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FINAL REPORT
GEOTHERMAL RESOURCES PROJECT-STAGE ONE

PART 10

CONCLUSIONS AND RECOMMENDATIONS

Prepared for
GOVERNMENT OF NICARAGUA
Ministry of Economy, Industry and Commerce

By
Staff and Consultants
TEXAS INSTRUMENTS INCORPORATED
Services Group

February 1971

PREFACE

This Final Report on STAGE ONE of the Nicaraguan GEOTHERMAL RESOURCES PROJECT is submitted to the Government of Nicaragua by TEXAS INSTRUMENTS INCORPORATED in Spanish and English versions.

The report is the work of several authors and consists of ten parts, or chapters, each of which is bound separately, as follows:

Part 1 - PROJECT SUMMARY by D. E. Heilner and L. T. Braun

Part 2 - REGIONAL GEOLOGY: Thermal Manifestations of Western Nicaragua, by John B. Thigpen

Part 3 - SURFACE GEOLOGY: San Jacinto-Tisate-Najo Area, by John B. Thigpen

Part 4 - SURFACE GEOLOGY: South Volcan Momotombo Fumaroles, by John B. Thigpen

Part 5 - GRAVITY AND MAGNETIC SURVEYS, by Mario Mazzolini

Part 6 - ELECTRICAL GEOPHYSICAL SURVEYS in Relation to the Location of Geothermal Power Resources in Northwestern Nicaragua, by George Keller and Norman Harthill

Part 7 - GEOCHEMISTRY of the Nicaraguan Geothermal Project Area, by R. Bennett

Part 8 - TEMPERATURE GRADIENT WELLS at San Jacinto and South Volcan Momotombo, by R. Bennett

Part 9 - DEEP BOREHOLE TEST at the South Volcan Momotombo Fumarole Area, by John B. Thigpen

Part 10 - CONCLUSIONS AND RECOMMENDATIONS, by Texas Instruments Staff and Consultants

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GEOTHERMAL RESOURCES PROJECT-STAGE I

PART 10

CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

The Stage I investigations undertaken by Texas Instruments to locate and delineate a potential geothermal field or fields in western Nicaragua included compilation of data on thermal manifestations, regional and detailed geologic mapping, geophysical and geochemical surveys, drilling of shallow temperature-gradient wells, and drilling of a deep borehole test. Foregoing parts of this Final Report describe these investigations and present the resulting data, with some preliminary interpretation. Final interpretation of the data obtained during Stage I, with conclusions and recommendations of Texas Instruments' Staff and Consultants, comprise this part of the Final Report.

CONCLUSIONS

On the basis of the data obtained during Stage I, Texas Instruments' Staff and Consultants concur in the conclusion that the South Volcan Momotombo fumarole area shows strong indications that it can be developed into a commercial reservoir of

geothermal energy capable of supporting a 25 megawatt or larger power plant. The San Jacinto-Tisate fumarole area also appears to be a potentially commercial reservoir of geothermal energy. In this part of the Final Report, these two potential geothermal fields will be referred to as the Momotombo prospect and the San Jacinto prospect, respectively.

RECOMMENDATIONS

Texas Instruments' Staff and Consultants, in full agreement, strongly recommend that Stage II of the Nicaraguan Geothermal Resources Project be carried out in order to evaluate the economic potential of the Momotombo and San Jacinto prospects by deep exploratory drilling. Specific recommendations concerning the drilling program, associated geophysical studies, and production testing are embodied in a work plan which will form the basis for a Scope of Work statement. The WORK PLAN follows. Additional recommendations are:

1. That the optimum drilling techniques for the wells to be drilled in Stage II be determined in advance of drilling by means of a thorough geologic and geophysical evaluation in conjunction with expert drilling engineering. The proposed drilling technique should be subject to constant review and modification.

2. That no attempt be made to rework the existing deep well (MT-1) at the Momotombo prospect in order to make it suitable for extensive production testing. It is

probable that even after expenditure of large sums of money, the well will still not be in sufficiently good condition to permit extensive testing.

3. That if further evaluation of the Momotombo prospect by limited testing of the deep well MT-1 is contemplated, such testing can be accomplished without extensive remedial work, but must be done with great caution. Full production data cannot be obtained from the well in its present condition and no such attempt should be made.

4. That the Government of Nicaragua formulate a policy pertaining to certain possible social, economic and environmental side effects that may result from the drilling and possible development of these geothermal prospects prior to the initiation of Stage II. We recommend in particular that this policy should provide a framework of social and economic responsibility to the citizens of the village of San Jacinto for any damage or relocation that might result as a consequence of geothermal drilling and/or development. This policy should also provide guidelines of economic and environmental responsibility for any stream, lake, or ground water contamination that may result through the further delineation and possible development of these geothermal resources.

5. That the drilling in Stage II be done by a competent drilling contractor familiar with drilling in areas having special problems such as are involved in these geothermal prospects. The contractor should be accustomed to drilling in remote areas

with severe logistical problems. This recommendation is based on the fact that drilling is a very specialized operation that usually can be accomplished most efficiently and economically by experts. For this reason, and because of the relatively limited size of the drilling program anticipated in Stage II, it does not seem desirable for the Government of Nicaragua to purchase the equipment necessary to undertake this drilling program.

6. That the nine-well drilling program proposed in the WORK PLAN be considered flexible and not rigidly fixed at the outset of Stage II. The success of the entire program should be constantly reevaluated and each evaluation should determine the location of the subsequent hole. We recommend that the location of the last two wells be designated as optional at the outset of the program, their location to be dependent on results of previous drilling at Momotombo and San Jacinto. One of these optional wells might be drilled as a possible injection well for disposal of saline waste water, or one of them might be drilled at some additional test site other than Momotombo or San Jacinto.

7. That Stage II geophysical investigations include engineering-type studies to aid in determining the best drill sites, in-hole measurements in the wells to better evaluate existing data in both prospect areas, dipole resistivity work, and a micro-earthquake study as detailed in the WORK PLAN. We recommend that some or all of the geophysical work be subcontracted. We urge that some discretionary funds for

geophysical work be budgeted for unspecified contingencies.

8. That all of the drilling, testing and geophysical work of Stage II be subject to continual review and overall evaluation by competent geologists, geophysicists and engineers.

WORK PLAN - STAGE II

This work plan is intended to serve as basis for SCOPE OF WORK statement if the Government of Nicaragua decides to proceed with Stage II of the Geothermal Resources Project.

A. Purpose

The stated objective of Stage II is the proving of a potential geothermal field or fields by deep exploratory drilling. The work completed during Stage I has demonstrated the existence of two promising geothermal prospects: Momotombo and San Jacinto. It is desired that sufficient information be available at the end of Stage II regarding the better of these two prospects that realistic plans can be made for the financing, design, and development of that prospect for steam and power production. It is important that data be obtained during Stage II which will indicate the probable capacity of the geothermal reservoir and the most efficient way to drill development wells.

B. Drilling

1. Nine wells ranging in depth from 1000 to 1500 meters should be drilled to accomplish the purpose of Stage II. Two of these wells should be drilled to depths of approximately 1500 meters and the remaining seven wells should attain depths of approximately 1000 meters.

2. There should be competent geologic and drilling engineering supervision during the drilling of these wells. Each of these wells should be logged by modern logging techniques, including acoustic velocity, neutron, temperature and induction techniques.

3. These wells are to be completed in such a manner that they can be tested extensively and could be converted to production wells.

4. It is necessary that a multiple casing and careful cementing program be employed in the drilling of these wells. In particular, an initial 17-1/2 inch hole should be drilled so that 13-5/8 inch casing can be cemented from a depth of at least 200 feet to the surface. In the Momotombo area, the 13-5/8 inch casing should be set below the base of the near-continuous surface basalts; 9-5/8 inch casing should be cemented from the surface to approximately 1000 feet. The remainder of the hole preferably should be drilled with an 8-5/8 inch bit. High quality imported oil-well type cement should be used to cement all casing strings. Cementing should be done

with a modern high-pressure cementing unit. All casing should be perforated and then block squeezed with cement in several places.

5. The first two wells of Stage II will be drilled at Momotombo. The success of these two wells then will be evaluated. The third well of Stage II probably will be drilled at San Jacinto. It is important that the San Jacinto well not be drilled until a successful drilling and compl ion program has been developed by drilling at Momotombo. Again, after the drilling of this third well of Stage II, the entire drilling program should be reevaluated. Assuming that the results of the first two wells at Momotombo are favorable and that the results from the San Jacinto well do not justify its evaluation at that time as being a clearly superior geothermal prospect to Momotombo, the next three or four wells of Stage II probably would be drilled at Momotombo.

6. Tentative location for the first Momotombo well is 250 meters north of Momotombo Gradient Hole No. 6 (M-6). Tentative location for the second Momotombo well is either of two possible sites: 900 meters northeast of Punta las Salinitas, or 1500 meters northwest of the site given above for the first well to be drilled at Momotombo. Final choice of well sites will depend upon results of geophysical work outlined below.

C. Geophysical Investigations

A program of geophysical work will be undertaken as a part of Stage II. It will include:

1. Limited engineering-type geophysical investigations to aid in determining the best drill sites. In particular, shallow seismic and/or shallow-penetration resistivity surveys will be conducted in the Momotombo area to try to locate sites where a well can avoid dense continuous basalt for the first 200 to 300 feet.

2. Brief additional dipole resistivity work near the village of San Jacinto to aid in the site location of a test of that prospect. In particular, this dipole work should redefine the resistivities on the west end of the original dipole line, east and south of Highway 26. The dipole work should be performed prior to the final site determination of the first well to be drilled at San Jacinto. On the basis of present information, this test well would be located approximately 400 meters west or northwest of the western edge of the mud pots at San Jacinto.

3. Extension of the geophysical investigation of the Momotombo geothermal anomaly on all sides so that the boundaries of this geothermal system can be delineated. The principal method of investigation would probably be a dipole resistivity survey accompanied by limited electromagnetic soundings.

4. A micro-earthquake study in the two geothermal prospects. This study should be initiated before the drilling program is completed so that it might be of assistance in determining the location and depth of investigation of at least some of the wells. The study should be continued during the production testing of the wells to aid in evaluation of the geothermal reservoirs.

5. In-hole geophysical work in the wells drilled during Stage II to better evaluate the existing geophysical investigations in both prospect areas. In particular, continuous resistivity surveys of these wells are needed. It would be helpful if modern Induction-Self Potential logs can be obtained for each well.

D. Production Testing

1. Each of the wells drilled in Stage II will be subjected to extensive production testing of all types. Accurate temperature and pressure determinations and chemical analyses will be made over a period of time sufficient to yield data adequate for calculation of the capacity of the geothermal reservoir.

2. It is probable that a large volume of saline water will have to be disposed of at Momotombo. The waste disposal problem at Momotombo and elsewhere will be studied carefully. It is probable that the anticipated saline production waters at Momotombo should not be disposed of in Lake Managua.

E. Personnel

The contractors' professional staff should include: one Project Manager, one Administrator, one Geologist, one Geophysicist, one Geochemist, one Production Engineer, and one Drilling Superintendent.

BUDGET FOR STAGE II

The following amounts are estimates based on drilling costs in El Salvador and on Stage I experience in Nicaragua.

Drilling	U.S.$900,000.00
Personnel (salaries)	325,000.00
Mobilization (and demobilization)	30,000.00
Geophysical Investigation (includes logging)	130,000.00
Vehicles	30,000.00
Operation and Maintenance (vehicles)	25,000.00
Production Testing (equipment, piping, etc.)	60,000.00
TOTAL	U.S.$1,500,000.00

CONSULTANTS' OPINIONS

The foregoing conclusions and recommendations represent the best professional judgement of Texas Instruments' Staff and Consultants. The Consultants are in full agreement with the Conclusions, Recommendations, and WORK PLAN. Their individual statements are appended to this part of the Final Report on Stage I of the Geothermal Resources Project.

Respectfully submitted,

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Services Group
TEXAS INSTRUMENTS INCORPORATED

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GEOTHERMAL RESOURCES IN NICARAGUA

Report prepared for the
Government of Nicaragua
Ministry of Economy, Industry and Commerce

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PART I

COMMENTS ON PRESENT INVESTIGATION (STAGE I)

Introduction

My comments in this section will be selective concerning only those matters where I believe that some additional information or opinion beyond those presented in the detailed reports might be helpful. Two principal geothermal prospects have been established as a result of this investigation: Momotombo and San Jacinto. Most of my comments in this section are concerned with these two prospects. I will not make any attempt to present a systematic evaluation of each phase of the present investigation. Detailed reports have been prepared by various members of the staff of Texas Instruments concerning each of the separate phases. These reports are excellent. I want to commend the staff of Texas Instruments for having done an excellent job in evaluating the geothermal resources of Nicaragua and in the presentation of their results. The project was very well administered; the geological, geophysical, and geochemical investigations were thorough and of high quality; the drilling program provided useful shallow-hole data and was successful in establishing that a definite but unevaluated geothermal reservoir exists at depth at Momotombo. Many adverse conditions were encountered during this project and had to be overcome by the TI staff. In view of these adversities, the very high quality of the final results is especially commendable.

General Geology

John Thigpen has ably summarized the present knowledge concerning the regional geologic picture. Certain aspects of the regional reology remain unclear. Professor Bodvarsson expresses this reservation in the second paragraph of Section 3.1 of his final report; I concur. In particular, the regional

surface water temperatures based on the relative content of these three parameters. As there is the possibility of quantification, the subsurface temperature calculations based on these two separate techniques have received considerable attention in this report. In general, the temperatures predicted by the Na/K ratios have been higher than the temperatures based on the SiO_2 content. Only at Momotombo can the relative accuracy of these predictions be checked. Twenty-two surface water samples gave an average subsurface temperature prediction of 163°C based on the SiO_2 curves and 195°C based on the Na/K content. Temperatures of 195°C were measured at a depth of 300 feet in the one deep well at Momotombo (MT-1); a maximum temperature of 209°C was measured in this well at 700 feet. Thus at Momotombo at least, it appears that the curves predicting the temperature at depth based on the SiO_2 content are in error.

Other geochemical factors that suggest possible subsurface temperatures are reviewed in the report; they do not appear to be very diagnostic in the areas investigated in Nicaragua. One factor that was not reviewed but that appears interesting to me is the boron content of various waters. Boron is increased in the waters above many high-temperature geothermal sources. The analyses attached as an appendix to the geochemical report show that most of the sites that are considered to have a geothermal potential based on surface geology, surface temperatures, and other aqueous geochemical indicators of subsurface temperatures have a boron content greater than 3 ppm. Only one site has a boron content greater than 3 ppm that is not one of the definite or potential geothermal prospects. That exception is spring #40 (analysis #121; B = 3.9 ppm) which is located at Juigalpa in the mountains on the extreme eastern edge of the area of investigation. The hot springs at Momotombo have a boron content that ranges from 3.2 to 13.2 ppm with the exception of two springs. Water blown out of gradient hole M-1A had a

structural picture as to the specific nature of the central Nicaraguan depression is not certain. McBirney and Williams (1965) proposed a graben; Thigpen explains in his present report that the gravity surveys made during this project and a careful interpretation of the surface geologic features do not suggest a graben but rather a westward-tilted fault block; however, the presumed major fault boundary on the southwest side of the depression cannot be established by surface work nor was there any expression of it in the regional gravity traverse.

