations within the island infrastructures than the conventional rigs normally used in the drilling of deep, high temperature geothermal resources.

Experience over the past decade with small, modular, binary (Rankine) cycle generating units indicates that geothermal energy can provide a reliable source of baseload electricity in the amounts required and at a cost that is competitive with other alternative energy sources. Development of shallow, moderate temperature, geothermal resources with small, modular binary cycle generating units can provide ideal additions to the energy sources of many of the Pacific island nations within the framework of their island economies.

INTRODUCTION

Geothermal resources are, by convention, divided into four general types: hydrothermal (steam and liquid), geopressured, hot dry rock, and magma. Of these four types, currently only hydrothermal resources in the form of liquid dominated (hot water) and vapor dominated (steam) are viable economically. Current technology converts the geothermal energy, or natural heat of the earth, into electricity or other direct uses such as process or space heating, dehydration, and refrigeration. Practical uses of geothermal energy are limited only by economics and the boundaries of the user's imagination.

In geothermal developments, high temperature hydrothermal fluids from the earth in the form of steam, hot water, or a mixture of both, have been used to drive turbines to produce electricity. Lower temperature fluids have been used for direct applications, but increasingly during the last decade, have been utilized for binary (Rankine) cycle electrical generation. Moreover, new applications in existing technology for electrical generation from lower temperature hydrothermal fluids have been on-line a sufficient time to obtain reliable and meaningful operational data and costs. Geopressured resource technology is approaching economic viability for reservoirs with high methane content discovered during the course of petroleum exploration, but hot dry rock technology is still only in the research stage. Although significant advances have been made in capturing useful heat from molten rock, magma technology is still, basically, only a theoretical concept.[1]

Today's geothermal industry contributes to the world's energy supply more than 5,000 megawatts of electrical power, or approximately the same quantity of electricity as five nuclear power plants.[2] Moreover, current geothermal technology can produce this power as baseload electricity that is on-line greater than 95% of the time, at costs ranging between six and seven cents per kilowatt hour! These costs are competitive with coal and nuclear electrical generation costs[1], and compare favorably with oil generation costs.

Further reductions in exploration uncertainty (risks) of discovering viable geothermal reservoirs and the cost of geothermal wells will improve the competitiveness of geothermal energy resources in relation to other conventional, alternative, and renewable energy sources. Research in reservoir analysis techniques will improve industry's ability to predict size, performance, and longevity. Improved conversion technologies will make it possible to use lower temperature liquids more efficiently for electrical generation. Moreover, these needed improvements in geothermal generation are solutions to basic engineering problems that can be solved within the parameters of existing technology.

Currently, the main sources of electrical energy in the Pacific Basin are diesel generation, hydropower, and biomass combustion. Diesel generation has all the disadvantages of price uncertainty, disruption of supply, and fuel import costs causing balance-of-trade problems in countries lacking oil production. Hydropower potential is an obvious solution to increased energy requirements of some of the larger islands, but is insignificant or nonexistent on most of the smaller islands and coral atolls. Biomass is in ample supply on many islands, but is lacking on a large number. On islands that currently have sufficient biomass supplies for present demand, increased usage could result in rapid depletion of the resource, and may face future restrictions as the greenhouse controversy heats up. Wind and photovoltaic generation is gaining general acceptance, but is interruptable, requires storage, and has not proved suitable for baseload service. Nevertheless, in scattered dwellings, villages and remote towns, wind and photovoltaic electricity currently are commonly the most practical, economical, and only sources of electrical energy available. Geothermal energy is not universally distributed throughout the Pacific Basin, and is absent throughout most of the eastern islands and the central and western equatorial atolls. Geothermal energy, however, is abundant on the Big Island of Hawaii, and on many volcanic islands in tectonically active zones along crustal plate boundaries. On many of these islands, geothermal energy represents the ideal solution for an economical, reliable, and nonpolluting energy supply.

