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LATIN AMERICAN
ENERGY ORGANIZATION

INTER-AMERICAN
DEVELOPMENT BANK

GUIDE FOR ASSESSING ENERGY POTENTIAL IN GEOTHERMAL ZONES PRIOR TO THE FEASIBILITY STAGE

Quito, Ecuador
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Prepared under Non-Reimbursable IDB/OLADE Agreement ATN-SF-3603-RE.

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ISBN 9978-70-056-0
OLADE 009-GE/94(En)

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PRESENTATION

In response to the oil crisis of the 1970s, in 1978 OLADE began a program of activities geared to fostering research on, and development of, geothermal energy as an alternative to conventional sources of energy. That program was framed within the Organization's objectives of a) promoting actions to develop, use and defend the natural resources of the OLADE Member Countries and the Region as a whole, and b) promoting a policy for the rational exploitation, transformation and marketing of energy resources.

To that end, one of the Organization's first actions was to compile a geothermal exploration and exploitation methodology adaptable to the conditions and characteristics of the Latin American and Caribbean countries.

With collaboration from various institutions and experts both from within the Region and outside it, in 1978 OLADE prepared the "Geothermal Exploration Methodology for the Reconnaissance and Prefeasibility Stages," in 1979 the "Geothermal Exploration Methodology for the Feasibility Stage," and in 1980 the "Geothermal Exploration and Exploitation Methodology for the Development and Production Stages." After the third methodology was reviewed, supplemented and updated, the Organization published the "Geothermal Exploitation Methodology" in 1986.

The availability of such methodologies has provided the countries of the Region with a useful, easy-to-apply tool to orient investigations of their geothermal resources. With support from OLADE and its methodologies, Haiti, Ecuador, Peru, the Dominican Republic, Grenada, Guatemala, Jamaica, Colombia and Panama, among others, carried out reconnaissance studies in their territories. Nicaragua, Panama, Ecuador-Colombia, Haiti and Guatemala, also with support from the Organization, developed prefeasibility studies in some thermal areas offering favorable conditions for the development of geothermal fields.

The application of the methodologies helped the countries of the Region to increase knowledge about their geothermal resources. By the end of the 1980s twenty of the twenty-six OLADE Member Countries had already done reconnaissance studies, 17 had carried out prefeasibility studies, 8 had conducted feasibility studies, and 4 were already generating electricity at some of their geothermal fields. Nonetheless, the rapid development of geothermal technologies made it necessary to once again update the methodologies.

Bearing in mind the fact that at different international forums the geothermal community recognized the need to review, modernize and even supplement the OLADE documents, ugh Technical Cooperation Agreement ATN-SF-3603-RE the Organization and the Inter-rican Development Bank (IDB) decided to review the existing geothermal exploration and oitation guides and to prepare six new ones. Those guides, in response to the requirements of technical groups of the Region, were to be on: Reconnaissance Studies, Prefeasibility Studies, sibility Studies, Evaluation of the Energy Potential (on the basis of information gathered in reconnaissance and prefeasibility stages), Operation and Maintenance of Geothermal Fields Plants, and Preparation of Geothermal Investment Projects.

The new documents on geothermal energy were prepared with assistance from seven rnational consultants and eight experts from the Region with broad experience in volcanology, geochemistry, geophysics, drilling, reservoir engineering, operation and ntenance of geothermal fields and plants, and plant engineering and design.

The results of the efforts made by OLADE and the IDB to contribute to Latin American and ibbean energy development are presented in this document containing the Guide for Assessing rgy Potential in Geothermal Zones Prior to the Feasibility Stage, for the purpose of providing countries of the Region with an instrument enabling them to estimate, in the initial stages of thermal investigations, the resource potential that could possibly be included in national rgy planning.

OLADE and the IDB especially acknowledge the work of Dr. Marcelo Lippmann, who was harge of the preparation of this document. They also thank Dr. Jesús Rivera, Dr. Paolo uori, and Messrs. Eduardo Granados and Antonio Razo for their contributions to the guide.

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1. INTRODUCTION

The existence of a geothermal system with prospects for economically viable energy production depends on the presence of an appropriate endogenous heat source, usually associated with a shallow body of magma (Barberi and Marinelli, 1987). Of course, the larger and more recent that body, the greater the heat anomaly and the greater the probability of finding a system that can be economically exploited.

The possibility of discovering a hydrothermal geothermal system (in which the endogenous heat is transported to near the Earth's surface mainly by convection) is favored by the presence of recent volcanism of an intermediate to acidic type and by the existence of rocky formations with permeability and porosity adequate for the circulation and accumulation of large volumes of fluids in the subsurface. Recent intermediate to acidic volcanism refers to andesitic to rhyolitic volcanos that are currently active or were active during the last million years.

In general, the most basic type of volcanism (for example, basaltic) is of less interest from a geothermal energy standpoint, because the magma source is usually deeper and when it rises to the surface it does so rapidly without heating large volumes of rock, one exception being the case of Puna, Hawaii, U.S.A.

In the case of acidic volcanism, the magma chamber tends to lie at lesser depths and the differentiated magma tends to remain in the chamber for longer periods before emptying, which permits greater heat transfer to the surrounding rocks (Barberi and Marinelli, 1987).

It is worthwhile to note that the mere presence of different types of volcanism and favorable geological structures and formations does not ensure the existence of an economically interesting geothermal system. The many factors involved complicate development and exploitation.

Inferring the existence of geothermal resources in a particular zone, in other words, estimating the accumulation of a certain amount of thermal energy in subsurface rocks and establishing the technical feasibility of transforming and/or transporting the energy to consumption centers, does not mean that the energy can be extracted economically or that the zone contains what is termed a "Geothermal Resource" as defined further on.

For example, geotechnical problems that could appear during the exploration, development and/or exploitation of the project (Table No. 1) could increase the costs related to building civil structures, drilling wells and producing sufficient volumes of geothermal fluids. These additional costs could negatively affect a geothermal production project from an economic standpoint and could make it of little commercial interest despite the large amount of underground heat that might be present.

