THE SGP-CFE GEOTHERMAL HYDROGEN STUDY

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ABSTRACT

Excess baseload geothermal electric power could be used to manufacture hydrogen as an alternate automotive fuel, providing several synergistic economic and environmental health benefits. A study is underway as part of the DOE-CFE Geothermal Agreement to estimate the potential for producing hydrogen at geothermal fields in Mexico with low-cost excess capacity and the concomitant potential for air pollution abatement in the Mexico City metropolitan area. Case studies have been made for excess capacity at three scales: (1) small (10 MWe) at a new developing field as an experimental facility; (2) moderate (100 MWe) at Cerro Prieto as a demonstration project; and (3) large (1000 MWe) using the entire output of Mexico's geothermal resources for significant air quality improvement.

INTRODUCTION

Geothermal power plants, which contribute some 3000 MWe to the US electrical power supply, are best used as base-load facilities to avoid the thermal stresses that accompany repeated flow regulation of the production wells for load following. Usually, the resources are operated at constant power capacity and increases in the variable demand are met by fossil-fuel resources. Potential exists for "dual-purpose" geothermal power plants, as shown in Figure 1, to operate at greater constant power level not only to meet the peak demand but also to provide a continuous excess capacity to produce hydrogen as a transportation fuel. Several synergies exist between geothermal energy and hydrogen production:

(1) increased efficiency in the use of geothermal resources, providing a optimal balance between conversion to electricity for local grid use and manufacture of hydrogen for use in the transportation sector;

(2) stimulus for further geothermal resource development with the economy provided by hydrogen production at geothermal resources which would otherwise go under-developed or non-developed because of higher unit generation cost;

(3) improved efficiency of the electrolyser by preheating the feedwater with geothermal heat;

(4) increased environmental benefit by avoidance of fossil-fuel combustion to provide the variable peak demand capacity.

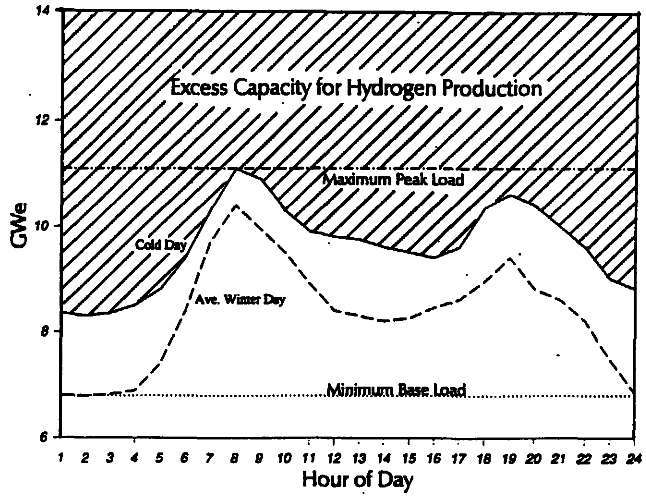

Fig.1. Daily demand curve for a 'dual-purpose' geothermal power plant operated at constant load well above daily peak demand to provide a continuous variable excess power capacity for production of hydrogen.

A joint study to examine the economic reality of this potential was initiated in 1992 by the Heat Extraction Project of the Stanford University Geothermal Program (SGP) and the Gerencia de Proyectos Geotermoelectricos of the Comision Federal de Electricidad (CFE) under the second of the two five-year DOE-CFE Geothermal Agreements. The study was focused on a small-size (10 MWe) hydrogen facility at the new geothermal field under development at Tres Virgenes in Baja California Sur where local demand is about 3 MWe. CFE plans are to install a small portable wellhead generator, currently supplied in units of 5-MWe capacity. The study has evolved over the past two years into a quantitative evaluation of two larger possibilities. The first is for a moderate-size (100 MWe) facility at the Cerro Prieto 620-MWe geothermal field to supply hydrogen for a large-scale demonstration project for hydrogen infrastructure development. The second is for a large-size (1000 MWe) national program to provide hydrogen for air quality improvement in the Mexico City metropolitan area. Conversion of the automotive fleet in Mexico City to hydrogen fuel would require more than the entire geothermal power capacity of Mexico.

Early evaluations of the potential of geothermal hydrogen from excess electric power capacity for use as a transportation fuel were reported by Fioravanti and Kruger (1994) and Kruger and Fioravanti (1995). Subsequent studies were carried out between SGP and CFE with specific data provided by CFE to further the evaluation of the three case studies. The preliminary results of these investigations are reported in this joint paper.