The line of Quaternary volcanoes on the southwestern side of this depression presumably is associated with deep-seated large-scale faulting. As all of the important geothermal manifestations in Nicaragua are associated with this Volcanic Range, it would be helpful to have a better understanding of the geologic factors that control its occurrence.

Gas Geochemistry

Gas samples were taken and analyzed from sites of fumarolic activity. The results from the point of view of being diagnostic or suggestive of certain high temperatures at depth are not at all impressive. The gases were uniformly low in H_2S and hydrogen -- the two components sometimes associated with subsurface sites of high temperature. The best that can be said is that the surface gases at the proven geothermal field at Ahuachapan, El Salvador, have similar low contents of H_2S and hydrogen. My own conclusion is that there is not any significant validity in these gas composition determinations from a geothermal exploration viewpoint.

Water Geochemistry

The two most important geochemical indicators of subsurface temperatures that are listed by Donald White are the SiO_2 content and the Na/K ratios. White has prepared very useful graphs in which he relates his best predictions of sub-

boron content of 20 ppm. (See revision of identification of sample numbers by Skyline Labs.) The lake water at Jiloa has boron contents that range as high as 6 ppm while the lake water at Apoyeque has boron contents that reach 12 ppm. Tipitapa, in contrast, has a maximum boron content of only 1.2 ppm. Mombacho also has a low boron content -- a maximum of only 0.7 ppm -- as does Hacienda California with a maximum of only 1.2 ppm. The chloride spring at Tisate, immediately north of San Jacinto, has a boron content of 3.1 ppm.

Current laboratory research here at the University of California, Berkeley, by Mr. Yusef Kharaka, shows that the passage of boron in aqueous solution through silicate membrane materials is greatly facilitated by an increase in temperature. This effect is interpreted as being a result of the relatively high susceptibility of these compounds to a significant increase in vapor pressure with an increase in temperature. The mobility of this species increases more than that, say, of chlorine with higher temperatures due to the greater volatility of boron compounds.

Evaluation of Prospect Areas -- Water Geochemistry

The chemistry of essentially all of the 22 water samples from the Momotombo area indicates that the area has great promise as a geothermal reservoir on the basis of every parameter that has been suggested as a geochemical indicator of high temperature. As the results from the deep well indicate, temperatures slightly in excess of 200°C have in fact been encountered at depth in the deep well. The surface chemistry suggests that the geothermal reservoir at depth is saturated with liquid water.

Only one spring in the greater San Jacinto area appears to contain water coming from depth. This spring is located south of Tisate. It is a chloride spring whose SiO_2, Na, K, and B contents suggest a high-temperature source at depth with some mixing with surface waters. Other thermal waters in the San Jacinto area

are simply surface waters that have been heated to the boiling point. The one diagnostic spring suggests that temperatures in the 200°C probably can be found at depth in the San Jacinto area. The chemistry of the spring per se suggests that the geothermal reservoir at depth also would be saturated with liquid water. However, the complete absence of other springs of this type, the fact that this one diagnostic spring is located beyond the northern edge of the geophysical anomaly that best defines at present the San Jacinto prospect, and the fact that all of the boiling springs directly over the anomaly contain no chemical parameters that are diagnostic either of reservoirs saturated with liquid water or that are dominated by vapor, makes any prediction in advance of deep drilling very questionable as to the probable nature of the reservoir type.

The water samples collected from Lake Jiloa and Lake Apoyeque continue to suggest a high-temperature geothermal source at depth. The Jiloa waters indicate a suitably high temperature based on Na/K but have a very low SiO_2 content; the boron content is high. Apoyeque, on the other hand, shows a higher temperature based on its SiO_2 than on its Na/K content; its boron content is exceptionally high. These areas continue to be of interest. It is surprising that no surface area of alteration or thermal activity can be found at Lake Apoyeque.

The springs at Hacienda California are of interest as high subsurface temperatures are predicted by both SiO_2 and Na/K calculations; these springs, however, have a rather low boron content.

The remaining sites are of more questionable interest. Tipitapa has one spring that shows a surprisingly high possible subsurface temperature (160°C) based on its SiO_2 content. However, its Na/K content does not suggest a particularly high-temperature reservoir and its B content is low. The chloride springs on the south flank of Mombacho suggest a high subsurface temperature (170°) based on SiO_2. The Na/K ratios appear to be very strange and probably are not very diagnostic; the boron content is low. The springs at San Luis simply do not appear to be very promising from any geochemical criteria.

Evaluation of Geophysical Surveys from a Geological Viewpoint

I conclude that the Schlumberger-type resistivity surveys are relatively worthless from the point of view of assessing a potential geothermal reservoir at depth. Wider spacing might be of greater assistance. The resistivity-depth soundings were not very definitive and the technique seems to be rather crude and primitive. The dipole resistivity studies were excellent for lateral definition at depth of the geothermal anomaly. The electromagnetic sounding technique was useful in providing some data on the depth of the geothermal anomaly. The construction of the interpretation, however, seems to be very complicated involving many assumptions; such techniques have tendencies at times to provide erroneous results. The magnetic studies were not a significant contribution; they measured, in essence, the area of the near-surface thermal areas and the near-surface altered rocks. The detailed gravity studies in the San Jacinto area were helpful in interpreting the geologic structure; the regional gravity traverse also was helpful in beginning to shed some information on the nature of the regional structure.

On the basis of the dipole resistivity studies, the lateral boundaries of the Momotombo geothermal anomaly have not been defined. The anomalous area is greater than 6 km long and greater than 2 km wide. The San Jacinto geothermal anomaly, in contrast, was defined laterally by the dipole surveys and is quite small in size. It is about 2.5 km long and about 1 to 1.5 km wide. By extended resistivity-depth soundings, the San Jacinto anomaly has a finite depth limit of 1 to 1.5 km whereas the Momotombo anomaly has no finite depth at a measured probe depth of 1 to 2 km. By the electromagnetic sounding technique, San Jacinto also has a limited depth to the thermal anomaly while Momotombo had an undefined lower depth.

Subsurface Geology--Momotombo

Important information about the subsurface geology at the Momotombo geothermal prospect was obtained by the drilling of the shallow gradient holes and the deep test well. From these wells, it appears that the Volcan Momotombo basalts with their minor interlayered tuffs that are present on the surface extend only to a relatively shallow depth. In the deep test well (MT-1), they were present to a depth of 215 feet. The rocks below that depth were principally tuffs with only minor interlayered basaltic lavas. If the distribution of rocks with depth in the MT-1 well is representative of the general subsurface distribution in the Momotombo geothermal prospect area, then these findings are very important. This shallow basalt-tuff contact suggests, as John Thigpen points out in his report on the MT-1 well, that the basalt lavas associated with the Volcan Momotombo eruption are a thin surface veneer on the south flank of the volcano. The Momotombo geothermal prospect and reservoir lies at depth within the pre-Volcan Momotombo tuffs. The shallow basalts are tough to drill but the deeper tuffs are soft and relatively easy to drill. The tuffs should provide a good reservoir rock with adequate porosity and transmissive characteristics.

Nature of Reservoir Fluid -- Momotombo

As indicated in the geochemical report and also earlier in this section, the geochemistry of the surface thermal waters and the water blown out of Gradient Hole M-1A indicates that the geothermal reservoir at Momotombo should contain liquid water at depth. The report on the deep well (MT-1) describes only steam as being produced from this well during the short intervals of time in which this well was allowed to flow. This result was surprising as all expectations were for a high-temperature liquid-water system in which case the well should have produced water and associated steam at the surface; water should have predominated. At the conclusion of the final consultant's meeting in Denver, John Thigpen showed

colored slides of the MT-1 well while it was flowing. There was a characteristic upside-down bell-shape to the plume at the top of the flow pipe where the reservoir fluids first entered the atmosphere. Don White, on seeing these pictures, was quite positive that the well in fact produced a steam-water mixture as he states that the bell shape is characteristic of a flow mixture of steam and finely-dispersed particles of water. In any event, the duration of the flow tests was insufficient to establish any definite characteristics of the reservoir fluids. Local flashing at depth could occur at some depth in the reservoir (the hole was uncased below 165 feet) giving a high steam/water ratio on initial testing.

Gradient Holes and MT-1 -- General Comments

a) Most of the gradient holes and the deep test at Momotombo (MT-1) were drilled essentially with water; only minor amounts of mud were used. Samples of the water returns were collected at frequent intervals during the drilling of the gradient holes for subsequent chemical analysis. These analyses were appended with no comment at the end of the report on the gradient wells. I have studied these chemical analyses; I conclude that they are meaningless as the waters analyzed were not valid subsurface water samples but remained essentially the drill water. These drill waters, moreover, were not in the hole for a sufficient time to establish equilibrium with the rocks with which they were in contact so their SiO_2, Na, and K contents are not at all diagnostic.

Extensive water samples were not collected during the drilling of the MT-1 test hole according to the report on that hole due to an implied recognition of the problems stated above. One sample was collected when the well was drilling at approximately 1500 feet and another of water from the first eruption were analysed. Again, the samples are not valid subsurface water samples and the chemical data are meaningless for the reasons stated above.

Valid subsurface water samples were obtained only from core hole M-1A amongst

all the holes drilled during this phase of the project. This is the core hole at Momotombo that erupted shortly after drilling. The erupted water sample is valid and the chemical analysis is diagnostic.

b) Valuable temperature data were obtained from the core holes. However, the particular technique employed was not very satisfactory as far as obtaining an accurate picture of the original temperature distribution in the wells. Valid measurement of the undisturbed temperatures in drilled wells is always a problem; the problems are increased around geothermal areas. Don White is a strong advocate of drilling only one 8-hour shift a day, letting the well stand overnight, and measuring the bottom-hole temperature with a maximum recording thermometer on a wire line before beginning to drill the next day. He believes that he obtains thereby the most accurate record of the virgin temperature distribution. After reviewing the results of the temperature measurements in the core holes at San Jacinto and Momotombo, I am convinced that Don White's technique is far superior to the one employed. The liability of White's technique is that the drilling must go much more slowly and therefore the drilling costs increase enormously. The superiority of White's technique was recognized prior to the drilling of the core holes; the decision was made to try alternate temperature-measuring techniques in order to hold down the drilling costs.

The technique employed was to use thermisters. The core holes were drilled as fast as possible. After drilling an insulated electric cable with thermisters was placed in the drill hole and left for the period of time during which temperature measurements were desired. Special high-temperature cables were obtained for a few thermister assemblies so that temperature could be recorded in very hot wells. In practice, there were problems. Thermister cables could not be installed along the entire length of several wells in some instances due to entanglement

and in other instances presumably due to hole caving. In one core hole, M-1A, that erupted shortly after drilling, no cable at all could be installed. The thermister cable could not be retrieved from some of the well bores; in others, the cable was damaged on retrieval. There was trouble initially in obtaining repeatable readings that could be converted to temperature data. Some of the thermisters definitely degenerated under the effects of high temperature. There is no interpretation problem when the degeneration resulted in no measurements; there is a problem with those measurements that are anomalous where it is possible that thermister degeneration may have resulted in erroneous measurements. However, the temperature distribution within well bores in geothermal areas oftentimes is very peculiar -- particularly as various thermal effects begin to manifest themselves in the open well bore with time. Thus, it is difficult to say with respect to certain anomalous measurements whether they are valid or not.

For various operational reasons not known to me but that probably were unavoidable, it was not possible in a few instances to place the thermister cable and begin taking temperature measurements immediately after drilling. In some instances, 10 to 30 days went by before the first temperature measurements. In most wells, temperature measurements were taken right after the hole was drilled and were continued at frequent intervals. In most instances, fortunately, the temperature distribution in each well bore was measured several times. As a result of the erratic times that temperatures were measured with respect to the time of drilling, it if oftentimes difficult to assess the true meaning of the temperatures that were measured in these well bores.

In general, I would recommend against trying to use thermister measurements in future holes. Of greatest importance is that the measurements of any type should begin immediately after completion of the well and should continue at regular time intervals.

Gradient Holes -- San Jacinto

The geothermal anomaly at San Jacinto is small; the spacing of the gradient holes was satisfactory. It is helpful that four of the five holes were removed from the surface anomalies. Only two of the core holes (SJ-2 & 3) encountered significant temperature anomalies. A true thermal gradient is present in SJ-2. The shallowest temperature is 20°C at 25 feet; this increases to 50°C at 200 feet. This temperature increase is linear over this depth range; if projected linearly, the depth where 200°C temperatures would be encountered is 750 feet. It is doubtful if this extrapolation provides anything but a minimum depth to the 200°C temperature region as the temperature-depth distribution is usually an exponental function where the rate of temperature increase with depth decreases with increasing depth. This exponental distribution is particularly true when the surface temperatures are low as they are in this well.

The temperatures in SJ-3 are near isothermal for most of the well in the 80°-90°C range. The temperature data are difficult to interpret; there is no date as to the time of measurement. If I extrapolate linearly along an average gradient from the 25 through the 200 foot depth level, then 200°C would be encountered at a depth of approximately 500 feet. This extrapolation is questionable.

The rock alteration was very moderate except in SJ-3. Even there, the alteration appears from the description to be significantly less than was encountered in the rocks at Momotombo. The rocks encountered in all but the westernmost well consisted of interlayered tuffs, ash deposits, and basalts. There were only minor lost circulation problems encountered and the drilling went relatively easily. Problems were encountered only in the westernmost location (SJ-1 & 1A) where huge lost circulation zones were encountered between basalt flows. These basalt flows associated with Volcan Santa Clara generally lie to the west of the San Jacinto geothermal prospect as defined geophysically and so should not be a significant problem in deep drilling.

Gradient Holes -- Momotombo

It is unfortunate, as pointed out by Don White, that most of the Momotombo gradient holes were located near areas of near-surface 100°C temperatures and within the grassy areas. The boundary of the trees and grasses probably approximates a heat flow contour; thus the grassy areas almost certainly are regions with higher heat flow than the tree-covered terrain. As a result, most of the gradient holes start in very hot ground and many are near-isothermal with depth.

The first temperature measurement in hole M-1 was made 32 days after the well was drilled. Even by that date, the well had not become isothermal. 150°C temperatures were present in two hot zones at depths of 115 and 190 feet; a temperature inversion existed in between. This first measurement was on September 19th. A second measurement was made on September 26th, it was similar but generally slightly lower than the first measurement with the exception of two measurements below 150 feet which were anomalously high. These two measurements were so anomalous that they were suspected of being erroneous. The third measurement was made on October 10th. These conformed to the first set entirely -- but at slightly lower temperatures. Hole M-1A was drilled to check these thermal measurements. It is most unfortunate that an earlier temperature measurement was not made in this bore hole; it is quite probable that some good gradient data would have been obtained. If a linear extrapolation is made on the thermal gradient measured from 140 to 190 feet in the first and third temperature measurement, then a temperature of 200°C is projected at a depth of approximately 240 feet. The well was drilled in heavily altered basalt to its total depth which probably accounts for the relatively fast drilling rates. Epidote and talc are reported from the samples.

Hole M-1A erupted about six hours after drilling; no thermister cable could be installed. The hole encountered an interlayered series of altered basalt, tuff, pumice, ash and vesicular basalt. This particular lithologic combination apparently

enabled the well to be drilled quite rapidly. Epidote was reported from the samples.