In the prefeasibility stage, before deep wells are drilled, it is possible to tentatively infer the size of a geothermal resource in a semi-quantitative way, based on preliminary data, since size tends to be reflected in: a) the heat flow measured in the area, b) the subsurface temperatures calculated on the basis of the chemical composition of the fluids produced by the hot springs (using geothermometers) or those measured in gradient wells, c) the size (area and discharge) of the surface hot springs, d) the area of hydrothermal alterations, and e) the size of geophysical anomalies (for example, of low resistivity) or geochemical anomalies that may have been detected.

It should be pointed out that, to infer the size of the resource, generally speaking fumaroles are much more important than hot springs. There is no universal rule, but in many geothermal fields fumaroles tend to be located in the geothermal reservoir's hottest regions, whereas springs tend to be associated with discharge zones (Figure No. 1[1]).

Large areas of abundant fumaroles reflect a notable rise of geothermal fluids, whereas the location of hot springs indicates how far the geothermal system extends and where it discharges. This explains the fact that many wells drilled in hot-spring areas have penetrated relatively shallow, low-temperature geothermal aquifers. When the system's discharge zone is intercepted, the wells find geothermal fluids that have lost a good deal of their initial temperature due to boiling, conduction or mixing with cold groundwater. However, it is worthwhile to mention that there are complex systems in which this does not represent the actual situation.

2. METHODOLOGY

The magnitude of the energy potential of a geothermal system of the hydrothermal type can be "estimated" considering the system's observable characteristics at the surface. In doing this analysis, it should be recalled that the existence of a hydrothermal system is due to the presence of: a) an endogenous heat source, b) fluids that capture and transport that heat, c) geological structures (faults, fractures) that permit the flow of these geothermal fluids, d) permeable geological formations in which to store the fluids (the reservoir) and e) not very permeable formations (cap rock) covering the reservoir, which prevent or reduce the rise of geothermal fluids and their mixture with colder groundwater not far below the surface.

During the initial stages of a geothermal project, different methods can be used to calculate an area's energy potential. Some of these are described succinctly below, with emphasis on the Volume Method, which, under the conditions of these stages, is the most rigorous and most widely used method (see for example ICE, 1991). The other methods tend to provide very approximate results, based mainly on assumptions rather than data obtained from specific investigations. Greater detail on the different methods can be obtained from the documents referred to further on.

In the evaluation of a geothermal system's energy potential, the first step consists of determining the Geothermal Resource Base. The nomenclature used below is from Muffler and Cataldi (1978); see Figure No. 2. This resource includes all of the thermal energy contained in the Earth's crust in the area under consideration, referenced to local mean annual temperature.

1 Figure at the back of the guide.

The Geothermal Resource Base is divided into: a) a shallow part that could very likely be reached by wells, the so-called Accessible Geothermal Resource Base (ARB) and b) a deep part that would be difficult to reach in the near future, the so-called Inaccessible Geothermal Resource Base (Figure No. 2). Obviously, the separation between these two categories is a function of drilling technologies and economic factors predicted for the future (Muffler and Cataldi, 1978).

The next step in this evaluation process consists of determining the Useful Accessible Resource Base or Geothermal Resource (Figure No. 2), since not all of the ARB can be extracted by the wells even if one is very optimistic about possible technological progress and future economic changes. The Useful Accessible Resource Base refers to the heat that is contained in the crust of the area under study and that could be reasonably exploited at costs competitive with those of other forms of energy.

The Geothermal Resource is subdivided into: a) the Economic Geothermal Resource, which corresponds to the geothermal energy that can be legally extracted at competitive costs at the time of the evaluation, and b) the Marginal Geothermal Resource, which cannot be exploited competitively at that time, but perhaps could be in the future under different economic and technical conditions.

The Economic Geothermal Resource is composed of two parts: a) the Geothermal Reserve that has been identified or proven using geoscientific techniques and b) the Undiscovered Economic Geothermal Resource, the magnitude of which can be inferred on the basis of the data collected (Rivera, 1983). Further on, when the Volume Method is described (Section 2.1.4), the term Geothermal Resource (GR) will be used; it corresponds approximately to the Economic Geothermal Resource. It is worthwhile to indicate that the nomenclature used in Section 2.1.4, based on the work of Brook et. al., differs somewhat from that of Muffler and Cataldi, which has been used in this section mainly because it is so clear and systematic.

2.1 Methods for Assessing the Geothermal Resource

The principal methods for evaluating the geothermal resources of a particular system during the stages prior to feasibility are as follows:

2.1.1 Surface Heat Flow Method

The surface heat flow method, which is quite simple, is based on the calculation of the amount of underground heat transmitted to the surface per unit of time (Muffler and Cataldi, 1978). This heat transfer is by conduction and convection ($Q_{cond} + Q_{conv}$). The Natural Thermal Power (NTP) is equal to the sum of the heat transferred by these two processes:

$$NTP = Q_{cond} + Q_{conv} = A * q_{cond} + q * c_f * (T_f - T_o)$$

where:

A = surface area studied (m^2)

q_{cond} = heat transmitted by conduction per unit of area (W/m^2)

q = mass flow of the fluid (kg/s)

c_f = calorific capacity of the fluid (J/kg - °C)

T_f = temperature of the fluid flowing from the hot springs (°C)

T_o = ambient temperature (°C)

This method makes it possible to establish the number of watts of thermal energy released by the system. If a recovery factor and a factor for the transformation of thermal energy to electrical energy are assumed, it is possible to estimate the system's electrical potential in a semi-quantitative form.

2.1.2 Planar Fracture Method

The Planar Fracture Method is based on the model of a planar fracture that receives heat from impervious neighboring rocks by means of conduction (Bodvarsson, 1974). The amount of thermal energy that can be extracted from the fracture per unit of area is a function of the temperature of the surrounding rock and the initial and final temperatures of the fluid in the fracture ("final" being after 25 or 50 years).

This method can be extended to a system of multiple fractures, provided that the distance between them does not entail any thermal interference. Theoretically, this proposal can be applied to geothermal systems located in igneous rocks, but the values obtained can be highly uncertain due to the lack of data on the spacing and orientation of the fractures in the geothermal system.

2.1.3 Magmatic Heat or Magma Chamber Method

Due to the fact that most geothermal fields are related to volcanic zones, volcanological principles are very useful in exploration but can also be used for a first approximation in the evaluation of geothermal systems' energy potential.

