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REPORT ON THE

Pre-Feasibility Power Generation Study for the Magadi Soda Company Magadi, Kenya

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PREFACE

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PRE-FEASIBILITY POWER GENERATION STUDY FOR THE MAGADI SODA COMPANY MAGADI, KENYA

U.S. DEPARTMENT OF ENERGY

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Following are two reports 1) by GeothermEx, Inc "Probable Subsurface Temperature at Lake Magadi, Kenya, As indicated by Hot Spring Geochemistry, and the Potential for Development of Geothermal Electric Power" and 2) by The Ben Holt Company "Geothermal Power Options, Lake Magadi, Kenya." Both of these reports constitute the total report for the project.

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PROBABLE SUBSURFACE TEMPERATURE AT LAKE MAGADI, KENYA, AS INDICATED BY HOT SPRINGS GEOCHEMISTRY, AND THE POTENTIAL FOR DEVELOPMENT OF GEOTHERMAL ELECTRIC POWER

for

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1. INTRODUCTION

1.1 Purpose and Scope

The purpose of this report is to:

(a) review the extensive published and unpublished literature on the geochemistry, hydrology and geology of Lake Magadi, Kenya, and its associated hot springs;

(b) based on this review and field visits, estimate the temperature in the geothermal reservoir beneath the lake; and

(c) from this, develop a plan to determine the potential for the development of geothermal electric power at Lake Magadi.

1.2 Data Base and Methodology

The data base of chemical information used in this report consists of some 135 published and unpublished chemical analyses and 8 unpublished isotope analyses of water samples from the Magadi area. These analyses were processed by visual scanning, by plotting a number of variables on graphs, and by calculating the geothermometers. In addition, several hot-spring analyses were processed using two different chemical-simulation computer codes, which calculate the distribution of ion species in the fluid at depth, and the effects of pH and ion-species distribution on the chemical geothermometers. Examples of printouts from these computer codes are presented as Appendix A.

Both the senior and junior authors had visited the Magadi basin in earlier years, as part of regional geothermal exploration projects in the Kenya Rift Valley. The senior author had conducted geological and geochemical sampling during his stay at Magadi in 1972. A 2-day visit to the Magadi area was made by the junior author for purposes of data collection and verification of prior work, during early September 1989. Subsequently, meetings and telephone conversations were held with various Kenyans and Americans who have worked on the geology and geochemistry of the Magadi area.

Published geologic mapping has been used, along with published and unpublished hydrological data, to evaluate the relationship of the thermal springs to the structural and volcanic geologic of the Magadi region. This, in turn, has been used to help construct a hydrogeologic model of the geothermal system. All of this material is then utilized in preparing a set of recommendations for exploratory drilling.

1.3 Acknowledgements

The Magadi Soda Company graciously provided field support and access to their facilities. Thanks are extended to them for this assistance.

2. LOCATION AND GEOLOGIC SETTING

Lake Magadi occupies one of the lowest-elevation sections of the African Rift, in southern Kenya near the Tanzanian border (figure 1). The lake elevation is about 1,950 feet (about 595 m). Climate is hot (mean annual air temperature about 28°C) and semi-arid (500 mm or 20 inches of rainfall annually). Extensive deposits of trona (sodium bicarbonate) have formed in the lake bed (figure 2), probably as the result of a complex process of groundwater upwelling and evaporation. The exploration and mining of these deposits, for use in the preparation of soda ash for the soap, glass and chemical industries, has led to widespread and important studies of the regional and local geology and hydrology, and the geochemistry of lake water, thermal springs and mineral deposits at Lake Magadi.

There is little surface inflow of water into Lake Magadi, and no surface outflow. Little Magadi Lake is a smaller soda lake, located within one km of the northern end of Lake Magadi and separated from it by a fault-bounded ridge. There is no surface connection between the lakes, although Little Magadi is several m higher in elevation, and no surface outflow from Little Magadi.

The Lake Magadi area is characterized by complex graben-and-horst structure, typical of large portions of the Rift Valley, resulting in rotated fault blocks with fault scarps of up to 600 feet (almost 200 m) of visible offset. Thermal springs (33° to about 85°C) issue from numerous locations on all sides of Lake Magadi and at the north end of

Little Magadi (figure 2). In general, flows are greater and temperatures are higher to the north. Many of the thermal springs, especially those at the north and west ends of Lake Magadi and along Little Magadi Lake clearly are fault controlled.

There is no evidence of historic or Quaternary volcanism in the immediate vicinity of the lake. The nearest major Quaternary volcanic centers are Suswa, some 40 miles (65 km) to the north in the Kenya rift; and Ol Doinyo Lengai, in Tanzania, some 60 miles (100 km) south of Lake Magadi (figure 1). A small scoriaceous volcanic vent at Kisamis and possibly one at Koriamat, both located about 15 miles (25 km) north of Lake Magadi, and several undisturbed ash cones at Ol Doinyo Nyegi, some 10 miles (18 km) northeast of the lake, may represent isolated Quaternary eruptive events. Whereas Suswa is fumarolic, and Ol Doinyo Lengai has an active magma chamber, no significant heat output is associated with Kisamis, Koriamat or Ol Doinyo Nyegi.

Lake Natron is a similar soda lake, located about 30 miles (50 km) south of Lake Magadi, in Tanzania, at an elevation only slightly higher than Magadi (about 2,000 feet or 610 m). Natron likewise is bordered by numerous thermal springs. These reportedly have enormous total flow (perhaps over 8,000 gpm) at temperatures of 32° to 50°C. The active volcano Ol Doinyo Lengai is located some 18 miles (30 km) south of Natron.

Magadi and Natron, have no surface drainage connection, and represent isolated hydrologic sumps in the Rift Valley. Because of this, it has been argued that each lake is the discharge point for subsurface groundwater flow, channeled north-south by major faults. The thermal waters of Natron have been attributed to outflow from a source in the Ol Doinyo Lengai area. The waters of Magadi are thought by some workers to have originated (at least in part) at some unidentified point to the north, perhaps at Suswa. This is discussed further in subsequent sections and in Appendix B.

Geology, as mapped by Baker (1958), consists of a series of Pliocene mafic and alkaline volcanic rocks, exposed in the escarpments at the east and west margins of the Rift Valley. These are overlain by lower Pleistocene alkaline and silicic flows and eruptive rocks, which form the Rift floor and faulted ridges within the Rift. In the vicinity of Magadi and Little Magadi these mainly are alkali trachytes. Very locally overlying these are lower to middle Pleistocene mafic and silicic vents (Kisamis, Koriamat or Ol Doinyo Nyegi).

In the Magadi basin, local lacustrine beds of chert, tuffaceous clay, silt and limestone were deposited in middle and upper Pleistocene epoch. In upper Pleistocene and Holocene time, silts and clays (High Magadi Beds), trona and interbedded clays (Evaporite Series), alluvium and slope wash have been deposited. All of the volcanic units except the youngest vents are fault-cut. The young sediments have formed in fault-bounded basins, but only the chert and some of tuffaceous clays are noticeably cut by faults. The High Magadi Beds, limestone and Evaporite Series, along with the recent alluvial deposits, post-date Rift Valley faulting. Therefore, it appears that active faulting largely had ceased by late Pleistocene time. Despite this, seismic activity is reported from many locations in the Rift Valley; and the Magadi basin may be seismically active still.

3. BACKGROUND ON CATION AND SILICA GEOTHERMOMETRY

Deep reservoir temperatures can be estimated from the chemistry of hot springs fed by these reservoirs, provided:

a. the chemistry of the hot springs is controlled by equilibrium reactions with the reservoir rock; and

b. spring-water chemistry has not been significantly changed by precipitation of minerals, or by mixing with near-surface waters after leaving the reservoir and ascending to the surface.

It is not clear that either of these conditions is fully met at Lake Magadi.

Therefore, for this report, we distinguish two possible types of mixing which can affect the estimates of reservoir temperature. Contamination mixing occurs when a more-dilute thermal water is mixed with higher-salinity near-surface water, and the latter comes to dominate most characteristics of the mixture; the precise identity of the thermal component remains masked. Dilution mixing is the case where the thermal water is more saline than the near-surface component; mixing lowers the reservoir-species concentrations, but usually there are only minor changes in the resulting ion ratios.

Mixing models can be used to help discern whether either type of mixing actually has occurred, and to determine the effects of contamination or dilution on reservoir-temperature estimates.

Two chemical geothermometers were used for this report, one based on the concentration of silica (SiO_2), and the other on the ratio of Na to K. Other commonly used geothermometers, which employ Ca and Mg as well as Na and K, were not applicable because Ca and Mg are below detection limit in these spring waters. The Na/K geothermometer is most reliable when reservoir temperatures exceed about 150°C. Below this, it at best indicates general temperature ranges.

The silica geothermometer has several forms, depending upon the form of silica believed to be present in the reservoir rocks. The 3 most-common forms are amorphous silica (such as volcanic glass), chalcedony, and quartz. Amorphous silica is significant only in cold to warm waters, because in hot systems it crystallizes to chalcedony or quartz. Chalcedony temperatures tend to be more reliable than quartz temperatures when the system is below about 180°C. Above 180°C, quartz temperatures are usually the most accurate.

A major objective of this report was to consider these two geothermometers, and the effects upon them of possible mixing in the Magadi thermal system.

4. GEOTHERMOMETRY INTERPRETATION

Silica geothermometers often are calculated by routine use of standard formulae; this can be misleading when the spring waters have a wide range of compositions and orifice temperatures, and mixing may be occurring. In such cases, graphical analysis is more reliable. In the Magadi case, graphic analysis is also advisable because of the high pH (8.82 to 9.90) of the hot and cool waters (table 1). This causes excess solubility of the various silica forms, and results in a wide range in the possible silica concentrations amongst the several mixing components. pH levels above about 9 cause a significant increase in silica solubility. Very high SiO_2 is found in the lake brines for precisely this reason.

Figures 3 and 4 illustrate silica versus temperature in waters of the Magadi area. Figures 5 and 6 are equivalent to 3 and 4, but show also the pH of the water sample (a designation of -1.0 indicates no pH data). The figures distinguish as "hot springs" all the samples which have been so-described in published or unpublished reports. (However, springs below about 38°C are less than 10°C above ambient air temperature, and might strictly not be called "thermal".) Some of the warm waters (about 45°C) clearly show the effects of mixing with a high-pH, very-high-SiO_2 lake brine, or of dissolution of volcanic glass (amorphous SiO_2).

The samples distinguished as lake brines on figures 3 through 6 are from the surface of the lake, because none of the samples of the brines found interstitial to lake sediments (collected from wells) included a temperature measurement. Among several dozen interstitial brine samples, pH ranged from 9.8 to 10.8, and SiO_2 from 72 to 1,350 ppm. Assuming that the interstitial brines have an average temperature of 25°C (slightly below average air temperature), they should plot parallel to the fields of samples from the lake brines and the warm springs.

On figure 6 we show the result of correcting the SiO_2 contents of the hottest spring waters to remove the pH effect. As a result, the hot springs appear to be in equilibrium with chalcedony at a temperature of about 85°C. Alternatively, they could be cooled from equilibrium with quartz at about 115°C. If the water at depth has a temperature higher than 85° - 115°C, it must be cooling and re-equilibrating SiO_2 before reaching the surface; this is possible, but cannot be determined from the available data.

Kamondo (1988) reported a probable silica reservoir temperature above 170°C. It is unknown if this represents a value corrected for very high pH; however, nothing reported by any other worker suggests such high temperature.

It is also possible that the hot-spring water is mixed. A simple mixing model based on dilution (see Chapter 3) would connect a low-temperature mixing component through the hot-spring sample points to a higher-temperature point somewhere on the solubility curve of chalcedony or quartz. In this case, possible low-temperature mixing components are poorly constrained, because the SiO_2 concentrations are highly variable. The range of low-temperature sample points (pH values in italics on figure 6) drawn through the pH-corrected hot-spring point intersects the quartz line across a range from about 115°C to 140°C. Mixing lines to these points are shown as dashed lines on the figure.

Thus, the possible temperature of a hot component at Lake Magadi could be as high as 140°C. However, because the hot-spring waters fall on the solubility curve of chalcedony, we cannot conclude definitely that mixing is occurring. If mixing does occur, it is followed by re-equilibration of SiO_2. The point where this re-equilibration occurs is unknown.

If contamination mixing is occurring, it is most likely that the cool component is an interstitial-sediment brine with SiO_2 concentration somewhere in the wide range <100 to >1000 ppm. Depending upon the assumptions made for the average SiO_2 content of the interstitial brine samples, and the quantity of this contaminant in the hot-spring water, the temperature of the hot, quartz-equilibrated component may range from less than 100°C to over 115°C.

The Na/K temperatures of the Magadi hot springs are 65° to 100°C, depending upon which formulation of the Na/K geothermometer is used. Different formulations have been calibrated using temperature and chemical data from different areas. The most general form gives temperatures of about 100°C. The Na/K method typically is very imprecise at temperatures as low as these. If temperatures are significantly above 100°C, there must be significant dilution with low-K waters.

To further investigate the Na/K temperatures, K was plotted versus Na for the area waters (figure 7). Ratios in the spring waters are maintained as they evaporate to form the lake brines. There is some discontinuity between ratios in the dilute groundwaters and in the springs, but the dilute waters have lower Na/K than the springs. The study of Jones *et al*. (1977), discussed in Appendix B of this report, concluded that the spring waters ultimately are evaporated equivalents of the dilute waters. To explain the relative loss of K as salinity increases, they suggested (but did not specify) the action of a sorption or precipitation mechanism.

Because there is some scatter in Na/K amongst the hot spring waters on figure 7, these data were replotted as Na/K versus spring temperature (figure 8). This shows that the lowest Na/K (highest Na/K temperatures) are characteristic of the hottest springs as a group.

The effect of mixing on cation temperatures depends upon whether the mixing is contamination or dilution (see Chapter 3). If there is dilution, there should be little to no effect on the Na/K ratio. As a result, although dilution mixing should lower the silica temperature, it may not significantly affect the cation temperature, which should still yield some indication of the deep reservoir conditions. Silica and cation temperatures of the Magadi hot springs are somewhat similar, with silica tending to yield higher temperatures than Na/K. Dilution mixing, therefore, would occur only if dilution was followed by SiO_2 re-equilibration. This cannot be assessed at present.

Contamination mixing, in contrast, would involve a high-salinity lake brine or interstitial brine, having very high Na/K. This could totally mask a very hot, less-saline component having low Na/K. There is no way to constrain the possible Na/K temperature of the hypothetical hot component, except by reference to a silica mixing model. As we have seen, a silica mixing model for contamination mixing is very poorly constrained, and yields a range of values between the highest spring temperature (about 85°C) as the lower value, and about 140°C as the maximum.

5. DISCUSSION OF THE MAGADI GEOTHERMAL SYSTEM

A detailed discussion of groundwater and surface waters in the Magadi basin, giving one possible origin of the spring waters, is presented as Appendix B. In summary, dissolved solids in waters throughout the basin are dominated chemically by Na and HCO_3; but there is a wide range in water salinity, from 100 to 1,000 ppm in the cool, dilute surface and ground waters, to 300,000 ppm in lake brines (figure B1). The hot and warm springs (figure 2) have salinities of about 10,000 ppm to 38,000 ppm. This broad range of values indicates that the thermal springs probably are affected by mixing.

The hot and warm springs discharge at the lake shore and flow into lagoons in the lake; on good evidence they are considered to be the major source of the lake water, which becomes increasingly concentrated by evaporation. The springs may also be the historic source of similar brines found interstitially in the lake sediments in wells drilled to depths of 75 m; and in a single well drilled into lavas at the eastern edge of the lake to a depth of 297 m (well K; figure 2). There are some data showing that brine salinity decreases with depth, but the water from 297 m depth still carries 125,000 ppm solids.

The hot springs at the north end of the lake have temperatures of 60° to 85°C (table 1). Those at the southern end are below 50°C, and occasionally below 35°C, which is not far above temperatures of lake and lagoon waters. The temperature of cool groundwater is between about 25° and 30°C; mean annual air temperature is about 28°C. Dilute, potable groundwaters are scarce, because evaporation throughout the basin causes considerable build-up of salinity. Fresh water is brought into the area by pipeline from streams located at very high elevation on the Nguruman Escarpment to the west (figure 1).

Despite extensive efforts by Magadi Soda Company to monitor and understand flow conditions, there is still some uncertainty concerning flow rates of individual hot and warm springs. Several workers have commented on the apparent stability in temperature and flow rate through a 60-year period in which trona has been produced. However, at least one recent worker (K. Crane, unpublished manuscript, probably 1980) has drawn a contradictory conclusion: temperature and flow rates have had both cyclic and progressive variation with time. These she related to earthquake activity within the Rift, and possibly to volcanic activity at Ol Doinyo Lengai, 60 miles (100 km) to the south, or to yearly variations in local rainfall.

In the 1930s, measurements of evaporation rate were used to calculate the total recharge into the lagoons and lake, assuming that evaporation was matched by spring and subsurface inflow (there is no perennial surface inflow, and only episodic rainfall, or runoff into the lake after major storms). Total inflow to all lagoons and the lake was estimated to be 70 million gallons/day. Into Little Magadi Lake alone, which is fed by the northernmost and hottest springs, the rate was 21 million gallons/day, or 14,500 gpm.

There is considerable doubt that this can be inflow from the hot springs alone. Measurements made at the Little Magadi thermal springs by the junior author in September 1989 indicate the total surface springs discharge to be about 2,000 gpm. Therefore, spring flow may either: (a) vary sharply by season or year; or (b) the surface flow rate of the thermal springs must be exceeded greatly by sub-lacustrine spring discharge or (c) surface flow rate must be exceeded by groundwater upflow from deeper thermal aquifers.

Even if the inflow comes from combined surface and sub-lacustrine hot springs, this combined flow rate is remarkably high. Given the relatively limited rainfall directly into the Rift Valley, it is necessary to consider that the ultimate source of water in the springs is subsurface flow across a larger region, including rainfall infiltration from the Nguruman Escarpment to the west. This water travels down-gradient to the regionally lowest point (Lake Magadi basin), where it discharges into the lakes and saturates the sub-lacustrine sediments.

A typical spring composition is as follows (sample M1018, Jones et al., 1977), from the high-temperature springs located at the northern end of Little Magadi Lake:

T°C	83
pH-field	9.44
pH-lab	9.05
SiO_2, ppm	85
Ca	below detection
Mg	below detection
Na	10,500
K	198
HCO_3	10,400
CO_3	4,450
SO_4	168
Cl	4,890
F	146
Br	20
B	8.3
TDS, ppm	25,600 mg/l

Ca is absent because the very high concentration of carbonate species (CO_3) causes precipitation of calcite. Mg is below detection either because of carbonate precipitation, or because Mg-silicate is precipitated. Typically, Ca is reduced in abundance and Mg is absent from high-temperature geothermal systems. Also, both Ca and Mg are absent from the other regional waters whose TDS exceeds about 10,000 ppm.

The origin of the hot spring waters remains in doubt. Jones *et al*. (1977) described the hottest springs as mixtures of two principal components, dilute shallow groundwater, and hot saline brines interstitial to sedimentary deposits beneath the lake (figures B1 and B2). The quantities and concentrations of the various components are not fully described, and the model is not fully in agreement with the trends observed in chemistry of spring, lake and interstitial-sediment waters (figures 3 through 8). In the Jones *et al.* model, the thermal component could be significantly above 140°C.

Another possibility, favored by the senior author of the present report, is that the thermal springs originate largely as outflow from the major volcanic systems to the north or south of Magadi, at a distance of several tens of miles (dozens of km). This outflow cools conductively, and may be mixed with cooler water of different composition and origin, en route to Magadi or beneath the lake at unknown depths.

In 1981, Harmon Craig collected water samples from the Magadi basin for stable-isotope analysis and water and gas samples for analysis of stable and radiogenic helium. His unpublished data graciously have been made available for the present report (table 2 and figure 9). His results are discussed in the following paragraphs.

There is a significant difference in the He/N_2 ratio, and the ^{3}He/^{4}He ratio, for gas samples taken from Little Magadi and Magadi thermal springs, and in the interpreted component of mantle-derived helium for each sample. Craig pointed out that the number of samples is limited, and that further sampling may change the results and interpretations. However, from the available data he has concluded that the mantle helium component from Little Magadi is comparable to that of active volcanic systems in other geologic settings. This does not suggest a volcanic source for the Little Magadi thermal springs. It does suggest that hot gases are rising from great depth beneath the Magadi basin, and are dissolving in the waters having the deepest circulation, namely those supplying the Little Magadi hot springs. This, in turn, allows the inference that a very high-temperature source exists at some unknown (but possibly great) depth beneath the Magadi basin.