With the exception of the larger island nations, such as Japan, the Philippines, Taiwan, Indonesia, and New Zealand, many of the island populations in the Pacific Basin are either small in number, scattered, or both. Locally, electrical utilization is minimal to nonexistent. Throughout large portions of the Pacific Basin, large-scale electrical generation is measured in tens of megawatts, with generation plant sizes more commonly measured in hundreds of kilowatts rather than in megawatts. In most instances, oil generation presently meets this demand most efficiently and economically, as is shown in Table I, which lists current power generation on Fiji, Tonga, and American Samoa.[3] To successfully compete against oil generation in the Pacific Basin, an energy source must be: indigenous to the islands; highly reliable; reasonably competitive in price with available diesel, hydropower, and biomass generation; within acceptable pollution and waste product limitations; and perhaps most importantly, be suitable to the scale of the island economies.

GEOLOGY OF THE VOLCANIC PACIFIC ISLAND NATIONS

The Pacific Ocean is rimmed by the "Ring of Fire," a tectonically active zone of earthquakes and volcanism, which truly represents the greatest zone of geothermal activity and potential on earth. Of the 5,003 megawatts of electricity generated by geothermal energy at the end of 1987, approximately 4,376 megawatts, or 87%, were generated from the Circum-Pacific and Pacific Basin areas.[2]

Although electricity is generated geothermally in Hawaii, and geothermal potential exists at other sites in the eastern Pacific, such as the Galapagos, Tahiti, and the Chile Islands, these locations represent special geological conditions, and are off the main island arc zones of volcanism, tectonism, and geothermal activity. The Philippines, New Zealand, Indonesia, and Japan have extensive geothermal developments, and lie along these major zones of tectonism. The area of geothermal and volcanic activity specifically covered in this discussion is the southwestern and western Pacific along the western marginal zone of the Pacific crustal plate. An excellent summary of the geology and volcanism of this area, as well as the occurrence of geothermal activity, is given by Cox.[4] This area is a region of diverse tectonic features that include continental land masses and oceanic crust, crustal subduction and associated island-arc formation, backarc basins, and elevated areas of seafloor in which new crust is being formed. The zone is characterized by belts of intense seismic activity with shallow earthquakes which are related to zones of crustal consumption or formation and large-scale crustal faulting, occurring below many land masses and adjacent shallow basins (Figure 1).[5]