GEOTHERMAL HYDROGEN SYSTEMS

Hydrogen, although an abundant element on Earth, does not occur naturally in a free state to any recoverable degree, and therefore, must be manufactured for use as a fuel. Thus, hydrogen, like electricity, is produced with energy derived from other resources. Both hydrogen and electricity are energy carriers, means of storing and transmitting energy from one place to another. Several factors make hydrogen a more expensive form of energy, primarily that the conversion of a primary energy source to hydrogen introduces several conversion losses. Additional costs for infrastructure outlays are incurred during the switch to hydrogen due to the needed production facilities, delivery networks, and end-use technologies. Public willingness to pay a premium price is determined by factors such as convenience, cleanliness, and efficiency of use. Hydrogen has the potential to make up for possible cost disadvantages because of factors such as essentially zero emission of smog-forming, toxic, greenhouse, or other pollutants at end-use and the potential for significant improvement in epidemiological health in metropolitan areas.

A hydrogen energy economy generally consists of four building blocks:

(1) Production: where an energy resource is converted into hydrogen. Examples include electrolysis, biomass gasification, and direct fossil fuel production.
(2) Transport: where hydrogen is transported from production facilities to end-users. Examples include long-distance pipeline transport and local delivery to filling stations.
(3) Storage: where hydrogen is retained in large or small volume for later use. Examples include storage in underground caverns (large-scale) and as on-board fuel supply in vehicles (small scale).
(4) End-Use: where the potential energy in hydrogen is converted into useful work. Examples include vehicle propulsion and load leveling in electric power plants. For the joint study, the end use is supplying hydrogen fuel at a competitive cost (DeLuchi and Ogden, 1993) of $25/ GJ.

Production

The status of geothermal energy development in Mexico is reviewed by Gutierrez (1995). Geothermal power plants in Mexico are generally constructed as single-flash units at the many high-quality hydrothermal resources distributed throughout Mexico. Future power plants could be dual-flash or binary systems constructed for liquid-dominated or hot dry rock (HDR) geothermal resources, which are also abundant in Mexico.

The hydrogen production method selected for the SGP-CFE study is electrolysis of water as the most relevant for the geothermal power industry presently developed in Mexico. The advantages of electrolytic hydrogen include high product purity, flexibility of operation over a wide range of capacities, convenience for small applications, and valuable by-products (oxygen and heavy water). Currently, electrolytic production of hydrogen accounts for less than 1% of the existing hydrogen market, now dominated (95%) by ammonia producers, methanol producers, and refineries (Heydorn, 1990). However, niche markets for electrolytic hydrogen are expanding. These include production of hydrogen with off-peak electricity (Stucki, 1991) or from remote or intermittent sources of electricity (Braun, 1991), where lower electricity costs make the produced hydrogen economic.

The major capital equipment required for a geothermal hydrogen production facility is the electrolyser. Several types of electrolyser are available, including alkaline water electrolysers (AWE), solid polymer electrolysers (SPE), and high temperature electrolysers (HTE). Dutta (1990) provides a comprehensive and critical assessment of the most promising electrolyser technologies.

AWE is the technology presently used for large-scale electrolytic hydrogen production. It is a proven commercial technology, relatively simple, and does not require specialty materials. However, AWE technology is limited by low efficiency (77%-80%) and low current density as well as problems with a corrosive electrolyte (25%-35% KOH). SPE utilizes a solid ion exchange membrane, nafion, as an electrolyte. The strong nafion membrane eliminates the corrosive electrolyte of the AWE, and also allows for compact design, large current densities, and high pressure operation. Efficiencies of 85%-90% are reported. SPE has been adopted by the World Energy Network (WE-NET) program in Japan for extensive research. HTE achieves very high efficiency (90-100%) and uses water vapor as a raw material. HTE technology allows for geothermal preheating of the feedwater, thus reducing the cost of the produced hydrogen. Jonsson, et al. (1992) showed that a HTE using geothermal-heated steam at 200°C reduces the specific electricity requirement by 30% compared to conventional electrolytic processes, resulting in a reduced production cost of 19%. The cost components for a 100 MWe HTE are shown in Figure 2. It is noted that electricity costs comprise 60% to 70% of the total hydrogen cost.