Stable-isotope data (^{18}O and deuterium) also show a difference between thermal waters from the south end of Magadi Lake and those of Little Magadi. This suggests that the waters either have a different initial origin, or have undergone significantly different mixing histories. Craig also presented two unpublished stable-isotope analyses performed at some earlier time by J. Stevens at Magadi. Unfortunately, the precise location of these sample points is not known. Together with Craig's results, these define a trend which, again, suggests different mixing histories or different origins.

Kathleen Crane (unpublished manuscript, probably 1980) has reviewed the historic data on spring temperature and flow rate, collected over the decades by personnel of Magadi Soda Company, and has attempted to correlate these data with levels of earthquake activity. She concluded that there is such a relationship, although it is obscure in detail. Spring temperatures have shown progressive changes (table 1), either increasing or decreasing, which she relates to the opening or closing of upflow channels by earthquake activity. (Cementation by chemical precipitation could have the same effect.) Crane also reported that fumarolic activity occurred at the southern end of Magadi lake after one earthquake, but does not have specific details.

Crane also calculated the power output of the several groups of thermal springs, based on ground and aerial-infrared surveys done in 1979. She concluded that:

(a) the Little Magadi thermal springs have a different, deeper circulation path than the other spring groups; and

(b) approximately two-thirds of the power output of the combined thermal system comes from the Little Magadi group.

This supports a higher-temperature origin for Little Magadi.

All of this permissively allows the conclusion that the surface thermal discharges are significantly modified from the deeper conditions, by some unknown combination of processes that probably includes mixing and conductive cooling, and possibly mineral precipitation and chemical re-equilibration. It is concluded also that the Little Magadi thermal system has a deeper and higher-temperature circulation than the other springs (with the possible exception of the northeastern lagoon of Magadi Lake). Hot, mantle-derived gases may contribute to heating the Little Magadi reservoir at depth. If this is indeed the case, the chemical geothermometry (100° to 140°C) is only a crude approximation of the thermal regime at depth.

6. EXPLORATION AND ASSESSMENT PROGRAM

As described above, the geothermal energy potential of the Magadi basin cannot be resolved from the geological, geochemical and hydrological data that have been collected by the various workers. A brief consideration of surface geophysical techniques yields the conclusion that no additional surface surveys are likely to be of any help in answering the questions of reservoir temperature, depth and size.

For example, all electrical resistivity, electromagnetic and magnetotelluric techniques would be affected greatly by the presence of a thick, highly conductive evaporite sequence at and just below the surface. It is to be anticipated that a major conductance-high /resistivity-low would be found across the evaporite bodies, having its greatest intensity in the areas of highest fluid salinity and temperature. This feature thus would likely mask any underlying resistivity/conductance anomaly.

Gravimetry would be expected to yield further evidence of block faulting, and possibly the angle of the block-forming faults. However, gravimetry and magnetic surveys would not be likely to identify areas of changed rock density or magnetic properties, even if they exist, because of the complications and uncertainties in the subsurface geology. Microseismicity has no proven record in resolving questions of reservoir temperature, size or depth. Seismic refraction and reflection surveys are very expensive to perform and typically are of post-dictive rather than predictive value in geothermal exploration.

The only remaining technique is thermal measurement. This could consist of the measurement of temperature in numerous shallow (50 to 200 m) holes, to create a set of maps of shallow temperature, temperature gradient, and (by the use of thermal conductivity data from the rock suite encountered in drilling) heat flow. However, the shallow regime unquestionably is distorted by both the thermal springs that discharge at many places across the basin (figure 2), and the very high thermal conductivity of the saline sediment and groundwater. Results from shallow drillholes thus would be almost meaningless.

A smaller number of deeper holes or a single very deep hole are the remaining alternatives. These would have to be located and designed to accomplish the following:

a) Intercept a major fault along which thermal springs are discharging to the surface, at a depth of several hundred m.

b) Penetrate beneath the perched water tables of very saline brine believed to be present in the upper few hundred m under the lake basin.

c) Allow the recovery and sampling of the deeper, presumedly hotter, source fluid of the thermal springs en route to the surface, before there has been significant mixing with shallow, cool, possibly saline aquifers.

d) Allow the repeated measurement of temperature within a cased and cemented hole, to yield stabilized in situ temperature profiles.

e) Allow the repeated measurement of pressure within any hole(s) that encounter the permanent water table beneath the basin.

To accomplish this, the holes must go to a minimum depth of approximately 600 m (2,000 feet). Diameter at bottom should be at least 4 inches, and preferably larger, to allow downhole measurements and the induced flow of water to the surface. Given the saline conditions within the lake basin, no disposal well will be needed if flow is induced. It is anticipated that the static water level in any deep hole in the Magadi basin will be near to the ground surface. If flow cannot be induced, pumping may be necessary. Accommodating a pump would require a bottom-hole diameter of approximately 5 inches at a minimum.

Geothermometry predicts temperatures in the upper zone between 100°C and 140°C, with only a slight chance of temperatures above 140°C. In order to obtain the highest possible temperature, it is proposed that the holes to be drilled into areas of probable strongest upflow and highest surface temperature. The highest surface temperatures are found in the Little Magadi hot springs, at the northern end of Little Magadi Lake; the next-highest are at the northeastern lagoon of Lake Magadi (figure 2 and table 1).

There is a passable track across the ridge between Magadi and Little Magadi Lakes; but this track ends at a bluff above the lake, and a road would have to be constructed with some difficulty downslope to the hottest springs. Alternatively, a 2-km-long extension of an existing road also would have to be constructed to the springs of the northeastern lagoon.

In order to minimize the construction costs and maximize data collection, it is proposed that a single passable track be constructed into the Little Magadi thermal area, and that 3 holes be drilled to 600 m (2,000 feet) at locations approximately one km apart into the 3 major clusters of thermal springs there. By drilling 3 holes, it will be possible to explore the highest-potential area thoroughly; the cost of mobilization and road building will be spread over 3 holes; therefore, the cost per foot drilled should be the minimum possible for such a project.

By contrast, a single hole to about 1,500 m (4,900 feet) would cost approximately the same as the 3-hole program, but would yield information at only one location. The risk of not intercepting an upflow zone is therefore increased. A compromise third alternative would be to drill 2 holes to 800 m (2,600 feet), thereby providing data from an intermediate depth at 2 locations, with a corresponding lessened risk. The principal advantage of a 3-hole program is that if one hole is lost because of mechanical problems, there still remains sufficient data for feasibility assessment.

Cost for the 3-hole program will depend upon:

a) The availability of a suitable drilling rig within Kenya. It is known that Kenya Power and Lighting Company has a rig capable of going to these depths at its Olkaria geothermal field, with full crew and support equipment. If this rig cannot be made available on suitable contract terms, other possibilities may exist within the country.

b) The level of support for the project given by Magadi Soda Company. Magadi Soda should be asked to provide living accommodations at the Magadi facilities, along with the use of its earth-moving equipment at cost, for road construction and site preparation.

c) The subsurface conditions to be encountered. It is expected that high-temperature flows, lost circulation, and difficult formation conditions will be encountered. The effects of this can be minimized by the provision of adequate lost-circulation and cementing materials, an air compressor and a blow-out preventor, on-site, and by the use of drillers experienced in geothermal conditions.

Although the actual cost cannot be estimated closely, it is projected that cost, including road building, site preparation, drilling, logging and reporting, will be approximately US$300 per m (US$90 per foot), or US$180,000 per hole. A recommended 3-hole program would, therefore, cost approximately US$540,000. With a 15% contingency allowance to cover the imponderable additional costs, the total comes to US$621,000.

The expenditure of this sum would provide a convincing answer as to whether geothermal reservoir conditions are suitable for the development of electric power at Magadi. Technical feasibility would consist of demonstrating that there is water above about 120° - 130°C, suitable for power generation by binary-cycle method, present at a suitably shallow depth, with a suitably dilute chemistry.

If technical feasibility is shown as a result of this program, the next steps would be to determine economic feasibility on the basis of data provided by the drilling program, and to begin the design of production wells and a power-generation station. If feasibility is not shown by drilling, the project can confidently be abandoned with no second thoughts.

Once the decision is made to begin this stage of exploratory drilling, as described above, a period of approximately 8 months will be needed for all operations, as follows:

a) Contract negotiation and mobilization of a drill rig to the site: 3 months.

b) Construction of access road and drilling sites: 3 months, simultaneous with contract negotiation and mobilization.

c) Drilling of 3 holes each to 600 m: at an average penetration rate of 30 m (100 feet) per day, plus 5 days between hole to move and erect rig, 25 days will be needed per hole, or 75 days (2.5 months) for the entire drilling operation.

d) Logging and testing of 3 holes: to be carried out simultaneously with drilling, and extending until 45 days (1.5 months) after completion of drilling.

e) Data analysis and reporting: to begin during drilling of the second hole, and to continue until 30 days (1 month) after completion of all logging and testing.

7. SUMMARY

The ultimate source of the Magadi hot spring system is not well-understood. Possible sources are:

(a) infiltration of rainfall and deep circulation along one or other of the Rift faults; or

(b) lateral flow of heated fluid from a fumarolic volcanic center some distance to the north or south.

Whatever the origin, mixing of a deep thermal component with a cool component is likely, although the exact nature of both the thermal and the cool components remains speculative. Heating by degassing of the mantle may occur. Conductive cooling, precipitation and chemical re-equilibration also may occur.

Geothermometry of the hot-spring chemistry is compatible with temperatures of 100° to 140°C. If the spring waters are dilution-mixed, a silica mixing model indicates possible temperatures to about 140°C. However, silica concentrations and Na/K ratios together suggest that dilution mixing would have to be followed by re-equilibration. The location and nature of this re-equilibration is unknown.

Data from isotopic analysis, hydrology, geology and geochemistry indicate that the Little Magadi springs have a different, and probably deeper-seated, origin than the other thermal springs. It is likely that the regionally highest temperatures are found beneath the Little Magadi area.

Given these conditions and uncertainties, no estimate of the geothermal energy potential can be made with comfort. Instead a drilling program is required, in order to obtain the necessary information on temperature, fluid composition and system depth, to allow a calculation of the developable geothermal energy. It is distinctly possible that a fluid system suitable for power generation by the binary-cycle method can be found at relatively shallow depth.

Therefore, it is recommended that three 600-m (2,000-foot) holes be drilled to intercept upflow along faults controlling the Little Magadi thermal springs (temperature to 85°C). Cost is estimated at US$621,000. Approximately 8 months would be required for contracting, drilling, logging, testing and preparation of reports. This would allow a decision regarding the technical feasibility of development.

8. REFERENCES

Baker, B. H., 1958, Geology of the Magadi Area: Kenya Geological Survey Report #42, 82 p.

Craig, Harmon, unpublished letter and data tabulation, September 20, 1989.

Crane, Kathleen, 1980(?), Thermal and seismic oscillations in the Gregory Rift of southern Kenya: unpublished manuscript provided to Magadi Soda Company.

Eugster, H.P., 1970, Chemistry and origin of the brines of Lake Magadi, Kenya. Mineralogical Society of America Special Paper 3, pp.213-235.

Jones, B.F., Eugster, H.P., and Rettig, S.L., 1977, Hydrochemistry of the Lake Magadi basin, Kenya. Geochemica et Cosmochemica Acta, vol.41, pp.53-72.

Kamondo, W.C., 1988, Possible uses of geothermal fluids in Kenya. Geothermics, vol.17, no.2/3, pp.489-501

Table 1. Maximum temperature, pH, SiO_2 and temperature-change data, Magadi thermal springs

	Baker (1958)	Jones *et al.* (1977)			Kamondo (1988)			Crane (unpublished)		
									ΔT°C	
Spring (1)	T°C	T°C	pH	SiO_2 mg/l	T°C	pH	SiO_2 mg/l	T°C	1931-79	1973-79
1	35.5								-3 to -8	-1 to -2.5
2	37	36.5	9.6	59	38.5-45.3	8.82-9.65	48-105	34		
3	39									
4	45.5									
5	~44							41		
6	~48	42	8.98	104				41		
7	38							40	+1 to +7	+0.5 to +3
8	39	37	9.66	55				37		
9	37							43		
10	37.5								-3 to -8	
11	38.5									
12	38.5	37	9.9	74				37	+0.2 to +0.6	+0.8 to +1
13	42.8	44.8	9.88	74				44		
14	44.2	44.2		79				45		
15	40								+1 to +7	+0.5 to +3
16	40	43.5						40		
17	35	42.5	9.84	46				42		
18	85	80	9.3	85	81.3-85.3	8.85-9.47	80-86	77	-3 to -8	-2 to -3
19	81.5	83	9.44	85				83		
20	81							77		
21	67	71	9.22	81	66.6	8.96	83	71	+3	
22	33							35	+0.2 to +2	+3.2
23	34							34.5		
24	36							36.2		

(1) Spring number from Baker (1958) - see figure 2, this report; however, additional thermal springs or seeps exist along shores of both Magadi and Little Magadi lakes, whose exact locations cannot be determined from available data.

Table 2. Helium chemistry and isotopy of Magadi gases (from H. Craig, unpublished)

		He/N_2 (ppm)	R/R_A*	Percent Mantle Helium
M-1.	North end Little Magadi, 81°C, (Baker, 1958, #20). Fluid sample.	5,900	3.68	46
M-2.	Little Magadi, 85°C. (Baker, 1958, #18). Fluid sample.	8,030	3.74	47
M-4A.	Magadi, south end of SW Lagoon. 45°C. Fluid sample.	2,340	2.01	25
M-4B.	Gas collection at M-4.	7,184	2.06	26
Air		6.7	1	--

---

* $^3He/^4He/(^3He/^4He)_{Air}$

$R_A = 1.40 \times 10^{-6}$ $\qquad$ $R_{MORB} = 8\ R_A$

Note: M-1, M-2: Noncondensible gas = 42 and 48% CH_4
M-4 = 0.4%

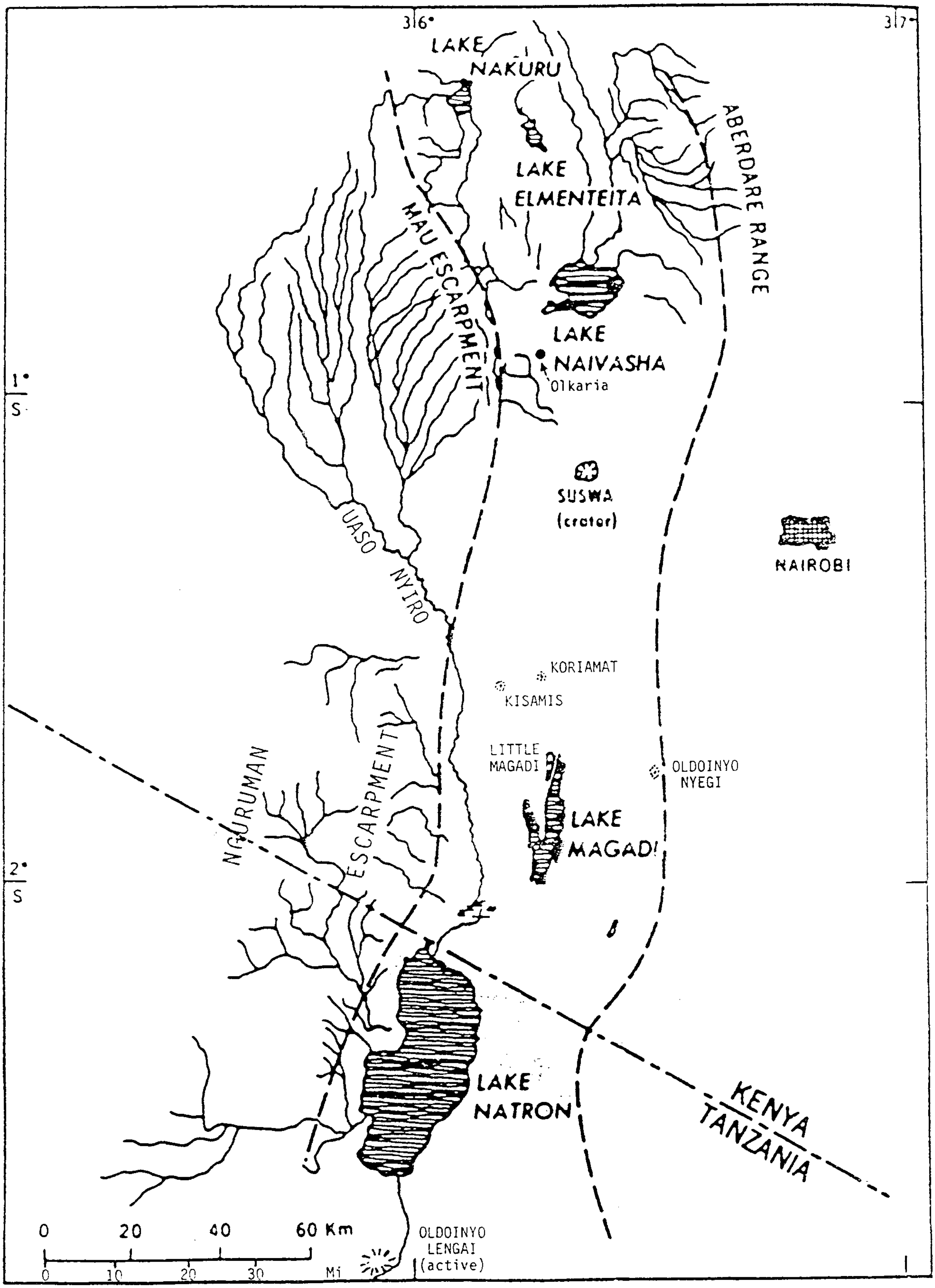


Figure 1. Location of Lake Magadi and Little Magadi Lake, Kenya.

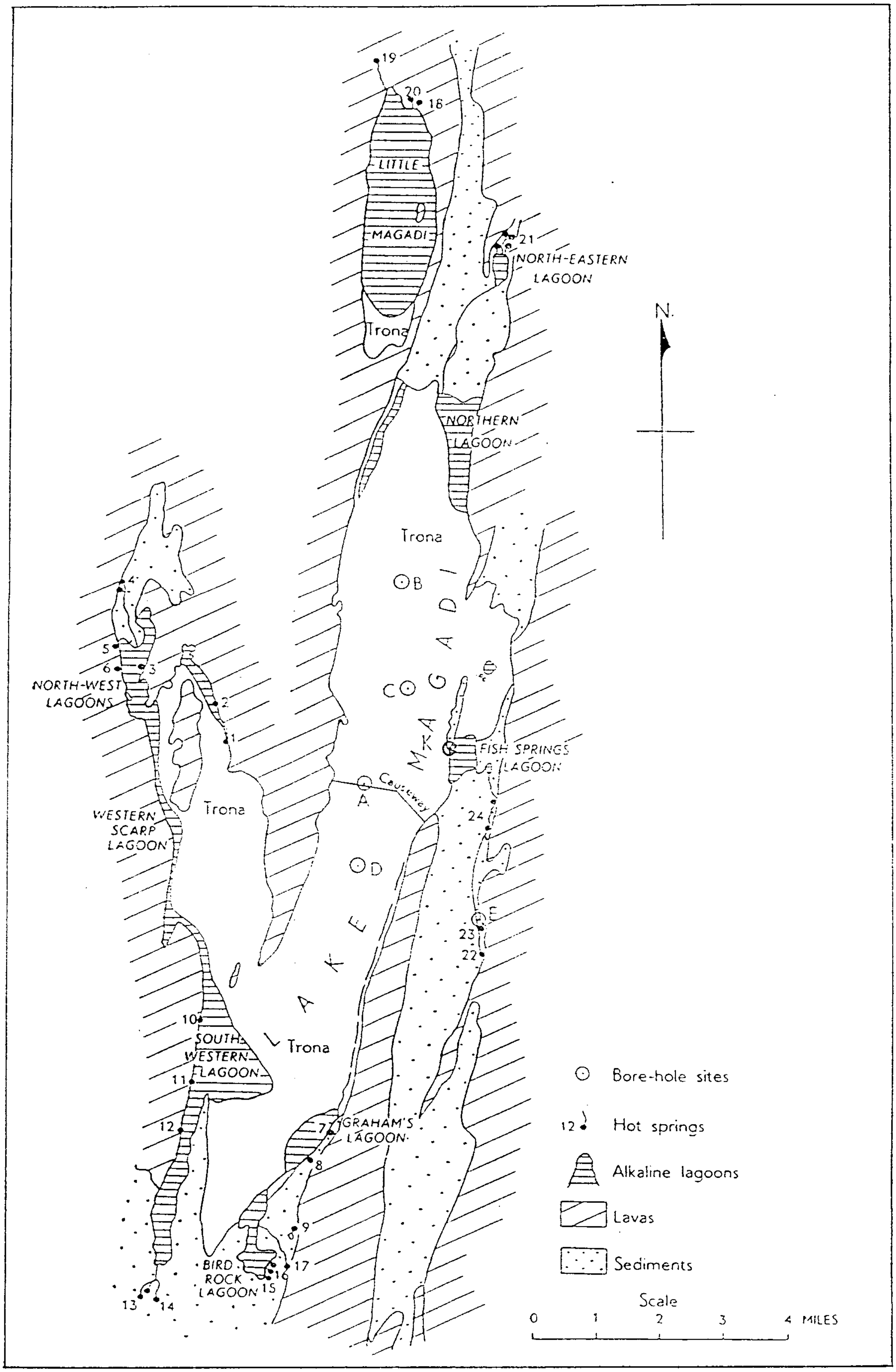


Figure 2: The thermal springs and alkaline lagoons of Lake Magadi.