The first temperature measurement was made in hole M-2 29 days after it was drilled. If a thermal gradient ever existed in that hole, it is probable that it would have disappeared by that length of time. At the time of first measurement, the well was near-isothermal. Through two subsequent temperature measurements, the well remained near-isothermal but was slowly cooling with time. Basalt was encountered throughout the 200 feet of this well; the drilling rates were moderate to good. The basalt was altered almost from the surface but there are no details as to the nature of the alteration in the sample description. Presumably the higher drilling rates were a result of the alteration.

The first temperature measurement was made in hole M-3 24 days after it was drilled. By that time the well was near-isothermal; however a hotter zone with temperatures of 140°C was present at a depth of 150 feet. With time, the well cooled uniformly; the temperature anomaly at 150 feet gradually was eliminated by convection. It is quite possible that a very interesting gradient might have been present in this well from the near surface to the hot zone at 150 feet if measurements had been made earlier. The sample descriptions are not very illuminating. Basalt with varying degrees of alteration was encountered; zeolites and sulfide mineralization are reported. The well drilled quite well through the first 100 feet where the basalts were altered; the relatively unaltered basalts in the second 100 feet drilled quite slowly.

There is a modest but definite thermal gradient in hole M-5 from 100°C at 10 feet to 130°C at 165 feet as measured on September 26th. A linear extrapolation of this gradient gives a 200°C temperature at a depth of 465 to 500 feet. This result is very interesting as this hole is located immediately adjacent to the deep hole (MT-1) where two separate Amerada gauge measurements indicated that a temperature of 200°C was reached at a depth of 500 feet. The agreement between extrapolated prediction and the actual result is surprisingly close. There is a tempe-

rature inversion at the bottom of the hole on the September 26th measurement. This inversion is probably related to the high circulation losses that were encountered while drilling the bottom of the hole ten days earlier. By October 24th, this inversion had disappeared and the temperature had begun to rise at the 160 foot depth level. This bore hole erupted one month later. From 110 feet to the total depth of 190 feet there was an abundance of sulfide mineralization and some zeolites. Massive basalts were present and were altered to various degrees. The drilling rate was very slow below 100 feet.

Hole M-6 was drilled only to a depth of 100 feet where it was terminated due to high circulation losses. The first temperature measurement on September 26th was on the date the drilling was terminated; the temperatures are near-isothermal from 70°-80°C. This condition is probably a result of cooling in the well by drill fluid circulation. By October 10th a thermal gradient had developed. Linear extrapolation along this gradient indicates a depth of approximately 300 feet for a 200°C temperature. Despite the limitations on linear extrapolations discussed earlier, it is probable that this and other extrapolations in the Momotombo area probably are significant even though the actual depths may be greater than indicated. By October 24th, the thermal gradient that had developed in this hole had been wiped out and the well was again near-isothermal at 90°C -- a higher temperature than the first near-isothermal condition. This second isothermalstate probably was controlled by thermal convection in the open hole which always tends with time to eliminate vertical thermal gradients. These three measurements at varying times are an example of how important a time sequence of temperature measurements is in any geothermal bore hole. Zeolites were encountered in this well bore as were interlayers of basalt, tuff, ash and vesicular basalt. The massive dense basalts common to the Momotombo area were not encountered and

the drilling rates were quite high; however, the interval from 100 to 200 feet, where most of the Momotombo wells encountered very slow drilling, was not penetrated.

A thermal survey one day after drilling hole M-7 shows a very nice thermal gradient along the entire length of the well bore -- from 75°C to 145°C. Linear extrapolation along this gradient indicates, like hole M-6, a depth of approximately 300 feet for a temperature of 200°C. Eight days later the bottom 50 feet of the well had become isothermal. This well later erupted. Basalts were encountered over essentially all of the 195 feet of this well. Drilling was very slow to a depth of 145 feet and then became relatively rapid. From the sample description, this was the most heavily altered of any of the Momotombo gradient holes. Sulfide mineralization, zeolites, argillization, and epidote were present to varying degrees in the hole at depths below 30 to 40 feet. This apparent increase in alteration may be a result of the samples being described by a person different than the one who described the other gradient-hole samples.

No thermal gradient developed in hole M-4. The two thermal measurements indicate near-isothermal conditions at 80°-90°C; the first measurement was made four days after the well was drilled. The well encountered massive basalts and had intermediate drilling rates. Very little alteration is described in the samples. The well was stopped because of large lost circulation.

I conclude that the projected gradients from four of these Momotombo gradient holes really do mean that zones with 200°C are present at moderate depths. The projection and the measured result of approximately 500 feet for this temperature in hole M-5 and MT-1 agreed remarkably well. The other three projections give a shallower depth -- 300, 300, and 240 feet. Those depths may be too shallow. Nonetheless, I believe that these gradient data suggest the presence of 200°C zones at shallow depths over a wide area of the Momotombo prospect.

Comparison--Momotombo and San Jacinto Geothermal Prospects

	San Jacinto	Momotombo
Area of Prospect	Relatively small from surface geology, geophysics and gradient drilling. Geophysics indicates an area 2.5 km long by 1 - 1.5 km wide.	Very large. Prospect covers extensive area based on surface geology, geophysics, geochemistry, gradient and deep drilling. Geophysics indicates an area greater than 6 km long and greater than 2 km wide.
Depth of Prospect	Limited. Finite depth limit of 1 - 1.5 km indicated by geophysical depth-sounding techniques.	Unlimited. No finite depth measured at a probe depth of 1-2 km.by geophysical depth-sounding techniques.
Gradient Drilling Results	Anomalously high temperatures in two of the four successful gradient holes. One thermal gradient gives a linearly extrapolated depth of 750 feet while another gives a 500 foot depth for 200°C temperatures. These depths probably are minimal. Highest recorded temperature is 105°C.	Anomalously high temperatures present in all eight gradient holes; all eight had temperatures equal to or greater than 90°C. Four holes had temperatures equal to or in excess of 140°C. Linearly extrapolated gradients in four holes give depths of 500, 300, 300, and 240 feet for temperatures of 200°C. The 500 foot extrapolation was verified by measured temperatures in MT-1 which was drilled adjacent to that particular gradient hole. The other three extrapolations may indicate a depth slightly less than what actually exists. The gradient holes suggest the presence of 200°C temperatures at moderate depths over a wide portion of the Momotombo prospect.
Deep Drilling Results	No deep hole drilled.	One deep hole (MT-1) drilled to a total depth of slightly less than 2000 feet. A maximum temperature of 209°C was measured at 700 feet--thus establishing with certainty a base temperature at least as high as the 200°C value that is required for successful geothermal reservoirs. Pre-Volcan Momotombo tuffs probably were encountered from 215 feet to total depth. These tuffs should have a rather wide extent; they should provide a good geothermal reservoir rock. No valid results were obtained as to the nature of the reservoir fluids, productivity rates, pressures, etc.

Geochemistry	Negligible information except for one spring site on north edge of anomaly which suggests liquid-water saturated reservoir at depth. Temperature prediction of 156°C (SiO_2) and 210°C (Na/K).	Abundant surface springs and one valid subsurface sample from gradient hole M-1A; all suggest liquid-water saturated geothermal system at depth. Temperature prediction of 195-200°C (Na/K) and 150-165°C (SiO_2). Siliceous sinter on the surface indicates the presence of subsurface temperatures in excess of 180°C.
Accessibility for drilling and possible power plant	Good	Fair to difficult.
Water supply for drilling and power plant cooling.	Very limited supply--a major problem.	Unlimited supply in Lake Managua; no problem exists.
Drilling	No deep hole drilled so no experience. From gradient hole data, there should be no significant drilling problems within the first 200 feet.	Most important drilling problem is to drill large diameter hole through surface basalts (215 feet in MT-1). Probably will require surface location at sites with temperatures significantly below 100°C and hopefully in a local area where the shallow basalts are not so dense. Cable tools probably will be required for shallow drilling. Very little drilling penetration problems should be encountered in the tuffs below the shallow basalts. Significant lost circulation zones were present in the tuffs within MT-1; the problem was minimized by the abundant water supply.
Expected Reservoir Temperature	Indications from surface geochemistry and gradient hole data presented above. I expect that a geothermal reservoir with the required minimum temperature of 200°C is present at depth.	Data from geochemistry, gradient and deep holes presented above. Minimum required temperature of 200°C for a geothermal reservoir already established by the single deep drill hole (MT-1). Most other data also indicate temperatures of 200°C or higher.
Expected type of geothermal reservoir	Uncertain. Single valid surface spring indicates liquid-water geothermal system. Complete absence of other chloride waters in boiling mud pots directly above center of geophysical anomaly is peculiar. A vapor-dominated system could be present.	Liquid-water saturated geothermal system is indicated by all chemical analyses. Production data from MT-1 are insufficient to be conclusive. Only steam was observed at well site during limited flow periods; Don White interprets pictures of flowing well as indicating a flow mixture of steam and finely-dispersed liquid water. It is very probable that this geothermal system is a liquid-water type.

Social Problems	Very significant social considerations--a major problem. Geophysical work indicates that the village of San Jacinto is directly over the heart of the anomaly. There will be significant noise problems during testing. If water pollution occurs, it will be an immediate social problem. Relocation of the village would probably be required should drilling indicate the desirability of development and power plant construction.	No social problems exist; there are no people living on or adjacent to the geothermal anomaly.
Legal Problems	There will be considerable legal problems associated with exploration drilling and any possible development drilling and power plant construction. These problems arise from the fact that San Jacinto is located directly on the anomaly and the surrounding land is used agriculturally. Extensive legal permits will be required.	Negligible legal problems.
Water Disposal Problem	Uncertain, depending principally on the nature of the geothermal reservoir. There would be essentially no problem if a vapor-dominated system were present; should a liquid-water system be present, then there would be a problem. However, there is an abundance of readily accessible land nearby. Hopefully, waste brine could be disposed of in injection wells located beyond the boundary of the geothermal reservoir.	A considerable problem-- probably the most significant problem that can be anticipated at this time for the Momotombo prospect. Large quantities of noxious waste brine water most probably will be produced along with steam at Momotombo. Dumping that waste water into Lake Managua probably would irretrievably contaminate the waters of the lake with certain inorganic chemical species. Injection wells would have to be drilled at a site beyond the immediate boundary of the geothermal reservoir that would be capable of disposing of large quantities of water. I expect that the tuffs encountered below the shallow basalts in the MT-1 hole may be widespread. If so, then rocks suitable for such disposal probably can be found. in other words, I anticipate that the water disposal problem can be solved satisfactorily.

Conclusions - Relative Comparison of Momotombo and San Jacinto

Momotombo is by far the superior prospect at the present time on the basis of nearly every consideration. The most important evaluation is that the size of the Momotombo prospect appears to be huge, both laterally and vertically, while the San Jacinto prospect appears to be quite small. Temperatures of 200°C have definitely been established at Momotombo; they are still predictions at San Jacinto. San Jacinto has very considerable social, legal, and water supply problems; Momotombo has none. San Jacinto rates more favorably as regards accessibility for drilling and ease in drilling the upper 200 feet. These considerations, however, do not seriously lessen the greater attractiveness of the Momotombo prospect. If deep drilling establishes that San Jacinto has a liquid-water reservoir, then San Jacinto is definitely a very poor second-place prospect as compared to Momotombo. It is my opinion that only if a vapor-dominated geothermal reservoir exists at San Jacinto would further exploration or development be warranted at the present time.

Evaluation of Other Potential Prospects

There are much less data on any of the other areas than Momotombo and San Jacinto. On the basis of the modest available information, I believe that I would rate the Jiloa-Apoyeque area as being the most interesting amongst this group of potential future geothermal prospects. The most attractive aspect of the Jiloa-Apoyeque area is its chemistry - which consistently indicates high temperatures at depth. The area deserves further investigation despite the absence of surface alteration or thermal activity. Likewise, the Hacienda California area deserves further attention based on its surface chemistry.

The Tipitapa and Mombacho areas are of questionable interest based on the chemistry of their surface waters; neither of these areas have any surface features of alteration or of extensive thermal activity that suggest the presence at depth of a geothermal reservoir.

Volcan Casita does not appear to be an attractive geothermal aspect. An extensive area of surface alteration and fumaroles is present; there are no springs. The gases do not contain any appreciable content of anything but air. It is probable that this area is high above the water table due to the local topography. The lack of springs is almost certainly related and the gas content also may be influenced by this factor. I am uncertain as to whether or not Casita is an area perched high above an active thermal system or represents a thermal area that formerly was much more active. In either case, Casita does not appear attractive as a current geothermal prospect. The relative inaccessibility is an additional factor that makes this site unattractive.

There are hot springs and other thermal occurrences scattered within the depression to the east and northeast of the San Jacinto prospect. This general area continues to interest me even though there is no single site known where a possible geothermal prospect might exist. None of these thermal waters reach 100° C nor do their waters indicate the presence at depth of temperatures that would be of interest for possible geothermal exploration. There is no surface alteration. If any geothermal prospect exists, it is present at considerable depth and there is little surface manifestation. Only minimal geophysical work has been done but some anomalously low resistivities were found by resistivity-depth soundings at Stations 34 and 35. No deep hole evtr has been driller within this depression. There is no knowledge of the rock types, thermal distribution, or hydrology of this region. It is of interest to continue to collect data on this area. In particular, dipole resistivity studies would be helpful. If a

geothermal power generating site is developed at Momotombo or San Jacinto, I hope that one or more deep wells will be drilled in the central part of this depression for thermal gradient and all other possible geologic data.

PART II

RECOMMENDATIONS FOR FUTURE WORK (STAGE II)

Introduction

An overall series of requirements and recommendations for Stage II have been prepared by the consultants and the contractor. I concur with all of these opinions as regards work to be done in Stage II. As a result, I am only including in this section of my report selected items on which I wish to elaborate.

Arguments Against Reworking Deep Well (MT-1)

I wish to emphasize the concensus recommendation against trying to rework MT-1 well in order to prepare it for extensive testing. There has been a considerable experience in drilling a variety of geothermal test holes over the last twenty years. There are several occasions of which I am aware where a well ended up, for one reason or another, in a crippled state -- incapable of being able to produce for production tests. It is tempting to try to remedy what may be wrong; the anticipated effort and cost never seems very large in advance. In every instance of which I am aware, attempts to remedy the crippled state of such wells have been very costly and have been failures. The result has been that the recompletion effort was abandoned at some stage when the cost became too great; usually another well was then drilled. In most instances with which I am familiar, the cost of the new well was less than the cost of the attempted recompletion.

The procedures that were suggested as possible remedial techniques within the report on the MT-1 well might or might not work. Grouting in some situations somewhat similar to those of the MT-1 well has helped and in others it has not.

The critical question is whether or not the surface boiling around the casing that occurred during the flow periods is in fact related to high heat transfer from the well bore, as suggested in the MT-1 report, or if there could be the introduction of steam and/or high temperature water below and around the casing in such a manner as to cause heating at the surface alongside the well bore. The first situation might be alleviated by grouting; the second probably would not.

After drilling and completing additional wells in the Momotombo area, considerable knowledge and experience will be gained as to the behavior of wells under various conditions. It is possible that at some future time, a plan that has some reasonable assurance of working might be developed so that an attempt then might be made to rework the MT-1 well. Nothing is lost by leaving the well suspended in its present state.