The raw materials for electrolysers are pure water and electricity. A 100% efficient electrolyser requires 3.5 kWh of electricity to produce 1 normal (20 °C and 1 bar) cubic meter (Nm^3) of hydrogen. Electrolysis requires 1 liter of purified feedwater (and 24 liters of cooling water) per Nm^3 of H_2. A 10 MW electrolyser that operates at 90% efficiency for 1 hour will require 2.57 m^3 of feedwater and 61.7 m^3 of cooling water to produce 2570 Nm^3 of hydrogen.

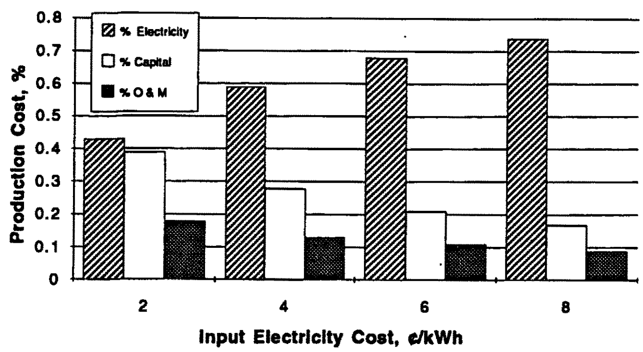

Fig.2. Component costs for capital, O&M, and electricity supply as a function of input electrical cost for a High Temperature Electrolyser (from Fioravanti, 1994).

By-products of hydrogen from electrolysis of water include oxygen and heavy water (HDO). Heavy water is used in CANDU-type nuclear reactors both as a neutron moderator and as a coolant). The Electrolyser Corporation (Stuart and Fairlie, 1994) developed the Combined Electrolysis and Catalytic Exchange Process to extract heavy water using electrolysis. For one hour of operation, it was estimated that a 100 MW AWE electrolyser would produce 16 tons of oxygen and 1.5 to 3.4 kg of heavy water in addition to 2 tons of hydrogen. By-product values range from $25 - $125 per ton of oxygen and $200 - $275 per kg of HDO.

Transport

Hydrogen is transported by pipelines in several industrial areas, such as Houston- Beaumont, Texas, Baton Rouge-New Orleans, Louisiana, and the Ruhr District in Germany. A general description of hydrogen transport in pipelines is given by Moore and Nahmias (1990). The hydrogen pipeline in the Ruhr District is a seamless steel pipeline 127 miles long with hydrogen at pressures of 225 to 600 psi; there are no compressors in this line. Pipelines in the US and Europe range up to 300 miles in length with diameters of 6 to 12 inches. At conventional pipeline pressures, the energy flowrate of hydrogen is about 25% less than the energy flowrate of natural gas through the same line. Fluor Daniel, Inc. (1991) estimated that an 8 inch pipeline would be sufficient to deliver hydrogen from a 100 MW electrolysis plant at a cost of $275,000 per mile.

Storage

Although hydrogen has a high heat of combustion per unit mass, it has a very low heat of combustion per unit volume. This creates a need for innovative technologies to store hydrogen. Technologies for hydrogen storage include compressed gas, cryogenic liquid, and chemical compounds such as metal hydrides. Hydrogen storage is needed on both small and large scales. Small-scale storage is required for end-use applications such as on-board storage for transportation applications. Important factors for small-scale storage are determined by the particular end use. Geothermal hydrogen systems require consideration of large-scale storage options. Large-scale storage is required to smooth out discrepancies between the rate of production and the rate of consumption. Key factors for large-scale storage of hydrogen are capital cost, storage efficiency, land requirements, and throughput rate (DOE, 1992). For small fleets, hydrogen can be stored at filling stations in steel pressure cylinders similar to those used in the chemical industry. For larger fleets, hydrogen can be stored more economically underground in depleted natural gas wells, aquifers, or caverns (Taylor, et al.,1986).

CASE STUDIES UNDER THE DOE-CFE GEOTHERMAL AGREEMENT

Mexico has an installed capacity of 753 MWe at its geothermal resources making it the third largest geothermal electricity country in the world. An additional 120 MWe of geothermal capacity are under construction. The potential for further commercial growth of geothermal electrical capacity in Mexico over the next 20 years was included in a survey of North American electric utilities (Kruger and Hughes, 1993). The SGP-CFE joint study on geothermal hydrogen is part of the DOE-CFE Geothermal Agreement between the United States and Mexico. The objective of the study is an evaluation of the technical and economic feasibility for developing sufficient excess electric power capacity for hydrogen production at selected geothermal fields under investigation by CFE. Three case studies are being evaluated as a function of excess capacity size:

(1) Small (2-7 MWe) at Tres Virgenes for local use
(2) Moderate (100 MWe) at Cerro Prieto for sale of hydrogen as a product
(3) Large (1000 MWe) for automobile fuel use in Mexico City for potential air pollution abatement.