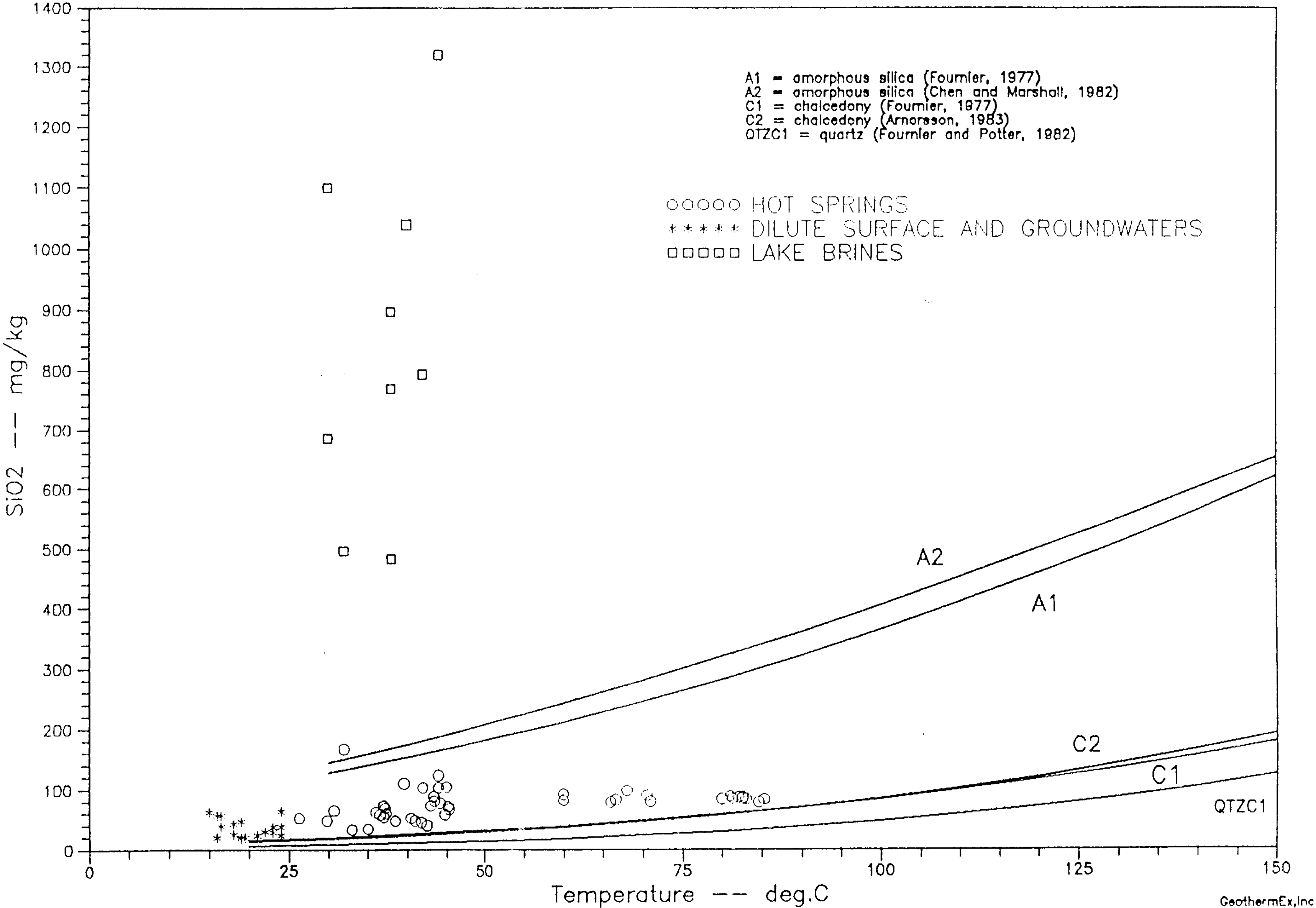
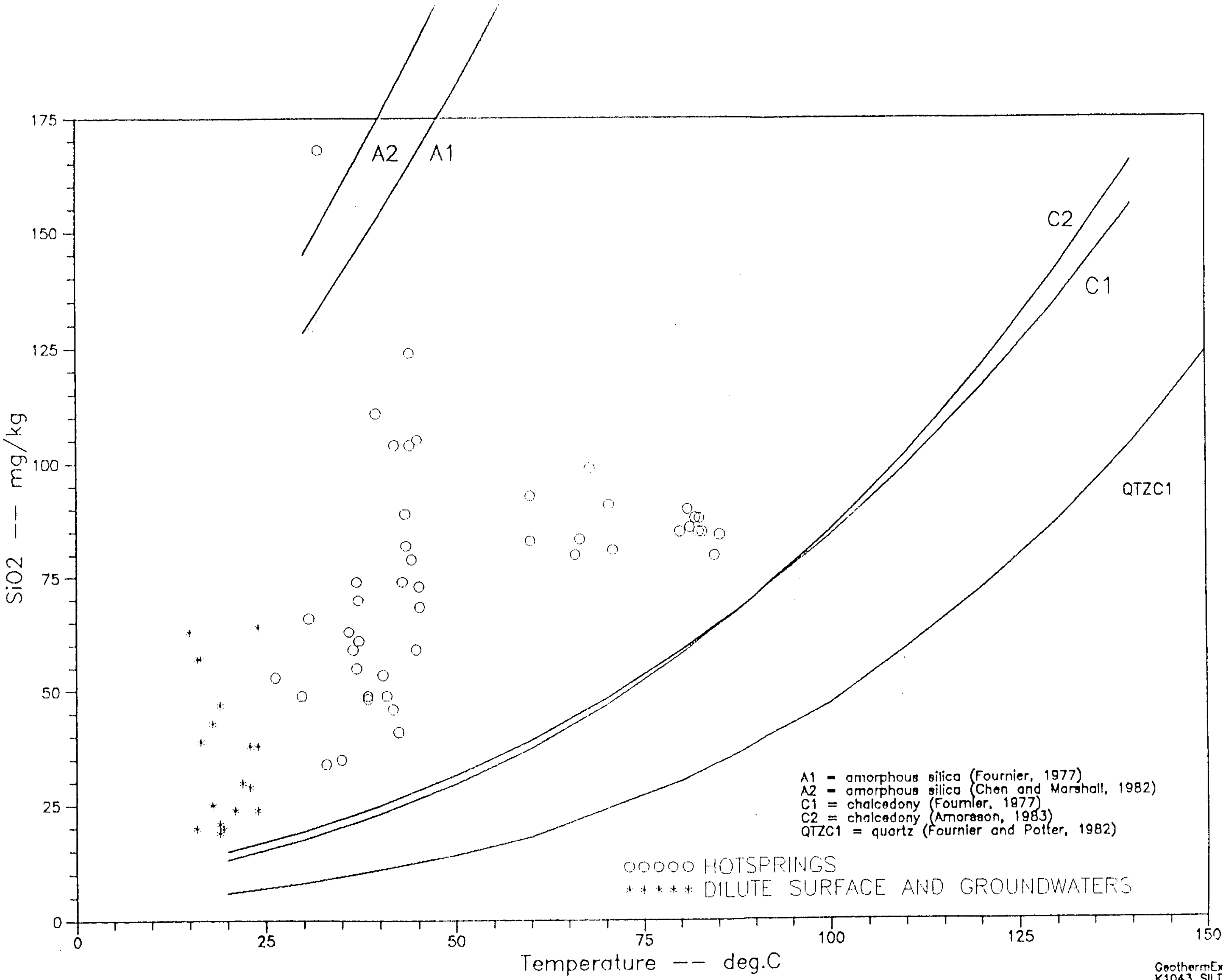


Figure 3 : Dissolved silica vs. temperature Magadi Hot Springs

GeothermEx,Inc.
K1043 SILTC1
890901



GeothermEx,Inc.
K1043 SILTC2
890901

Figure 4 : Dissolved silica vs. temperature, Magadi Hot Springs detail

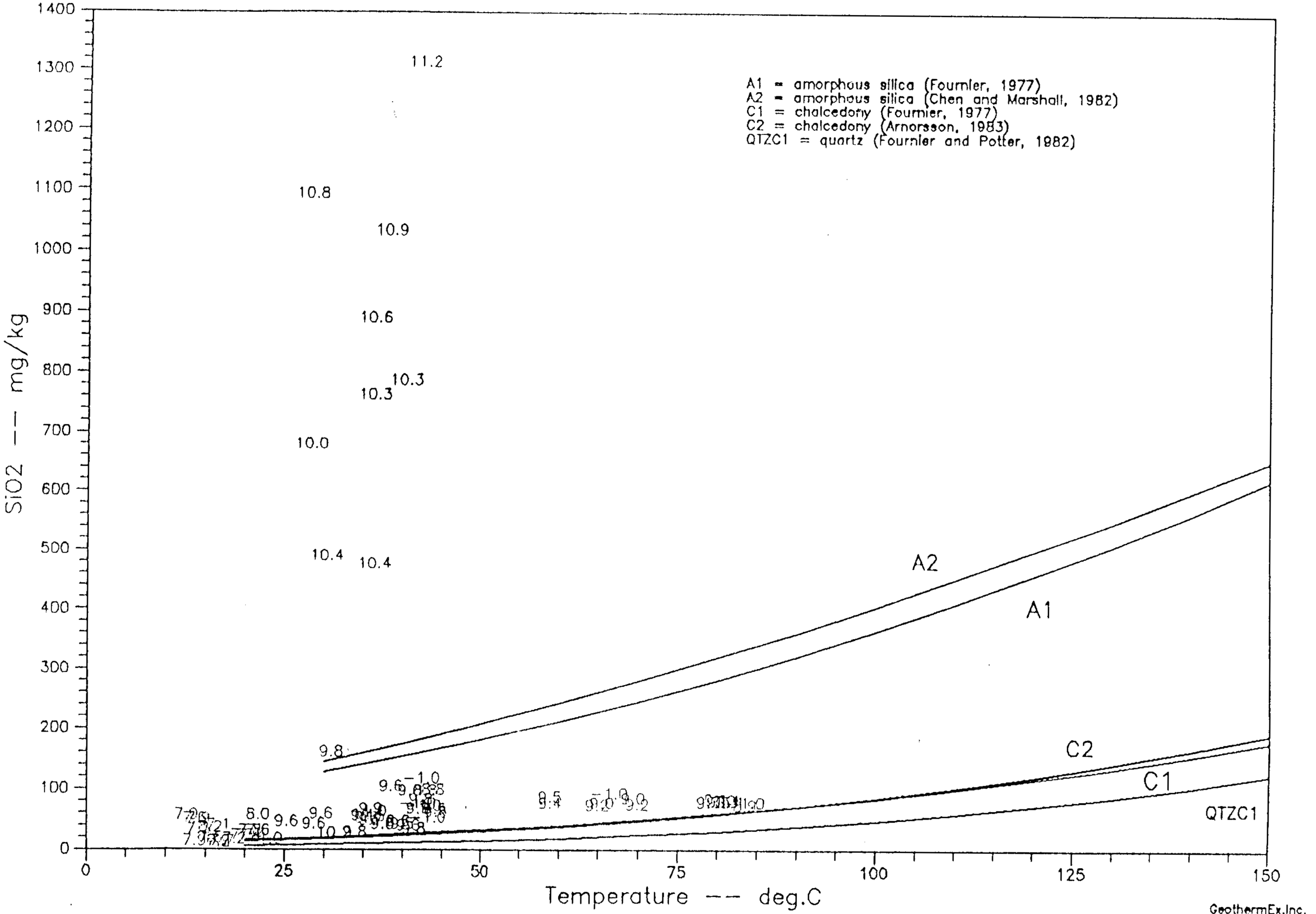
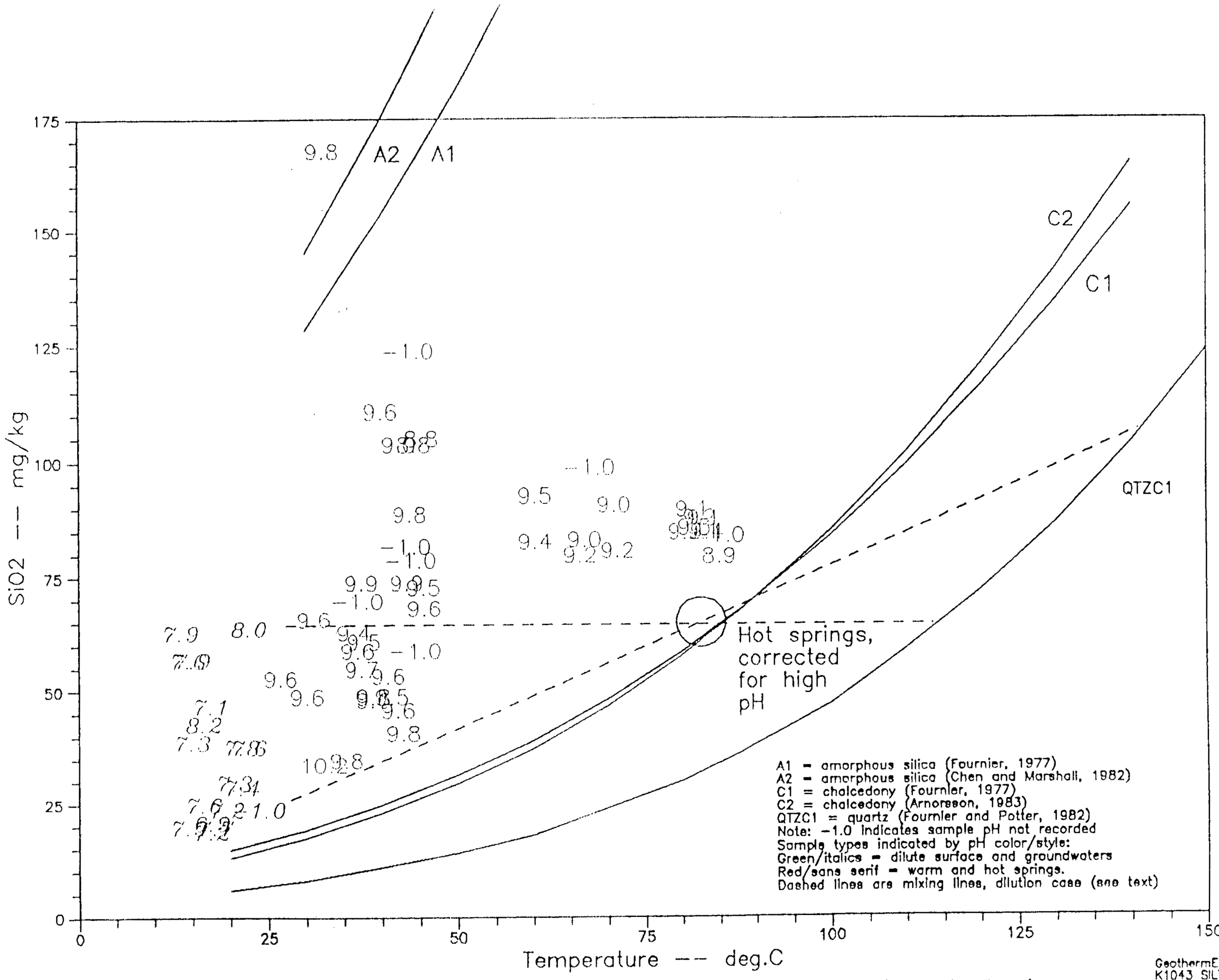


Figure 5 : Dissolved silica vs. temperature, Magadi Hot Springs showing sample pH

GeothermEx,Inc.
K1043 SILTCPH1
890901



GeothermEx,Inc.
K1043 SILTCPH2
890906

Figure 6 : Dissolved silica vs. temperature, showing sample pH detail Magadi Hot Springs