Testing of MT-1 Well

As recommended, limited testing of MT-1 should be carried out without any extensive remedial work. These tests should be carried out with care so as to avoid the possibility of a blow-out. The tests probably should be conducted initially for very short flow intervals; if successful, these intervals should be gradually increased. An accurate pressure gauge should be installed at the well head prior to any testing so that the surface pressure under various flowing and shut-in conditions can be measured. Don White believes that valid water samples can be obtained from fluids similar to those described as flowing from the MT-1 well during its limited test periods. He interprets this fluid as being a mixture of steam and finely-divided water particles. He suggests that a sample might be obtained by placing a long stick or rod in the bell-shaped fluid cone; water then might run down the stick and be collected. This technique should be tried.

Drilling Problems and Recommendations -- Momotombo

The most important drilling problem at Momotombo will be to drill a very large diameter hole through the near-surface massive basalts which extended to a depth of 215 feet in MT-1. It is probable that the thickness of these shallow basalts will increase at sites north of MT-1 which are located closer to Volcan Momotombo itself and at a higher surface elevation. The near-surface basalts are very difficult to drill; the underlying tuffs are quite easy.

Unaltered basalts are always difficult to drill. When they are encountered on the surface, the drilling is especially difficult. Penetration rates in rotary drilling depend to a very large degree on the weights that can be applied. At shallow depths, penetration rates in any kind of rock always are low because an insufficient number of drill collars has to be used.

This problem is compounded at many of the areas around the Momotombo geothermal prospect by the existence of extensive surface areas with temperatures at or near 100°C. Drilling down an actual or near-boiling point curve from the surface is much more difficult than drilling through a relatively cool near-surface zone.

Great care must be used to pick the surface locations -- particularly in the earlier wells. The sites should be relatively cool on the surface; they should not be located within the grassy areas of probable high heat flow. It will not be possible to avoid the near-surface Volcan Momotombo basalts that were encountered in all of the gradient holes and geologically can be expected everywhere over the geothermal prospect. However, there were significant differences in the lithologies and drilling rates through these shallow basalts in the various gradient holes. The most heavily altered basalt, naturally, drilled the fastest. Faster drilling rates also were encountered when the basalts were less massive due to the presence

of vesicular basalts and/or interbeds of tuff. The optimum drill site would be one that was relatively cool at the surface and at shallow depths, but where the shallow basalts have a lower density than that of the massive basalts due to tuffaceous or vesicular interbeds that hopefully are altered at depth. It is probable that some highly portable geophysical techniques to determine the densities of the shallow rocks, such as simple seismic and/or shallow resistivity surveys, might help to locate areas where the shallow basalts are less dense.

Even with the location of an optimum site, the expense of drilling a large-diameter hole through these shallow basalts may be very large. The cheapest way would be not to use a rotary rig but to use cable tools to drill through these shallow basalts. Cable tools almost always have much cheaper penetration costs through shallow basalts and similar igneous material. With cable tools, it is particularly desirable to have temperatures below the boiling point curve through the penetrated interval. Even if the boiling point is reached, it is possible even probable that the hole could be fought down through the shallow basalts with the use of stuffing boxes. Large diameter casing, such as 13-5/8 inch, should be cemented below the shallow basalts and well into the underlying tuffs. While drilling the well with cable tools, bottom-hole temperature measurements should be taken before drilling is resumed after each cessation of drilling for a significant length of time. In other words, Don White's technique of temperature measurements should be employed wherever possible. The cost is minimal; the information is valuable.

Rotary tools should be moved in to drill the tuffs below the large surface casing. The bit size should be large -- probably 12-1/4 inches. An attempt always should be made while drilling with rotary tools to stay with larger sizes -- say, between 8-1/4 and 12-1/4 inches. The bits are much stronger in these larger sizes;

thus more drilling weight can be applied. Likewise, the bits are less susceptible to in-hole breakdowns. Fishing jobs are always expensive; they are particularly troublesome in geothermal holes due to the necessity of maintaining circulation in order to avoid heating and eruption. The penetration rate possibly is not quite as great with these larger bits as it is with bits in the 5 to 8 inch range, but the greatly-increased insurance factor during drilling and the great superiority of a larger rather than small diameter production hole more than offset this disadvantage. At Momotombo in particular, moreover, it does not appear that penetration rates in the pre-Volcan Momotombo tuffs should be a significant problem.

Once the well is below the 200°C temperature level, it is possible that air drilling might work. That level was encountered at 500 feet in the MT-1 hole. Intermediate diameter casing, such as 9-5/8 inch, should be cemented several hundred feet below that temperature level. For air drilling to work, it would be essential that the shallower zones of lower temperature be cased off; however, even should the well be continued essentially with water then this intermediate casing string still should be set. Drilling inside this intermediate casing string probably should be done with an 8-5/8 inch bit.

Air drilling can work in a liquid-water saturated reservoir if the temperatures of the uncased hole are sufficiently high that the water flashes to steam. The maximum air pressure that can be supplied is approximately 1000 psi. Air drilling would not work if the well produced so much water that it could not be handled by the combination of natural steam flashing and air circulation. Air drilling was employed successfully to drill the brine-saturated geothermal reservoir at Niland, near the Salton Sea in California. This technique, once adapted to the particular conditions, proved to be by far the most efficient drilling method.

Air drilling has great advantages over water or mud for geothermal holes even when an abundant water supply is available as at Momotombo. The penetration rate is at the maximum. More importantly, the greatest possible knowledge as to the temperature distribution, nature of the reservoir fluids, and transmissive characteristics of the reservoir rocks is obtained while drilling the hole with air. Almost none of this knowledge can be obtained while drilling with mud or water. Wells can be drilled with mud or water, and the deep tuffs at Momotombo probably would drill rather easily with water, but they have to be drilled blind -- with little knowledge of the reservoir conditions. As a result, the decisions as to how and in what intervals to attempt to complete them are largely guess work. Unlike petroleum drilling, there is very little in the way of rock sample evaluation and electric log analysis that permits a satisfactory prediction of productive zones. Drill-stem tests are impractical on high-temperature geothermal holes as the temperatures are so high that the rubber packers are destroyed. Drill-stem tests were attempted on some of the early deep holes at Niland; they were failures.

Continual temperature measurements on the blooey line while drilling with air permit a near-instant surface reflection of the temperatures being encountered at the drill bit in the subsurface. The type and quantity of the fluids emitted at the blooey line also permit a constant monitoring of the type and relative production rates of the fluids present at depth. If waters are emitted at the blooey line, they will be valid formation water samples thus providing a means of obtaining such samples for chemical analysis. No other drilling technique has so many advantages for geothermal drilling. Its advantages in the way of information gained are so great, that it is worth a great deal of time and trouble to try to drill with air.

Drilling Problems and Techniques -- San Jacinto

As no deep well yet has been drilled at San Jacinto, there is much greater uncertainty as to the possible drilling problems. The most obvious problem is the lack of a large water supply nearby. The only local water supply is from the springs that also supply the village of San Jacinto. The springs produce an average of approximately 600 gallons per minute. This is an insufficient quantity to meet the worst lost circulation zones that might be encountered. Circulation was lost in the deep well (MT-1) at Momotombo at rates of 20 to 25,000 gallons per hour. It appears probable to me that a large pit would have to be dug with a bulldozer, lined with polyethylene sheeting, and then filled with water in advance of drilling to provide an adequate emergency supply. Pits of this type are prepared in the United States in connection with petroleum exploration that are up to 300 feet long by 100 feet wide in which water volumes up to 100,000 barrels (4.2 million gallons) are stored. The alternative would be to try to drill a water well. Only one well has been drilled in the area -- the cotton gin well to the west of San Jacinto. This well has highly saline water and low productivity. Pit storage seems the best. However, the breccia zones interlayered between basalt flows to the west of the geothermal prospect (mentioned below) might provide extraordinarily large water wells. No significant lost circulation was encountered in any of the San Jacinto gradient holes drilled over the geothermal anomaly. Very large lost circulation intervals were encountered in breccia zones interlayered between Volcan Santa Clara basalt flows in the two gradient holes (1 and 1A) attempted west of the geothermal anomaly. Locations must be avoided, if possible, where these basalt flows are present. In general, that should be possible. If not, then a cable tool rig is mandatory for drilling through these recent surface lavas.

Drilling penetration rates in the gradient holes over the geothermal anomaly were satisfactory. This rate, however, will go down drastically when a large-diameter surface hole is drilled. In general, I think it might be advantageous to attempt the same drilling method as I suggested for Momotombo. This would mean using a cable tool rig to drill a large-diameter hole to a depth of 200 feet or so; cementing large-diameter casing; moving in a rotary rig and drilling with mud/water several hundred feet below the 200°C level; cementing an intermediate casing string; then attempting to drill with air with an 8 5/8 inch bit. There are uncertainties. There is no information beyond the gradient hole data with which to attempt to predict the 200°C depth level and it will not be possible to measure it in place without withdrawing the tools, hopefully letting the well erupt, and then measuring the temperature with an Amerada bomb -- an awkward and time-consuming procedure while drilling a well and one involving a certain amount of risk of losing the well. In the absence of other information, I would choose the depth of 1000 feet as the level to which to set the intermediate string. Drilling with air below the intermediate string level has obvious advantages if successful. One, of course, is that no water is required. The others were discussed in the section concerning Drilling Problems and Techniques at Momotombo. If the geothermal reservoir at San Jacinto is a vapor-dominated type, then air drilling should work particularly well. Air drilling now is being used almost exclusively in the development drilling of The Geysers vapor-dominated geothermal system in the United States with great success.

There are problems and responsibilities that stem from the fact that the village of San Jacinto is located directly on top of this geothermal anomaly. The first test site should be removed as far as possible from the village. Care should be exercised so that none of the local people are injured in case of an accident, blow-out, etc. Providing that the initial test or tests are located in a position safely removed from the village, then the principal social problem will

arise during the testing of any completed geothermal well. The noise emitted from a steam well while blowing is equivalent to that from a jet engine on a Boeing 727. If deep drilling is successful, and one or more wells are tested for a protracted period of time, then the inhabitants of the village are going to be subjected to an incredible amount ot incessant and continuous noise, with no relief. Noise pollution of this level is injurious to humans. The length of time to which the villagers might be subjected to this noise pollution before a decision definitely would be made as to whether or not to attempt the development of a geothermal power generating facility cannot be accurately predicted. That interval is dependent to a large degree on the subjective feelings of the various people who would be involved. Pacific Gas & Electric Co. insisted that the first wells at The Geysers in northern California be tested for over a year before they were satisfied that a long-lived steam resource truly was present. If the decision is ever reached for the construction of an actual power-generating facility, then the village and all of its inhabitants would have to be moved. As indicated in the general recommendations, all of the consultants and the contractor recommend that the Government of Nicaragua consider these social problems and formulate a general program whereby these responsibilities can be met in advance of any drilling at San Jacinto.

The consultants and contractor also recommended that at least the first two wells of Stage II be drilled at Momotombo before drilling the deep test at San Jacinto. I believe this procedure is prudent from all considerations, i.e., relative merits of the prospects, relative drilling costs, and relative safety for people. The well at San Jacinto almost certainly can be drilled more efficiently and safely after more successful drilling techniques have been worked out at Momotombo.

Miscellaneous Recommendations -- Drilling, Completion or Production Testing Procedures

An effort should be made to obtain good drilling samples from every well;

these samples should be described, collected, and stored for future study. It is not desirable that any coring be done in the initial wells that will be drilled in Stage II. However, after more geological knowledge has been obtained through additional drilling, it is probable that selective zones of interest then should be cored. Better well site geology and much better sample description is desired than existed for the wells drilled during Stage I with the exception of gradient hole M-7 and the deep hole, MT-1. Large mud pump capacity is one of the important keys to successful and safe geothermal drilling; such high capacity should be mandatory for the drilling rig that will be used in the Stage II drilling. Expansion joints should be installed as part of each casing string. The cementing of all casing should be done with first-class cement by a modern cementing unit; all cementing procedures should include, as a matter of course, perforation and block squeezing with cement after the initial cement job.

Extensive production tests of all types are recommended for future wells. It is virtually certain that Momotombo is a liquid-water saturated geothermal system; therefore a steam-water separator will be required for testing.

The Amerada temperature device should be the most useful tool for temperature determinations in future wells. Whenever drilling is not being conducted around the clock in any cable tool hole or whenever circulation is broken for a significant period of time in a rotary hole, I strongly recommend that a bottom-hole temperature be obtained either with a maximum-recording thermometer on a wire line or with an Amerada device before resuming drilling or reestablishing circulation. Thermisters should be used only on a limited basis and should not be the principal method of temperature measurement.

Recommendations for Drilling Engineering Personnel

It is absolutely necessary that a first-class, highly imaginative drilling engineer with considerable experience in air and geothermal drilling be obtained on

a full-time basis during the drilling of the Stage II wells. However, in practice, it probably will be impossible to obtain such a man. Thus, the best available drilling engineer should be found and outside drilling advisors should be retained on a selective basis.

Union Oil Company of California has the only drilling engineers with whom I am familiar who would meet all of the qualifications. However, Union is not desirous to take on contract work. I have explored this matter with them and they would prefer that they not be asked. It is possible that Union of California might be induced to permit some of its knowledgeable personnel to serve as drilling advisors; however, an official request from the U.S. Department of State probably would be necessary.

There is a toolpusher by the name of Skees Ajax, with Magma Power Company, who is recommended by the Union personnel as being a good geothermal drilling man. Magma was the operator of The Geysers geothermal development until Union of California bought an interest in the area several years ago.

Waste Disposal Problem

All liquid-water geothermal systems require that large amounts of water be produced along with the steam. This water will be a brine whose total concentration cannot be predicted in advance; however, it will contain noxious substances that are injurious to animal and/or plant life such as arsenic, boron, etc. Waste brine water in general should be disposed of by subsurface injection. There is no significant waste-disposal problem associated with production from a vapor-dominated geothermal system.

As it is highly probable that Momotombo is a liquid-water geothermal system, it is therefore equally probable that there will be a significant waste brine disposal problem associated with production from Momotombo. It is also very probable in my opinion that careful study after more data are available will indicate

that these waste brines should not be dumped into Lake Managua. It is true that Lake Managua is now badly polluted with organic wastes (sewage) from the city of Managua. However, this pollution can and probably will be reversed at some future date by the installation of an adequate sewage-treatment plant. Dumping into Lake Managua of the geothermal waste brine water from a commercial power plant development at Momotombo probably would mean, in my opinion, an irretrievable inorganic contamination of the waters of that lake by various chemical species.

Subsurface injection of these waste brine waters probably will afford the best solution. It will require careful study and testing to obtain a suitable site for such injection. The injection of these waste brines directly into the geothermal reservoir probably would interfere with the production characteristics of the reservoir. Injection must also be located so that these brines do not make their way into the lake via subsurface hydraulic flow. It would seem preferable to try to locate the injection site immediately outside the subsurface boundaries of the geothermal system and at such a depth that the natural convective hydraulic flow would circulate the waste brines into the geothermal system and thus recycle them. The optimum site probably would be on the north side of the geothermal anomaly as far away from the lake as possible. However, this would mean a site on the north side of Volcan Momotombo; logistic difficulties probably would prevent such a location. The next best site probably would be on the northwestern side of the geothermal anomaly -- somewhere to the west of Volcan Momotombo. The nature of the reservoir rocks will be extremely critical for satisfactory injection. Hopefully, the pre-Volcan Momotombo tuffs that were found in the MT-1 well will prove to be widespread. Great care also must be exercised to insure that the chemistry of the injected brine and that of the receiver rocks and their waters are compatible.