Several economic parameters were set for the three case studies including a 10% discount rate and an amortization lifetime of 20 years. For the Tres Virgenes study, the cost of electricity was assumed to be 4 ¢/kWh, the average price of geothermal electricity in Mexico. For the Cerro Prieto case study, a range of 2 to 6 ¢/kWh was considered. Calculation of key parameters was based on the higher heating value of hydrogen, 142.4 MJ/kg, as generally used for liquid water as an end product.

A. TRES VIRGENES, BAJA CALIFORNIA SUR

The Tres Virgenes geothermal field is located in the middle portion of the Baja Peninsula, in the state of Baja California Sur (BCS), Mexico. The geothermal zone is approximately 35 km northwest of the city of Santa Rosalia. The population of BCS in 1988 was estimated at 327,000 (CNP, 1988) with a population density of 3 inhabitants per square kilometer. The Tres Virgenes field has been explored by CFE for several years with geological, geochemical, and geophysical studies in the area and drilling of several wells for reservoir testing and resource evaluation. The results indicate a commercial-size resource with a mean reservoir temperature of 265°C. The electric power potential of the explored region is about 18 MWe over an amortization life of 20 or more years, sufficient to satisfy about 30 % of local demand.

The Tres Virgenes field site has favorable characteristics for small-scale hydrogen production: small local population with a low load factor, no connection to outside electrical markets, and no indigenous fossil or hydropower resources. CFE plans for the Tres Virgenes geothermal field include the early installation of a 5-MWe portable generating unit. The site is interconnected to a small, isolated electricity grid and demand is projected to be 3.3 MW (Rangel, 1994). Operation of the 5 MWe unit for this demand would result either in a decreased conversion efficiency or an excess capacity of 1.7 MW. This prospect has led to two geothermal hydrogen scenarios for the Tres Virgenes field. One scenario consists of operating the 5-MWe generating unit as a "dual-purpose" unit with 3.3 MWe for meeting local demand and 1.7 MWe for producing hydrogen. The second scenario is the early installation of a second 5-MWe generating unit, with 3.3 MWe for local electricity demand and 6.7 MWe for hydrogen production.

In either scenario, the excess power capacity would provide sufficient hydrogen for an experimental facility to test prospective hydrogen-fueled vehicles under a full infrastructure development. Preliminary estimates of the cost of the electrolyser for both scenarios were obtained from the Electrolyser Corporation. The key parameters for the two scenarios under study are listed in Table 1. The data show that total hydrogen costs are somewhat higher than the target cost of $25/GJ, mainly due to the high electricity consumption by the low-efficiency electrolysers.

This case study highlights an important aspect of geothermal hydrogen; location of the hydrogen production facility. Production on-site provides an opportunity to use geothermal pre-heating in the process. Production at the utilization site reduces capital cost and efficiency losses associated with pipeline transport. Several factors in this case study suggest that hydrogen should be produced in the nearby city of Santa Rosalia rather than at Tres Virgenes. One factor is the large cost of a hydrogen pipeline for the low production volume. A second factor is the plan to install a transmission line to the city, making construction of a pipeline redundant. A third factor is the location of Tres Virgenes in an arid region, making the city a better source of feedwater for the electrolyser. Production of hydrogen at other geothermal fields will require similar consideration of site-specific conditions.

Table 1
Key Parameters for Experimental Facility at Tres Virgenes

	Facility Size (MWe) 1.7	Facility Size (MWe) 6.7
Production Data (AWE technology)		
Electrolyser reliability (%)	95	95
Electricity cost (¢/kWh)	4	4
Geothermal capacity factor (%)	81	81
Production at rated capacity (Nm^3/hr)	300	1200
Average Daily Production (Nm^3	5540	22160
(MMSCF)	0.196	0.783
(GJ)	71	283
Capital Costs ($ million)		
Electrolyser	1.25	4.00
Transport (not applicable)	0.00	0.00
Storage	0.31	1.23
Filling Station(s)	0.20	0.68
Total	1.76	5.91
Hydrogen Production Cost ($/GJ)		
Electrolyser	7.00	5.61
Electricity	18.65	18.38
Transport (not applicable)	0.00	0.00
Storage	1.50	1.50
Filling Station(s)	2.50	2.50
Total	29.65	27.99
Number of Automobiles Fuelled*	1420	5660
Water Requirements (m^3/ day) filtered	5.5	22
cooling	132	528

* for fuel cell powered vehicles with 74 miles per gallon fuel economy, driven 10,000 miles per year.