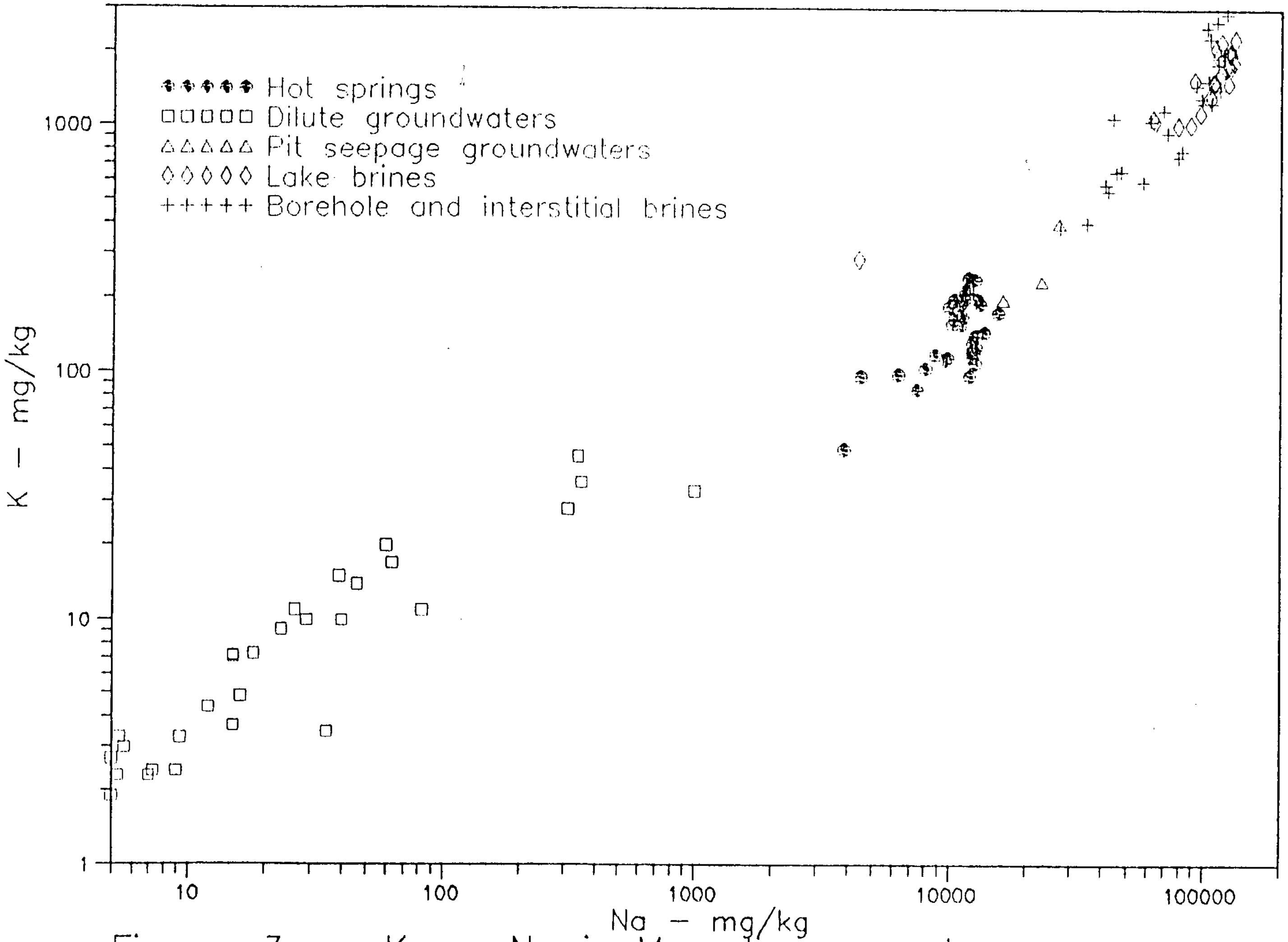


Figure 7 : K vs. Na in Magadi area waters

GeothermEx,Inc.– K1043–K NA–890906

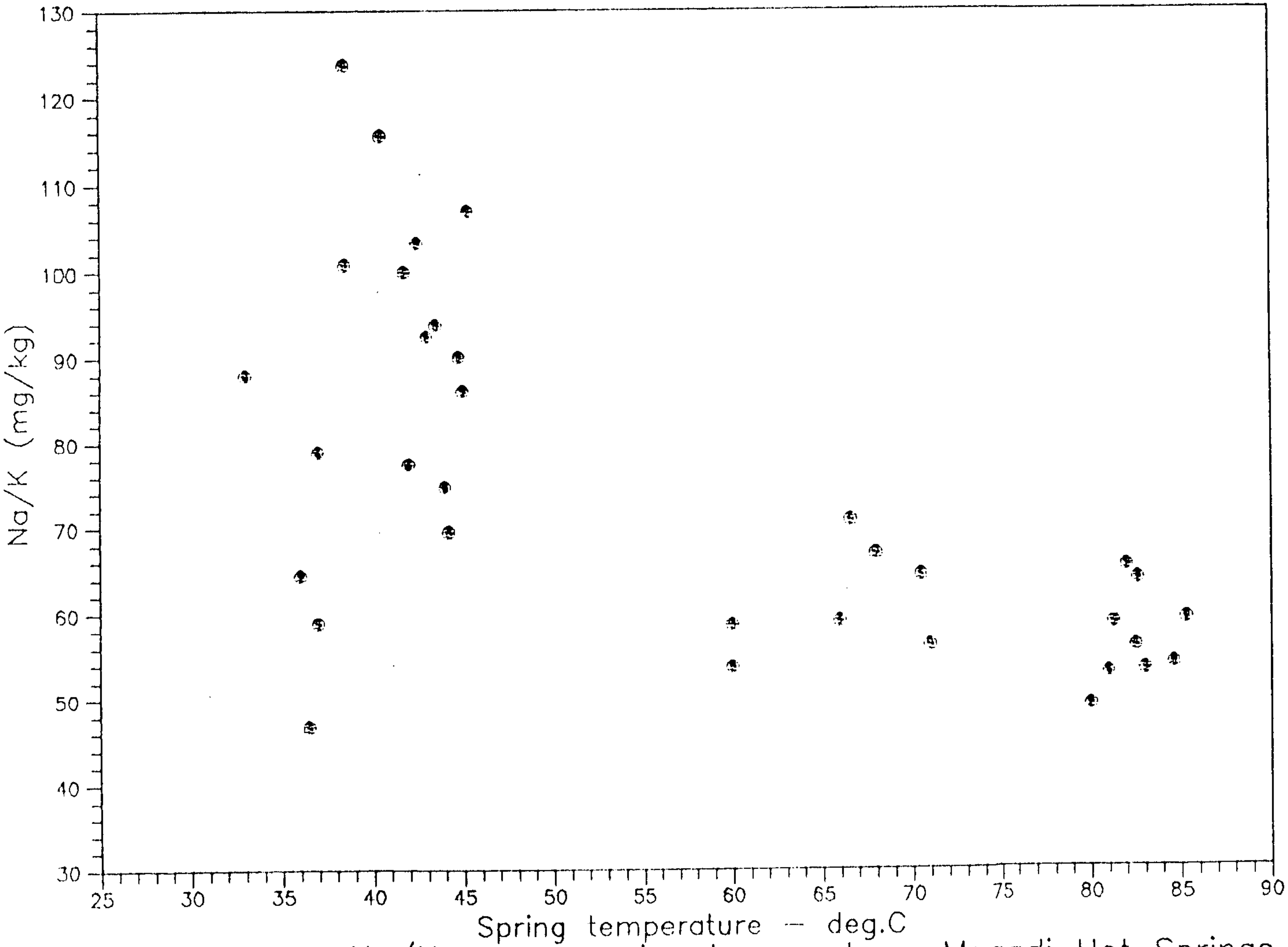


Figure 8 : Na/K versus spring temperature, Magadi Hot Springs

GeothermEx,Inc. – K1043-K NAHOTS – 890906

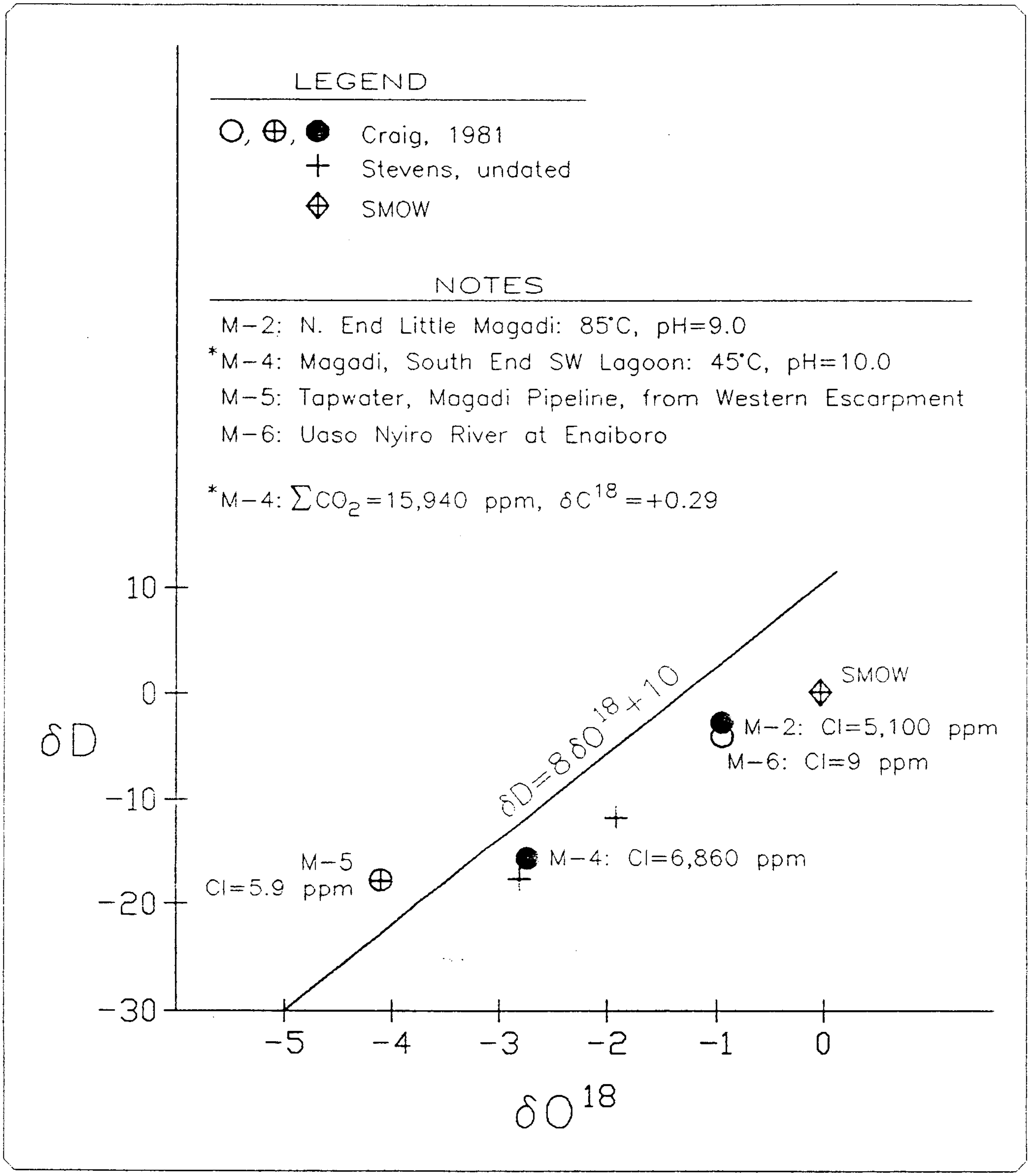


Figure 9: Stable isotopes of hydrogen and oxygen, Magadi basin (collections by H. Craig, February 1981, and J. Stevens, undated)

GeothermEx, Inc.

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5221 CENTRAL AVENUE
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CABLE ADDRESS GEOTHERMEX
TELEX 709152 STEAM UD
FAX (415) 527-8164

APPENDIX A

Computer Simulation Printouts

89905-8

≡ run 89905

```
MAGADI EUGSTER 62          ASSUME FIELD PH MEASURED AT 25C; REPEAT RUN 890905-5 FOR 82.5C

                           INPUT DATA FILE WA3.ASC

WATER SAMPLE (PPM)         STEAM SAMPLE

PH/DEG.C          9.13/25.0  GAS (VOL.%)              REFERENCE TEMP.       DEGREES C      82.5 (MEASURED)
SIO2                85.00    CO2
NA               11100.00    H2S                      SAMPLING PRESSURE     BARS ABS.
K                  199.00    H2                       DISCHARGE ENTHALPY     MJOUL/KG
CA                    .01 (arbitrary) O2              DISCHARGE               KG/SEC.         .0
MG                   .000    CH4
CO2              13828.00    N2                       MEASURED TEMPERATURE DEGREES C       82.5
SO4                179.00                             RESISTIVITY/TEMP.    OHMM/DEG.C      -1.0/-1.0
H2S                   .00                             EH/TEMP.               MV/DEG.C      -1.0/-1.0
CL                5240.00
F                  144.00    LITERS GAS PER KG
DISS.SOLIDS         -1.00    CONDENSATE/DEG.C              MEASURED DOWNHOLE TEMP.     FLUID INFLOW
AL                  .0000                                    DEGREES C/METERS         DEPTH (METERS)
B                  8.3000
FE                  .0000    CONDENSATE (PPM)                     .0         .0               .0
NH3                 .0000    PH/DEG.C                             .0         .0               .0
-1                           CO2                                  .0         .0               .0
 -1                          H2S                                  .0         .0               .0
 -1                          NA                                   .0         .0               .0
                                                                  .0         .0               .0
                                                                  .0         .0               .0
                                                                  .0         .0               .0
                             CONDENSATE WITH NAOH (PPM)           .0         .0               .0
                             CO2                                  .0         .0               .0
                             H2S                                  .0         .0               .0

IONIC STRENGTH =    .56142      IONIC BALANCE :    CATIONS (MOL.EQ.) .48651750
                                                   ANIONS  (MOL.EQ.) .52619030
                                                   DIFFERENCE    (%)      -7.83

DEEP WATER (PPM)                                      DEEP STEAM (PPM)              GAS PRESSURES (BARS ABS.)

SIO2         85.01        CO2      13828.00           CO2             .00           CO2         .398E-01
NA        11100.00        H2S           .00           H2S             .00           H2S         .000E+00
K           198.99        H2            .00           H2              .00           H2          .000E+00
CA             .01        O2            .00           O2              .00           O2          .000E+00
MG            .000        CH4           .00           CH4             .00           CH4         .000E+00
SO4         179.00        N2            .00           N2              .00           N2          .000E+00
CL         5239.56        NH3           .00           NH3             .00           NH3         .000E+00
F           144.02                                                                  H2O         .523E+00
DISS.S.      -1.00                                                                  TOTAL       .563E+00
AL           .0000
B           8.2992                                    H2O (%)                 .00
FE           .0000                                    BOILING PORTION         .00

CONVENTIONAL GEOTHERMOMETERS USING DEEP WATER PPM COMPOSITIONS:
FOURNIER & POTTER(1982) QUARTZ TEMP. (85-330C) =     128.49 DEGREES C
FOURNIER(1977) CHALCEDONY TEMP. (C.20-240C)    =     100.69
FOURNIER(1979) NAK TEMP. (>150 TO 200C)        =     103.69
NA-K-CA TEMP, BETA 1/3 CASE (4-340C)           =     238.12
```

```
ACTIVITY COEFFICIENTS IN DEEP WATER
H+              .700        KSO4-           .624        FE++            .199        FECL+           .580
OH-             .561        F-              .561        FE+++           .064        AL+++           .064
H3SIO4-         .580        CL-             .541        FEOH+           .613        ALOH++          .180
H2SIO4--        .180        NA+             .580        FE(OH)3-        .613        AL(OH)2+        .624
H2BO3-          .518        K+              .541        FE(OH)4--       .167        AL(OH)4-        .597
HCO3-           .580        CA++            .199        FEOH++          .167        ALSO4+          .597
CO3--           .151        MG++            .258        FE(OH)2+        .624        AL(SO4)2-       .597
HS-             .561        CAHCO3+         .640        FE(OH)4-        .624        ALF++           .180
S--             .167        MGHCO3+         .580        FESO4+          .613        ALF2+           .624
HSO4-           .597        CAOH+           .640        FECL++          .167        ALF4-           .597
SO4--           .135        MGOH+           .652        FECL2+          .613        ALF5--          .151
NASO4-          .624        NH4+            .518        FECL4-          .580        ALF6---         .015

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)
H+ (ACT.)       .00   -8.840       MG++              .00     .000        FE(OH)3          .00      .000
OH-            5.80   -3.467       NACL           183.73   -2.503        FE(OH)4-         .00      .000
H4SIO4        35.52   -3.432       KCL              1.07   -4.844        FECL+            .00      .000
H3SIO4-       32.57   -3.465       NASO4-          37.82   -3.498        FECL2            .00      .000
H2SIO4--        .60   -5.196       KSO4-            2.03   -4.823        FECL++           .00      .000
NAH3SIO4      82.24   -3.157       CASO4             .00   -9.726        FECL2+           .00      .000
H3BO3         19.75   -3.496       MGSO4             .00     .000        FECL3            .00      .000
H2BO3-        27.27   -3.348       CACO3             .02   -6.739        FECL4-           .00      .000
H2CO3         30.18   -3.313       MGCO3             .00     .000        FESO4            .00      .000
HCO3-      15913.08    -.584       CAHCO3+           .00   -7.321        FESO4+           .00      .000
CO3--       3176.32   -1.276       MGHCO3+           .00     .000        AL+++            .00      .000
H2S             .00     .000       CAOH+             .00  -10.450        ALOH++           .00      .000
HS-             .00     .000       MGOH+             .00     .000        AL(OH)2+         .00      .000
S--             .00     .000       NH4OH             .00     .000        AL(OH)3          .00      .000
H2SO4           .00  -20.750       NH4+              .00     .000        AL(OH)4-         .00      .000
HSO4-           .00   -9.558       FE++              .00     .000        ALSO4+           .00      .000
SO4--        147.03   -2.815       FE+++             .00     .000        AL(SO4)2-        .00      .000
HF              .00   -7.538       FEOH+             .00     .000        ALF++            .00      .000
F-           144.01   -2.120       FE(OH)2           .00     .000        ALF2+            .00      .000
CL-         5127.60    -.840       FE(OH)3-          .00     .000        ALF3             .00      .000
NA+        11004.41    -.320       FE(OH)4--         .00     .000        ALF4-            .00      .000
K+           197.84   -2.296       FE(OH)++          .00     .000        ALF5--           .00      .000
CA++            .00   -7.714       FE(OH)2+          .00     .000        ALF6---          .00      .000

IONIC STRENGTH =    .55803      IONIC BALANCE :   CATIONS (MOL.EQ.) .48372070
                                                  ANIONS  (MOL.EQ.) .52340580
                                                  DIFFERENCE    (%)     -7.88

CHEMICAL GEOTHERMOMETERS DEGREES C                1000/REFERENCE TEMP. DEG.K =   2.81
FROM ACTIVITIES H4SIO4, NA+, AND K+:
QUARTZ        67.7 -FOURNIER & POTTER (1982)       FINAL DISCHARGE ENTHALPY (HO)      .0000 MJOUL/KG
CHALCEDONY    37.7 -ARNORSSON (1982)               STEAM FRACTION (YHL) =       .0000
NAK           64.3 -ARNORSSON (1982)

OXIDATION POTENTIAL (VOLTS) :      EH H2S= 99.999    EH CH4= 99.999    EH H2= 99.999    EH NH3= 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER
                 TEOR.    CALC.                        TEOR.    CALC.                        TEOR.    CALC.
ADULARIA       -17.963   99.999     ALBITE LOW       -17.161   99.999     ANALCIME         -13.705   99.999
ANHYDRITE       -5.366  -12.101     CALCITE           -9.154  -10.512     CHALCEDONY        -2.986   -3.432
MG-CHLORITE    -80.915   99.999     FLUORITE         -10.576  -13.157     GOETHITE          -5.310   99.999
LAUMONTITE     -28.085   99.999     MICROCLINE       -19.469   99.999     MAGNETITE        -31.034   99.999
CA-MONTMOR.    -90.260   99.999     K-MONTMOR.       -44.195   99.999     MG-MONTMOR.      -91.318   99.999
NA-MONTMOR.    -44.145   99.999     MUSCOVITE        -22.296   99.999     PREHNITE         -37.457   99.999
PYRRHOTITE    -108.558   99.999     PYRITE          -159.997   99.999     QUARTZ            -3.271   -3.432
WAIRAKITE      -25.222   99.999     WOLLASTONITE      11.389    5.833     ZOISITE          -36.414   99.999
```

890905-10

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-RECALCULATE AT SPRING TEMP W/CHARGE BALANCED CL-, CALCULATE PH



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        RHO=   .10240E+01     TDSPKG=    .00000E+00      TDSPL=    .00000E+00
        FEP=  -.70000E+00     UREDOX=
     TOLBT=   .00000E+00      TOLDL=    .00000E+00     TOLSAT=    .00000E+00
    ITERMX=  0
                  1     2     3     4     5     6     7     8     9    10
  IOPT1-10=       0     0     0     0     0     0     0     0     0     0
  IOPG1-10=       0     0     0     0     1     0     0     0     0     0
  IOPR1-10=       0     0     0    -2     0     0    -1     0     0     0
 IOPR11-20=       0     0     0     0     0     0     0     0     0     0
  IODB1-10=       0     0     0     0     0     0     0     0     0     0
     UEBAL= H+
    UACION= CL-
     NXMOD=  0
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   SWITCH WITH SPECIES=
   JFLAG=  3   CSP=    .10500E+05
DATA FILE MASTER SPECIES= K+
   SWITCH WITH SPECIES=
   JFLAG=  3   CSP=    .19800E+03
DATA FILE MASTER SPECIES= CL-
   SWITCH WITH SPECIES=
   JFLAG=  3   CSP=    .49712E+04
DATA FILE MASTER SPECIES= SO4--
   SWITCH WITH SPECIES=
   JFLAG=  3   CSP=    .16800E+03
DATA FILE MASTER SPECIES= HCO3-
   SWITCH WITH SPECIES=
   JFLAG=  3   CSP=    .10400E+05
DATA FILE MASTER SPECIES= CO3--
```

```
    SWITCH WITH SPECIES=
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    SWITCH WITH SPECIES=
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    SWITCH WITH SPECIES=
    JFLAG= 16   CSP=  -.94400E+01
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    SWITCH WITH SPECIES=
    JFLAG=  3   CSP=   .14600E-02
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    SWITCH WITH SPECIES=
    JFLAG= -1   CSP=   .00000E+00
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    SWITCH WITH SPECIES=
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ENDIT.