If a magma chamber is assumed to be the heat source of a geothermal system, the heat stored in the subsurface within a certain interval of depths can be quantified approximately by estimating the volume, depth, age and temperature of the chamber and calculating the heat transfer between the chamber and the surface.

The method used by Smith and Shaw (1975, 1979) is based on the determination of the amount of heat accumulated in the upper 10 km of the crust. This amount is calculated by inferring the probable volumes of the shallow magma chambers and determining the ages of the most recent volcanic products that have come from those chambers. (Note: These authors refer to magma chambers as the regions of the crust where the current existence of molten or partially molten rock is inferred.)

The calculations of Smith and Shaw are based on the assumption that there is a fixed volume of magma with an initial temperature of 850°C, which at a given moment begins to cool. In their work, these authors present a figure showing the theoretical cooling of recent igneous bodies as a function of age and size.

The methodology outlined below to obtain the parameters that characterize the magma chamber, and to calculate the heat accumulated in the reservoir, corresponds largely to that described by Barberi and Marinelli (1987); more details are provided in that reference.

First, a model of the chamber is developed; in other words, its depth, volume, age and initial and final temperatures are estimated. Then, the crust's temperature (or thermal gradient) distribution is calculated considering only conduction. As indicated by Barberi and Marinelli (1987), this method of evaluating the heat source is very rudimentary and a conduction-convection model would be more in keeping with reality. Unfortunately, in initial project stages in which there are usually no deep wells, there are not enough data to accurately calculate heat transfer by convection.

2.1.3.1 Evaluation of the Heat Source

Determination of the Magma Chamber's Volume and Depth

The interpretation of data obtained using the various geophysical techniques (gravimetry, seismography, magnetometry, crust deformation studies, etc.) can provide approximate information on the presence, depth and dimensions of the presumed magma chamber (see for example Goldstein and Flexer, 1984; Donnelly-Nolan, 1988; Harjono et al., 1989).

Furthermore, the minimum volume of the chamber can be estimated on the basis of the volume of the differentiated volcanic products ejected and their degree of fractional crystallization. The volume of the collapsed part of the caldera can be used as a measure of the volume of ejected materials. The products' degree of fractionation can be estimated using geochemical or petrological methods (see for example Carmichael et al., 1974; Baker and McBirney, 1985).

Considering the existing thermal gradient, it is possible to estimate the depth at which the temperature where outcropping volcanic rocks would form could be reached. The depth of the magma chamber can also be estimated by establishing the pressure conditions for crystallization within the chamber or by using other petrological techniques. Barberi and Marinelli (1987) stress that the determination of that depth is a difficult task requiring careful reconstruction of the crystallization process.

Determination of the Magma Chamber's Age

The magma chamber's age is established by determining the ages of the different volcanic rocks that come from it. Isotope methods can be used (K/Ar, Carbon-14, Argon-40/Argon-39, etc.; see for example Faure, 1986; González P. et al., 1991), or else paleomagnetism (see for example Boer, 1979), pyroclastic deposits chronology (tephrochronology, see for example Steen-McIntyre, 1977; Rieck et al., 1992) or rock-varnish chemical analyses (see for example Dorn et al., 1990).

Determination of the Magma Chamber's Temperature

The chamber's temperature can be inferred on the basis of studies of glass inclusions in phenocrystals (see for example Chapter 16 of Roeeder, 1984; Cortinin et al., 1985), or it can be estimated on the basis of petrological studies (see for example Carmichael et al., 1974; Tsukui, 1985).

2.1.3.2 Heat Transfer Modelling

The distribution and evolution of temperatures in the region between the magma chamber and the surface can be calculated using analytical or numerical mathematical models. In general, in calculating the thermal energy accumulated in a given interval of depths, it has been assumed that the heat of the magma chamber is transferred to surrounding rocks only by conduction. It would be much more realistic to incorporate the convection process in the calculations, but that is difficult to do given the lack of data on the properties of rocks at depth.

The physical characteristics of the magma chamber mentioned previously (temperature, dimensions, depth) are important but not sufficient to calculate the distribution of underground temperatures resulting from the conduction of heat between the magma chamber and the surface. The thermal properties of the rocks (conductivity, capacity) should also be specified, as well as initial conditions (temperature distribution) and surrounding conditions (boundaries open or closed to heat flows, areas with constant temperatures). Many of these parameters have to be assumed on the basis of the lithological characteristics of the zone and inferences. Elders et al. (1984) give an example of this type of calculation, as applied to Cerro Prieto.

The distribution of temperatures in the region located over the magma chamber changes over time as the chamber cools and the heat moves towards the surface. On the basis of the age and initial temperature of the magma chamber, it is possible to calculate the current temperatures in the upper levels of the crust where a geothermal reservoir supposedly lies. This in turn will make it possible to estimate the amount of heat currently built up in the reservoir.

2.1.4 Volume Method

The volume method is based on the calculation of the thermal energy contained in the volume of rock corresponding to the area under evaluation. The many authors that have described and used this method include Nathenson and Muffler (1975), Muffler and Cataldi (1978) and Brook et al. (1979).

The methodology described by Brook et al. to estimate the amount of electricity that could be generated by harnessing the fluids of hydrothermal systems having temperatures of over 150°C is presented here. This description will be limited to detailing the steps to be followed in evaluating geothermal systems of the liquid-dominated type, since they are more common worldwide. In Latin America, only one seems to be steam-dominated (Copahue, Argentina). Nathenson (1978) and Brook et al. (1979) provide further details on how the methodology described below was developed, and how to estimate the geothermal potential of steam-dominated systems.

The first step in determining the potential of a geothermal system consists of establishing the Accessible Resource Base (ARB), and then determining its Geothermal Resource (GR) and calculating the amount of electricity that could be generated from the latter.

It is worthwhile to stress once again that the values obtained using volume methods are only estimates. This is due to the fact that some of the parameters used in the calculations are inferred and may differ from those obtained in the future, once deep exploratory wells and/or development wells have been drilled and the results of tests and measurements have been analyzed.