The possible waste disposal problem at San Jacinto cannot be assessed at present. If a vapor-dominated geothermal system is present then there will not be a significant waste disposal problem. If a liquid-water geothermal system exists, then disposal by subsurface injection of the waste brines will be necessary. I would imagine that suitable injection sites could be found beyond the immediate boundaries of the geothermal reservoir.

Hydrologic Studies

If definite geothermal reservoirs worthy of development are found at either of the two prospect sites, then serious studies must begin to try to understand as well as possible the hydrologic regime of that geothermal system. Hydrologic considerations have proven to be the most important limiting factors on the economic life of several geothermal reservoirs. In addition to conventional hydrologic data, oxygen isotopic studies of formation waters and their host rocks obtained at varying depths from well bores have proven to be very helpful. This technique has been used successfully at The Geysers to help establish the main productive zones and to aid in understanding the hydrologic problems. Air drilling at The Geysers has permitted extensive sampling of formation waters and their host rocks.

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GEOTHERMAL INVESTIGATIONS IN NICARAGUA

Report prepared for the

GOVERNMENT OF NICARAGUA

Ministry of Economy, Industry and Commerce

by

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Abstract

Two high-temperature geothermal prospects have been recognized in Nicaragua. They are (1) the thermal area at the volcano Momotombo at the north-western end of Lake Managua and (2) the thermal areas at San Jacinto-Tisate west of Volcan Santa Clara. The possibility for thermal resources in the Managua area are also being pointed out. The thermal areas (1) and (2), mainly the Momotombo area, appear to be connected with geothermal reservoirs of an economically significant energy potential. Test drilling and further exploration in these areas is being recommended.

Acknowledgements

The writer wishes to express his thanks to the members of the Texas Instruments Incorporated staff under the leadership of Mr. L. T. Braun and to the members of the Nicaraguan Geological Survey as well as to Drs. F. Berry, G. Keller and D. E. White for the very pleasant cooperation during the work on the present project.

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(1) INTRODUCTION

The following report has been written in order to summarize the writer's results and impressions gained during his joint work with Drs. F. Berry, G. Keller and D. E. White and the staff of Texas Instruments Incorporated on the Nicaraguan Geothermal Project. The report, which is the final report on the writer's work during Stage I of this project, has been prepared for the Government of Nicaragua, Ministry of Economy, Industry and Commerce.

The present report represents the writer's personal views which were gained mainly during his three field visits to Nicaragua. Preliminary reports were written following each field visit.

(2) ECONOMICAL BACKGROUND

(2.1) Electrical Power

Central America has practically no resources of fossil fuel. Hydroelectrical resources are not abundant and are characterized by considerable seasonal variations. The annual load characteristic is therefore relatively poor. For power generation the region has consequently had to rely to a considerable degree on conventional thermal plants burning imported fuel.

The total capacity of present power plants in Nicaragua is of the order of 200 MW. During the coming one or two decades the demand for electric power may increase by as much as 20 to 25 MW/year.

Estimates of comparative costs of electrical energy in Central America, based on data from various sources, are given in the following Table 1. The data are quoted as generating costs at the plants excluding taxes, profits and other non-essential overhead.

Table 1 indicates that geothermal power, if available, has a considerable economical advantage over other sources in Central America. Since good hydroelectrical sources are relatively rare in the region, the data on the geothermal plants should be compared with the conventional steam plant under (a). The data are based on present

interest rates and fuel prices, but these may, of course, vary from time to time. The data are, therefore, only indicative.

Table I

Comparative energy costs in Central America

	mills/kWhr
(a) Conventional steam plants of modern design, capacity 50 to 100 MW, burning residual fuel oil, base load power	8-10
(b) Hydroelectrical plants, capacity 100-250 MW, data from 2 projects, annual load 2,500 to 4,500 hr/year	6-9
(c) Geothermal steam plant, capacity 50 to 100 MW, based on natural steam from an easily accessible high-temperature reservoir, base load power	4-6

Moreover, it should be noted that the data under (c) are based on the assumption of steam production from a relatively favorably located reservoir producing from depths of the order of 500 to 1,000 meters, and at a rate equivalent to 4 to 6 MW/ borehole.

One of the principal conclusions to be drawn from Table 1 is that considerably more adverse source conditions can be dealt with without losing the economic advantage of producing electrical power by natural steam. An elementary investigation shows that sources as deep as 2,000 to 2,500 meters can still compete favorably with the conventional

steam plants.

It is of interest to note that a fluid phase geothermal reservoir with a base temperature of 250°C will on the basis of natural steam plants of conventional design yield an energy of about 20 kWhr/metric ton of reservoir fluid. A plant of 50 MW power will thus require a total flow of 700 kg/sec from the reservoir. The integrated flow during a period of 25 years is thus about 1/2 cubic kilometer of reservoir fluid. Moreover, the energy conversion within geothermal reservoirs is generally rather poor. The total solid phase reservoir contact volume required for the period of 25 years will probably be of the order of 10 cubic kilometers. For a period of 100 years the reservoir volume will thus have to be about 40 cubic kilometers. This figure gives the order of magnitude of the reservoir volumes required for plants of this size.

(2.2) Utilization of Heat

Although geothermal energy is now being used mainly for power generation, other fields of application are of interest. Natural steam and hot water are generally sources of heat at extremely low cost. It is of interest to point out that the data under (c) in Table 1 imply a steam production cost of 0.10 to 0.15 $/metric ton,* that is, in terms of sensible heat content a cost of 0.20 to 0.30 $/Gcal (One Gcal = one giga-calorie= 10^9 cal = $4x10^6$ B.T.U.). The cost of heat from residual fuel oil is of the order 2 to 3 $/Gcal. This figure indicates the extreme advantage of using geothermal steam as a

* All dollar amounts in this report represent U.S. $

source of heat.

Moreover, it is of interest to note that even very deep relatively low-temperature geothermal sources can produce heat at a low cost. To take an example, let thermal water at 150°C be available at the depth of 2,000 meters and be produced at the surface by relatively low yield pumped boreholes. If drilling costs can be kept at a reasonable level and each borehole yields 25 kg/sec, the cost of the unit heat at a temperature of 100°C will be of the order of one $/Gcal. This is still considerably below the cost of heat from fuel oil. The example shows that the utilization of low-enthalpy deep resources should be given due consideration if there is a market for the heat. Such market is likely to be in an industralized area as, for example, in the area around Managua.

(3) GEOTHERMAL RESOURCES IN NICARAGUA, RESULTS OF PRESENT INVESTIGATION

(3.1) Geological Setting

The volcanic geology of Nicaragua has been described by Weyl[1] and McBirney and Williams [2]. The results obtained during the present investigation are described in thorough and detailed reports by Thigpen (Parts 2,3 and 4 of Final Report on Geothermal Resources Project-Stage I). There is no reason to repeat the results described in these papers.

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[1]Weyl, R. 1961 - Die Geologie Mittelamericas, Beitraege zur regionalen Geologie, Bd.1, Gebrueder Borntraeger, Berlin.

[2]McBirney, A. R. and H. Williams, 1965 - Volcanic History of Nicaragua, University of California Publ. in Geolog. Sciences, Volume 55.

The most prominent volcanic and thermal feature of the geology of Nicaragua is the almost perfectly aligned chain of active volcanoes from Cosegüina in the northwest to Madera in the southeast. This chain would appear to be controlled by faults along the southwestern border of the Nicaraguan depression or graben. The depression which has a width of 40 to 70 km continues into El Salvador to the northwest and into Costa Rica to the southeast. Although the depression has the features of a graben, details of its structure are by no means clear, and its relation to the volcanism is obscure. The gravity survey over the depression carried out during the present investigations did not reveal clear results. The results obtained over the western flank of the depression in the San Jacinto area appear to indicate a number of faults with a total throw of 500 to 1,000 meters.

It is of interest to note that the structural control of the volcanism along the Central American depression appears to change gradually along the northern end of the structure. The setting of the volcanoes of Guatemala appears different from that of Nicaragua. Moreover, it is worthwhile noting that the dimensions and certain other features of the depression are reminiscent of the Permian magmatic province of the Oslo region of Norway, the Taupo volcanic zone in New Zealand and other non-orogenic volcanic zones extruding material of mixed composition.

It is quite clear that the uncertainty as to the structure of the Nicaraguan depression

is one of the main problems encountered in determining the structural control of the geothermal areas. This problem should therefore be given proper attention in any future work.

(3.2) Volcanic Explosions

The relatively great number of Krakatoan collapse calderas is a prominent feature of the Nicaraguan volcanic chain. McBirney [1] lists 8 structures of this kind. Moreover, there is a number of typical explosion craters such as the Laguna de Tiscapa in Managua and possibly also the Laguna de Asososcoa and Laguna de Nejapa a few km west of Managua. Steam-gas and pure steam explosions have no doubt been the main force in creating these structures.

It should be noted that volcanic explosions of this kind constitute just another form of releasing geothermal energy--although in a rather violent manner. In the case of the smaller craters, at least, such as the Laguna de Tiscapa, the exploding medium may be water having a temperature of only 250 to 300°C. An elementary computation shows that water at 250° can by expanding to atmospheric pressure and 100°C release a total of 1.4×10^5 joule/kg of mechanical energy. Theoretically this energy suffices to lift the water 14 km above the surface of the earth. Of course, explosions of this kind have a very low mechanical efficiency, perhaps of the order of a few per cent only. If

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[1] McBirney, A. R. 1956 - The Nicaraguan Volcano Masaya and Its Caldera, Trans. Am. Geophys. Union, 37, 1.

the ejecta are thrown a few hundred meters into the air, these results indicate that the mass of water involved in a pure steam explosion may very roughly be of the same order as the mass of the solid phase ejecta if the heat content of the solid phase is ignored. In the case of the Laguna de Tiscapa, the total volume of ejecta may have been of the order of 5×10^7 cubic meters. Allowing for some of the heat content of the solid phase the volume of thermal water involved is estimated at the order of 2×10^7 cubic meters, that is, about 1/50 cubic kilometer. In accordance with the data given in paragraph (2.1) this amount of water at 250°C would be able to produce about 4×10^8 kWhr of electrical energy, that is, operate a power plant of 2 MW for a period of 25 years. Of course, the energies involved in the Krakatoan explosions are many orders of magnitude greater than the case of Laguna de Tiscapa. In 1835 the Coseguina in Nicaragua threw out several tens of kilometers of pumice and ash. Even allowing for high temperatures, the amount of water involved must have been of the order of many cubic kilometers.

It is well known that the relaxation time for subsurface thermal anomalies is quite long. The data given about therefore indicate that the most recent explosion craters and calderas should not be overlooked as indicators of sources of geothermal energy. It is rather likely that each explosion throws out only a part, perhaps a small part, of the thermal water available.

(3.3) Main Geothermal Resources

The geothermal areas in Nicaragua discovered during the present survey are described in the reports by Thigpen (Parts 2, 3 and 4). There is no reason to repeat details of his findings.

Two main geothermal prospects have been recognized; these are (1) the geothermal area at the southern flank of the volcano Momotombo and (2) the geothermal area at San Jacinto-Tisate.

In view of the present writer, both of the above areas appear to be typical high-temperature prospects. Both are characterized by quite extensive surface display of thermal activity of the type which is generally found in areas having base temperatures above 200°C. There is extensive thermal alteration, hot ground and a considerable number of fumaroles and mud-pots. Moreover, there are typical deposits of elemental sulphur.

The surface display is more prominent and extensive in the Momotombo area. In this connection it should be noted, however, that the Momotombo is an active volcano and the thermal activity therefore appears to be of a syn-volcanic nature, that is, it may be directly connected with the active neck of the volcano. Activity of this type may possibly be rather localized.

Comparing observations in Nicaragua and other Central American countries, the writer is of the opinion that the Momotombo and the San Jacinto-Tisate thermal areas

compare quite favorably with other thermal areas in the region. Their geological setting and elevation are favorable. There is no doubt that both areas should be regarded as good geothermal prospects.

The surface display at Tipitapa and San Luis is not indicative of high-temperature conditions beneath the areas. At this juncture, these areas are, therefore, of less practical interest.

The thermal area at Volcan Casita is no doubt of a syn-volcanic nature. The location and altitude are unfavorable.

To these findings, the writer would add that there appear to be prospects for hyperthermal conditions along the entire western flank of the Nicaraguan depression. This is indicated by the present volcanism and the many explosion craters as discussed in paragraph (3.2) above. Thermal waters of moderate to high temperature may be available at some depth within the western sections of the depression.

(3.4) Geophysical and Geochemical Results

The field data obtained during the present investigations have been described and discussed in the reports by Bennett, Harthill, Keller and Mazzolini (Parts 7 and 8, 6 and 5, respectively). Again, there is no reason for repeating their findings.

Only a few comments will be made.

Geoelectrical results. A considerable effort has been devoted to the measurement of subsurface electrical conductivity in the San Jacinto-Tisate and Momotombo areas. Moreover, EM measurements have been performed along a profile across the Nicaraguan depression extending from Poneloya at the coast to Los Zarzales at the eastern flank of the depression.

It is well known that there are particular difficulties in deriving subsurface conductivity values on the basis of surface data. Moreover, there is a considerable ambiguity involved in interpreting the conductivity data in terms of subsurface temperature fields. Rock conductivity is far from being a unique function of the temperature. As a matter of fact, the conductivity may depend to a greater extent on various other physical and chemical rock parameters than on the temperature. These difficulties are most clearly demonstrated by the Poneloya-Los Zarzales profile. This profile crosses the San Jacinto thermal area, but there is no clear conductivity anomaly connected with the region of surface thermal manifestations.

On the other hand a local dipole DC survey at San Jacinto (Part 6, Fig. G7) indicates a clear quite localized anomaly. The surface area within the 0.16 mho/m isoconductivity line is about 3 km^2, and the area within the 0.11 mho/m line is about 6 km^2. Moreover, the local EM soundings (Fig. G18) indicate a surface layer of 400 to 600 meters thickness having a conductivity of a few hundred millimho/m resting on a basement having a conductivity of 30 to 50 millimho/m.

The dipole DC survey at Momotombo is incomplete since no closed contours could be obtained. EM soundings at Momotombo (Fig. G19) indicate a surface layer having a conductivity of several hundred millimho/m resting on a basement at 1,400 to 1,600 meters having a conductivity of about 2 mho/m.

The electrical results in both San Jacinto-Tisate and Momotombo areas indicate clear local anomalies, but the results differ considerably in magnitude. The basement conductivity at Momotombo is about 50 times higher than at San Jacinto-Tisate. This difference is no doubt caused by petrological and chemical factors. The basement at San Jacinto is probably crystalline whereas the basement at Momotombo may be composed of tefras, tuffs and sediments invaded by saline waters.

Gravity and magnetic results. The gravity and magnetic field data have apparently no direct bearing on the geothermal conditions in the areas under investigation, with the possible exception of the gravity high observed at San Jacinto. However, at this juncture, we have no ways of interpreting the gravitational data in terms of the geothermal situation at San Jacinto.

Geochemical results. From a global point of view, both thermal waters and gases in the main Nicaraguan thermal areas appear to display some abnormalities.

The amount of SiO_2 in water samples from natural springs in the various thermal areas is quite uniform despite the fact that the areas differ considerably in terms of surface display. Thus, samples from San Luis, Tipitapa, Momotombo and San Jacinto all

contain 100 to 200 p.p.m. of SiO_2. On the other hand, Cl varies from about 15 p.p.m. in the McBirney drill hole at San Jacinto to 3,500 p p.m. at Momotombo. Tipitapa and San Luis have Cl in the amount of 100 to 300 p.p.m.