B. CERRO PRIETO, BAJA CALIFORNIA NORTE

The Cerro Prieto geothermal field in Baja California Norte (BCN) is located approximately 65 km south of Mexicali which borders Calexico, CA. It is one of the largest geothermal fields in the world and has been operational since 1973. The field has 620 MW of installed capacity in four generating units with another 80 MW under construction (Quijano, 1993). Currently, CFE is shipping 150 MWe to San Diego Gas and Electric Co. and 70 MWe to Southern California Edison under an international power contract that expires in January 1996, with an option for extension to 1997. The power is delivered via three 230 kV transmission lines (USDOE, 1992). It may be expected that shipment of additional electricity, or an equivalent amount of hydrogen, via pipeline, to the Mexico-USA border area would be feasible.

Under the SGP-CFE joint study, the potential for geothermal hydrogen production at Cerro Prieto is being evaluated for a capacity of 100 MWe. This scenario assumes production by High Temperature Electrolysis, with use of geothermal energy to preheat the feedwater. Based on HTE specifications given by Jonsson, et al. (1993), the average hydrogen production rate would be 498,000 Nm^3 of hydrogen per day. With shipment to population centers in Mexicali and Calexico, the available automotive fuel, after transport and storage losses, would be 5444 GJ of hydrogen per day. This is sufficient to power 110,000 fuel-cell passenger vehicles. Key parameters for this study are included in Table 2. The case study includes significant infrastructure for a local delivery network and filling stations entailing a large fraction of the capital cost. The total hydrogen production cost reaches the target cost of $25/GJ for the high-efficiency electrolyser.

The case study for Cerro Prieto also includes a scenario to use geothermal hydrogen in the Los Angeles metropolitan area to improve air quality. Calculations are underway on potential savings in epidemiological cost resulting from reduction in vehicle emissions. The savings could offset some of the higher cost of hydrogen. Further savings could result from avoided regulatory costs. In a study by the California Air Resources Board (CARB, 1992) the cost of air pollution regulations ranged between $2000 and $10,000 per ton of nitrous oxides (NOx) reduced and between $4000 and $10,000 per ton of reactive organic gases (ROG) reduced. From these data, the reduction in emissions of ROG and NOx for a fleet of vehicles fueled by hydrogen from Cerro Prieto would be 700 tons per year of each pollutant. With mid-range values of the avoided cost of air pollution regulations ($7000/ton for ROG and $6000/ton for NOx), the cost of hydrogen would be reduced by $5.16 per GJ. This potential credit would significantly enhance the economics of using hydrogen as a fuel.

C. MEXICO CITY AIR QUALITY IMPROVEMENT

Concentrations of ozone and particulates often exceed air quality standards in the Mexico City metropolitan area (LANL, 1993). Surrounding mountains and frequent thermal inversions trap these pollutants in the air basin. A air quality improvements have come slowly; regulated abatement programs have achieved only limited success. The major source of air pollution emissions in the Mexico City air basin is motor vehicles. They produce an estimated 70% of hydrocarbon emissions, 62% of nitrous oxide emissions, and 99% of carbon monoxide emissions (Gomez Diaz, et al., 1992). Clean transportation technologies, such as hydrogen vehicles, will be an important component of the overall plans to improve air quality in the Mexico City metropolitan area.

The third case study is the scenario for using all of Mexico's geothermal resources to produce hydrogen to fuel vehicles in Mexico City. The objective is to estimate the extent of air quality improvement that could be achieved. The forecasted geothermal capacity by the year 2005 (Kruger and Hughes, 1993) was 1200 MW, which could produce enough hydrogen to fuel 40% of the vehicle fleet in Mexico City. The potential reduction in emissions of nitrous oxides could be 10% to 25% and hydrocarbons 17% to 28% (Kruger and Fioravanti, 1995).