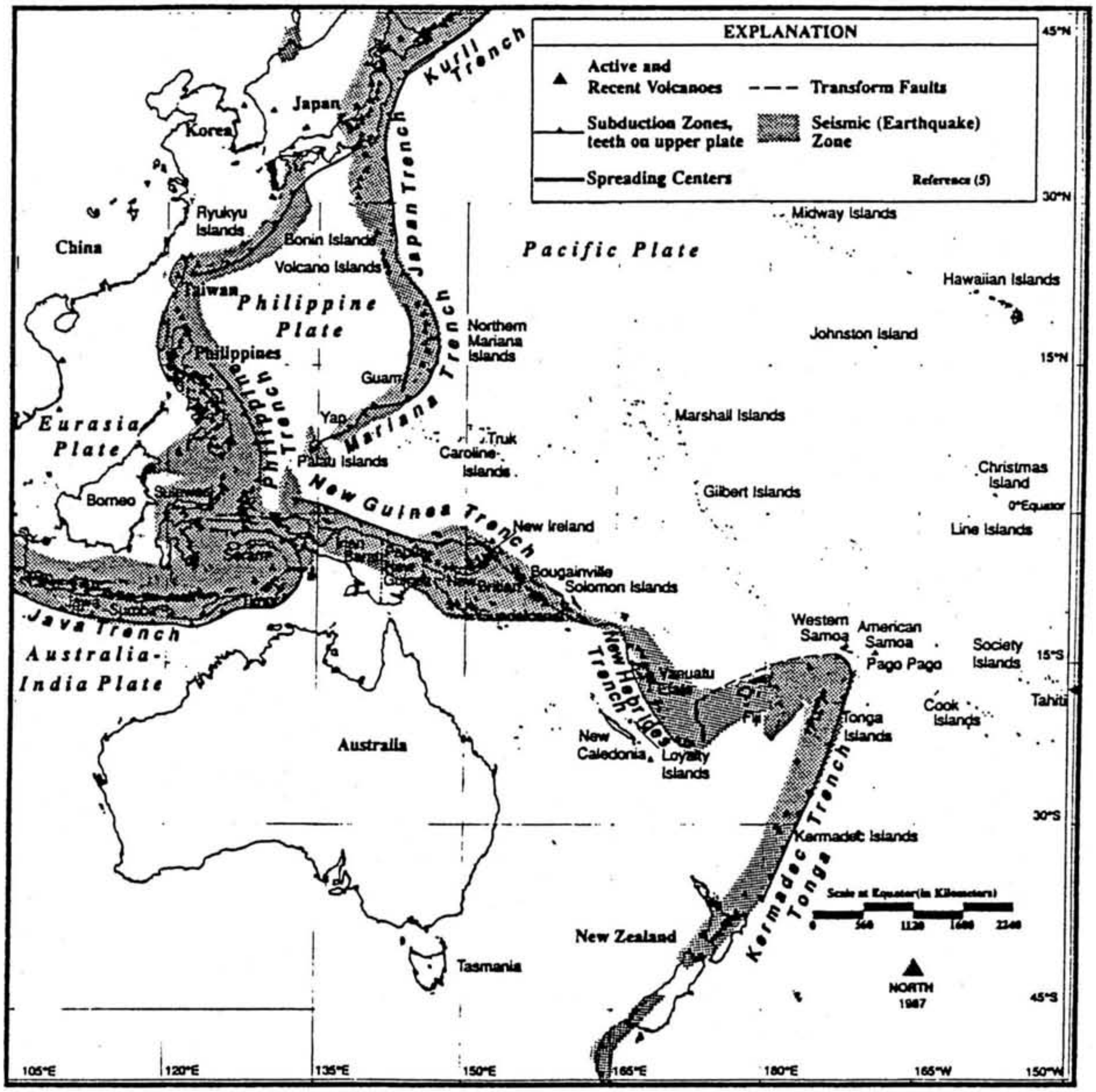

Figure 1. Recent Volcanism and Tectonic Features of a Portion of the Pacific Ocean Basin

TABLE I

POWER PLANT DATA FOR THREE PACIFIC ISLAND NATIONS[3]

Plant Location		1986 Installed Capacity (MW)	Energy Source
AMERICAN SAMOA			
Satala	Island of Tutuila	7.0	Diesel
Tafuna	" " "	18.0	"
Faleasao	" " Ta'u	0.5	"
Ofu	" " Ofu	0.5	"
		26.0	
FIJI			
Wailoa		83.20	Hydropower
Kinoya		26.00	Diesel
Vuda		11.86	"
Nadi		8.00	"
Suva		4.80	"
Labasa		3.97	"
Lautoka		3.35	"
Sigatoka		3.35	"
Deuba		2.20	"
Levuka		0.84	"
Savusavu		0.84	"
Rakiraki		0.68	Bagasse
		149.09	
TONGA			
Tongatapu		5.85	Diesel
Vava'u		0.60	"
Ha'apai		0.11	"
'Eua		0.11	"
		6.67	

In this area of the Pacific Basin, the Pacific Plate descends westward along the Tonga-Kermadec trench beneath the Australian Plate. The Australian Plate descends north or northeastward beneath the Pacific Plate, from Vanuatu and the Solomons to at least New Britain and possibly into the Papua New Guinea mainland. To the west of Papua New Guinea the zone of tectonism becomes highly complex, with one zone extending northwestward along the Indonesian Archipelago, and another complex, northerly-trending zone which extends off the eastern coast of the Philippines, Taiwan, and Japan. Another tectonic zone extends southerly from Japan along the easterly coast of the Volcanic and Northern Mariana Islands.

Most of the land masses along these zones are island-arcs with continuous and active tectonic and volcanic histories during Tertiary and Quaternary times. As this is a dynamic tectonic zone, frequent volcanic activity is common. Many of the island groups are formed mainly by andesitic volcanism, but contemporaneous or later episodes of basaltic volcanism are common also. Basaltic material is now considered to be intruding some of the shallow basins, where it is forming new oceanic crust. This seafloor formation is occurring in both backarc and marginal basins with the development of numerous, young lithospheric plates. These areas are complex in terms of plate tectonics, especially north and south of New Britain and east and west of Fiji, and are areas for which many models, both of components and mechanisms, continue to be presented as more evidence is gathered and analyzed. Most of these basins have variable heat flows, which are often as high as 10 HFU, and suggest localized zones of mantle intrusion and elevated crustal temperatures. Along these features, terrestrial and submarine volcanoes are associated with crustal fractures, and commonly occur at fracture intersections. In some localities, these terrestrial structures continue into the adjacent shallow basins where they are associated with seafloor igneous intrusion.