Almost all gas samples taken from fumaroles and natural springs appear to indicate atmospheric contamination. Disregarding totally abnormal samples, the amount of CO_2 in the gases at San Jacinto and Momotombo varies from about 10 to 45 vol. %. The H_2S at San Jacinto is found to be only 80 p.p.m. of the gases. Tisate has considerably higher values of up to 4,600 p.p.m. and Momotombo has values up to 10,000 p.p.m. Since the total gas content of the natural steam was not measured, no data are available on the absolute gas content of the steam.

The chemical composition of the thermal gases in Nicaragua displays a certain similarity to results obtained in El Salvador. The natural steam in the Ahuachapan area in El Salvador contains unusually small amounts of CO_2 and H_2S. Moreover, H_2 appears almost absent in both countries. In the case of Nicaragua it is possible that the atmospheric contamination may partially account for the relatively small amounts of H_2S found in the samples.

Borehole data. The most significant borehole data were obtained from hole MT-1. A temperature of 209°C was measured at the depth of 220 meters in this hole. Moreover, a water sample taken from the hole turned out to contain 210 p.p.m. of SiO_2. It is significant that this SiO_2 content is considerably below the value of about 300 p.p.m. which

should be expected if the water had obtained equilibrium with quartz at 209°C. On the other hand, the temperature of 209°C is quite close to the temperature of boiling of water at a depth of 220 meters. Despite the low SiO_2 content of the water it therefore appears unlikely that the temperature measured represents the base temperature of the area.

It should be noted that Ahuachapan in El Salvador has a measured base temperature of 228°C and the thermal waters there contain 550 to 650 p.p.m. of SiO_2. The low SiO_2 values observed at Momotombo may be the result of an unrepresentative sample and/or it may display a significant chemical disequilibrium in the system. The latter case would be of practical significance. Unfortunately, no deep borehole was drilled in the San Jacinto area and no deep water samples have therefore been available from this area.

(4) OUTLOOK PRO TEMPORE

(4.1) Field Conditions for Large Scale Power Generation

In brief terms, the following conditions appear to be required in order to sustain with reasonable certainty an economical generation of electrical power on the basis of geothermal heat involving a total energy production of the order of 10,000 MW years or more.

(1) High base temperature, preferably above 200°C.

(2) Large active permeable reservoir volume, preferably of the order of

hundred cubic kilometers or more.

(3) Adequate supply of recharge water.

(4) Relatively shallow ground water surface.

(5) Acceptable chemical quality of the reservoir water.

(6) Adequate drillability of the reservoir rock.

In the present case of Nicaragua, the main concern centers around items (1) and (2). Due to relatively favorable geographical, geological and meteorological conditions, items (3), and (4), and (6) are less likely to be of concern. There is some uncertainty as to item (5) since no reliable deep water samples have been available. However, in view of the possibility of disposing effluent waters by reinjection, an adverse chemical composition of the reservoir water is not likely to be a decisive factor.

(4.2) The two main prospects, San Jacinto-Tisate and Momotombo

Due to inadequate temperature data, mainly the lack of data from depths greater than 500 meters, we are at this juncture unable to come to definite conclusions as to the base temperature in these two areas. However, in the case of Momotombo, the temperature data from hole MT-1 indicate a base temperature at or above 209°C. Moreover, the present writer is under the impression that the surface display of thermal activity at both San Jacinto-Tisate and Momotombo indicates base temperatures in excess of 200°C. These semi-quantitative conclusions are, of course, not supported by the water

chemistry in both areas, but the present writer wishes to underline that no deep samples have been obtained in the areas. Moreover, there are indications of chemical disequilibria.

The situation as to the reservoir volumes is considerably more uncertain. In the case of Momotombo, the electrical conductivity data indicate a lower limit of a few cubic kilometers, but the data are incomplete and the active volume may be considerably greater. Moreover, as already stated, the high conductivity values can be interpreted as indicating thick layers of tefras, tuffs and sediments.

The problem at San Jacinto centers around the nature of the basement indicated by the electrical conductivity data to be within 400 to 600 meters of the surface. This is probably a crystalline basement of an intrusive or extrusive nature. Since there is no escape from the fact that the thermal activity at San Jacinto-Tisate must have its origin deep in the basement, it is by no means unlikely that the basement complex is the host of a large geothermal reservoir. Only deep exploratory drilling can lead to definite conclusions.

Comparing the two thermal areas, there is apparently not much doubt that Momotombo appears to be a more favorable geothermal prospect than San Jacinto-Tisate. However, as expressed in previous reports, the present writer wishes to emphasize the syn-volcanic character of the Momotombo area. Its close connection with the active volcano Momotombo can possibly be interpreted as indicating a relatively transient and localized phenomenon around the active neck of the volcano.

Summing up his observations and impressions, the present writer is of the opinion that in spite of a number of uncertainties both the San Jacinto-Tisate and the Momotombo areas should be regarded as favorable geothermal prospects which warrant further investigation by deep drilling.

(4.3) Geothermal Heat for Industrial Purposes in the Managua Area

The possibilities for hyperthermal conditions along the entire western flank of the Nicaraguan depression have already been discussed above. Moreover, an estimate has been given of the production cost of heat from low-enthalpy waters from depths as large as 2,000 meters.

There may be some market for heat for small-scale industry in a rather densely populated area such as in and around the city of Managua. The city happens to be located just on the main axis of volcanism along the western flank of the depression and should therefore have close access to hyperthermal sources. As a prospective market for the geothermal heat, we may mention,

(a) water purification and sterilization,

(b) water for industrial cleaning, washing and boiling,

(c) cooling and refrigeration on the basis of the absorption principle,

(d) processing of pulps,

(e) sugar refining.

The list is most probably incomplete. The writer is of the opinion that the possibilities in this field should not be overlooked. They may turn out to be of some economical importance. A further investigation of thermal resources in the Managua area may therefore be warranted.

(5) FUTURE EXPLORATION AND DRILLING

(5.1) Outstanding Field Problems

The apparently favorable outlook for economically exploitable geothermal resources in two or three locations in Nicaragua calls for an open-minded planning of future research and exploration. It is important to recognize problems at an early stage and to take the necessary steps to solve them. A number of important problems which future geothermal investigations in Nicaragua will have to cope with are listed below. Progress in the solution of these problems will be of economical importance for the future exploitation of the resources. Work on the problems listed below should therefore be included in Stage II of the geothermal investigations.

(1) Reliable estimations of main geothermal parameters such as the base temperature and the active reservoir volume in the case of the Momotombo and San Jacinto-Tisate areas. These data have to be obtained mainly by exploratory drilling. Further geoelectrical work is also warranted.

(2) Uncovering of the geological setting of the areas with regard to the regional volcanism and the structure of the depression, including depth to the regional crystalline basement. Further geological mapping and seismic field work will supply important data.

(3) Derivation of the structural control and hydrology of the main thermal areas. Local microearthquake surveys and a regional survey of hydrogen and oxygen isotopes in waters will be of importance to uncover the main pattern of ground water flow.

(4) Finding of the optimum way of disposing of effluent thermal waters from boreholes and power installations. The effluent waters are often loaded with components such as fluorine and boron which are harmful to flora and fauna. Reinjection of the waters into suitable subsurface formations offers an attractive possibility. However, this method involves the danger of a thermal contamination of production zones and has therefore to be applied with care. The design of reinjection systems has to be based on sufficient field data which have to be obtained by special investigations.

(5.2) Exploration and Initial Production Drilling

The purpose of further exploratory drilling has already been outlined in the preceding paragraph. In order to obtain sufficiently detailed and complete data on the base temperature and other field conditions, the exploratory boreholes should be 1,000 to 1,500 meters deep. Although base temperatures below 250°C can be established with boreholes

which are not deeper than about 600 meters, we are also interested in detecting temperature inversions which are often of considerable diagnostic importance. In the case of the Momotombo area, such deep temperature profiles would have a direct bearing on the volcanic relations of the area.

As to the initial production drilling, we may envisage the construction of a 50 MW power plant as a proper initial step in the exploitation of geothermal resources in Nicaragua. The thermal area at Momotombo may be the site of this plant. Assuming a wet reservoir with a base temperature of, for example, 250°C, the total flow of reservoir water required for the operation of this plant would be about 700 kg/sec. Assuming a flow reserve of 30%, that is, a total integrated capacity of the boreholes of 900 kg/sec, and a relatively low average capacity of each borehole of 75 kg/sec, we find that the total number of active boreholes would have to be about 12. To this we have to add an estimated number of unsuccessful or "dry" boreholes. Taking a somewhat pessimistic point of view, let this number be 6, that is, the total number of boreholes required for the 50 MW plant be 18. As already stated in (2.1) above, the total output of these holes during a period of 25 years would be of the order of 1/2 cubic kilometer.

As a first step in proving the necessary geothermal resources for this project we may envisage the drilling of 1/3 of the required number of holes, that is, a total of 6 boreholes. The completion of these holes will have to be followed by a test period of not less than one year. Following successful tests, the drilling for the 50 MW plant will be

completed and all boreholes tested for another minimum period of one year before going ahead with plant construction. As stressed above, at least one of the initial boreholes should be drilled to a depth of not less than 1,500 meters. The depth of the production holes may range from 500 to 1,000 meters, but it appears advisable to plan for an average depth of 1,000 meters.

Due to the limited amount of field data available, the siting of the initial boreholes appears somewhat problematic. This is a common situation in geothermal work. The pertinent problems have been discussed at the consultants' meetings with the Texas Instruments staff and joint recommendations have been worked out.

(5.3) Drilling Equipment and Casing Program

The deep exploratory and production drilling will preferable have to be carried out with a rotary drilling rig having a capacity of not less than 1,500 meters with a 4-1/2 inch drill pipe. The rig will have to be equipped with an adequate pumping capacity, safety equipment for pressure control and cementing gear.

Casing program would involve shallow surface casing, then about 100 meters of 13-5/8 inch O.D. pipe and finally a few hundred meters of 9-5/8 inch O.D. pipe. The main production hole would have a width of 8-5/8 inches.

(5.4) Comments on an Initial Light-Rig Drilling Phase

The question arises whether it would be economical to carry out some of the initial exploratory drilling with a shot-hole or a slim-hole rig. This initial phase could be completed before the decision is made to move in the larger rig, and could thus act as a precautionary step.

The present writer is of the opinion tha e only alternative which comes into consideration would be to continue some drilling with the Mayhew 1500 drilling rig which was used during Stage I. There is no economical or technological advantage in moving in a special slim-hole rig.

As a matter of fact, it might be advisable to initiate the drilling at San Jacinto-Tisate by drilling one or two slim holes of 600 meters depth with the light rig

However, the field work at Momotombo appears to have furnished such positive results that further work with the light rig appears superfluous. Moreover, due to reasons already discussed, the exploratory boreholes in this area have to be drilled to greater depths than 600 meters. The drilling program in this area therefore requires full scale drilling equipment which would then also be used at San Jacinto-Tisate.

(6) RECOMMENDATIONS AS TO STAGE II OF THE NICARAGUAN GEOTHERMAL PROJECT

Based on the discussion above, the writer recommends the following procedures for Stage II of the project.

Drilling should be initiated at Momotombo and should involve the drilling of one or

two deep wells, at least one of them to a depth of 1,500 meters. Following this, one deep well should be completed at San Jacinto-Tisate. Further drilling in one of the areas should be carried out in accordance with the results obtained as to reservoir temperatures, permeability and chemical quality of the water. A total of 6 wells should be completed in the area selected for production drilling. The drilling program should include contingency plans for the drilling of two additional boreholes, for example, one in the Managua area. The total program is estimated to include the drilling of 3 boreholes to the depth of 1,500 and 6 boreholes to the average depth of 900 meters, that is, a total of about 10,000 meters. The unit cost of a completed borehole is estimated at U.S.$110/meter. Recommendations as to the initial drilling sites are presented in a joint report of the consultants to the project.

Moreover, it is being recommended that Stage II involve an adequate program for testing the continuity of the steam production obtained for a minimum period of one year. These tests will have to include the monitoring of the mass flow, temperature and chemistry of waters and gases.

Finally, Stage II should involve further geological, geophysical and geochemical work as indicated under (5.1) above. This will include the following special investigations:

(1) Further detailed geological mapping with special emphasis on the structure of the Nicaraguan depression.

(2) Further geoelectrical work as recommended by the consultants.

(3) A seismic refraction survey of the active areas.

(4) Local microearthquake surveys at selected stations.

(5) Isotope survey on meteoric, ground and thermal waters.

(6) Contingency plans as to further gravity, microgravity, magnetic and other geophysical methods.

Based on the assumption that Momotombo will be selected as the main geothermal prospect, the financial plans for Stage II appear as follows:

Drilling

Momotombo	6 boreholes = 6,000 meters	U.S.$0.66x10^6
San Jacinto	1 " 1,500	0.17
Contingency, San Jacinto and/or other areas	2 " 2,500	0.27
		1.10

Testing, Exploration and Research

Testing, piping, disposal, geology, geochemistry, logging	0.25
Geophysics	0.15
	U.S.$1.50x10^6

The figures, which are based mainly on experience in El Salvador, include overhead costs and salaries.

Permanent or almost-permanent personnel:

One drilling engineer

One petrologist

One geologist

One geophysicist

One "steam" engineer (for testing)

One geochemist

Office personnel

Special field work will have to be carried out under the supervision of specialists brought in from time to time.

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SUMMARY EVALUATION OF GEOPHYSICAL SURVEY RESULTS

NICARAGUAN GEOTHERMAL RESOURCES PROJECT-STAGE I

Report prepared for the
Government of Nicaragua
Ministry of Economy, Industry and Commerce

By

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SUMMARY EVALUATION OF GEOPHYSICAL SURVEY RESULTS NICARAGUAN GEOTHERMAL RESOURCES PROJECT-STAGE I

George V. Keller

The economical development of electrical power from naturally-occurring hot water in the ground requires that large volumes of steam be produced from underground water at a steam pressure adequate to operate an electrical generating plant. There are at least three primary requirements to be met by underground resources of hot water before an area can be considered to have potential for the production of geothermal power; these are, a reservoir with adequate hot water reserves to last the proposed plant over its projected lifetime, a sufficiently high temperature so that the thermal energy can be converted to electrical energy efficiently, and a sufficiently great permeability so that the heated water can be removed from the reservoir with a reasonable investment in drill holes. In addition to these main requirements, there may also be subsidiary considerations about the economic potential of a geothermal power source related to the convenience of the source to power markets or possible difficulties in handling the water produced from the ground if it contains a large amount of impurities. The program of geophysical surveys carried out in northwestern Nicaragua had three parallel objectives related to these questions; they were directed toward regional evaluation of geological structure and its control over the occurrence of geothermal reservoirs, they were directed toward the location and delineation of several specific reservoirs, and they were directed toward the evaluation of the probable productivity of these reservoirs once they had been adequately located. In conjunction with the geological and geochemical studies and drilling tests, they provide a reasonably reliable estimate of the amount of power producing capacity that may be

available in two geothermal reservoirs in northwestern Nicaragua, the one at the village of San Jacinto, and the one on the southern flank of Volcan Momotombo. I shall review here the conclusions that may be drawn from the geophysical studies in each of these three applications.