2.1.4.1 Accessible Resource Base

The Accessible Resource Base (ARB) of a hydrothermal system is the amount of stored heat that can be reached by wells. This value is determined by calculating the thermal energy contained in a given volume of rocks and fluids (volume termed "the reservoir"), taking 15°C as the reference temperature. Considering the variety of characteristics that different regions of the crust may have within the area of interest, these regions can be subdivided as subvolumes.

That volume (or volumes) extends from the top of the reservoir to a depth of 3000 m. Brook et al. in 1979 considered that the high cost of wells deeper than 3 km tends to make them uneconomic, and generally speaking this premise remains valid. The ARB of Brook et al. corresponds to what White and Williams (1975) and Renner et al. (1975) called the "Resource Base". However, it differs from the ARB defined by Muffler and Cataldi. Brook refers to a given interval of depths whereas Muffler and Cataldi refer to the volume encompassed between the surface and a given depth (not necessarily 3 km).

In estimating the ARB, only the heat currently stored in the reservoir is considered, and it does not include any heat recharge that might exist. This is due to the lack of data and the uncertainty that exists with respect to the magnitude of a recharge during the lifetime of a geothermal project. The recharge can only be quantified in advanced project stages, once an appreciable number of wells has been drilled and reservoir modelling studies have been done. However, in those stages the ARB estimates are of secondary interest; it is much more important to design reservoir management plans that will optimize the exploitation of the geothermal system.

This means that, if a possible recharge is not taken into account during the project lifetime, the ARB calculated using the method of Brook et al. will correspond to a minimum heat value, which could prove to be higher once more details are available on the system.

Calculation of the Accessible Resource Base

The amount of thermal energy stored in the reservoir (q_y), in other words the Accessible Resource Base, is calculated using the following equation:

$$q_y = C_v * A * E * (T - T_r)$$

where:

q_y	=	thermal energy accumulated in the reservoir (J)
C_v	=	calorific capacity of the reservoir per unit of volume, including rocks and fluids ($2.7 * 10^6$ J/m^3 - °C)
A	=	area of the reservoir (m^2)
E	=	thickness of the reservoir (m)
T	=	temperature of the reservoir (°C)
T_r	=	reference baseline temperature (15°C)

Calorific capacity per unit of volume (C_v) is calculated considering characteristic values for geothermal reservoirs, using a porosity of 15% and a volumetric thermal capacity for the rock of $2.5 * 10^6$ J/m^3 - °C. The reference baseline temperature (15 °C) corresponds to the mean annual surface temperature in the United States (Brook et al., 1979). These values can be adjusted to the characteristics of the system to be evaluated.

Estimation of area.- According to Brook et al., the greatest uncertainty in estimating the ARB is associated with the area of the reservoir, which is usually inferred on the basis of available geological, geochemical and geophysical data.

In geothermal areas where the existence of a reservoir is based on the presence of a single thermal manifestation (or a group of thermal manifestations within a small zone), it is assumed that the most likely area is 2 km^2. If there is information on several such manifestations that have similar chemical characteristics and are located in an area with surface geology suggesting that they come from a single reservoir, the area is defined so as to encompass all of them.

In some cases, reservoir area at depth can be inferred on the basis of the size of the area showing hydrothermal alterations at the surface, the extent of the zone having high thermal gradients or heat flows, or the area of geophysical anomalies (for example, resistivity anomalies).

Calculation of thickness.- To simplify the estimate of a reservoir's volume, it is considered to have a uniform thickness. Due to the fact that the ARB calculations take a maximum depth of 3 km (unless there is information indicating otherwise), the bottom of the reservoir is assumed to lie at that depth.

In the prefeasibility stage, the location of the top of the reservoir can be inferred on the basis of the findings of geophysical studies or data obtained from multi-purpose wells, if they exist. Temperature logs for gradient wells are also very useful for this purpose. If this type of information were not available, Brook et al. propose that 1.5 km be taken as the most likely depth for the top.

Based on the foregoing, and assuming that the reservoir extends to a depth of 3 km, Brook at el. indicate that 1.5 km is the most likely reservoir thickness. There is usually less uncertainty regarding a reservoir's thickness than its area.

Estimation of temperature.- During the stages prior to feasibility, the reservoir's temperature is usually estimated using chemical geothermometers. These methods are based on reactions between rocks and fluids, which depend on temperature and control the chemical and isotopic composition of the geothermal fluids.

This document does not discuss the application of the various types of geothermometers and the precautions that must be taken when they are used since this subject has been covered in detail by many authors (for example, Henley et al., 1984; UNITAR/UNDP, 1991).

2.1.4.2 Geothermal Resource

The Geothermal Resource (GR) is only a portion of the ARB; it corresponds to the thermal energy that can be recovered from the system at wellhead, taking into account technological and economic factors.

Estimation of the Geothermal Resource

Due to physical, technical and economic reasons, not all of the thermal energy accumulated in the reservoir can be tapped. The Geothermal Resource (GR) of a liquid-dominated system is calculated using a Geothermal Recovery Factor (GRF) defined as the ratio between the energy that can be extracted at wellhead (q_{WH}) and the energy originally contained in the reservoir (q_y):

$$GRF = q_{WH} / q_y$$

This factor reflects the physical and technological constraints for the extraction of all the thermal energy accumulated in the reservoir (referring to 15° C) and therefore represents the efficiency of energy recovery.

For liquid-dominated systems, the GRF value is calculated on the basis of heat extraction models of the intergranular flow or sweep type (Bodvarsson, 1974; Nathenson, 1975). Figures Nos. 3 and 4 provide theoretical values for the GRF, as a function of reservoir temperature and porosity. Due to the non-ideal behavior of geothermal systems, in practice the recovery factors are lower; Nathenson and Muffler (1975) and Brooks et al. (1979) propose a GRF of 0.25.

A geothermal power plant converts part of the thermal energy contained in geothermal fluids into mechanical energy which is then used to generate electrical energy. Even under ideal conditions, during the conversion of thermal energy to mechanical energy (or work) some heat is always lost in the atmosphere. Based on thermodynamic principles, it can be shown that only a maximum amount of work, known as useful work (Wu), can be obtained from a certain amount of thermal energy.