POTENTIAL FOR GEOTHERMAL DEVELOPMENT

The Pacific island nations encompass a wide range of geographic, demographic, linguistic, cultural, and economic characteristics. Although the islands have relatively small land areas, they are scattered over enormous expanses of the Pacific Ocean, and through their Exclusive Economic Zones control large oceanic areas with their associated resources. Currently, petroleum is the dominant energy source for transportation, commerce, and electricity in the Pacific island nations, and most island communities depend almost exclusively on diesel-powered generators for electrical energy. As such, these countries have become increasingly vulnerable to supply and price fluctuations of imported oil. The governments are concerned that future energy costs will cause the loss of valuable foreign exchange, disrupt economic management and growth, and undermine or limit the region's potential for future development. These island nations are anxious to secure economically competitive energy sources that are not vulnerable to natural disasters, unreliable fuel supplies, political uncertainties, and unpredictable costs.

Many of the Pacific island nations currently are investigating alternative energy sources such as wind, solar, and biomass, but have been unable to proceed because of lack of reliable technology and funds, the need for small incremental sources of electrical power, and lack of experience and expertise in developing their indigenous energy sources. Geothermal energy may have an important role to play in fulfilling the energy needs of this area of the Pacific. Geothermal resources, as discussed in this paper, have wide distribution throughout this region, and countries such as Tonga, Fiji, Vanuatu, the Solomons, and Papua New Guinea, to name a few, have an obvious potential for resource development. Moreover, geothermal energy has many advantages in fitting into the island economies. Besides being cost-effective and economically competitive with alternate energy sources, geothermal energy is relatively nonpolluting, and can be developed in a relatively small area. Operating histories have shown it to be able to provide reliable baseload power. With the recent availability of modular binary cycle generating units, and other well-head generating devices, small-scale power plants can now be ordered on an "off-the-shelf" basis, and installed or expanded in a timely manner in relatively small incremental generating sizes.

Techniques for geothermal resource discovery and evaluation are now well-known and explorationists with extensive experience are readily available. By scaling exploration objectives to those suitable for the island economies, costs can be kept within reason. By developing lower temperature geothermal reservoirs, the risk of exploration failure can be reduced, and production complications and expenses resulting from high temperatures minimized. As lower temperature reservoirs are usually found at shallower depths than higher temperature reservoirs, it should be possible to drill shallow exploration and production wells with truck-mounted equipment that can be off-loaded onto existing port facilities. Truck-mounted drills could traverse existing roads or do so with minimal road upgrading. Drilling supplies would be less than required for drills used for production drilling on the U.S. mainland, further reducing logistical problems and costs. Modular binary cycle or other well-head generating equipment can be ordered in the 100- to 1,000-kilowatt plus sizes needed for island power requirements, and can be expanded quickly and at reasonable cost by drilling additional wells and adding modular units. By injecting waste brine back into the reservoir, reservoir properties can be maintained, reservoir life extended, and the cost of expensive surface abatement equipment avoided.

GEOTHERMAL COSTS

Exploration techniques for geothermal resources are well developed, but as exploration success cannot be predicted with certainty, costs can vary widely, and risk, no matter how well represented by explorationists or quantitatively required by management, always will be essentially unknown! However, exploration costs can be controlled, and risk can be minimized by carefully selecting exploration targets and lowering the criteria for successful economic discovery.

Exploration results over the past two decades have confirmed that high temperature (>200°C) resources are less numerous than low temperature (<150°C) resources. Large geothermal reservoirs also are less numerous than small reservoirs. Generally speaking, higher temperature resources usually are deeper than lower temperature resources. As drilling costs tend to increase geometrically with depth, by confining exploration to relatively shallow depths of 750 meters or less, drilling costs can be minimized and multi-million dollar drilling projects or exploration failures avoided. Geothermal wells to depths of 750 meters or deeper can be drilled by truck-mounted rotary drills. These relatively small drilling rigs can be unloaded onto marginal dock facilities and moved on unimproved road systems much easier and less expensively than the deep (3,000 to 6,000 meter), oil-field type rigs normally used for geothermal exploration and production programs.