1. Regional tectonic setting

Large reserves of heated ground water may be found in several types of geological environment. These include the cases of an igneous intrusion into porous water-bearing rocks, deep burial of water-rich sediments in sedimentary basins, and downfaulting of porous water-filled rocks to great depth. Of these three types of hot-water occurrence, the one which has been most easy to exploit is that associated with intrusion of molten rock into water-bearing rocks. Molten rock intruded into the upper part of the earth's crust causes fracturing in the overlying rock so that commonly there is permeability for the vertical movement of heated ground water. Being of relatively low density, heated water rises toward the surface, forming a convection cell. The heat transport in such a hydrothermal system is mainly by mass transfer, with relatively little contribution from conduction through the surrounding rocks.

Geothermal systems associated with intrusives appear most commonly to be a feature of areas with well expressed modern volcanic or tectonic activity, for reasons that may be explained by modern concepts of crustal mobility and plate tectonics. According to these concepts, lithospheric plates of rock move laterally away from mid-ocean ridges, leaving behind a gap which is filled by repeated intrusions of mantle material. At a continental margin, the lithospheric plate is sometimes thrust under the continental crust and into the upper part of the mantle. In its descent, the downgoing slab carries with it water-rich rocks, the addition

of this water to the upper mantle rocks lowers the melting point, and phase changes occur. A volcanic cycle is thus initiated, starting with andesitic to basaltic volcanism, and followed by rhyolitic ignimbrite eruptions and intrusion of granitic plutons in turn. The leading edge of the downthrust slab may drag with it the edge of the continental crust, giving rise to linear tensile fractures in the crust over the slab. The surface manifestations of these tensile fractures can be grabens and linear composite volcanoes.

The Middle-America trench, lying off the west coast of Mexico and Central America, bounds the northeast spreading Cocos plate on the northeast. The axis of this trench lies 160 kilometers southwest of the Nicaraguan coast. Epicentral data from earthquakes for the period 1961-1967 (Barazangi and Dorman, 1969) show that the landward side of this trench is one of the most active downthrusting zones in the world. The seismic activity extends from the west end of the Trans-Mexican volcanic belt into Costa Rica, an area which is also the site of extended volcanism from Miocene time to the present. It appears that the rhyolitic ignimbrite phase of activity listed above is currently in progress or has just finished. The abundance of highly porous pyroclastic rocks from this phase of activity and of intrusions accompanying the volcanic activity make the area extremely favorable for the occurrence of geothermal convection cell systems.

Geophysical surveys related to regional investigation of the tectonics of the volcanic belt in northwestern Nicaragua included some of the gravity measurements and the electromagnetic sounding surveys, both described in preceding parts of this report. Assuming that the subsurface structure giving rise to the character of the gravity profile from Poneloya to

San Isidro (Part 2, Fig. 3) is basically two-dimensional in origin, some idea of the depth extent of the volcanic pile and the size of the intrusions in the crust may be derived. Volcanic rocks may be expected to give rise to two anomalies in gravity; one will be a negative anomaly, or reduction in the strength of gravity, over areas underlain by low density pyroclastic and extrusive rocks, and the other will be a positive anomaly, or increase in the strength of gravity, over areas beneath which high density igneous rocks have been intruded into the crust.

The highest observed values for gravity were noted on the profile at the location of the village of San Jacinto (see Part 2, Fig. 3). The effect of the mass contributing to this gravity high seems to be removed quite well by subtracting the effect for a cylinder of circular cross section, centered at a depth of 13.5 kilometers. The amplitude of the anomaly so subtracted is 31.5 milligals. On the residual gravity profile obtained after removing the effects of such a deeply buried cylinder, there is a marked decrease in gravity at each end of the Poneloya-San Isidro traverse; it is assumed that these features are related to geological structure outside of the volcanic belt and not of immediate concern to us. The effect of low-density pyroclastic rocks is apparently present on the residual profile from a location of a few kilometers southwest of Leon to a point about 22 kilometers northeast of Malpaisillo. Over this interval, the gravity is depressed uniformly by about 10 milligals. In addition, there are three local anomalies with amplitudes of 2 to 4 milligals between San Jacinto and Malpaisillo.

These data may be used with the electromagnetic sounding data to obtain some information on the properties of the pyroclastic rocks. The electromagnetic soundings provided a depth of close to 500 meters for the pyroclastic rocks relatively uniformly across the region of

depressed gravity values. Using an expression given by Nettleton (1940) for the gravity of a slab, the density contrast between the slab and the underlying rock was found to be 0.48. This is quite a large density contrast between the surficial pyroclastic deposits and the older volcanic rocks beneath.

Both the resistivity and density contrasts affirm that there is a major change in properties between the surficial porous pyroclastics and the underlying rocks. If we assume that the surficial rocks have a porosity of 35 to 40 percent by volume, a value that is compatible with the resistivities of 1.1 to 3.0 ohm-meters observed with the electromagnetic soundings, and a grain density of 2.4, a value that is typical for a volcanic glass rich in ferromagnesian minerals, the density of the pyroclastic pile will be 1.95 to 2.00 when saturated with water. The surrounding and underlying rocks must therefore have a density of 2.45 to 2.50, representing a very marked decrease in porosity or an increase in grain density, or both. If there is to be any significant reservoir capacity in a hydrothermal system, it must be found in the surficial pyroclastic rocks.

The center of mass of the high density material giving rise to the high gravity values near San Jacinto probably lies at a depth of 13.5 kilometers, if it is a cylinder of circular cross section. The apparent radius of such a cylinder may be estimated from an assumed density contrast between the intrusive rocks and the host rocks, assumed to have a density of 2.5 to 2.7. Basic intrusions in the crust should have a density of 2.7 to 2.9, providing a contrast of 0.20. Again, using a simple formula by Nettleton (1940), it is possible to find the radius of a

circular cylinder which might give rise to the observed gravity anomaly as 3000 meters.

These figures cannot be considered to be very precise because of the paucity of data on which they are based. However, if the subsurface structure shows the same marked lineation as the surface features, the calculations should be roughly correct with respect to order of magnitude. The source of heat driving the geothermal systems could be an intrusion with a volume of the order of 20 cubic kilometers per kilometer of distance along the strike of the volcanic zone. The enthalpy available on cooling of such a rock amounts to about 400 calories per gram in the anhydrous state, and perhaps a hundred calories per gram more if the melt is water-rich (Keller, 1960). The total energy from the intruded rock mass is then of the order of 10^{21} calories per kilometer of length. This is a very crude figure, but indicates that the scale of the geological phenomena is appropriate for the development of significant amounts of geothermal power.

2. Delineation and Evaluation of Geothermal Systems

Detailed geophysical surveys were done about two areas, one near the village of San Jacinto and the other along the shore of Lake Managua on the south flank of Volcan Momotombo. These two areas were selected on the basis of surface geology and the occurrence of hot springs as being favorable for the existence of geothermal systems at depth. Geophysical surveys were carried out to determine the size of these geothermal systems and locate the boundaries. Most of the geophysical surveying was done with a variety of electrical prospecting methods; some of the surveying was done also with the gravity method. Selection of the electrical methods as

a primary tool was based on the fact that an increase in temperature may affect the electrical properties of a rock to a greater degree than any of the other physical properties.

It has been well established that the resistivity of a rock depends on several factors, primarily the amount of water present in a rock and the conductivity of that water (Keller, 1971). In turn, the conductivity of the water in a rock is a function of the salinity and of the temperature. As a consequence, the resistivity of a rock cannot be used to estimate the temperature unless variations in porosity and of water salinity can be taken into account.

The variation of resistivity in volcanic rock as a function of water content should be similar to that shown in Figure 1, which was taken from a compilation of data for volcanic rocks in the southwestern United States (Keller, 1960). Not enough samples were recovered from the holes drilled in the course of the present project to improve on this relationship.

Water resistivity may be estimated from salinity. Numerous data were acquired with respect to the salinity of water samples taken from the holes drilled at both San Jacinto and Momotombo (see Part 8 of this report), and these are summarized statistically for our purposes in Figure 2. On this figure, the cumulative frequency of occurrence for total cation salinity has been plotted separately for samples taken from the wells at San Jacinto and at Momotombo. A conversion scale for converting cation salinity to approximate water resistivity is also given on this plot. From this, it may be seen that the median water resistivities for these two locations are:

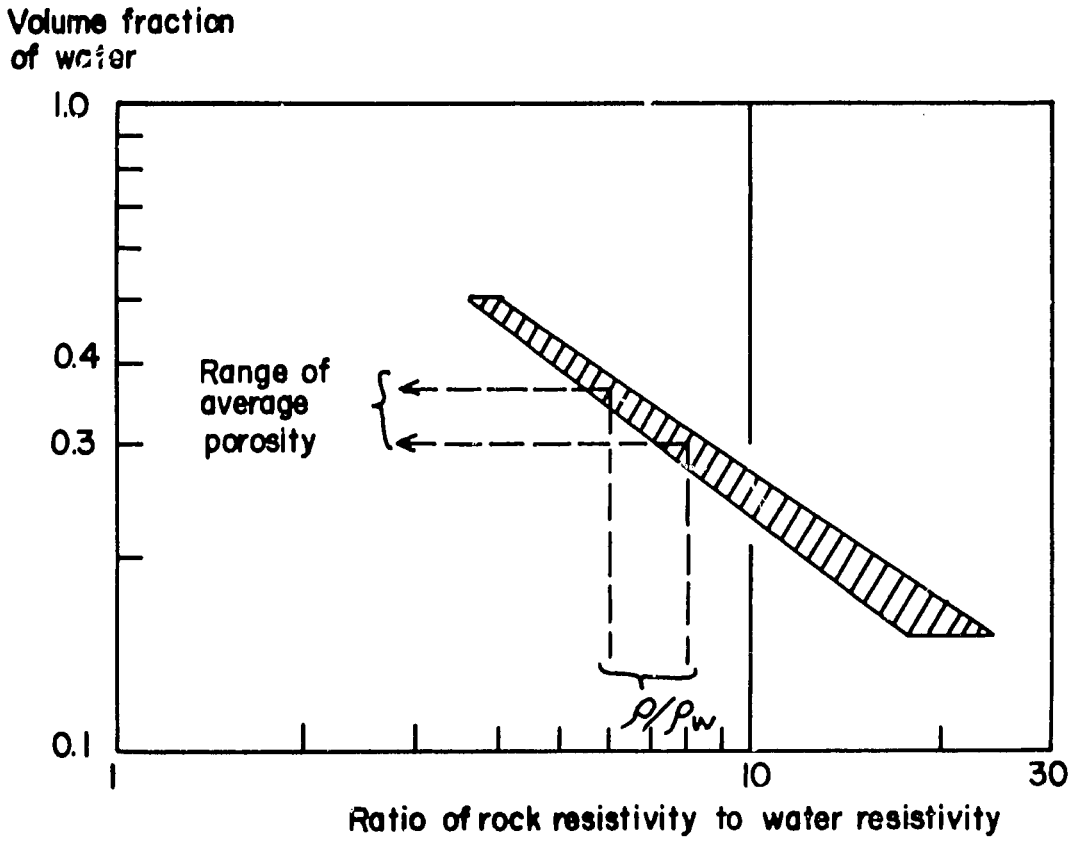

Figure 1. Empirical relationship between rock resistivity and water content for typical pyroclastic rocks.

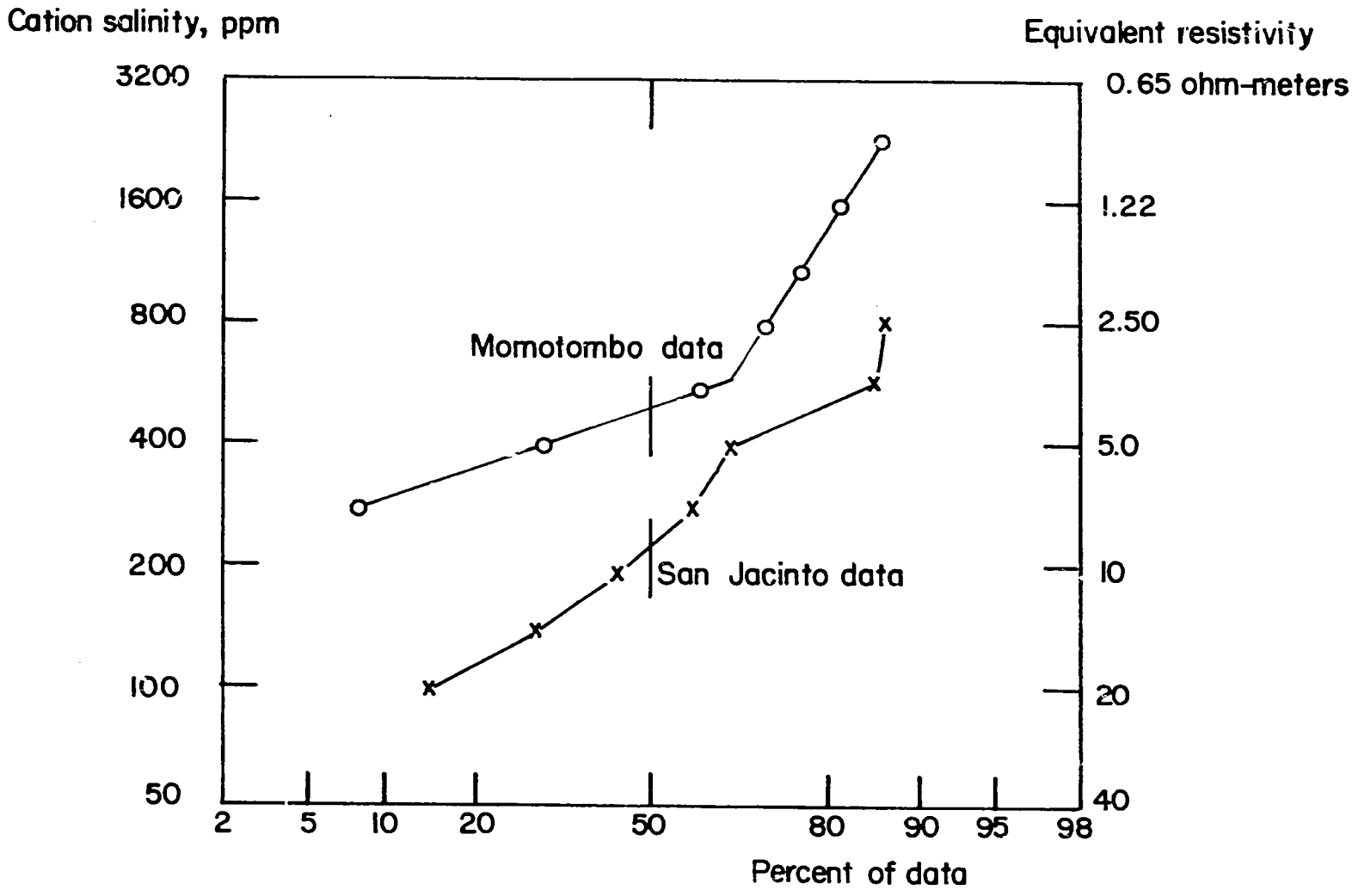

Figure 2. Cumulative frequency of occurence for salinities determined on samples taken from the wells at San Jacinto and Momotombo.