 --- THE INPUT FILE HAS BEEN SUCCESSFULY READ ---

 --- READING THE DATA1 FILE ---

 --- THE DATA1 FILE HAS BEEN SUCCESSFULLY READ ---
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 -RECALCULATE AT SPRING TEMP W/CHARGE BALANCED CL-, CALCULATE PH



 DATA FILE DATA0.3245R54
          1 ATM STEAM SATURATION CURVE DATA
 LAST MODIFIED 08AUG89   (DAOR)
```

```
  THE ACTIVITY COEFFICIENTS OF AQUEOUS SOLUTE SPECIES
AND THE ACTIVITY OF WATER ARE CALCULATED ACCORDING TO
B-DOT EQUATION PLUS OTHERS



TEMPERATURE=  83.00 DEGREES CELSIUS
PRESSURE=    1.0134 BARS


        47 ELEMENTS ARE IN THE DATA BASE
        80 ELEMENTS CAN BE LOADED INTO MEMORY
         9 ELEMENTS ARE ACTIVE IN THIS PROBLEM


       687 AQUEOUS SPECIES ARE IN THE DATA BASE
       128 AQUEOUS SPECIES WERE LOADED INTO MEMORY
       800 AQUEOUS SPECIES CAN BE LOADED INTO MEMORY
        49 AQUEOUS SPECIES ARE ACTIVE IN THIS PROBLEM

       639 AQUEOUS REACTIONS ARE IN THE DATA BASE
        80 AQUEOUS REACTIONS WERE LOADED INTO MEMORY
       719 AQUEOUS REACTIONS CAN BE LOADED INTO MEMORY


            714 MINERALS ARE IN THE DATA BASE
             38 MINERALS WERE LOADED INTO MEMORY
            850 MINERALS CAN BE LOADED INTO MEMORY
             37 MINERALS ARE ACTIVE IN THIS PROBLEM

             15 SOLID SOLUTIONS ARE IN THE DATA BASE
             50 SOLID SOLUTIONS CAN BE LOADED INTO MEMORY

             11 GASES ARE IN THE DATA BASE
              7 GASES WERE LOADED INTO MEMORY
             80 GASES CAN BE LOADED INTO MEMORY
              7 GASES ARE ACTIVE IN THIS PROBLEM



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     IOPT2  =  0 (AUTOMATIC BASIS SWITCHING SWITCH)
     IOPT3  =  0 (INTERFACING OUTPUT CONTROL SWITCH)
     IOPT4  =  0 (TURN-ON SOLID SOLUTIONS SWITCH)
     IOPT5  =  0 (NOT USED)
     IOPT6  =  0 (CONV. TEST CRITERIA SWITCH)
     IOPT7  =  0 (0/1 3245/POST-3245 PICKUP FILE)
     IOPT8  =  0 (NOT USED)
     IOPT9  =  0 (NOT USED)
     IOPT10 =  0 (NOT USED)
```

```
          IOPG1  =  0 (ACT. COEFF. CHOICE)
          IOPG2  =  0 (PH SCALE CONVENTION SWITCH)
          IOPG3  =  0 (IOPG1=3 - 0/1 UELAM= ON/ONPLUS)
          IOPG4  =  0 (IOPG1=3 OR 4 - F SWITCH - 0/1 DHOA/DHCA)
          IOPG5  =  1 (USE BDOT TERM INSTEAD OF CO2 POLYNOMIAL)
          IOPG6  =  0 (APPROX. OF J(X) FUNCTION)
          IOPG7  =  0 (NOT USED)
          IOPG8  =  0 (NOT USED)
          IOPG9  =  0 (NOT USED)
          IOPG10 =  0 (NOT USED)


               IOPR1  =  0 (LIST LOADING OF SPECIES)
               IOPR2  =  0 (LIST REACTIONS AND LOG K VALUES)
               IOPR3  =  0 (AQUEOUS SPECIES PRINT ORDER CONTROL)
               IOPR4  = -2 (AQUEOUS SPECIES PRINT CUT-OFF CONTROL)
               IOPR5  =  0 (MASS BALANCE PERCENTAGES PRINT CONTROL)
               IOPR6  =  0 (MEAN IONIC ACT COEFF PRINT CONTROL)
               IOPR7  = -1 (MINERAL AFFINITY PRINT CONTROL)
               IOPR8  =  0 (ION SIZE AND HYDR. NO. PRINT CONTROL)
               IOPR9  =  0 (PITZER COEFFICIENTS TABULATION)
               IOPR10 =  0 (PRINT CONCBS ARRAY)
               IOPR11 =  0 (NOT USED)
               IOPR12 =  0 (NOT USED)
               IOPR13 =  0 (NOT USED)
               IOPR14 =  0 (NOT USED)
               IOPR15 =  0 (NOT USED)
               IOPR16 =  0 (NOT USED)
               IOPR17 =  0 (NOT USED)
               IOPR18 =  0 (NOT USED)
               IOPR19 =  0 (NOT USED)
               IOPR20 =  0 (NOT USED)


                    IODB1  =  0 (PRINT INFO. MESSAGES SWITCH)
                    IODB2  =  0 (PRINT PRE-NEWTON-RAPHSON OPTIMIZATIONS SWITCH)
                    IODB3  =  0 (REQUEST ITERATION VARIABLES TO KILL)
                    IODB4  =  0 (PRINT NEWTON-RAPHSON ITERATIONS SWITCH)
                    IODB5  =  0 (LIST STOICHIOMETRIC EQUIVALENCES)
                    IODB6  =  0 (CONTROLS IODB5 LEVEL OF DETAIL)
                    IODB7  =  0 (WRITE REACTIONS ON FILE RLIST SWITCH)
                    IODB8  =  0 (NOT USED)
                    IODB9  =  0 (NOT USED)
                    IODB10 =  0 (NOT USED)


     THE DEFAULT REDOX STATE IS CONSTRAINED BY LOG FO2 =        -.7000 (LOG BARS)


               SOLUTION DENSITY =  1.02400 G/ML

               TOTAL DISSOLVED SALTS =         .00 MG/KG SOLUTION
               TOTAL DISSOLVED SALTS =         .00 MG/L
```

```
           TOLBT  =   .10000E-05 (CONVERGENCE TOLERANCE ON RESIDUAL FUNCTIONS)
           TOLDL  =   .10000E-05 (CONVERGENCE TOLERANCE ON CORRECTION TERMS)
           TOLSAT =   .50000E+00 (PHASE SATURATION TOLERANCE, DOES NOT AFFECT
                                  CONVERGENCE)


                                 ----- INPUT CONSTRAINTS -----

      SPECIES           CSP        JFLAG  TYPE OF INPUT      CONTROLLING PHASE

    NA+                           .10500E+05    3   TOT CONC, MG/KG
    K+                            .19800E+03    3   TOT CONC, MG/KG
    CL-                           .49712E+04    3   TOT CONC, MG/KG
    SO4--                         .16800E+03    3   TOT CONC, MG/KG
    HCO3-                         .10400E+05    3   TOT CONC, MG/KG
    CO3--                         .45000E+04    3   TOT CONC, MG/KG
    SIO2(AQ)                      .85000E+02    3   TOT CONC, MG/KG
    H+                           -.94400E+01   16   LOG ACTIVITY
    F-                            .14600E-02    3   TOT CONC, MG/KG

 THE ION THAT DEFINES EQUIV. STOICH. IONIC STRENGTH
   IS CL-

 ELECTRICAL BALANCE WILL BE ACHIEVED BY ADJUSTING
   THE CONCENTRATION OF H+


                     --- INACTIVE AQUEOUS SPECIES ---

  (O-PHTH)--                 KCO3-


                              --- MODIFIED INPUT CONSTRAINTS ---

      SPECIES           CSP        JFLAG  TYPE OF INPUT      CONTROLLING PHASE

    CL-                           .14022E+00    0   TOT CONC, MOLAL
    F-                            .76849E-07    0   TOT CONC, MOLAL
    H+                           -.94400E+01   16   LOG ACTIVITY
    HCO3-                         .17044E+00    0   TOT CONC, MOLAL
    K+                            .50642E-02    0   TOT CONC, MOLAL
    NA+                           .45672E+00    0   TOT CONC, MOLAL
    SIO2(AQ)                      .14147E-02    0   TOT CONC, MOLAL
    SO4--                         .17490E-02    0   TOT CONC, MOLAL
    CH4(AQ)                       .00000E+00   30   ELIMINATED SPECIES
    CO2(AQ)                       .00000E+00   30   ELIMINATED SPECIES
    O2(AQ)                                          NOT PRESENT IN THE MODEL
    H2(AQ)                                          NOT PRESENT IN THE MODEL
    CH3COO-                       .00000E+00   30   ELIMINATED SPECIES
    CLO4-                         .00000E+00   30   ELIMINATED SPECIES
    CO3--                         .74989E-01    0   TOT CONC, MOLAL
    HS-                           .00000E+00   30   ELIMINATED SPECIES
```

```
  (O-PHTH)--                          .00000E+00   30   ELIMINATED SPECIES
   OH-                                .00000E+00   30   ELIMINATED SPECIES


 --- ARRSET - OPTIMIZATION ENDED WITHIN REQUESTED LIMITS ---

 ITER=    0, DELMAX=  0.00000E+00 (UNRELAXED)
         DEL(                   )=  0.00000E+00, DELFNC =  0.00000E+00
        BETA(CONC     SIO2(AQ))= -4.06102E-02, BETFNC =  0.00000E+00
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  0.00000E+00, UBBIG= NONE
         BNEG= -4.06102E-02, UBNEG= SIO2(AQ)
        BGAMX=  4.68515E-02, UBGAMX= H4(H2SIO4)4----
          BXI= -5.48901E-02, BXISTQ= -8.48144E-04
 ITER=    1, DELMAX=  1.32416E+00 (UNRELAXED)
         DEL(CONC     H+        )=  1.32416E+00, DELFNC =  0.00000E+00
        BETA(CONC     SIO2(AQ))=  1.45862E+00, BETFNC = -3.49176E+01
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  1.45862E+00, UBBIG= SIO2(AQ)
         BNEG= -8.51355E-04, UBNEG= SO4--
        BGAMX=  5.63945E-03, UBGAMX= H4(H2SIO4)4----
          BXI=  6.82778E-03, BXISTQ=  8.34515E-04
 ITER=    2, DELMAX=  2.28966E-01 (UNRELAXED)
         DEL(CONC     SIO2(AQ))= -1.14483E-01, DELFNC =  8.27086E-01
        BETA(CONC     SIO2(AQ))=  8.30741E-01, BETFNC =  4.30462E-01
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  8.30741E-01, UBBIG= SIO2(AQ)
         BNEG= -2.98099E-04, UBNEG= SO4--
        BGAMX=  7.50940E-04, UBGAMX= H4(H2SIO4)4----
          BXI= -9.05527E-04, BXISTQ=  9.37182E-06
 ITER=    3, DELMAX=  1.83288E-01 (UNRELAXED)
         DEL(CONC     SIO2(AQ))= -1.83288E-01, DELFNC =  1.99498E-01
        BETA(CONC     SIO2(AQ))=  1.65063E-01, BETFNC =  8.01307E-01
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  1.65063E-01, UBBIG= SIO2(AQ)
         BNEG=  0.00000E+00, UBNEG= NONE
        BGAMX=  8.40356E-04, UBGAMX= H4(H2SIO4)4----
          BXI= -1.01335E-03, BXISTQ=  7.41817E-06
 ITER=    4, DELMAX=  6.13012E-02 (UNRELAXED)
         DEL(CONC     SIO2(AQ))= -6.13012E-02, DELFNC =  6.65547E-01
        BETA(CONC     SIO2(AQ))=  1.11614E-02, BETFNC =  9.32381E-01
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  1.11614E-02, UBBIG= SIO2(AQ)
         BNEG=  0.00000E+00, UBNEG= NONE
        BGAMX=  5.86549E-05, UBGAMX= H4(H2SIO4)4----
          BXI= -7.07650E-05, BXISTQ= -2.28177E-06
 ITER=    5, DELMAX=  4.79123E-03 (UNRELAXED)
         DEL(CONC     SIO2(AQ))= -4.79123E-03, DELFNC =  9.21841E-01
        BETA(CONC     SIO2(AQ))=  6.13732E-05, BETFNC =  9.94501E-01
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  6.13732E-05, UBBIG= SIO2(AQ)
         BNEG=  0.00000E+00, UBNEG= NONE
        BGAMX=  1.56406E-06, UBGAMX= H4(H2SIO4)4----
```

```
ITER=   6, DELMAX=  2.66553E-05 (UNRELAXED)
         DEL(CONC     SIO2(AQ))= -2.66553E-05, DELFNC =  9.94437E-01
        BETA(CONC     SO4--    )=  3.71501E-09, BETFNC =  9.99939E-01
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  3.71501E-09, UBBIG= SO4--
         BNEG=  0.00000E+00, UBNEG= NONE
        BGAMX=  2.18596E-08, UBGAMX= H4(H2SIO4)4----
          BXI= -2.63738E-08, BXISTQ= -4.50283E-09
ITER=   7, DELMAX=  1.58510E-09 (UNRELAXED)
         DEL(CONC     SO4--    )= -1.58510E-09, DELFNC =  9.99941E-01
        BETA(CONC     SO4--    )=  4.12281E-11, BETFNC =  9.88902E-01
        NO. OF UNDER-RELAXATION CYCLES=  21
         BBIG=  4.12281E-11, UBBIG= SO4--
         BNEG= -1.14263E-12, UBNEG= SIO2(AQ)
        BGAMX=  2.42597E-10, UBGAMX= H4(H2SIO4)4----
          BXI= -2.92694E-10, BXISTQ= -6.31154E-11


HYBRID NEWTON-RAPHSON ITERATION CONVERGED IN   7 STEPS



                   ----- SUMMARY OF THE AQUEOUS PHASE -----


             ----- ELEMENTAL COMPOSITION OF THE AQUEOUS PHASE -----


          ELEMENT       MG/L            MG/KG            MOLES/KG

            O       921610.0804     900009.8441      .5625272474E+02
            CL        5090.5392       4971.2297      .1402202842E+00
            F            .0015           .0015       .7684858037E-07
            H       114753.9124     112064.3676      .1111859982E+03
            C         3018.6396       2947.8902      .2454325365E+00
            K          202.7520        198.0000      .5064159040E-02
            NA       10752.0005      10500.0005      .4567249041E+00
            SI          40.6855         39.7320      .1414679110E-02
            S           57.4171         56.0714      .1748950713E-02

             ----- ELEMENTAL COMPOSITION AS STRICT BASIS SPECIES -----


          SPECIES      MG/L            MG/KG            MOLES/KG

            H2O    1037725.7847    1013404.0867      .5625272474E+02
            CL-       5090.5392       4971.2297      .1402202842E+00
            F-           .0015           .0015       .7684858037E-07
            H+      114753.9124     112064.3676      .1111859982E+03
            HCO3-    15334.9956      14975.5816      .2454325365E+00
            K+         202.7520        198.0000      .5064159040E-02
            NA+      10752.0005      10500.0005      .4567249041E+00
            SIO2(A      87.0400         85.0000      .1414679110E-02
            SO4--      172.0320        168.0000      .1748950713E-02
```

```
        --- EQUIVALENT COMPOSITION OF THE AQUEOUS PHASE (CTE BALANCES) ---

          ORIGINAL BASIS                                  EXISTING BASIS

    SPECIES                 MOLES/KG H2O   SPECIES              MOLES/KG H2O

      H2O                 .5602775922E+02     H2O              .5602775922E+02
      CL-                 .1402202842E+00     CL-              .1402202842E+00
      F-                  .7684858037E-07     F-               .7684858037E-07
      H+                  .1111859982E+03     H+               .1111859982E+03
      HCO3-               .1704440312E+00     HCO3-            .1704440312E+00
      K+                  .5064159040E-02     K+               .5064159040E-02
      NA+                 .4567249041E+00     NA+              .4567249041E+00
      SIO2(AQ)            .1414679110E-02     SIO2(AQ)         .1414679110E-02
      SO4--               .1748950713E-02     SO4--            .1748950713E-02
      CO3--               .7498850533E-01     CO3--            .7498850533E-01

    SINGLE ION ACTIVITIES AND ACTIVITY COEFFICIENTS ARE HERE DEFINED
    WITH RESPECT TO THE MODIFIED NBS PH SCALE


                                          PH           EH           PE

      MODIFIED NBS PH SCALE             7.9916        .6441     9.1152E+00
      RATIONAL PH SCALE                 7.8657        .6530     9.2411E+00

    PHCL =       9.0491


                          ACTIVITY OF WATER =      .99535
                      LOG ACTIVITY OF WATER =    -.00202

                 TRUE OSMOTIC COEFFICIENT=      .31166
        STOICHIOMETRIC OSMOTIC COEFFICIENT=      .27895

                 SUM OF TRUE MOLALITIES=      .8299994683542
        SUM OF STOICHIOMETRIC MOLALITIES=      .9273140017661

                 TRUE IONIC STRENGTH=      .5136538009774
        STOICHIOMETRIC IONIC STRENGTH=      .5767218518702

      EQUIV. STOICH. IONIC STRENGTH (CL-    ) =      .1402202842108

         ----- ELECTRICAL BALANCE TOTALS -----


                                          EQUIV/KG

                    SIGMA(MZ) CATIONS =      .4411359186E+00
                    SIGMA(MZ) ANIONS  =     -.4411359186E+00
```

```
                          MEAN CHARGE =      .4411359186E+00
                     CHARGE IMBALANCE =     -.4785061236E-12

          TOTAL CHARGE = SIGMA(MZ) CATIONS + ABS ( SIGMA(MZ) ANIONS )
          MEAN CHARGE = 1/2 TOTAL CHARGE


          THE ELECTRICAL IMBALANCE IS

                            .00 PER CENT OF THE TOTAL CHARGE
                            .00 PER CENT OF THE MEAN CHARGE
                            .00 PER CENT OF SIGMA(MZ) CATIONS
                            .00 PER CENT OF ABS ( SIGMA(MZ) ANIONS )


         ----- ELECTRICAL BALANCING ON H+     -----

              LOG ACTIVITY

        INPUT       -9.4400
        FINAL       -7.9916
        ADJ          1.4484


                    ----- ACTIVITY RATIOS OF IONS -----

         LOG ( ACT(CL-          ) X ACT(H+)XX 1 ) =      -9.0491
         LOG ( ACT(F-           ) X ACT(H+)XX 1 ) =     -15.3137
         LOG ( ACT(HCO3-        ) X ACT(H+)XX 1 ) =      -8.9628
         LOG ( ACT(K+           ) / ACT(H+)XX 1 ) =       5.4592
         LOG ( ACT(NA+          ) / ACT(H+)XX 1 ) =       7.4257
         LOG ( ACT(SIO2(AQ)     )               ) =      -2.9199
         LOG ( ACT(SO4--        ) X ACT(H+)XX 2 ) =     -19.6864
         LOG ( ACT(CH4(AQ)      )               ) =    -120.2729
         LOG ( ACT(CO2(AQ)      )               ) =      -2.5738
         LOG ( ACT(CH3COO-      ) X ACT(H+)XX 1 ) =    -132.0529
         LOG ( ACT(CLO4-        ) X ACT(H+)XX 1 ) =     -30.8549
         LOG ( ACT(CO3--        ) X ACT(H+)XX 2 ) =     -17.8594
         LOG ( ACT(HS-          ) X ACT(H+)XX 1 ) =    -125.2554
         LOG ( ACT(OH-          ) X ACT(H+)XX 1 ) =     -12.5467


         ----- DISTRIBUTION OF AQUEOUS SPECIES -----

              (SPECIES WITH CONCENTRATIONS .LT. 1.E-12 ARE NOT LISTED)

     SPECIES          MOLAL CONC   LOG CONC     LOG G    ACTIVITY     LOG ACT

   NA+                 .4361E+00    -.3604     -.2055   .2717E+00     -.5659
   HCO3-               .1534E+00    -.8142     -.1571   .1068E+00     -.9712
   CL-                 .1384E+00    -.8590     -.1985   .8759E-01    -1.0575
   CO3--               .7133E-01   -1.1467     -.7295   .1330E-01    -1.8763
   NAHCO3              .1438E-01   -1.8423      .0000   .1438E-01    -1.8423
   K+                  .5041E-02   -2.2975     -.2348   .2935E-02    -2.5324
   NACO3-              .3659E-02   -2.4367     -.1692   .2478E-02    -2.6059
```

```
   CO2(AQ)                     .2668E-02    -2.5738       .0000     .2668E-02     -2.5738
   NACL                        .1855E-02    -2.7317       .0000     .1855E-02     -2.7317
   SO4--                       .1188E-02    -2.9252     -.7780      .1980E-03     -3.7033
   SIO2(AQ)                    .1144E-02    -2.9416       .0217     .1203E-02     -2.9199
   NASO4-                      .5512E-03    -3.2587     -.1692      .3734E-03     -3.4278
   NAH3SIO4                    .1813E-03    -3.7417       .0000     .1813E-03     -3.7417
   H3SIO4-                     .8936E-04    -4.0489     -.1692      .6053E-04     -4.2180
   OH-                         .4244E-04    -4.3722     -.1829      .2785E-04     -4.5551
   KCL                         .1371E-04    -4.8629       .0000     .1371E-04     -4.8629
   KSO4-                       .9884E-05    -5.0051     -.1692      .6695E-05     -5.1743
   NAOH                        .4567E-05    -5.3404       .0000     .4567E-05     -5.3404
   F-                          .7256E-07    -7.1393     -.1829      .4762E-07     -7.3222
   H2SIO4--                    .5511E-07    -7.2588     -.7780      .9187E-08     -8.0368
   KOH                         .2596E-07    -7.5858       .0000     .2596E-07     -7.5858
   H+                          .1362E-07    -7.8657     -.1258      .1020E-07     -7.9916
   NAF                         .4283E-08    -8.3682       .0000     .4283E-08     -8.3682
   H6(H2SIO4)4--               .4097E-08    -8.3875     -.7780      .6831E-09     -9.1655
   HSO4-                       .1677E-08    -8.7756     -.1692      .1136E-08     -8.9447
   HCL                         .1987E-09    -9.7017       .0000     .1987E-09     -9.7017
   HF                          .2375E-11   -11.6244       .0000     .2375E-11    -11.6244