For liquid-dominated fields, an approximate figure for the ideal conversion (or efficiency) factor (ICF) for transforming thermal into mechanical energy using a steam cycle can be obtained from the following equation (Paolo Liguori, personal correspondence, 1993):

$$ICF = (T - T_r)/(T + T_r + 546)$$

where T_r is the reference baseline temperature (in °C).

The results of the calculations done by Brook et al. and those obtained using the preceding formula are given in Figure No. 5, which plots the ratio between useful work (Wu) and thermal energy accumulated in the reservoir (q_y) versus reservoir temperature (T). The figure shows curves for average reservoir depths (Z_y) of 3 km and 1 km (from Brook et al., 1979), as well as curves for reference temperatures (T_r) of 15° and 40°C, respectively (Paolo Liguori, personal correspondence, 1993). It should be pointed out that these calculations used a recovery factor (GRF) of 0.25.

The electrical energy (E) that can be obtained from the useful work is given by the Utilization Factor (UF), which represents the efficiency of actual conversion with respect to ideal conversion, so that:

$$E = UF * Wu$$

This factor is less than one (1) due to the losses that occur during the conversion process, even with respect to the ideal conversion (ICF). The UF value depends on the fluid temperature and the work cycle used. Brook et al. have calculated the UF value for different reservoir or wellhead temperatures and cycles (Figure No. 6). For liquid-dominated systems with temperatures higher than 150°C, a UF value of 0.4 is considered to be representative. For such temperatures and steam cycles, the UF value varies between 0.5 and 0.6 (Paolo Liguori, personal correspondence, 1993).

The overall assessment process, from the Accessible Resource Base to available electricity, is illustrated in Figure No. 7, developed by Paolo Liguori (personal correspondence, 1993).

3. CONCLUSIONS

In the development of geothermal projects, one of the most important studies is the assessment of the energy potential (in MWe-years or GJ) and the economically useful lifetime of the field. In the more advanced stages of feasibility, field development and project operation, this is done by applying complex but reliable methods based on mathematical models that use information from surface studies and others. done in deep wells drilled in the reservoir.

In initial project stages (reconnaissance and prefeasibility), when the amount of information available on the geothermal system is limited, the potential of a possible reservoir can only be assessed using methods based on estimated dimensions, temperatures, porosities and other parameters; these data are not usually known accurately during the stages prior to feasibility and field development.

In the reconnaissance or prefeasibility stages, with only scant information available on the geothermal system, the energy potential can be "estimated" by applying one or more of the methods described in this document, using preliminary data on the system's geological conditions and certain physical and chemical parameters.

According to some authors, including Muffler and Cataldi, any of the four methods described herein would be simple to apply but would not be entirely satisfactory. However, there seems to be a certain preference for the volume method, which is the most rigorous and the most widely used.

Taking into account the fact that during the reconnaissance and prefeasibility stages of a geothermal project there are usually no deep-well data, when estimating the energy potential using one of the previously discussed methods it will be necessary to consider that the amount calculated may differ widely from the one actually obtained during the later stages of project development and, of course, exploitation. This is due to the lack of precision of the methods applied and to reservoir behavior, which can vary, among other reasons, as a function of the rate of system exploitation and the density of wells in operation.

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ANNEXES

Table No. 1
GEOTECHNICAL PROBLEMS THAT AFFECT THE COSTS OF A GEOTHERMAL EXPLOITATION PROJECT

PROJECT SITE

- Access.
- Climate/altitude.
- Erosion/instability of the terrain.
- Water supplies and other services.

WELL DRILLING AND/OR COMPLETION

- Unstable formations.
- High fluid pressures (especially at shallow depths).
- Zones with (frequent and significant) circulation losses.

FLUIDS

- High contents of salts and/or dissolved gases.
- Corrosion and/or incrustation (scaling) characteristics.

RESERVOIR CHARACTERISTICS

- Low formation permeability (low well productivity and/or injectability indexes).
- Rapid recharge of cold groundwater (entry of cold water in production wells).
- Precipitation of minerals in reservoir pores and/or fractures (reduction of porosity and permeabiltiy).