The distribution of geothermal resources in Mexico is important in determining which fields might produce hydrogen for use in Mexico City. The goal is to minimize transport costs for competitive distribution to the vehicle fleet. A recent review of the status of geothermal power in Mexico was given by Gutierrez (1995). Table 3 lists the presently installed geothermal electric power capacity in Mexico and planned additions through the year 2000. The expected total by 2000 almost meets the prior forecast for 2005. The total capacity for Los Azufres and Los Humeros, both within 150 miles of Mexico City, could supply enough hydrogen to fuel more than 300,000 fuel-cell passenger vehicles.

Figure 3 (from Gutierrez, 1995) shows the several locations of current geothermal exploration for new electric power capacity. Most of these resources are in the neovolcanic belt across Mexico, which includes the Mexico City metropolitan area.

Table 2
Key Parameters for Demonstration Project at Cerro Prieto

	Available Capacity (100 Mwe)
Production Data (HTE technology)	
Electrolyser reliability (%)	95
Electricity cost (¢/kWh)**	4
Geothermal capacity factor (%)	81
Production at rated capacity (Nm^3/hr)	27,000
Average Daily Production (Nm^3)	497,800
Energy Equivalent (GJ)	6368
Capital Costs ($ million)	
Electrolyser	75.9
Transport	11.0
Storage	17.9
Distribution and Filling Station(s)	102.0
Total	205.8
Hydrogen Production Cost ($/GJ)	
Electrolyser	6.64
Electricity	10.23
Transport	0.50
Storage	1.00
Filling Station(s)	5.70
Total	24.07**
Number of Automobiles Fuelled*	110,000
Water Requirements (m^3/ day) filtered	498
cooling	11,950

* for fuel cell powered vehicles with 74 miles per gallon fuel economy, driven 10,000 miles per year.

** Total production cost would be $18.96/GJ for electricity cost of 2¢/kWh and $29.19/GJ for electricity cost of 6¢/kWh.

Thus it is realistic to assume that some fraction of the electric power needed to build a hydrogen production industry near Mexico City could be obtained from the geothermal resources in the neovolcanic belt. The more distant resources could be used for other metropolitan areas, such as Cerro Prieto for southern California and La Primavera for the Guadalajara area in Jalisco.

CONCLUSIONS

Several synergies between the existing geothermal power industry and future hydrogen energy systems have been identified. Analysis of the three case studies provides support that hydrogen production with geothermal energy could stimulate development of both existing and new geothermal fields. Also important is the potential for other goals, such as environmental benefit, baseload operation of geothermal power plants, and high-efficiency hydrogen production. The worldwide distribution of geothermal resources suggests that hydrogen production with geothermal power could happen on a broad basis. The three case studies considered indicate that geothermal hydrogen production can be appropriate over a wide range of geothermal electricity capacity.

A further consideration is the mix of electric power sources that would provide an optimum benefit to a metropolitan area. The scenario of hydrogen use for transportation in Mexico City could incorporate a number of energy sources for hydrogen

Table 3
Geothermal Electric Power Capacity in Mexico*

Geothermal Field	Installed Capacity (MWe)	Planned Additions (MWe)	Total thru 2000 (MWe)
Cerro Prieto, BCN	620	165	785
Los Azufres, Mich.	98	130	228
Los Humeros, Pueb.	35	43	78
La Primavera, Jal.	0	50	50
Total	753	388	1141

* from Gutierrez (1995).

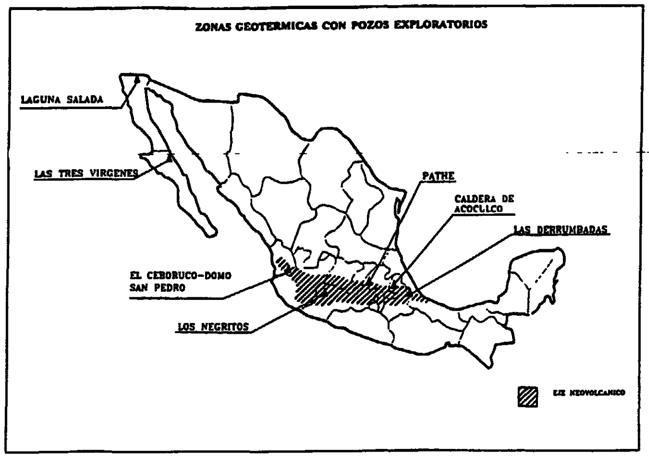

Fig.3. Geothermal areas in Mexico under exploration with drilled wells. (from Gutierrez, 1995).

production including non-electrolytic processes. Major factors are the cost of electricity from the primary energy sources, the delivery costs of transport to Mexico City, and the replacement of the electric power capacity.

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