           ----- MAJOR AQUEOUS SPECIES CONTRIBUTING TO MASS BALANCES -----

  AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF CL-

     SPECIES              MOLAL CONC    PER CENT

   CL-                      .1384E+00     98.67
   NACL                     .1855E-02      1.32
 - - - - - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                  99.99

  AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF F-

     SPECIES              MOLAL CONC    PER CENT

   F-                       .7256E-07     94.42
   NAF                      .4283E-08      5.57
 - - - - - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                 100.00

  AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF HCO3-

     SPECIES              MOLAL CONC    PER CENT

   HCO3-                    .1534E+00     90.00
   NAHCO3                   .1438E-01      8.44
   CO2(AQ)                  .2668E-02      1.57
 - - - - - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                 100.00
```

```
 AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF K+

     SPECIES              MOLAL CONC    PER CENT

   K+                      .5041E-02     99.53
 - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                 99.53

 AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF NA+

     SPECIES              MOLAL CONC    PER CENT

   NA+                     .4361E+00     95.48
   NAHCO3                  .1438E-01      3.15
   NACO3-                  .3659E-02       .80
 - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                 99.43

 AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF SIO2(AQ)

     SPECIES              MOLAL CONC    PER CENT

   SIO2(AQ)                .1144E-02     80.87  x 85 = 69 ppm
   NAH3SIO4                .1813E-03     12.81
   H3SIO4-                 .8936E-04      6.32
 - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                 99.99

 AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF SO4--

     SPECIES              MOLAL CONC    PER CENT

   SO4--                   .1188E-02     67.92
   NASO4-                  .5512E-03     31.52
 - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                 99.43

 AQUEOUS SPECIES ACCOUNTING FOR 99% OR MORE OF CO3--

     SPECIES              MOLAL CONC    PER CENT

   CO3--                   .7133E-01     95.12
   NACO3-                  .3659E-02      4.88
 - - - - - - - - - - - - - - - - - - - - - - -
   TOTAL                                100.00


          ----- SUMMARY OF AQUEOUS REDOX REACTIONS -----
```

```
      COUPLE            EH, VOLTS      PE-         LOG FO2      AH, KCAL

   DEFAULT                 .644     .9115E+01       -.700        14.855
   CH4(AQ) /HCO3-          .644     .9115E+01       -.700        14.855
   CH3COO- /HCO3-          .644     .9115E+01       -.700        14.855
   CLO4-   /CL-            .644     .9115E+01       -.700        14.855
   HS-     /SO4--          .644     .9115E+01       -.700        14.855

          ----- SUMMARY OF AQUEOUS NON-EQUILIBRIUM NON-REDOX REACTIONS -----

      COUPLE        AFFINITY, KCAL

      CO3-- /HCO3-      -2.174


     0 APPROX.  SATURATED PURE MINERALS
     0 APPROX.  SATURATED END-MEMBERS OF SPECIFIED SOLID SOLUTIONS
     0 SATURATED END-MEMBERS OF HYPOTHETICAL SOLID SOLUTIONS


     0 SUPERSATURATED PURE MINERALS
     0 SUPERSATD.  END-MEMBERS OF SPECIFIED SOLID SOLUTIONS
     0 SUPERSATD.  HYPOTHETICAL SOLID SOLUTION PHASES



                    ----- SUMMARY OF GASES -----


       GAS                        FUGACITY    LOG FUGACITY

    CH4(G)                       .475393-117   -117.32295
    CO2(G)                       .192438E+00      -.71571
    H2(G)                        .829016E-33    -33.08144
    H2S(G)                       .578528-117   -117.23768
    O2(G)                        .199526E+00      -.70000
    S2(G)                        .794642-189   -189.09983
    STEAM                        .519177E+00      -.28468