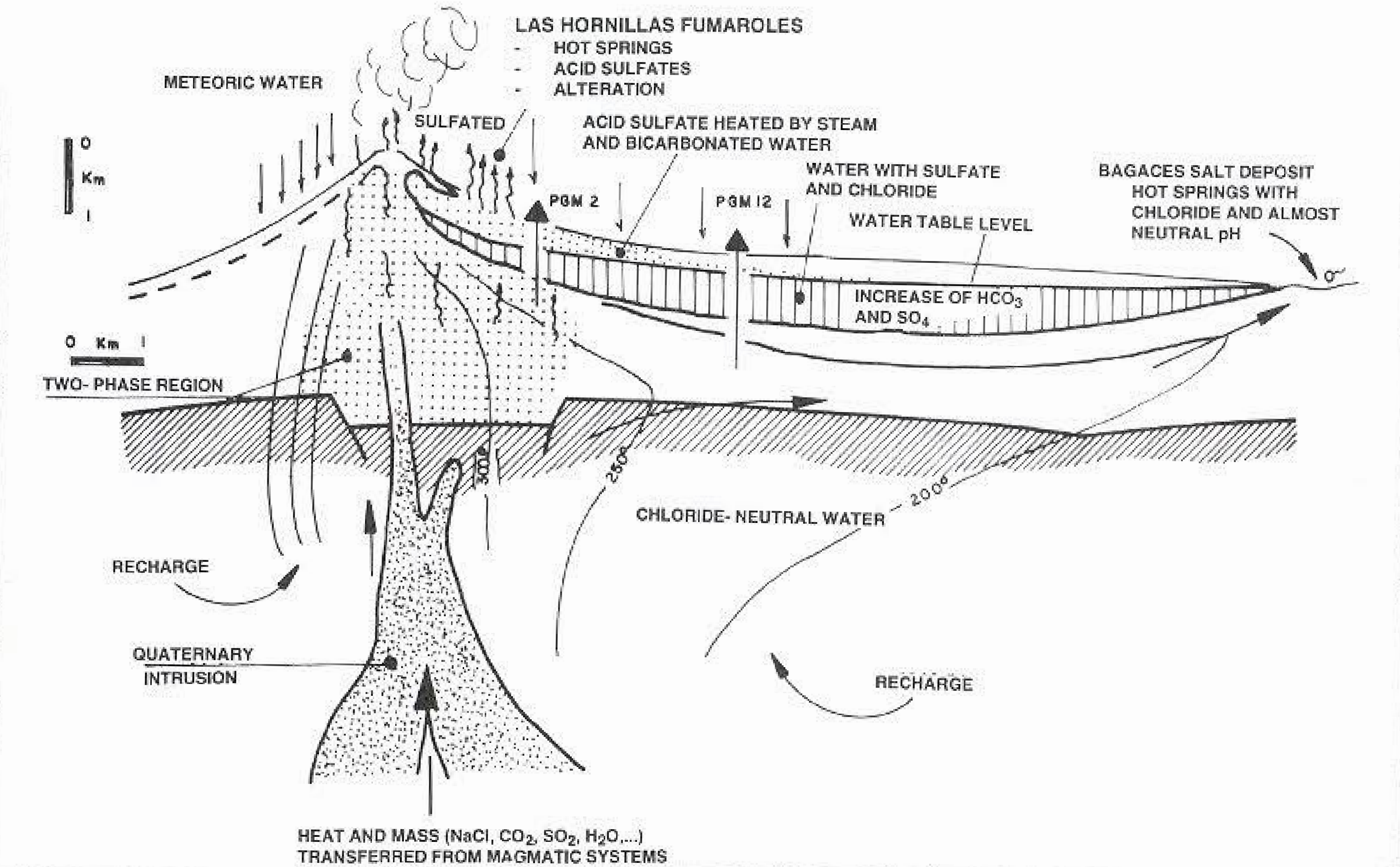
WELLS AND CASINGS

- Scaling.
- Corrosion.
- Collapsing or cracking.

ENVIRONMENT

- Pollution of aquifers or bodies or water due to brine disposal.
- Air pollution due to the discharge of noncondensable gases.
- Land settling.

FIGURE No. 1



Conceptual model of the Miravalles Geothermal Field in Costa Rica. Example of a geothermal system associated with a volcanic apparatus (from Grigsby and others, 1989; adapted in Henley and Ellis, 1983). The Las Hornillas fumaroles are located over the hottest part of the reservoir, whereas the Bagaces Salt Deposit hot springs are found in the system's discharge zone.

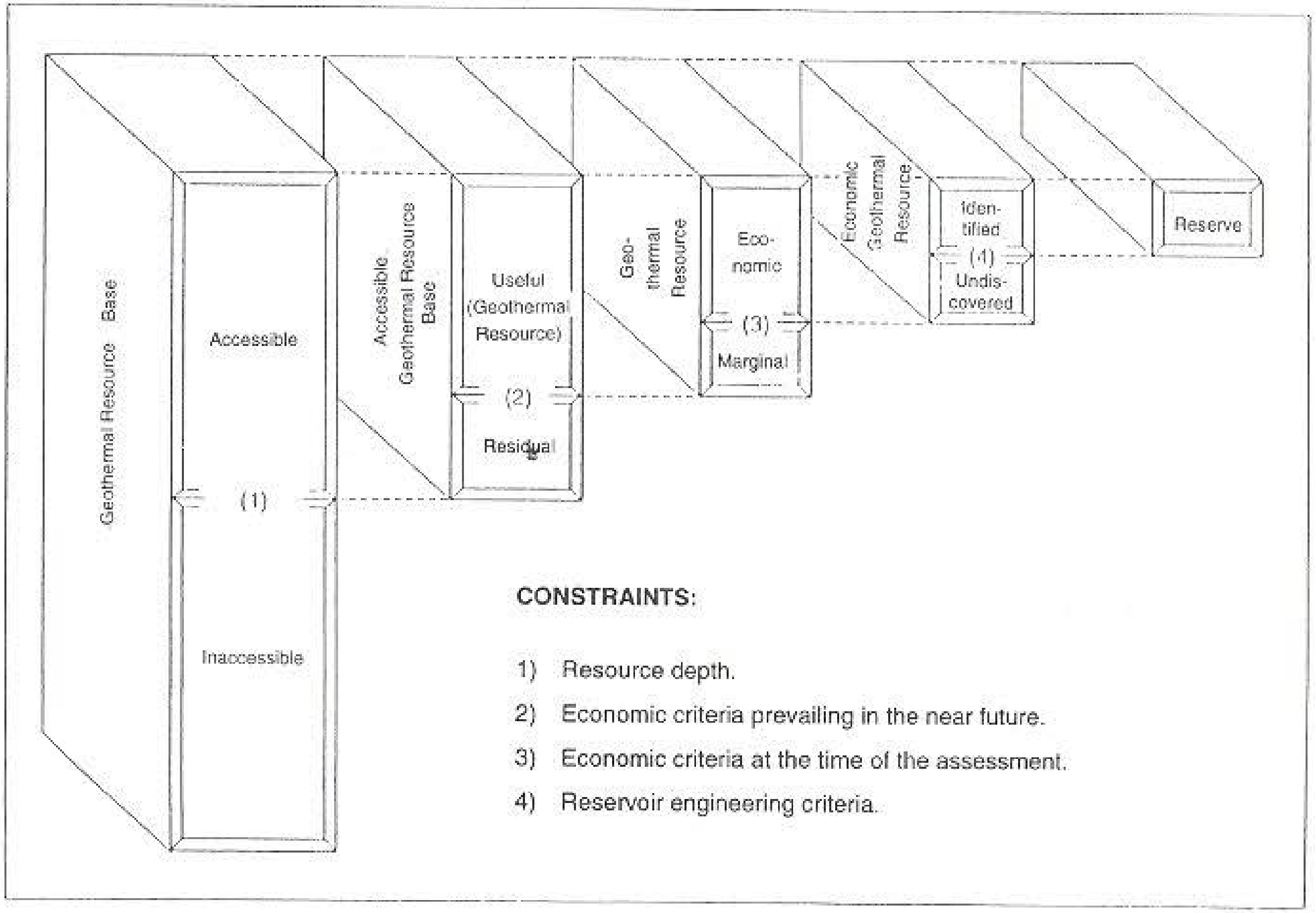


Figure No. 2

The Concept of Geothermal Reserve according to Technological and Economic Constraints