A geothermal exploration program for islands in the Pacific Basin normally would involve five phases, each generally increasing in cost and contingent upon positive results of the preceding phases. As in all exploration programs, costs should be kept in line with a realistic risk/reward ratio, and as the island nations usually have relatively small electrical demands, only small power plants will be needed. The small demand for power, and relatively small income potential, will preclude numerous and expensive exploration surveys, and result in programs designed to discover and develop relatively obvious targets at relatively shallow depths.

The first phase of an exploration program generally involves a literature search of the geology, geography, and geothermal indications in the study area. If sufficient potential or interest is indicated in the literature search, a reconnaissance visit is scheduled to the area of interest to determine the general geology, access, availability of supplies and services, land status, etc., and to discuss need, regulations, permits, costs, and working conditions with the regulatory authorities and local service providers.

If all conditions are generally positive, a second exploration phase is initiated that involves geologic mapping and geochemical and geophysical surveys designed to define the geologic and hydrologic conditions, and areas of geothermal potential. During this phase, maximum use is made of geochemistry, as water chemistry is a powerful geothermal exploration tool in that sampling and analysis are relatively inexpensive, and ratios of dissolved elements in the groundwater can be used to predict with considerable accuracy minimum reservoir temperatures, and the potential for scaling, corrosion, or possible abatement problems. Geophysical surveys such as self-potential (SP) can give indications of faulting and flowing groundwater; and electrical resistivity surveys can give indications of rock alteration, structure, and possible reservoir conditions. Induced Polarization (IP) is normally offered with active electrical resistivity surveys at nominal additional cost, and should be utilized if possible, as IP can identify sulfide mineralization which often occurs with gold and other valuable metals that are frequently associated with near-surface geothermal resources. Aerial photography and other geophysical surveys such as magnetics or gravity, if available at nominal cost, should be acquired and interpreted for geothermal potential. However, high cost surveys providing indirect evidence of geothermal resources should be minimized or avoided. All the surveys incorporated in second phase exploration should serve to define drilling targets for the next exploration phase.

If the geology, geochemistry, and geophysical surveys indicate that the geothermal potential remains encouraging, the third exploration phase should involve drilling shallow temperature-observation holes to depths of 3 to 50 meters, depending upon the geological conditions. Optimum drilling depths can be established by experience and the results of several of the initial drill holes. These holes will give direct evidence of subsurface rock types, temperatures, geology, hydrology, and drilling conditions, and will serve to delineate deeper drilling targets for thermal observation holes or production test wells.

If conditions continue to remain favorable after the shallow temperature surveys, deeper temperature-observation holes, to depths of approximately 150 meters, should be drilled during the fourth exploration phase to further define deeper geologic and hydrologic conditions. These holes may be drilled with local water well drill rigs. However, if suitable rigs are not available, off-island rigs will have to be mobilized for subsequent drilling.

If a viable exploration drilling target is defined by the two preceding temperature surveys, a fifth exploration phase of development drilling is warranted to test for possible discovery of producible geothermal fluids. Nominally for the development of a one-megawatt facility, provision for four wells would be needed: the test-for-discovery well which could be used for production; a second production or stand-by well; an injection well; and a contingency for a "dry" well with little or no production value. If the initial test-for-discovery well is an outstanding success, and subsequent wells are also successful, all four wells need not be drilled. A "dry" well drilled after one or more successes can generally be used as an injection well. On the other hand, if neither of the first two wells are successful, serious consideration should be given to discontinuing the drilling program, or drilling elsewhere. As exploration is a contingency undertaking, an exploration program always should remain completely flexible. If the evidence suggests that the program can be condensed, or that different surveys should be used, the program should be modified to test the new conditions as they are understood.

The number of wells required to supply a one megawatt binary cycle generating facility will depend upon the flow capability of the geothermal fluids that are discovered. As shown in Figure 2, approximately 1,000 gallons per minute (gpm) of 250°F fluid or 500 gpm of 300°F fluid are required to produce one net megawatt of electricity after accounting for parasitic losses.[6] If wells in the geothermal reservoir are capable of producing 500 gpm of 250°F fluids, two wells would be required to support the generating unit. If the well produces at a rate of 1,000 gpm, only one production well would be required. The binary cycle units are adjusted to differences in geothermal fluids by adjusting working fluid composition and mixture.

Costs for this generalized exploration program are summarized in Table II[5]. If any of the assumptions described above or given in the table should vary, costs could vary also. If more wells, or deeper drilling is required, costs would increase as it would if lower temperatures than assumed were developed.