San Jacinto -- 8 ohm-meters

Momotombo -- 3.5 ohm-meters

These resistivities are computed for a water temperature of 20° C. The variation of electrical resistivity with temperature in dilute solutions of sodium chloride has been studied by Quist and Marshall (1966, 1968), and on the basis of their data, the correction chart for the effect of temperature on water resistivity shown in Figure 3 may be prepared. The two curves shown apply for ambient pressures of 0.5 and 1.0 kilobars, as indicated. In volcanic rocks with a density of 2.0, pressure increases at the rate of 1 kilobar per 5 kilometers of burial; the pressures of interest in a geothermal system should be 0.1 to 0.5 kilobars. At these pressures, the resistivity of water passes through a minimum value at a temperature of 280° to 300° C, with the minimum resistivity being less than the resistivity at 20° C, by a factor of approximately 7. The increase of resistivity at higher temperatures is associated with the development of a gas phase in the water.

To make use of these data, we need to select representative values of resistivity from the field data. One approach to this is through the use of cumulative frequency curves for the apparent resistivity values measured in the dipole mapping surveys (see Part 6 of this report). Cumulative frequency of occurrence curves for the dipole data acquired at San Jacinto and at Momotombo are shown separately on Figure 4. Resistivity values for a single rock type commonly show a log-normal statistical distribution (Keller, 1968), which would plot as a straight, rising

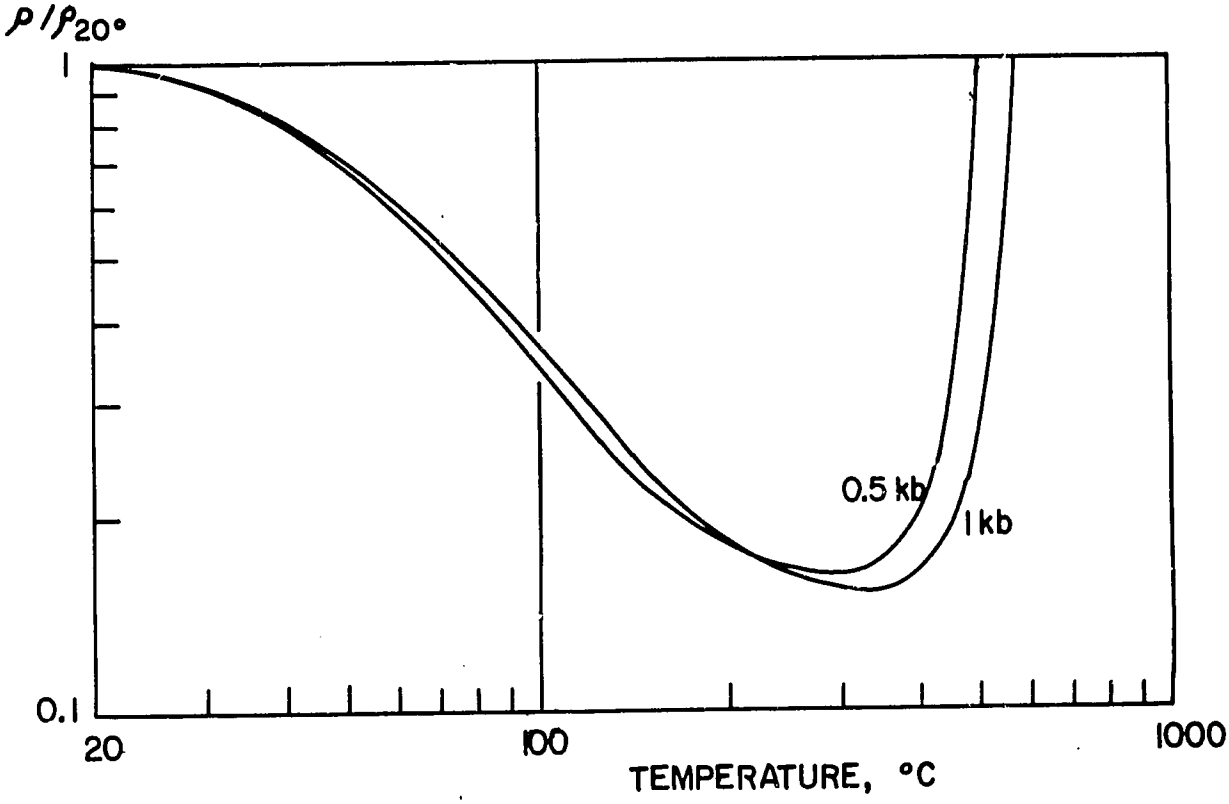

Figure 3. Variation of the resistivity of a dilute solution of sodium chloride with pressure and temperature.

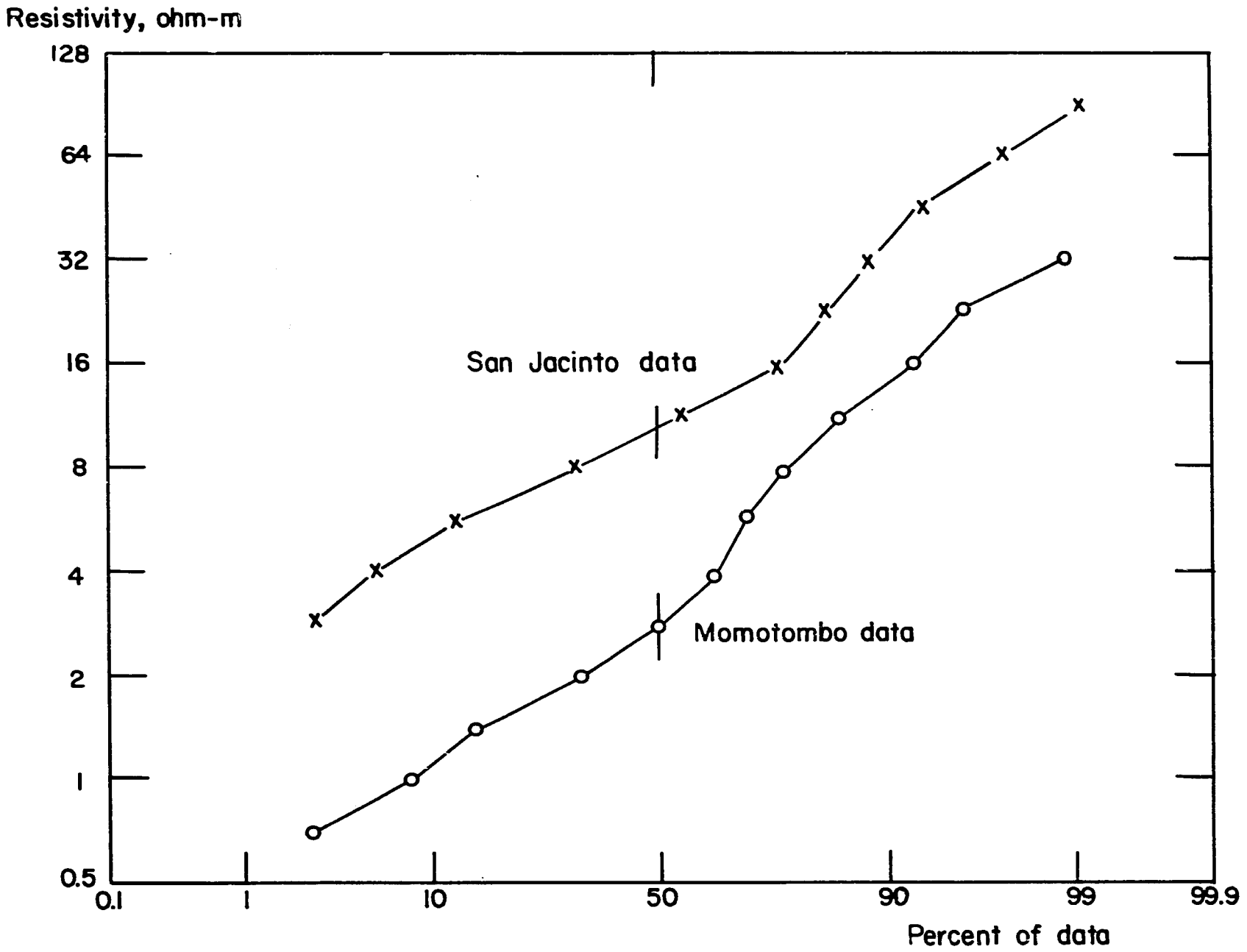

Figure 4. Cumulative frequency of occurence plots for dipole mapping data. The percent of the measurements of resistivity less than a given value is plotted against that value.

line in a presentation such as that in Figure 4. The actual data in Figure 4 appear to be the sums of two such log-normal distributions. The median values for each of the sub-distributions in each area are:

San Jacinto -- 8.0 ohm-meters and 24 ohm-meters

Momotombo -- 2.0 ohm-meters and 8.0 ohm-meters

It is reasonable to conclude that the median values of 8.0 and 2.0 ohm-meters in San Jacinto and Momotombo respectively represent hot-water-saturated rocks, while the median values of 24 and 8.0 ohm-meters, respectively, for these two areas apply to "normal" volcanic rocks outside the areas appreciably affected by the thermal activity. These distributions allow us to draw boundaries on the dipole mapping survey results for the limits of the geothermal systems. In the case of San Jacinto, if the boundary is taken as the 9 ohm-meter contour (see Part 6), the area enclosed amounts to 7.6 square kilometers, of a total area surveyed of 36.4 square kilometers. In the case of Momotombo, if the boundary is taken as the 3 ohm-meter contour, the area amounts to 3.8 square kilometers, out of a total area surveyed of 15.0 square kilometers. A significant difference in the results from the two areas, though, is the fact that the 9 ohm-meter contour at San Jacinto is closed, and the entire area within it is known reasonably accurately, while at Momotombo, there is a strong suggestion that the area within the 3 ohm-meter contour may be much larger than that actually mapped.

The depth extent of each geothermal cell is required to estimate the volume. At San Jacinto, the electromagnetic sounding data indicate that the depth to more resistant rock, presumably the "basement" for the reservoir, is about 700 meters. The maximum volume of the

porous reservoir is thus about 5.3 cubic kilometers. At Momotombo, the electromagnetic sounding data indicate a much greater depth to basement, at least greater than 2 kilometers. At a depth of one kilometer, the rock becomes even more conductive than it is at shallower depths, perhaps indicating the transition from brackish to saline water. The volume of the porous reservoir at Momotombo is thus mapped as 7.6 cubic kilometers, with no limit given to the boundaries in any direction except to the west.

The apparent resistivities from the dipole mapping surveys are not "true" resistivities for the rock in the geothermal systems, but represent averages over considerable volumes of ground. Model studies and computer studies may be used to convert such apparent resistivities to the correct values for underground structures of specific types (Furgerson, 1970). Considering the results from such model studies, it is probable that the resistivity of the geothermal system at San Jacinto is between 2.0 and 3.0 ohm-meters, and at Momotombo, between 0.7 and 1.0 ohm-meters. The ratios between the "normal" resistivities in these two areas and these values for the geothermal systems are:

San Jacinto -- geothermal resistivity ratio = 8 to 12

Momotombo -- geothermal resistivity ratio = 8 to 11

In both cases, the ratio is larger than that which is theoretically possible, as shown in Figure 3, to a minor extent. This greater contrast probably represents the fact that the reservoirs may be somewhat more saline and somewhat more porous than the host rocks, as a consequence of the upward convection of ground water. However, it is reassuring that the resistivity data are

compatible with the existence of high temperatures in the geothermal systems, and do not preclude the existence of temperatures as high as 250 to 300° C.

All of these data and inferences may be combined to provide an estimate of the power producing potential of the geothermal systems at San Jacinto and Momotombo. According to Banwell (1970), the heat energy available on cooling the geothermal fluid to 50° C is of the order of 3500 megawatt-years per cubic kilometer of reservoir. Not all this energy is available for the generation of electricity because of inefficiencies in production of steam and conversion; Banwell gives a realizable yield as being 900 megawatt-years per cubic kilometer of reservoir. On this basis, the energies available at San Jacinto and Momotombo should be:

San Jacinto -- 4800 megawatt years

Momotombo -- 6800 megawatt-years

These estimates must be regarded as very rough, and it is better to conclude merely that the geophysical evidence does not contradict the possible existence of power sources of this size at these two locations. Whether they actually exist and may be produced cannot be determined until an extensive drilling program has been undertaken.

Recommendations for future use of Geophysics

Numerous geophysical techniques were used, many briefly, in the survey of northwestern Nicaragua. Some of these were standard and conventional techniques, others were less standard. It is appropriate here to summarize the conclusions we have drawn concerning

the merits of specific techniques for prospecting for geothermal systems under the conditions prevailing in northwestern Nicaragua.

1. Resistivity profiling and sounding, using either the Schlumberger or Wenner arrays. These techniques are widely used in other areas of the world for reconnaissance for geothermal cells. However, in Nicaragua, these methods were found to be less effective than we had hoped, primarily because high surface resistivity in the volcanic rocks led to erratic measurements of resistivity, and difficulty in driving sufficient current into the ground to make accurate measurements.

2. Dipole mapping surveys were found to be extremely effective in delineating the boundaries of geothermal systems, as in other parts of the world. Some effort is required to find a location where the dipole source can be sited. On the basis of our results, it is not clear whether it is preferable to have one end of the source line in the geothermal area of interest, or to have both ends outside the area. Siting one end of the source line in the geothermal area makes it difficult to detect the boundaries of the system within about 0.5 kilometers distance from the electrode. On the other hand, for elongate cells such as exist at Momotombo and San Jacinto, the boundary away from the source cannot be located accurately when both ends of the source are located outside the conductive area. In most cases, the location of one end of the source line inside or outside the target geothermal cell is an academic problem, because the boundaries are not known beforehand so this choice can be made.

3. Electromagnetic soundings proved to be quite effective in determining the thickness of conductive rocks, both in the Nicaraguan Depression, and in the thermal areas. This technique can be recommended as being superior to resistivity sounding because of its insensitivity to problems caused by resistant surface rocks.

4. The magneto-telluric method appears to offer promise as a reconnaissance technique for a rapid evaluation of surface manifestations of geothermal activity, as indicated by the results reported in Part 6. However, the method will have to be evaluated further to determine whether or not the limited accuracy with which resistivity can be determined is a serious limitation.

5. The "slingram" or two-loop electromagnetic profiling method was found to be quite useless for two reasons; first, because of the difficulty involved in traversing with the two loops in heavily vegetated terrain, and second, because the method did not provide sufficient penetration to reach through the highly resistant surface lavas to detect conductive rock beneath.

Our recommended approach for further search for geothermal systems would include the use of the magneto-telluric method as a reconnaissance tool to evaluate areas with geothermal manifestations such as hot springs, followed by dipole mapping surveys to determine the dimensions of the systems. The dipole mapping surveys should be supplemented by electromagnetic soundings to determine the depth extent of conductive rock. If drilling is decided upon, resistivity surveys with the Schlumberger method will be useful in picking suitable drilling sites.

Summary

In summary, the conclusions which may be drawn from the geophysical data are as follows. The volcanic belt of northwestern Nicaragua is a particularly favorable area in which to prospect for geothermal reservoirs because of its tectonic setting, the modern volcanism and the existence of porous pyroclastics in the Nicaraguan Depression. Geophysical surveys of two areas with surface geothermal manifestations, San Jacinto and Momotombo, provided results which would not be incompatible with an energy production capacity of 4800 megawatt-years at San Jacinto and 6800 megawatt years at Momotombo. The system at San Jacinto was well defined, while the system at Momotombo was not, and may extend eastward under Lake Managua and northward under Volcan Momotombo. The Momotombo system may also be considerably more saline than the one at San Jacinto, especially at depths greater than 1000 meters. Either system is worthy of further investigation by development drilling.

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