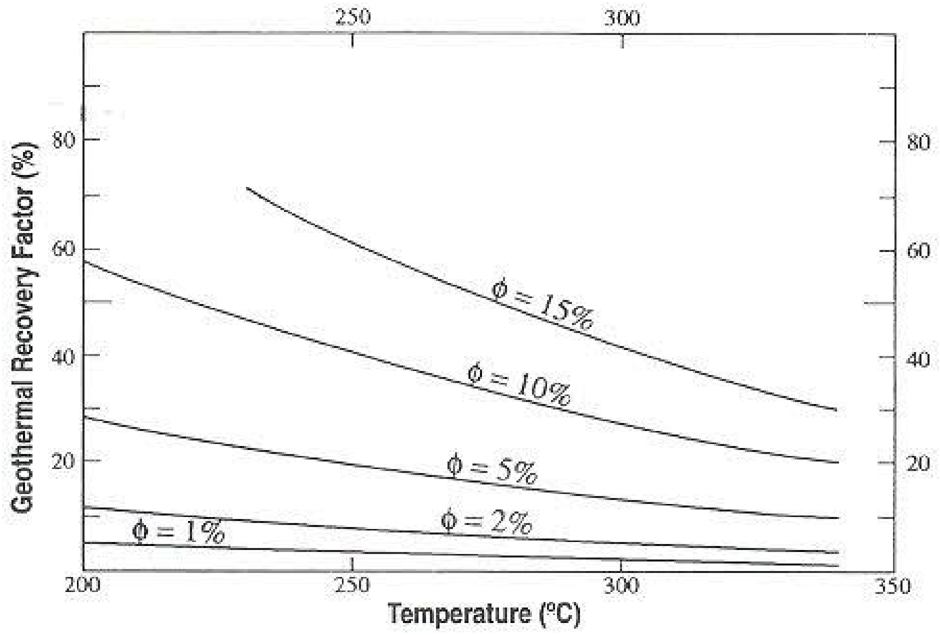


Figure No. 3

Theoretical Geothermal Recovery Factors (GRF), relative to 40°C, given as a function of temperature and porosity (ø), (from Muffler and Cataldi, 1978). These values should be considered as upper limits since the actual factors obtained in practice are lower.

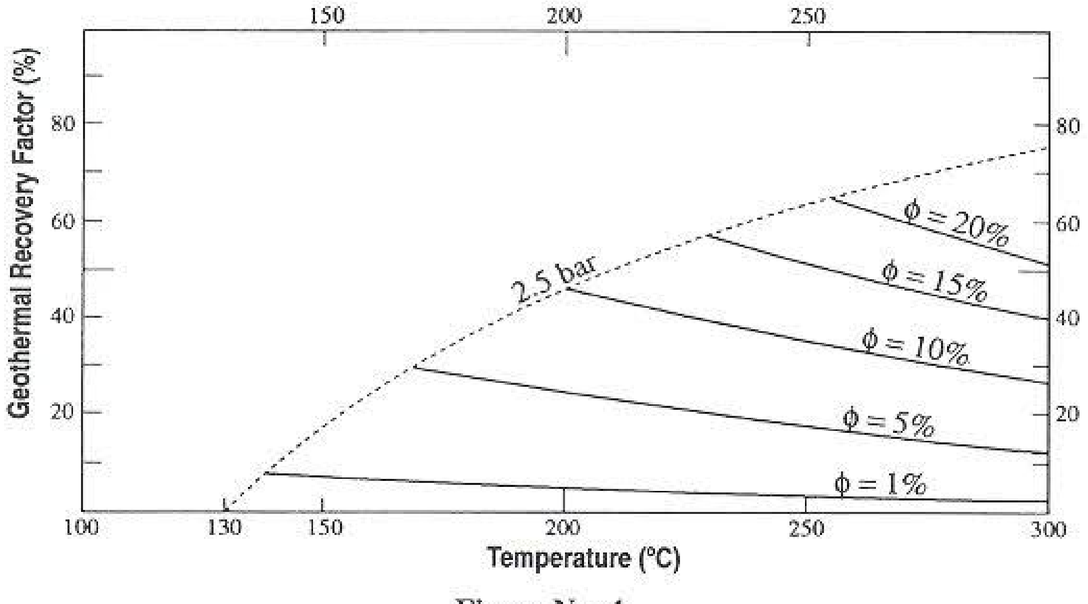
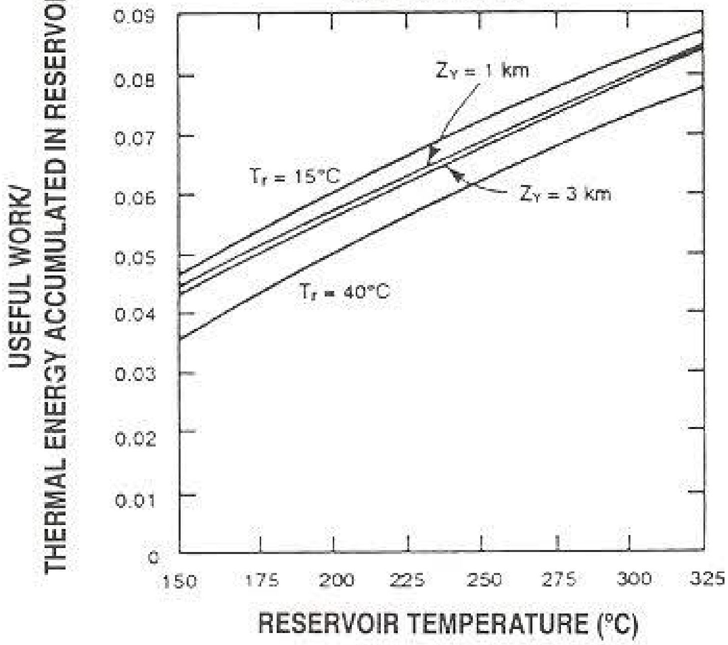


Figure No. 4

Theoretical Geothermal Recovery Factors (GRF), relative to 15°C, given as a function of temperature and porosity (ø). The dotted-line curve corresponds to a maximum final pressure of 2.5 bars (from Muffler and Cataldi, 1978). These values should be considered as upper limits since the actual factors obtained in practice are lower.