  ----- END OF OUTPUT -----
  ----- PICKUP FILE SUCCESSFULLY WRITTEN -----

  --- READING THE INPUT FILE ---

  --- NO FURTHER INPUT FOUND ---

         START TIME = 16:56      05SEP89
           END TIME = 16:57      05SEP89

         USER TIME =  61021.000
          CPU TIME =  61021.000
```

GeothermEx, Inc.

SUITE 201
5221 CENTRAL AVENUE
RICHMOND, CALIFORNIA 94804-5829

(415) 527-9876
CABLE ADDRESS GEOTHERMEX
TELEX 709152 STEAM UD
FAX (415) 527-8164

APPENDIX B

Hydrochemical Model of Lake Magadi Basin

GeothermEx, Inc.
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5221 CENTRAL AVENUE
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(415) 527-9876
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APPENDIX B

HYDROCHEMICAL MODEL OF LAKE MAGADI BASIN

The hydrochemistry of the Magadi basin has been investigated in detail by several workers including Baker (1958); Eugster (1970); and Jones *et al*. (1977). Kamondo (1988) reported several analyses of the Magadi hot springs, and the water chemistry also has been reviewed in several unpublished studies. The most comprehensive work, by Jones *et al*. (1977), divided the area waters into 11 separate but interrelated groups by occurrence and chemistry (figure B1):

1) Rim streams: cool, dilute surface water.

2) The Ewaso Ngiro River: cool, mildly saline surface water.

3) Runoff within the Rift Valley: warm to hot, dilute to saline groundwater.

4) Dilute Rift Valley groundwater: cool to hot, dilute to mildly saline groundwater.

5) Seepage in shallow lake sediments: cool to warm, mildly saline to saline groundwater.

6) Deep brines interstitial to older lake sediments: hot, saline groundwater.

7) Brines interstitial to trona deposits in the lake bed: warm, hypersaline groundwater.

8) Lake brines: cool to warm hypersaline surface water.

9) Lagoon brines and brine of Little Magadi Lake: cool to warm, saline to hypersaline surface water.

10) Warm springs at the southern end of Lake Magadi: warm, saline springs.

11) Hot springs at the northern end of Lake Magadi: hot, saline springs.

Dissolved solids in all of these waters are dominated principally by Na and HCO_3, but there is a wide range in total salinity. The dilute surface waters and groundwaters have 100 to 1,000 ppm total dissolved solids (TDS). At the other extreme, brines in Lake Magadi carry up to 300,000 ppm. According to the Jones *et al.* (1977) model, all waters in the basin system develop from the dilute surface water and groundwater by evaporative concentration. This includes at least some cyclic evaporation to dryness and re-dissolution. Some recirculation and mixing also occurs. Ion ratios change as evaporation proceeds, because mineral precipitation removes certain chemical species. Major ions such as Na, HCO_3+CO_3 and Cl are little affected until the last precipitation occurs, when the lake brines become saturated with Na and HCO_3 and deposits trona, a sodium carbonate-bicarbonate mineral.

Figures B1 and B2 illustrate the circulation system according to Jones *et al.* (1977). The lagoon and lake brine samples have TDS of 120,000 to 300,000 ppm, and are fed directly by evaporated inflow from the hot and warm springs (TDS 10,000 to 38,000 ppm). Samples from spring outflow channels have up to 45,000 ppm, probably reflecting evaporation in process during flow into the lake. Ion ratios in the spring water, spring outflow, lagoon and lake brines are all very similar, except in the brines affected by trona formation. This confirms the visual evidence that the lake waters form by evaporation of the spring waters.

Figure B1 further illustrates Jones *et al.'s* conclusions that:

(a) the northern hot springs (to 85°C; TDS 26,000 to 30,000 ppm) are a mixture of deep brines found interstitially in the older lake sediments with dilute groundwater; and

(b) the southern warm springs (to 45°C; TDS 10,000 to 38,000 ppm) are a more-complex mixture of lake brines, brines interstitial to trona, dilute groundwater, and perhaps some seepage in the shallow lake sediments.

Their reasons for postulating two distinct spring systems probably are related to the higher temperature and flow rates of the northern springs versus the lower temperature and wider range of salinities at the southern springs.

Borehole data show that brines beneath the lake are stratified into a more-saline upper layer, and a less-saline lower layer. "Deep" brines found interstitially within the older lake sediments are only half as saline (100,000 to 125,000 ppm) as the shallower lake brines and the brines interstitial to trona (250,000 ppm and up). Apparently, Jones *et al.* (1977) correlated the hotter, less-saline and higher-flow-rate northern springs with the "deep" brines, and the southern springs with the shallow brines. (The "deep" brines actually are encountered locally at depths as shallow as 50 m).

The model of Jones *et al.* is reasonable; however, the spring origins are not well-established, because the depth distribution, composition and temperature of the shallow and deep brines is not well defined. If the local geothermal gradient is 60°C/km (twice the world-wide average, but typical of active rift systems), and if local mean annual air temperature is about 28°C, then the northern spring water must circulate to about 1 km to reach the observed temperatures (discounting possible cooling caused by shallow mixing). Conductive cooling and/or cooling by mixing would require circulation to much greater than 1 km depth. This is reasonable, given the extensive faulting in the Rift Valley, but cannot be proven on the basis of presently available data.

In summary, then, the Jones *et al.* (1977) model (figure B2) interprets the warm and hot springs waters to be the pre-evaporation equivalents of the lake brines and waters trapped in sediments beneath the lake. The hotter and less-saline spring waters come from greater depth than the shallower springs. This is reasonable, but not necessarily complete. The depth of circulation, the temperature at that depth, the possible contribution from thermal systems outside of the Magadi basin, and the amount of inflow of cool water from the escarpment to the west, are not addressed and, indeed, cannot be resolved at present, given the complexity of the fluid system.

This points up the necessity for drilling exploratory holes in the Lake Magadi basin.

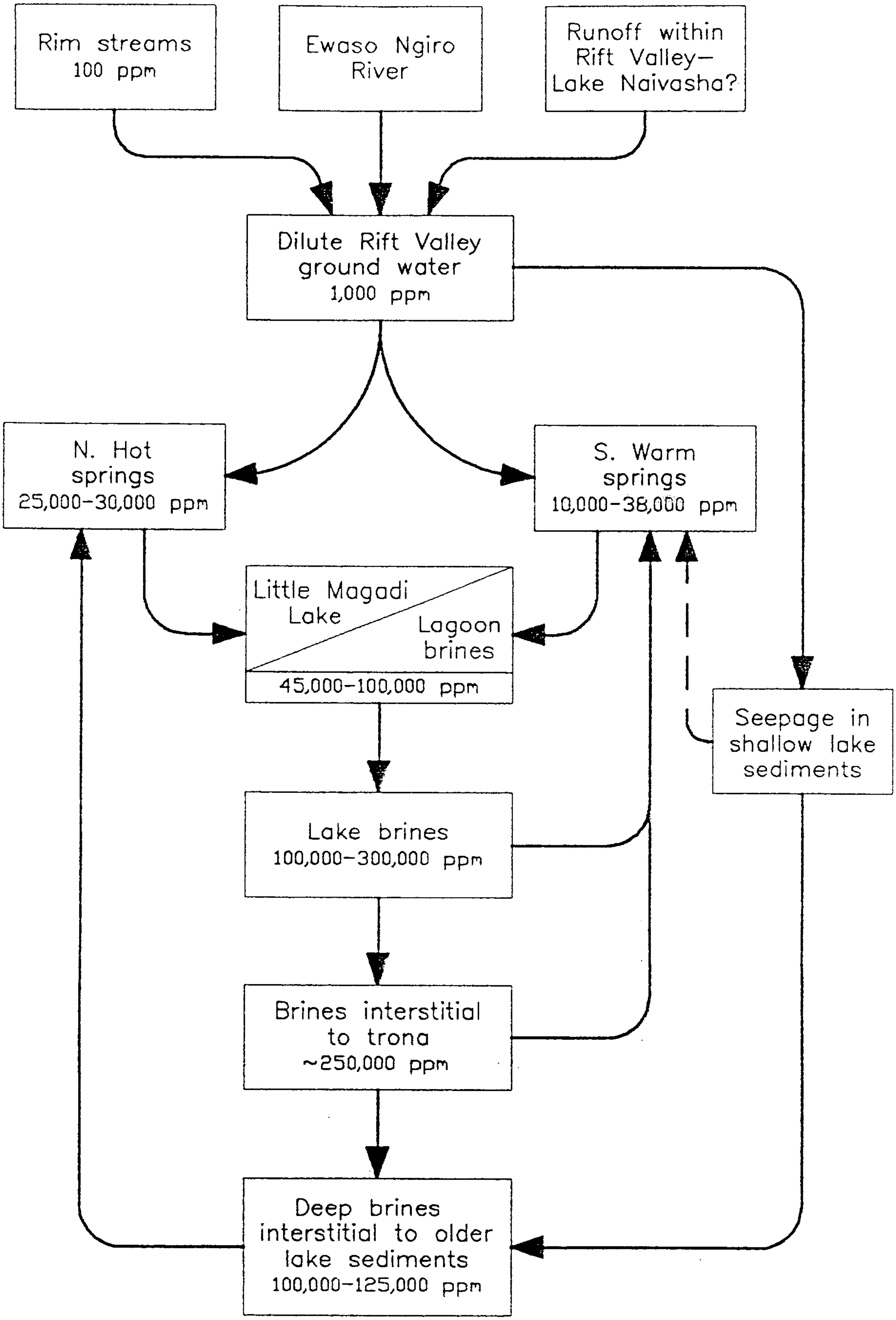


Figure B1: Schematic diagram illustrating the circulation system in the Magadi basin.

MAGADI2/110789/K1400

THE BEN HOLT CO.
201 South Lake Avenue, Pasadena, California 91101
(213) 684-2541 / (818) 795-6866
Fax: (818) 584-9210
Engineers & Constructors

June 21, 1990

Mr. David N. Anderson
Executive Director
National Geothermal Association
P.O. Box 1350
Davis, California 95617-1350

Subject: Lake Magadi, Kenya Pre-feasibility Study
Holt Job No. 10084

Dear Dave:

Enclosed are three copies of the final phase of the Lake Magadi, Kenya Pre-feasibility Study. You will see that the proposed installation, is not only profitable in its own right, but also has other important advantages. The first advantage is the prospect of its becoming a major development which could be tied into the Kenya power grid. The second is that it will provide a practical demonstration of the viability of small off-grid power plants developed to serve isolated communities with a reliable source of electricity.

The first phase was carried out by GeothermEx, Inc., whose report you already have. The final phase is a joint effort of The Ben Holt Co. and Karen Venable.

We evaluated three power cycle options for producing 2.5 MWe net from a 140°C. hydrothermal resource to be located near Little Magadi. These options are:

- Water-cooled binary
- Air-cooled binary
- Single stage steam flash plant

The economics favor the water-cooled binary and the steam flash cycle. The final choice will likely depend upon the availability and cost of cooling water. The capital cost for each case is about the same: $7,150,000 (1989 basis).

O & M costs slightly favor the steam flash cycle ($243,000 vs $254,000) and this case was used for the financial analysis.

The financial analysis is based upon U.S. experience and assumes that the project would be privately financed.

Reasonable escalation of power sales, power price and O & M costs are included in the financial analysis, which projects a 15% unleveraged internal rate of return. Based on 75% borrowed funds and 25% equity, the internal rate of return increases to 32%.

The Magadi Soda Company has an immediate need for replacing one of their existing diesel generators. They are also interested in decreasing their reliance on imported fuel oil. In addition to this, the Government of Kenya has expressed interest in expanding Magadi's soda ash facility to increase foreign exchange earnings. They have also discussed the possibility of having Magadi become connected to the national grid system. While Magadi Soda officials believe this expansion plan is not economic, if approved this could mean additional capacity requirements in excess of 20MWe.

The size of the resource is unknown. Preliminary exploratory work is encouraging. However, further substantial resource exploration will be required to determine the exact nature of the resource. Based on this we expect the economics presented in this report would become even more attractive.

Finally, given the high costs of diesel fuel, Kenya's foreign exchange requirements and increasing awareness over environmental concerns, we believe this project represents a significant business opportunity and warrants a major feasibility study to determine the nature and extent of the resource.

We very much appreciate the financial aid provided by the D.O.E. to support this report.

Sincerely,

Ben Holt

Ben Holt

BH:bc
Enclosures

cc: Ms. Karen Venable
Mr. James Koenig, GeothermEx, Inc.
Mr. Ralph Burr, D.O.E.
Mr. Mike Jones, Oak Ridge U.

NATIONAL GEOTHERMAL ASSOCIATION

GEOTHERMAL POWER PLANT OPTIONS
LAKE MAGADI, KENYA

BY

THE BEN HOLT CO.

PASADENA, CALIFORNIA

JUNE, 1990

HOLT REFERENCE NO. 10084

TABLE OF CONTENTS

INTRODUCTION

The National Geothermal Association (NGA) with funding provided by the Department of Energy authorized GeothermEx, Inc., The Ben Holt Co. and Karen Venable, Consultant to Mission Energy Company, to study the feasibility of generating electricity to supply the Magadi Soda Company and the adjacent community from a prospective geothermal resource near Lake Magadi, Kenya.

The first phase of the work has been carried out by GeothermEx, Inc. in a report entitled "Probable Subsurface Temperature at Lake Magadi, Kenya as indicated by Hot Springs Geochemistry and the Potential for Development of Geothermal Electric Power" dated November, 1989.

The GeothermEx report provided the basis for the final phase of the work which is to:

1. Analyze the existing power generation facilities and the future power demand at the Magadi Soda Company and determine the optimum type of geothermal power generation facility to install. This will require some knowledge of the results of the exploration study.

2. Prepare a financial analysis comparing the current cost of generating power from diesel engines with the projected cost of geothermal power.

This final phase was prepared jointly by The Ben Holt Co. and Karen Venable.

This report is based upon the following data sources:

- Mr. Holt's and Ms. Venable's visit to Lake Magadi in November 1988.
- Mr. Holt's discussion with Mr. Greg Stewart on Mr. Stewart's visit to the U.S. in June of 1989.
- The GeothermEx report.
- Memorandum from Mike Jones, ORAU, to Ben Holt dated April 4, 1990.

BACKGROUND

The Lake Magadi Soda Company is located on the shores of Lake Magadi about 100 kilometers southwest of Nairobi. About 200,000 tons of soda ash are produced from Lake Magadi brine and shipped by rail to Mombasa for export. The plant is not connected to the Kenyan power grid and instead power requirements are met by diesel engine generator sets. The power plant supplies the needs of the plant itself as well as the adjacent community of about 3,500 residents.

The Government of Kenya has approached the Magadi Soda Company about the possibility of expanding its soda ash facility. They have also discussed the possibility of connecting Magadi to the national grid system. Magadi has stated that world wide markets for soda ash are limited and that they are not interested in this possible expansion plan. Other logistical problems such as expansion of the port facility and railway improvements are of concern to Magadi officials. Nevertheless, Kenya is trying to find ways to increase their foreign exchange earnings and still have the proposal under consideration. This means that geothermal power development is of considerable interest to both Magadi Soda Company officials and the Government of Kenya.

Numerous hot springs are located on the shores of Lake Magadi as well as the northern end of Little Magadi, a distance of about 12 miles from the Soda Works. The GeothermEx report finds that "it is likely that the regionally highest temperatures are found beneath the Little Magadi area" and further that "it is distinctly possible that a fluid system suitable for power generation by the binary cycle method can be found at relatively shallow depth".

Accordingly, for the purpose of this study we have chosen to locate the geothermal power plant in the Little Magadi area.

Hot spring chemistry indicates that the brine temperatures in this area may be expected to range from 100°C to 140°C. We have chosen the higher temperature as a basis for preliminary design since this temperature is near the lower limit of economic generation from hot water resources.

Present (1989) peak demand for electricity is 2.5 MWe. Moderate increases (3% to 5% per year) are projected in the near future. For the purpose of this study, the design and cost estimates are based upon producing 2.5 MWe net, which will be sufficient to supply local needs and will permit shutting down the existing facilities and maintaining them only for standby use.

POWER CYCLE SELECTION

We selected three power cycles for study, each possessing important advantages and disadvantages.

Case I is a water cooled binary plant. In this case condensation of the working fluid exhaust from the power turbine is accomplished utilizing a conventional mechanical draft cooling tower. The advantage of this case is the lowest possible condensing temperature and hence maximum cycle efficiency. The disadvantage is the requirement of fresh make-up water to the cooling tower in a water short area.

Case II is an air cooled binary. Cycle efficiency is less because of less favorable condensing temperatures, but no consumptive use of fresh water is required.

Case III is a single flash steam cycle employing water cooling. The condensed steam from the turbine is used as cooling tower make-up, eliminating the need of an outside source of cooling water.

In each of the cases, a sufficiently large generator is provided to supply the plant parasitic loads (including well pumps) as well as exporting 2.5 MWe.

DESIGN BASIS

The design basis for each case is summarized as follows:

- Location: Little Magadi
- Net Power: 2.5 MWe
- Resource Temperature: 140°C (284°F)

Case I

- Power Cycle: Binary
- Water cooled
- Wet Bulb Temperature (design): 65°F

Case II

- Power Cycle: Binary
- Air Cooled
- Dry Bulb Temperature (design): 87°F

Case III

- Power Cycle: Single Steam Flash
- Water Cooled
- Wet Bulb Temperature (design): 65°F

DESCRIPTION OF PLANTS

Simplified process flow diagrams for each of the three cases are shown on Drawings No. 60324-D-3201, 3202 and 3203.

In all cases brine is pumped from shallow wells (estimated depth 600 feet) with vertical shaft driven centrifugal pumps. Surface disposal of the spent brine is proposed, although injection may be required for pressure maintenance at some future date.

The binary plants both use isobutane as a working fluid. Cycle efficiency could be improved somewhat by utilizing a lower molecular working fluid, but does not appear justified unless the project is strictly brine limited.

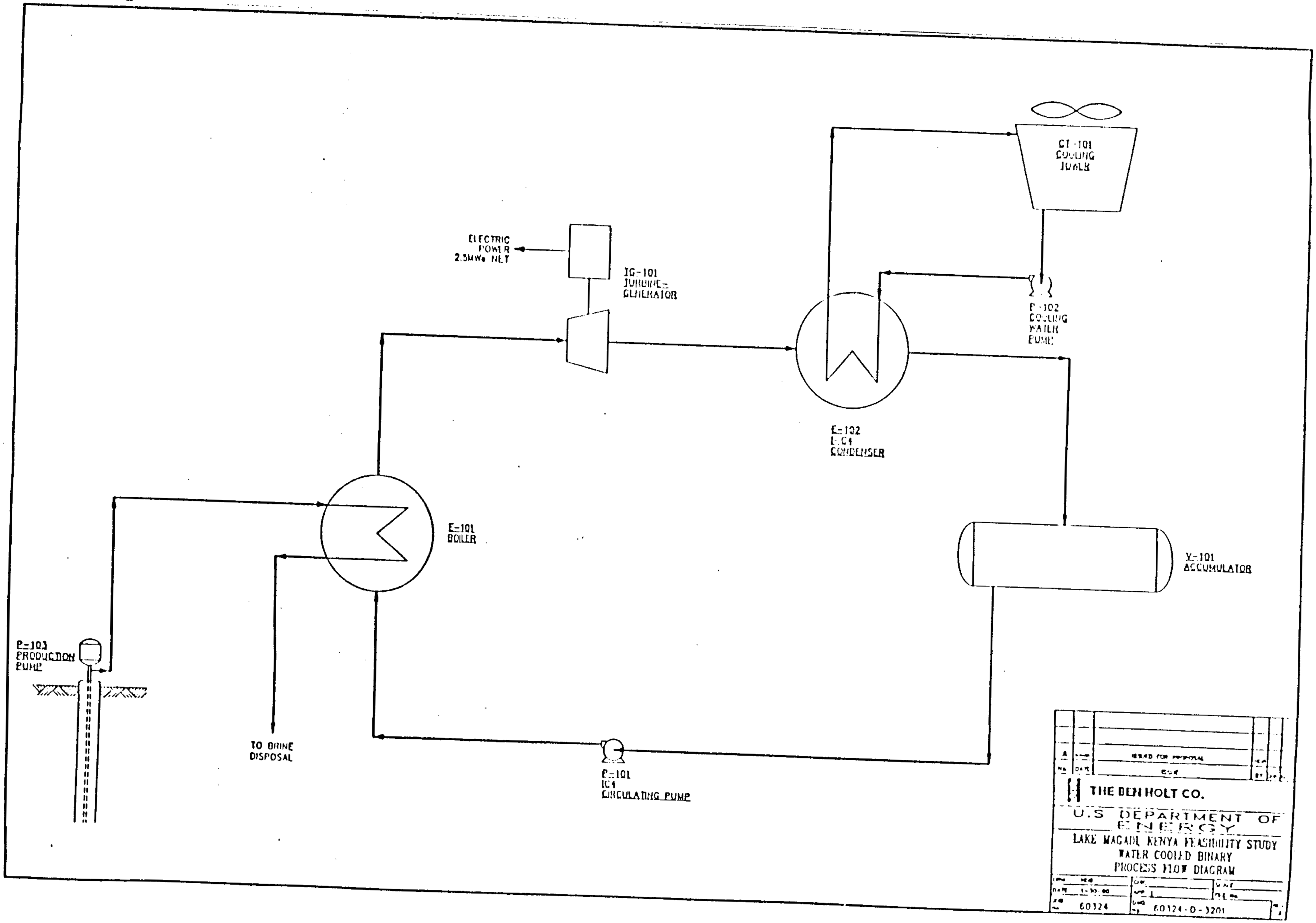
The isobutane is vaporized under pressure in shell and tube exchangers. The vapors are expanded in a turbine, generating the power required to operate auxiliary equipment.

In the water cooled case, the auxiliaries include production pumps, isobutane pumps, cooling water pumps and cooling tower fans. In the air cooled case, the auxiliaries include production pumps, isobutane pumps, and air condenser fans.

In Case III, the hot brine is flashed in a separator at near atmospheric pressure. The steam drives a condensing turbine and the exhaust steam from the turbine is condensed by cooling water in a surface condenser. Vacuum is maintained by a single stage liquid vacuum compressor.

Estimated brine consumption in each case is as follows:

Case I	2,800 gpm
Case II	3,500 gpm
Case III	3,050 gpm


CT-101
COOLING
TOWER
ELECTRIC
POWER
2.5MWe NET
TG-101
TURBINE-
GENERATOR
P-102
COOLING
WATER
PUMP
E-102
IC4
CONDENSER
E-101
BOILER
V-101
ACCUMULATOR
P-103
PRODUCTION
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TO BRINE
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THE BEN HOLT CO.
U.S DEPARTMENT OF ENERGY
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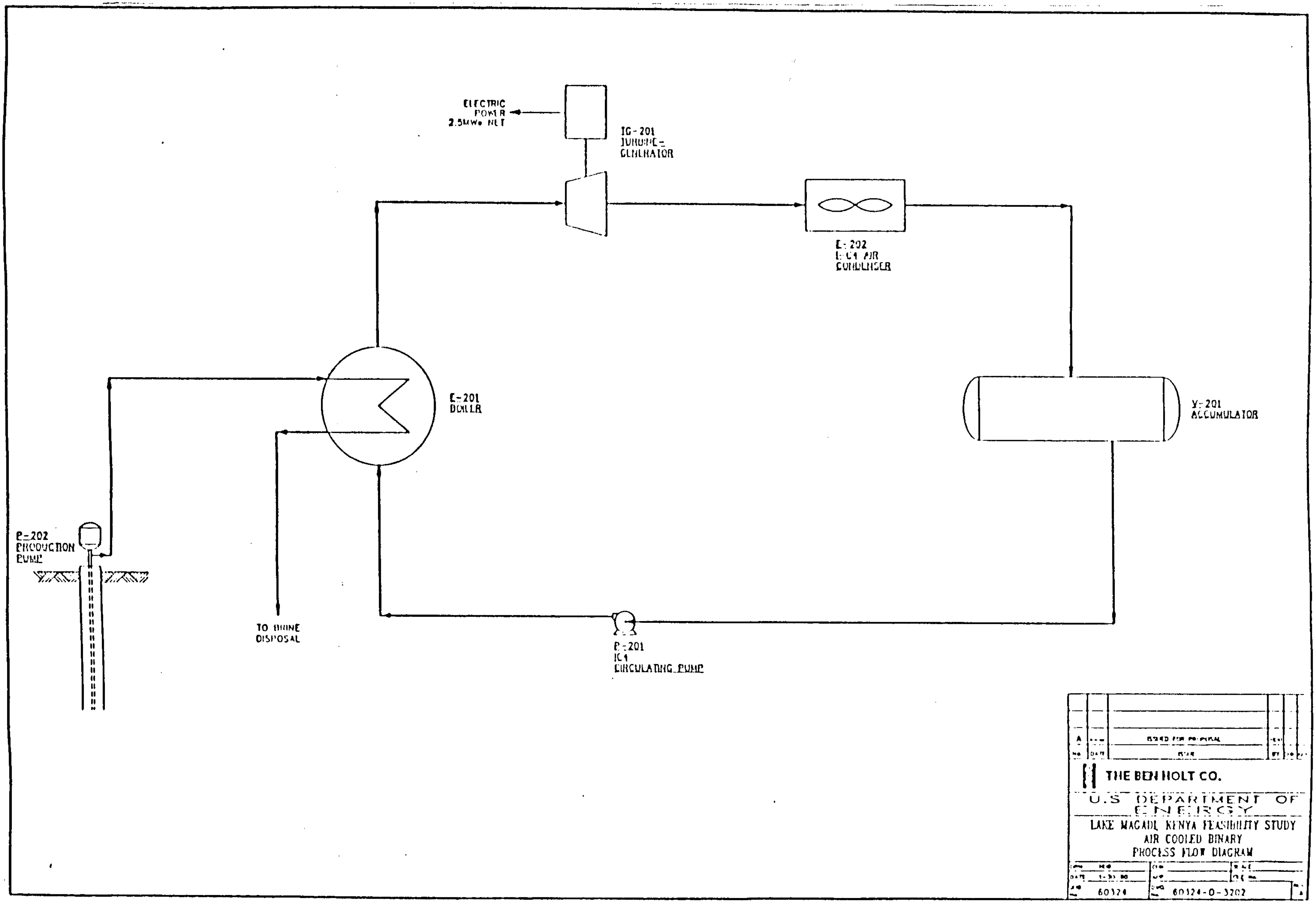
60124-D-3201


ELECTRIC POWER 2.5MWe NET
TG-201 TURBINE-GENERATOR
E-202 I-C4 AIR CONDENSER
E-201 BOILER
V-201 ACCUMULATOR
P-202 PRODUCTION PUMP
TO BRINE DISPOSAL
P-201 IC4 CIRCULATING PUMP
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THE BEN HOLT CO.
U.S DEPARTMENT OF ENERGY
LAKE MAGADI, KENYA FEASIBILITY STUDY
AIR COOLED BINARY
PROCESS FLOW DIAGRAM
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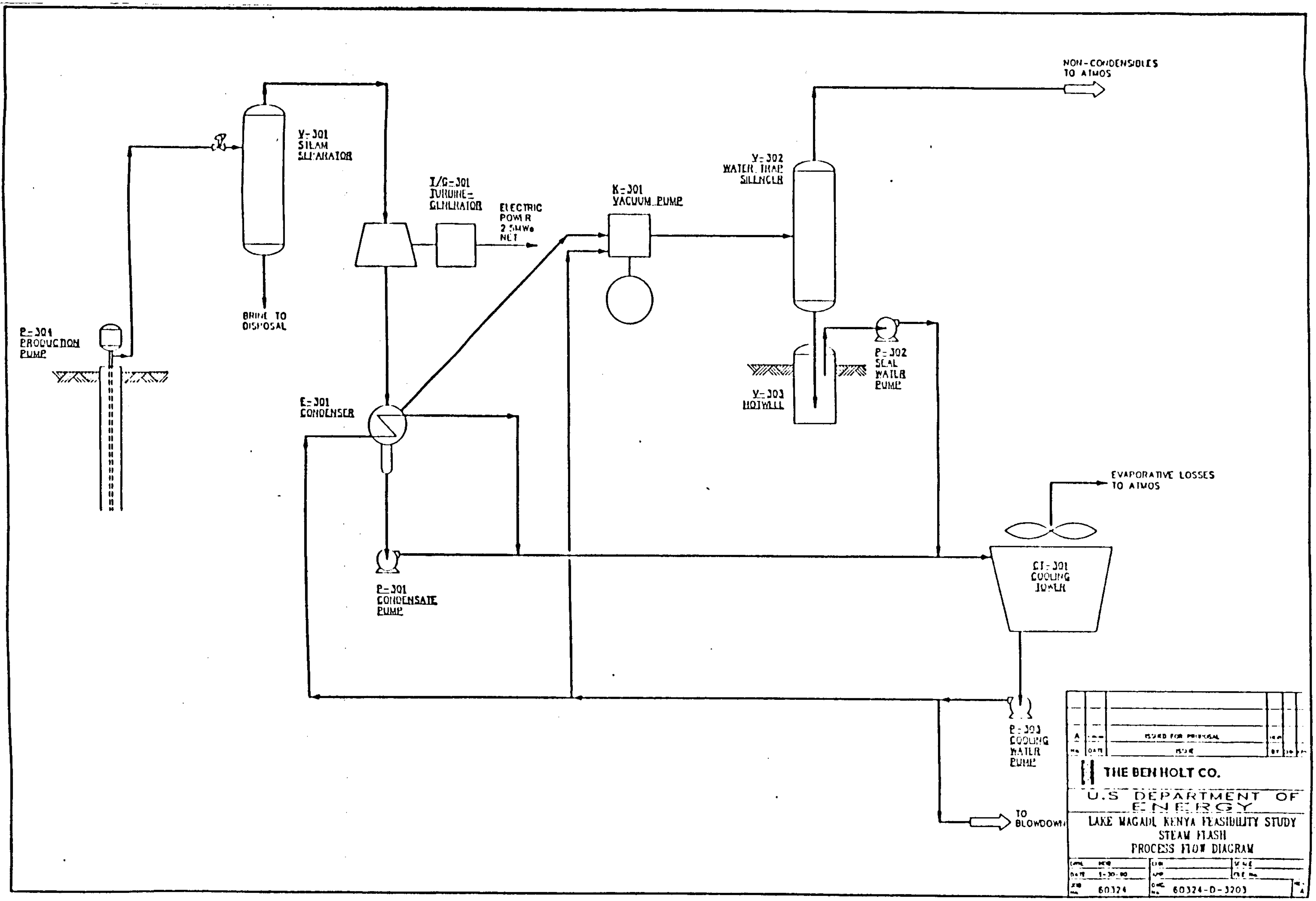
V-301
STEAM SEPARATOR
P-304
PRODUCTION PUMP
BRINE TO DISPOSAL
T/G-301
TURBINE-GENERATOR
ELECTRIC POWER 2.5MWe NET
K-301
VACUUM PUMP
V-302
WATER TRAP SILENCER
NON-CONDENSIBLES TO ATMOS
E-301
CONDENSER
V-303
HOTWELL
P-302
SEAL WATER PUMP
EVAPORATIVE LOSSES TO ATMOS
P-301
CONDENSATE PUMP
CT-301
COOLING TOWER
P-303
COOLING WATER PUMP
TO BLOWDOWN
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BY
THE BEN HOLT CO.
U.S DEPARTMENT OF ENERGY
LAKE MAGADI KENYA FEASIBILITY STUDY
STEAM FLASH
PROCESS FLOW DIAGRAM
DATE 1-30-80
JOB NO. 60324
DWG. NO. 60324-D-3203
REV. A

CAPITAL COST ESTIMATES

Capital cost estimates for the three cases are presented in Table I. These estimates are based on 1989 costs for plants built in the Western United States. They are installed costs and as such include design, procurement of materials and construction. In addition to the power plants we have also included the cost of wells, production pumps, gathering system, a transmission line and "soft" costs.

The "soft" costs are based on typical U.S. experience and include the following factors:

	$/kW	
Siting and permitting	65	
Financing Fees	80	
Owners costs	90	
	$235	x 2,500 = $587,500
		use $600,000

The cost of the planned next phase feasibility study is not included in soft costs, since the majority of the costs will be financed through U.S. foreign aid programs.

TABLE I

CAPITAL COST ESTIMATES

LITTLE MAGADI

(Figures in Thousands of Dollars)

	Case I	Case II	Case III
Type	Binary Water Cooled	Binary Air Cooled	Steam Flash Water Cooled
Plant Cost	4,000	4,800	4,600
Wells	800	1,200	800
Pumps	250	320	250
Gathering System	300	450	400
Transmission Line	500	500	500
Water Line	700	-	-
Soft costs	600	600	600
Total:	7,150	7,870	7,150
$/kW	2,860	3,148	2,860

O & M COSTS

The O & M costs for the three cases are shown in Table II and are based upon Holt's five years operating history of the 8 MWe Mammoth binary plant, the two year operating history of the 50 MWe Dixie Valley steam flash plant and projected costs of the 7 MWe direct steam admission plant now under construction in Utah.

Costs include operating labor, supplies and maintenance labor and materials. We assume that the plant will operate unattended, except for one man checking operation for two hours at the beginning of each 8 hour shift. Supplies include such items as isobutane, fuel, lube oil, small tools and miscellaneous items. No charge is made for cooling water except for the cost of pumping through a 12 mile pipeline.