Costs for geothermal modular binary cycle equipment, and for operation and maintenance are currently being established, and can be readily estimated - even for remote Pacific island locations. Modular binary cycle generation units completely installed and fully operational in the United States currently cost in the range of $1,300 to $1,500 per installed kilowatt of capacity for one-megawatt sized units, but this cost is expected to decrease as the demand for additional units increases.

To compare the cost of a small modular unit to larger binary cycle facilities, a commercial sized, 70-megawatt, binary cycle, demonstration plant operated by San Diego Gas and Electric at Heber, California, cost $128 million to design, construct, and start-up. This represents a cost in excess of $1,828 per kilowatt. Approximately 23.4 megawatts of electrical power are required to run auxiliary equipment including the brine production and injection pumps, and the plant has a design net output of 46.6 megawatts. Capital costs for the first commercial binary plants similar to the Heber unit are expected to be about $1,650 per installed kilowatt.[7]

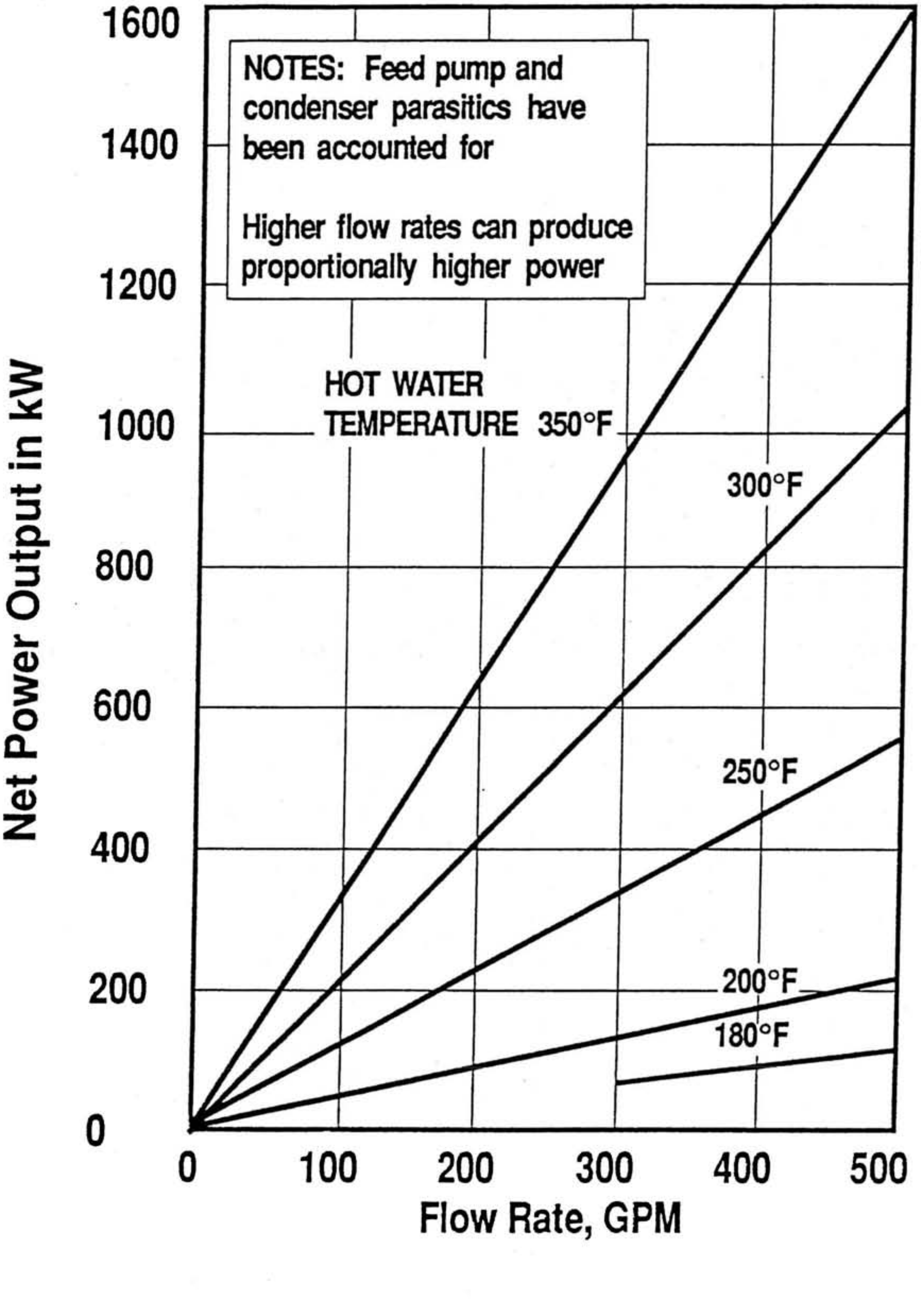

Figure 2. Power Generation Potential of a Geothermal Resource

TABLE II

ESTIMATED COSTS TO DISCOVER AND DEVELOP A GEOTHERMAL RESERVOIR CAPABLE OF PRODUCING ONE MEGAWATT FOR 30 YEARS

PHASE	ACTIVITY	EST. TIME (months)	EST. COST ($000)	
			Project	Total
I.	Reconnaissance			
	Literature Search	1/2	5	
	Site Examination	1/2	9	
				14
II.	Geology and Geophysics			
	Geology and Geochemistry	3	55	
	Geophysical Surveys	1	77	
	General & Administration		10	
				142
III.	Exploratory Drilling			
	180 - 3 Meter Temperature Observation Holes	1	22	
	36 - 50 Meter Temperature Observation Holes	1	54	
	General & Administration		20	
				96
IV.	Target Drilling			
	12 - 150 Meter Temperature Observation Holes	1	120	
	General & Administration		16	
				136
V.	Development Drilling			
	4 - 600 Meter Production Wells	2	1050	
	General & Administration		62	
	Decision Making	2		
				1112
	TOTAL	12		1500

As many of the modular binary generating units are designed to operate in remote locations, operation and maintenance costs should be nominal, and will probably vary between $50 and $80 per kilowatt annually.[8] Daily maintenance by part-time local staff should be limited to reading gauges, checking lubrication and fluid levels, and making minor adjustments. Major repairs would involve trained, local technicians, if available, or temporary duty factory staff. Parts not kept in inventory would be air freighted in for specific repairs. Assuming individual wells will slowly deplete and a five-year average life for production wells, replacement well drilling would add about $45 per kilowatt annually for a one-megawatt generation unit.