Figure No. 5



Ratio of Useful Work (Wu) and Energy Accumulated in the Reservoir (q_Y) versus Temperature, for geothermal systems of the liquid-dominated type. Two curves correspond to different average reservoir depths (Z_Y, from Brook et al., 1979) and another two to the different reference temperatures (T_r, from Paolo Liguori, personal correspondence, 1993). A Geothermal Recovery Factor of 0.25 was used to calculate Wu.

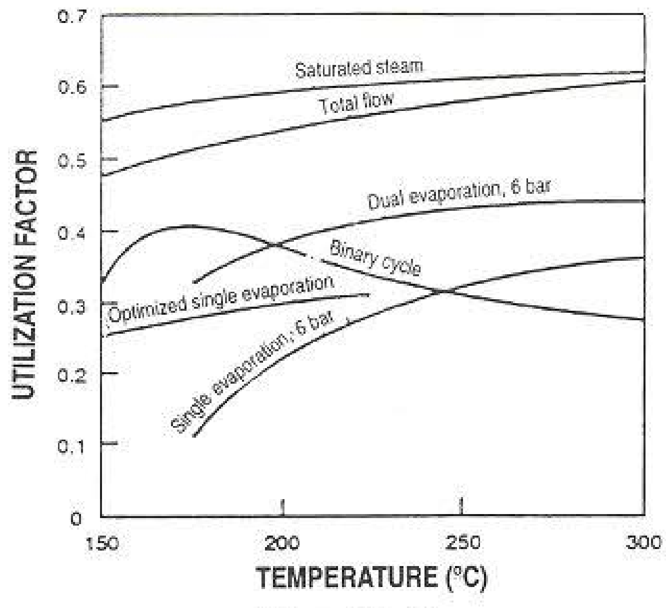


Figure No. 6

Utilization Factor (UF) for Different Electrical Work Cycles and Temperatures (The different cycles are shown to illustrate their behavior in general.) For saturated steam, the temperature is measured at wellhead. For liquid-dominated systems, the temperature corresponds to the wellhead enthalpy, considering that the fluid is liquid water. For all the cycles, the condensation temperature is taken as 40°C. For the single or dual instantaneous evaporation cycles, the first stage of separation is considered to occur at a pressure of 6 bars; in other words, those cycles are only appropriate for temperatures higher than approximately 200°C (Brook et al., 1979).

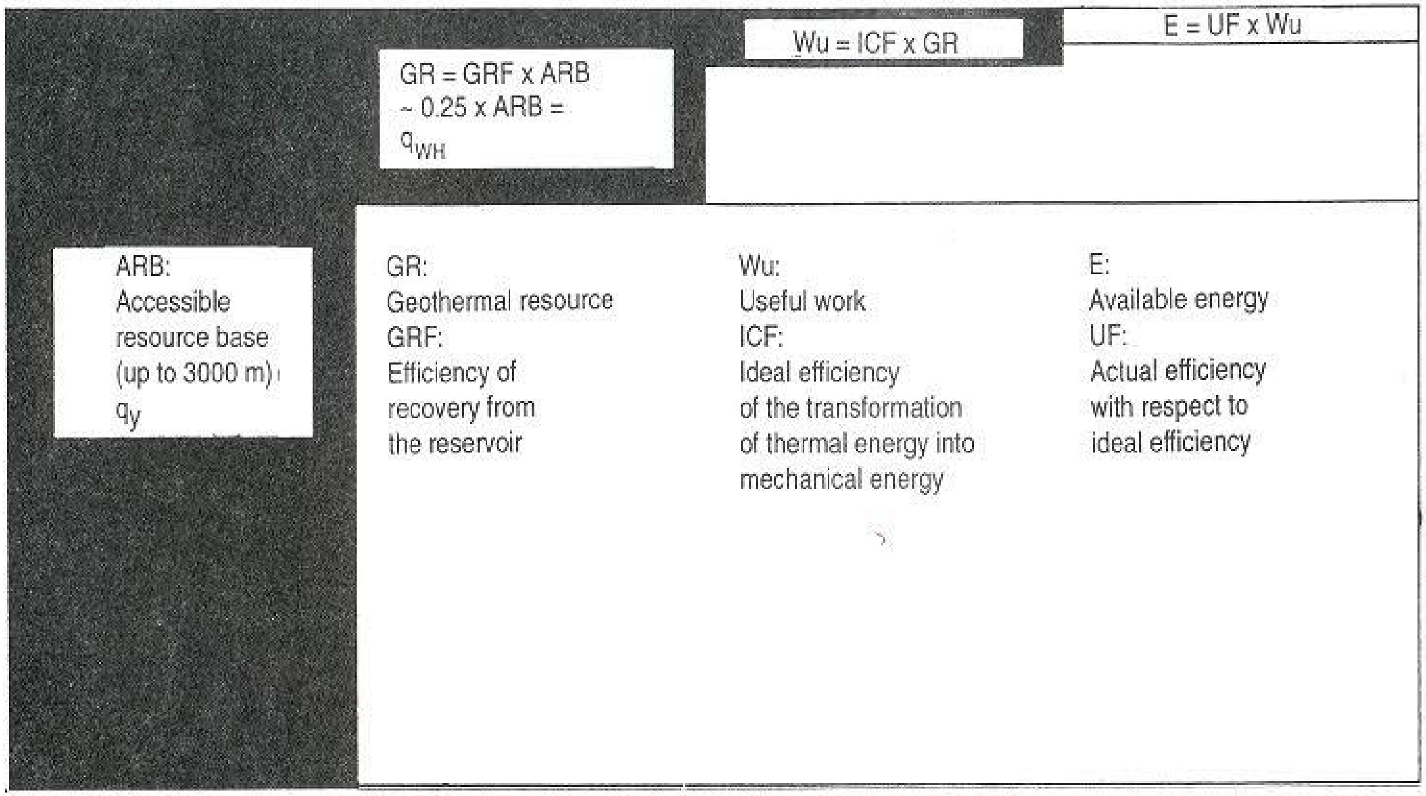


Figure No. 7

Overall Assessment of Energy Potential (from Paolo Liguori, personal correspondence, 1993)

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