Maintenance includes labor, materials and outside contract services. Operating and maintenance labor includes a burden of 40% to cover plant supervision and payroll burden. Labor rates are typical of 1989 U.S. rates.

TABLE II

O & M COST ESTIMATES

LITTLE MAGADI

(Figures in Dollars Per Year)

	Case I	Case II	Case III
Type	Binary Water Cooled	Binary Air Cooled	Steam Flash Water Cooled
Operating Labor	43,000	43,000	43,000
Supplies	35,000	26,000	23,000
Maintenance, Labor and materials	176,000	196,000	177,000
Total:	$254,000	$265,000	$243,000
¢/kWh*	1.22	1.27	1.17

* Based on production of 20,805,000 kWh/yr.

COST OF ELECTRICITY

The cost of generating power in MSC's diesel power plant is shown in Table III and is based upon data supplied by MSC personnel.

The cost includes fuel oil, personnel, lube oil, maintenance and electricity. This latter charge takes into account the parasitic loads such as cooling tower fans, pumping and similar uses.

TABLE III

COST OF ELECTRICITY

EXISTING DIESEL POWER PLANT

Basis: 1988 Costs in Kenyan Shillings
kWh produced = 14,700,000 (1.678 kW avg.)

Fuel Oil	11,400,000
Personnel	680,000
Lube Oil	850,000
Electricity	1,600,000
Maintenance	5,740,000
Total:	KS 20,270,000

Exchange Rate (1988)	18 KS/$
Electricity Cost	7.66 ¢kWh

FINANCIAL ANALYSIS

The objective of this section is to estimate the cost of producing electricity at Little Magadi and to compare the cost with the cost of producing power in the existing plant. An apple-to-apple comparison is complicated by the fact that we are comparing an old depreciated facility with a new facility.

Consequently we have made the basic assumption that The Magadi Soda Company (MSC) would be willing to purchase power from a privately financed geothermal plant at Little Magadi at MSC's "avoided cost".

Information recently received from MSC, as a result of a telephone conversation between Mike Jones of Oak Ridge Associated Universities and Greg Stewart of MSC indicated that, barring a geothermal development, MSC has two plans in mind for adding and replacing its diesel fuel generating capacity. Plan 1 calls for purchasing and installing retirements and additions as follows:

1.0 MWe in 1991
1.0 MWe in 1995
1.0 MWe in 1998

Plan 2 calls for purchasing and installing 1.5 MWe in 1991, 1.5 MWe in 1997 and no other purchases until well into 2000.

Estimated cost of these installations were furnished by MSC as follows:

- The installed cost of a 1.0 MWe diesel generator is estimated to be 54 million Ksh in mid-1991 including 5 million Ksh for improvements not a part of the project.

- The installed cost of a 1.5 MWe unit is estimated to be 60 million Ksh in mid-1991 including 5 million Ksh for improvements not a part of the project.

The above costs include the following duties and taxes:

- Generator set and alternator, 25% duty plus 15% for shipping and clearing and impact licenses.

- Other electrical equipment (switch gear/transformers, etc.) 46.8% duty and sales tax, plus 15% for shipping and clearing and import license.

MSC used a conversion factor of 27 Ksh/$ for 1991. Thus the estimated cost for a 1.5 MWe installation would be $2,037,000 or $1360/KW. The estimated cost for a 1.0 MWe installation would be $1815/kW.

In preparing the financial analysis we have made the following assumptions:

Income tax rate	40%
Project Life	20 years
Power price escalation	5% per year
Other escalation	5% per year
Power Usage	5% per year
Depreciation	20 years, St. Line

We assume that income taxes are comparable to combined California and Federal income tax rates. Power price escalation is our estimate of the increase in the cost of power produced by MSC, about half of which is the cost of fuel and the balance local costs of maintenance, labor and supplies. O & M escalation applies only to the geothermal plant. Power usage increase of 5% is based on MSC figures.

Based on the foregoing, we have estimated MSC's avoided cost of producing its own electricity for the next 20 years. The figures are shown in Table IV. The base year is 1991, at which time the 1988 O&M cost of $0.0766/kWh escalates to $0.0887/kWh and continues to escalate for the next 20 years at the same rate. However, in 1991 a new 1.0 MW diesel generating unit is installed at a cost of $1.815 million. This investment depreciates at the rate of 5% per year, leading to an annual surcharge of $90,750. The surcharge is increased in 1995 and again in 1998 to include depreciation of the next two units in MSC's avoided cost.

Multiplying the avoided cost figures times the estimated electrical requirements, we arrived at gross income, which is the revenue that the Lake Magadi geothermal plant could expect to receive by entering into a power sales agreement with MSC. After subtracting O & M costs we arrive at taxable income, net income and cash flow.

Standby Diesel Cost

It will be necessary to maintain the existing diesel power plant in standby condition to operate when the geothermal plant is shut down for maintenance, emergencies or other reasons. U.S. experience is that small geothermal power plants are very reliable and that availabilities of 95% or higher may be expected. We estimate that standby costs will be equivalent to one month's normal operation or $93,800/year (1988 basis).

Royalties

We have assumed that a royalty of 3 mils/kWh will be paid by the developer to the cognizant government agency. This figure is typical of royalty requirements of U.S. Government agencies on Federal lands.

Four Cases

Four cases are presented in the following pages. All assume that money can be borrowed at a rate of 8%. The ratio of debt to equity is different in each case. The results are summarized as follows:

Case	Debt/Equity	IRR, %
A	0	14.85
B	1.0	21.45
C	2.0	26.85
D	3.0	31.61

Table IV — Financial Analysis for Lake Magadi

				MMKsh	$MM
Geothermal Plant Cost, $MM	7.865	1991 Cost of 1.0 MW Diesel Plant		49	1.815
Tax Rate, %	40	1995 Cost of 1.0 MW Diesel Plant			2.206
O&M Escalation, %	5	1998 Cost of 1.0 MW Diesel Plant			2.554
Power Price Escalation, %	5	Depreciation Period, Years	20		
Capacity Factor Escalation, %	5				
Capacity Factor, Maximum, %	95	Maximum Power Produced, MW hours/year	20,805		

Year		1991	1992	1993	1994	1995	1996	1997	1998
Power Production, MW hours /year		17,017	17,868	18,761	19,699	20,684	20,805	20,805	20,805
Base Power Price, $/kWh (1988=$0.766)		0.089	0.093	0.098	0.103	0.108	0.114	0.119	0.125
Base Power Income, $M.		1,515	1,670	1,841	2,030	2,238	2,363	2,481	2,605
Avoided Cost, $M, 1991 Diesel Plant		91	91	91	91	91	91	91	91
Avoided Cost, $M, 1995 Diesel Plant						110	110	110	110
Avoided Cost, $M, 1998 Diesel Plant									128
Total Power Revenue, $M		1,605	1,760	1,932	2,120	2,439	2,564	2,682	2,934
Expenses									
O&M Expense, $M		267	281	295	309	325	341	358	376
Depreciation, $M		393	393	393	393	393	393	393	393
Diesel Engine Standby, $M		108	114	119	125	132	138	145	152
Royalty, $M		56	62	68	75	83	88	92	97
Property Taxes & Insurance, $M		118	118	118	118	118	118	118	118
Total Expenses, $M		943	968	994	1,021	1,051	1,078	1,107	1,137
Taxable Income		662	793	938	1,099	1,388	1,486	1,576	1,798
Income Tax		265	317	375	440	555	594	630	719
Net Income		397	476	563	659	833	892	945	1,079
Cash Flow, $M	-7,865	791	869	956	1,053	1,226	1,285	1,339	1,472

IRR 14.85 (100% Equity Basis)

CASE A

Table IV — Financial Analysis for Lake Magadi

1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805
0.131	0.138	0.145	0.152	0.160	0.168	0.176	0.185	0.194	0.204	0.214
2,736	2,873	3,016	3,167	3,325	3,492	3,666	3,849	4,042	4,244	4,456
91	91	91	91	91	91	91	91	91	91	91
110	110	110	110	110	110	110	110	110	110	110
128	128	128	128	128	128	128	128	128	128	128
3,064	3,201	3,345	3,496	3,654	3,820	3,995	4,178	4,371	4,573	4,785
395	415	435	457	480	504	529	556	583	613	643
393	393	393	393	393	393	393	393	393	393	393
160	168	176	185	194	204	214	225	236	248	261
102	107	112	118	124	130	136	143	150	158	166
118	118	118	118	118	118	118	118	118	118	118
1,168	1,201	1,235	1,271	1,309	1,349	1,391	1,435	1,481	1,530	1,581
1,897	2,001	2,110	2,224	2,345	2,471	2,604	2,743	2,889	3,043	3,204
759	800	844	890	938	988	1,041	1,097	1,156	1,217	1,282
1,138	1,200	1,266	1,335	1,407	1,483	1,562	1,646	1,734	1,826	1,922
1,531	1,594	1,659	1,728	1,800	1,876	1,955	2,039	2,127	2,219	2,316

CASE A

Table IV — Financial Analysis for Lake Magadi

				MMKsh	$MM
Geothermal Plant Cost, $MM	7.865	1991 Cost of 1.0 MW Diesel Plant		49	1.815
Tax Rate, %	40	1995 Cost of 1.0 MW Diesel Plant			2.206
O&M Escalation, %	5	1998 Cost of 1.0 MW Diesel Plant			2.554
Power Price Escalation, %	5	Depreciation Period, Years	20		
Capacity Factor Escalation, %	5				
Capacity Factor, Maximum, %	95	Maximum Power Produced, MW hours/year	20,805		

Year		1991	1992	1993	1994	1995	1996	1997	1998
Power Production, MW hours /year		17,017	17,868	18,761	19,699	20,684	20,805	20,805	20,805
Base Power Price, $/kWh (1988=$0.766)		0.089	0.093	0.098	0.103	0.108	0.114	0.119	0.125
Base Power Income, $M.		1,515	1,670	1,841	2,030	2,238	2,363	2,481	2,605
Avoided Cost, $M, 1991 Diesel Plant		91	91	91	91	91	91	91	91
Avoided Cost, $M, 1995 Diesel Plant						110	110	110	110
Avoided Cost, $M, 1998 Diesel Plant									128
Total Power Revenue, $M		1,605	1,760	1,932	2,120	2,439	2,564	2,682	2,934
Expenses									
O&M Expense, $M		267	281	295	309	325	341	358	376
Depreciation, $M		393	393	393	393	393	393	393	393
Diesel Engine Standby, $M		108	114	119	125	132	138	145	152
Royalty, $M		56	62	68	75	83	88	92	97
Property Taxes & Insurance, $M		118	118	118	118	118	118	118	118
Interest		315	307	299	290	280	270	259	247
Total Expenses		1,258	1,275	1,293	1,311	1,331	1,348	1,366	1,383
Taxable Income		348	486	639	809	1,107	1,216	1,317	1,551
Income Tax		139	194	256	324	443	486	527	620
Net Income		209	291	383	485	664	729	790	930
Principal Payment		95	102	111	120	129	139	151	163
Cash Flow	-3,933	507	582	666	759	929	983	1,033	1,161
Debt/Equity Ratio	1.00								
Money Borrowed	3,933								
Loan Balance	3,933	3,838	3,735	3,624	3,505	3,376	3,236	3,086	2,923
Project Term, years	20								
Interest Rate, Percent	8.00								
Loan Payment	409								
IRR	21.45								

CASE B

Table IV — Financial Analysis for Lake Magadi

1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805
0.131	0.138	0.145	0.152	0.160	0.168	0.176	0.185	0.194	0.204	0.214
2,736	2,873	3,016	3,167	3,325	3,492	3,666	3,849	4,042	4,244	4,456
91	91	91	91	91	91	91	91	91	91	91
110	110	110	110	110	110	110	110	110	110	110
128	128	128	128	128	128	128	128	128	128	128
3,064	3,201	3,345	3,496	3,654	3,820	3,995	4,178	4,371	4,573	4,785
395	415	435	457	480	504	529	556	583	613	643
393	393	393	393	393	393	393	393	393	393	393
160	168	176	185	194	204	214	225	236	248	261
102	107	112	118	124	130	136	143	150	158	166
118	118	118	118	118	118	118	118	118	118	118
234	220	205	188	171	151	131	109	84	58	30
1,402	1,420	1,440	1,460	1,480	1,501	1,522	1,544	1,566	1,588	1,611
1,663	1,781	1,905	2,036	2,174	2,320	2,473	2,635	2,805	2,984	3,174
665	712	762	814	870	928	989	1,054	1,122	1,194	1,270
998	1,068	1,143	1,222	1,304	1,392	1,484	1,581	1,683	1,791	1,904
176	190	205	221	239	258	279	301	325	351	379
1,215	1,272	1,331	1,394	1,459	1,527	1,598	1,673	1,751	1,833	1,918
2,748	2,558	2,353	2,132	1,893	1,635	1,356	1,055	730	379	0

Table IV — Financial Analysis for Lake Magadi

Geothermal Plant Cost, $MM	7.865
Tax Rate, %	40
O&M Escalation, %	5
Power Price Escalation, %	5
Capacity Factor Escalation, %	5
Capacity Factor, Maximum, %	95

		MMKsh	$MM
1991 Cost of 1.0 MW Diesel Plant		49	1.815
1995 Cost of 1.0 MW Diesel Plant			2.206
1998 Cost of 1.0 MW Diesel Plant			2.554
Depreciation Period, Years	20		
Maximum Power Produced, MW hours/year	20,805		

Year		1991	1992	1993	1994	1995	1996	1997	1998
Power Production, MW hours /year		17,017	17,868	18,761	19,699	20,684	20,805	20,805	20,805
Base Power Price, $/kWh (1988=$0.766)		0.089	0.093	0.098	0.103	0.108	0.114	0.119	0.125
Base Power Income, $M.		1,515	1,670	1,841	2,030	2,238	2,363	2,481	2,605
Avoided Cost, $M, 1991 Diesel Plant		91	91	91	91	91	91	91	91
Avoided Cost, $M, 1995 Diesel Plant						110	110	110	110
Avoided Cost, $M, 1998 Diesel Plant									128
Total Power Revenue, $M		1,605	1,760	1,932	2,120	2,439	2,564	2,682	2,934
Expenses									
O&M Expense, $M		267	281	295	309	325	341	358	376
Depreciation, $M		393	393	393	393	393	393	393	393
Diesel Engine Standby, $M		108	114	119	125	132	138	145	152
Royalty, $M		56	62	68	75	83	88	92	97
Property Taxes & Insurance, $M		118	118	118	118	118	118	118	118
Interest		419	409	398	387	374	360	345	329
Total Expenses		1,363	1,377	1,392	1,408	1,425	1,439	1,452	1,466
Taxable Income		243	383	539	712	1,014	1,126	1,230	1,468
Income Tax		97	153	216	285	406	450	492	587
Net Income		146	230	324	427	608	675	738	881
Principal Payment		127	137	148	159	172	186	201	217
Cash Flow	-2,622	412	487	569	661	829	883	931	1,058
Debt/Equity Ratio	2.00								
Money Borrowed	5,243								
Loan Balance	5,243	5,117	4,980	4,833	4,673	4,501	4,315	4,115	3,898
Project Term, years	20								
Interest Rate, Percent	8.00								
Loan Payment	546								
IRR	26.85								

CASE C

Table IV — Financial Analysis for Lake Magadi

1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805
0.131	0.138	0.145	0.152	0.160	0.168	0.176	0.185	0.194	0.204	0.214
2,736	2,873	3,016	3,167	3,325	3,492	3,666	3,849	4,042	4,244	4,456
91	91	91	91	91	91	91	91	91	91	91
110	110	110	110	110	110	110	110	110	110	110
128	128	128	128	128	128	128	128	128	128	128
3,064	3,201	3,345	3,496	3,654	3,820	3,995	4,178	4,371	4,573	4,785
395	415	435	457	480	504	529	556	583	613	643
393	393	393	393	393	393	393	393	393	393	393
160	168	176	185	194	204	214	225	236	248	261
102	107	112	118	124	130	136	143	150	158	166
118	118	118	118	118	118	118	118	118	118	118
312	293	273	251	227	202	174	145	113	78	40
1,480	1,494	1,508	1,522	1,537	1,551	1,566	1,580	1,594	1,608	1,621
1,585	1,707	1,837	1,973	2,117	2,269	2,429	2,598	2,777	2,965	3,164
634	683	735	789	847	908	972	1,039	1,111	1,186	1,265
951	1,024	1,102	1,184	1,270	1,361	1,458	1,559	1,666	1,779	1,898
234	253	273	295	319	344	372	401	433	468	506
1,110	1,165	1,222	1,282	1,345	1,411	1,479	1,551	1,626	1,704	1,786
3,664	3,411	3,138	2,843	2,524	2,180	1,808	1,407	974	506	0

CASE C

Table IV — Financial Analysis for Lake Magadi

Geothermal Plant Cost, $MM	7.865
Tax Rate, %	40
O&M Escalation, %	5
Power Price Escalation, %	5
Capacity Factor Escalation, %	5
Capacity Factor, Maximum, %	95

		MMKsh	$MM
1991 Cost of 1.0 MW Diesel Plant		49	1.815
1995 Cost of 1.0 MW Diesel Plant			2.206
1998 Cost of 1.0 MW Diesel Plant			2.554
Depreciation Period, Years	20		
Maximum Power Produced, MW hours/year	20,805		

Year		1991	1992	1993	1994	1995	1996	1997	1998
Power Production, MW hours /year		17,017	17,868	18,761	19,699	20,684	20,805	20,805	20,805
Base Power Price, $/kWh (1988=$0.766)		0.089	0.093	0.098	0.103	0.108	0.114	0.119	0.125
Base Power Income, $M.		1,515	1,670	1,841	2,030	2,238	2,363	2,481	2,605
Avoided Cost, $M, 1991 Diesel Plant		91	91	91	91	91	91	91	91
Avoided Cost, $M, 1995 Diesel Plant						110	110	110	110
Avoided Cost, $M, 1998 Diesel Plant									128
Total Power Revenue, $M		1,605	1,760	1,932	2,120	2,439	2,564	2,682	2,934
Expenses									
O&M Expense, $M		267	281	295	309	325	341	358	376
Depreciation, $M		393	393	393	393	393	393	393	393
Diesel Engine Standby, $M		108	114	119	125	132	138	145	152
Royalty, $M		56	62	68	75	83	88	92	97
Property Taxes & Insurance, $M		118	118	118	118	118	118	118	118
Interest		472	461	448	435	421	405	388	370
Total Expenses		1,415	1,428	1,442	1,456	1,472	1,484	1,495	1,507
Taxable Income		190	332	490	664	967	1,081	1,187	1,427
Income Tax		76	133	196	266	387	432	475	571
Net Income		114	199	294	398	580	648	712	856
Principal Payment		142	154	166	179	194	209	226	244
Cash Flow	-1,966	365	439	521	612	780	833	880	1,006
Debt/Equity Ratio	3.00								
Money Borrowed	5,899								
Loan Balance	5,899	5,756	5,603	5,437	5,257	5,064	4,855	4,629	4,385
Project Term, years	20								
Interest Rate, Percent	8.00								
Loan Payment	614								
IRR	31.61								

CASE D

Table IV — Financial Analysis for Lake Magadi

1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805	20,805
0.131	0.138	0.145	0.152	0.160	0.168	0.176	0.185	0.194	0.204	0.214
2,736	2,873	3,016	3,167	3,325	3,492	3,666	3,849	4,042	4,244	4,456
91	91	91	91	91	91	91	91	91	91	91
110	110	110	110	110	110	110	110	110	110	110
128	128	128	128	128	128	128	128	128	128	128
3,064	3,201	3,345	3,496	3,654	3,820	3,995	4,178	4,371	4,573	4,785
395	415	435	457	480	504	529	556	583	613	643
393	393	393	393	393	393	393	393	393	393	393
160	168	176	185	194	204	214	225	236	248	261
102	107	112	118	124	130	136	143	150	158	166
118	118	118	118	118	118	118	118	118	118	118
351	330	307	282	256	227	196	163	127	88	45
1,519	1,530	1,542	1,554	1,565	1,576	1,587	1,598	1,608	1,617	1,626
1,546	1,671	1,803	1,942	2,089	2,244	2,408	2,580	2,763	2,955	3,159
618	668	721	777	836	898	963	1,032	1,105	1,182	1,263
927	1,003	1,082	1,165	1,253	1,346	1,445	1,548	1,658	1,773	1,895
263	285	307	332	358	387	418	451	488	527	569
1,057	1,111	1,168	1,227	1,288	1,353	1,420	1,490	1,563	1,640	1,720
4,121	3,837	3,530	3,198	2,839	2,452	2,034	1,583	1,095	569	0

DISCUSSION

This section discusses the assumptions on which the financial analysis is based.

- The Reservoir

The existence of a suitable reservoir has not been established. Additional studies and actual test holes will be required. A major feasibility study costing about $750,000 will be necessary to confirm the reservoir. This cost has not been included in the capital cost.

- Power Cycle

Water cooled binary and steam flash plants are competitive and the selection will depend largely on the availability and cost of cooling water.

- Plant Cost

Estimate of capital costs are based on U.S. experience. It is likely that the plant will use one or two modules, skid mounted as much as possible in order to minimize shipping and field erection cost. We assume power plant equipment can be imported duty free.

Binary and steam flash units are available from several domestic sources.

O & M Costs

These costs are based on U.S. experience. We would expect that material costs would be higher than U.S. costs, offset at least in part by lower labor costs in Kenya.

The cost of maintaining the existing power plant in standby condition is estimated to be equal to one month's operation of the power plant (1/12 of the annual cost).

Financial Analysis

The analysis is based upon a set of reasonable assumptions which would be of interest to a typical U.S. corporate or private investor.

The base case of 100% equity shows an internal rate of return (IRR) of slightly less than 15%. A hurdle rate of 15% based on 100% equity is commonly used by U.S. based companies. IRR increases to an attractive 32% with a debt/ratio equity ratio of 3.0 (that is, 75% borrowed money and 25% equity).

It is to be noted that the investment in the geothermal plant is about $3,000 per kilowatt as compared to about $1,000 per kilowatt for the existing plant. In the long run this additional capital cost is justified by reduced operating costs which are less sensitive to the uncertainties of the world oil market.

Other opportunities for improving profitability include income tax concessions and higher escalation of power consumption and power rates.

CONCLUSIONS

The Magadi Soda Company has an immediate need for replacement of one of their existing diesel generators. They also want to evaluate using geothermal power for future capacity requirements as a way to decrease their reliance on importing diesel fuel. Because of this, The Ben Holt Co. and GeothermEx, Inc. have had numerous discussions with Magadi officials over the past two years. This has included site visits, sample analysis and economic calculations of geothermal power plant design.

The financial analysis presented in this report demonstrates that a private corporation could deliver power to Magadi Soda Company at a rate equivalent to Magadi's present power costs and provide the private corporation a satisfactory return on investment

The proposed installation, while profitable in its own right, has still other advantages, including the prospect of a major development which could be tied into the Kenyan power grid. It will also provide a practical demonstration of the viability of small off-grid power plants developed to serve isolated communities with a reliable source of electricity.

Finally, given Magadi Soda's interest in the project, the possibility of increased foreign exchange earnings and environmental considerations, this project warrants a major feasibility study to determine the nature and extent of the resource.