As shown in Table II, exploration costs leading to the discovery and development of a reservoir capable of producing one megawatt of electrical power for 30 years would be approximately $1,500 per kilowatt. Adding $1,500 per kilowatt, as the cost of the modular binary generating unit, gives a total program cost of $3,000 per kilowatt of capacity for exploration, development, and delivery of electricity to the system. Annual cost for operation, maintenance, and well replacement for a one-megawatt electrical development should range between $95 and $125 per kilowatt of capacity.

At sites of active volcanism, high temperature reservoirs capable of supporting much larger production rates could be discovered, and ultimately developed. If a reservoir capable of supporting at least ten megawatts of electrical generation for 30 years is discovered, and if subsequent development of an additional nine megawatts requires an average of only three wells to supply a one-megawatt generating unit, then development costs for the additional generating units would be approximately $745 per kilowatt of capacity - or less than half the cost of the initial one-megawatt development. Moreover, if the government or a private producer controlled both the geothermal wells and the generating units, the producer should be able to capitalize the wells together with the plant - thus in effect capitalizing fuel costs, which would bring current costs more in line with those of diesel generation.

If reservoirs with temperatures of 300°F or greater are discovered, the possibility also exists of developing the resource utilizing existing 5 to 10 megawatt single-flash generating units capable of being installed at the well-head in less than a year after being ordered. Depending upon the amount of power produced, these units could be installed at costs ranging between $700 and $1,000 per kilowatt of capacity.[9]

In addition to the electrical generation, fluids from the binary cycle heat exchangers could supply process heat for such uses as fish canning, copra drying, refrigeration for food storage and freezing, and air conditioning. Utilization of the waste heat from the binary heat exchangers, ultimately, is limited only by imagination and economics. Moreover, in the final analysis, the overriding factor for the development of indigenous geothermal energy in the Pacific island nations may not be economics, but may be strategic in nature, in providing a highly reliable baseload source of energy that is not dependent on outside forces beyond the control of island economies.

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