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GEOTHERMAL ENERGY POTENTIAL IN TAIWAN

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ABSTRACT

This paper is a brief survey of the Chingshui geothermal field in Taiwan, including an overview of early exploration efforts, well testing programs, and production history. In order to study well productivity as related to finite-conductivity fractures, a presentation of results from potentiometric and finite-element models follows. It appears that this geothermal field has been vastly under-produced due to a sharp decline in well productivity. New tools and techniques are required to confirm a sustainable production rate in the Chingshui field. Hopefully, a second wave of deep-well drilling programs will further prove the potential of geothermal energy development needed to generate electric power in Taiwan.

INTRODUCTION

Taiwan has shown a continual interest in generating electric power from geothermal energy. Two recent articles have demonstrated the importance of the Chingshui geothermal field: The first reviewed the micro-earthquake seismic P and S wave velocity structures in the Chingshui-Tuchang geothermal area (Lin and Yeh, 2001); the second reviewed the interpretation of a well interference test at Chingshui (Fan, et al. 2005).

The exact production rate from Chinghui needed to sustain a power plant has been debated. This paper begins with a review of one early performance evaluation of the field's geothermal reservoir and development wells.

EARLY EVALUATION

Geology

The Chingshui geothermal field is located at about 20 km southwest of Ilan, a city in northeastern Taiwan. Geologically, this area is located at the northeastern end of a sub-metamorphic zone, extending nearly N-S along the mountain backbone of Taiwan. The slightly fractured Lushan formation of Miocene age is the predominant rock widely cropping out in this area, which can be litho-logically divided into the Jentse, Chingshui, and Lulu members. In general, the Jentse member is composed of metasandstones intercalated by slates, while the underlying Chingshui and Kulu members consist mostly of slates. The bedding of the Lushan formation strikes approximately NE-SW and dips generally to the SE at angles from 35 degrees to nearly vertical. The schematic diagram of a hydrothermal system is presented in Figure 1 (Chiang et al., 1979). The Chingshui geothermal area is located on a monocline structure, which is cut internally by several thrust and normal faults.

The most prominent set of joints strikes NW-SE and dips between 65 to 80 degrees to the SW. Chingshui River runs almost parallel to the strike of the joints. The riverbed has cut through the slates, where some well-developed patterns of joints are shown. There are numerous hot springs and fumaroles along the riverbed within the geothermal field. It is reasonable to infer that the riverbed is the area where some major and vertical fractures reach and open to the surface (Fan et al. 2005).

Thermal Gradient

This area was first selected by ITRI (Industrial Technology Research Institute) for the survey of geothermal resources in 1973. Fifteen shallow wells, ranging from 161m to 501m, were drilled. Temperature surveys carried out in these wells concluded that the shallow reservoir provided limited capacity, therefore the drilling of deep wells became necessary. A temperature gradient of 93C/km was established in this area, which was useful to set a TD of 2000 m for the deep wells (Lee et al. 1981).

Drilling and Well Completion

Starting in 1976, CPC (Chinese Petroleum Corporation) drilled 8 wells, ranging from 1505 m to 3000 m, to generate electric power while a 1.5 MW power plant was installed in the field. The drill sites were located on the riverbed. Except for the well

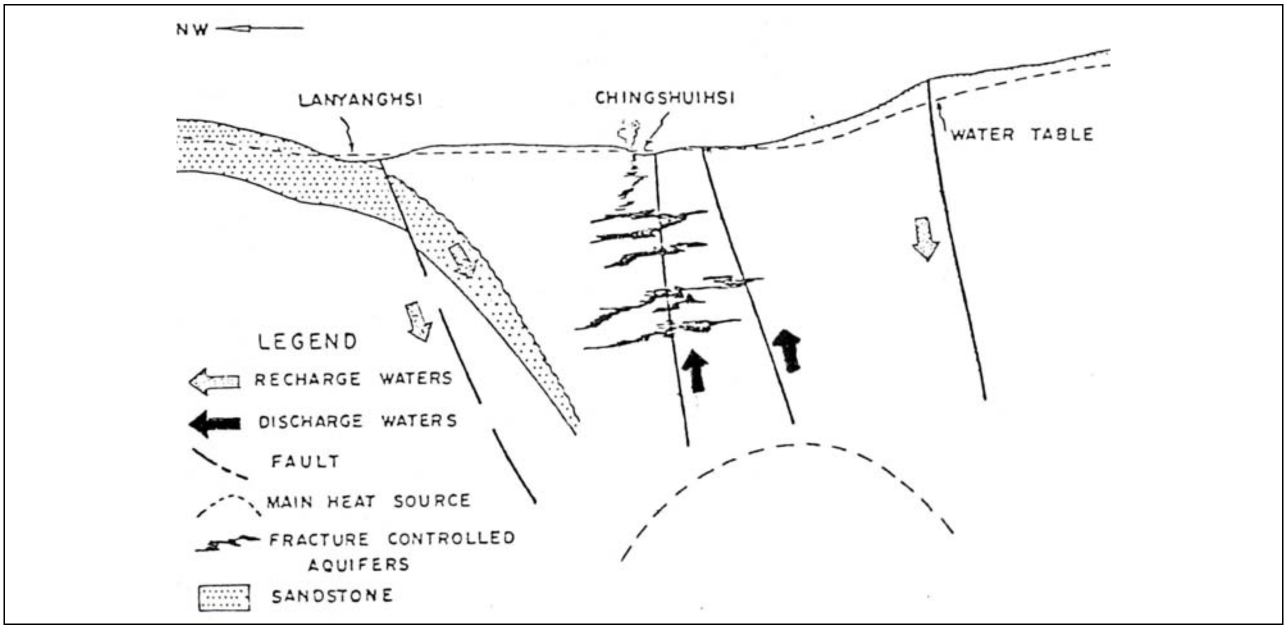

Figure 1 A Schematic Diagram of the Chingshui Hydrothermal System

15T, which was an exploration well drilled beyond the sandy Jentse member, all the other wells were deviated parallel to the predominant joints. Bentonite slurry treated with chrome lignosulfonate chemical was used for drilling mud, which was kept at a weight of 1.10 to 1.25 in gravity and 40 seconds in Marsh funnel viscosity. Heavy loss of mud circulation occurred when drill bits encountered major fractured zones. Temperature surveys were run at about every 500 m being drilled for evaluation of the reservoir temperatures and determination of the depths of running the production casing and slotted liners. Fresh water was injected and circulated to replace the drilling mud in the final stage of well completion. In each well, a 9-5/8in” production casing was set at either 500 m or 1000 m in depth and a 7” or a 4-1/2” slotted liner was followed to cover the 8-1/2” open hole. The length of a slotted liner in each well varies from 950 m to 2160 m (Chiang et al. 1979).

Well Productivity

In 1979, flow rates from 7 production wells were tested under a wellhead flowing pressure of 8 kg/cm**2 (114 psi). Table 1 presents a list of the individual well vapor and liquid rates, steam quality, and enthalpy.

It appears in Table 1 that, in general, the higher flow rate wells showed higher steam quality of 25% and lower rate wells showed lower steam quality of 15%. This difference in steam quality is due to the heat loss of hot fluids flowing upward from a long and un-insulated into the surroundings. All the surface flow lines in the field were insulated.

Table 1 Well Capacity from the Early Evaluation of Chingshui Wells

Well	Vapor (T/h)	Liquid (T/h)	Total (T/h)	Quality (%)	Enthalpy (kJ/kg)
4T	28.6	98.1	126.7	22.6	1182
5T	6.0	34.0	40.0	15.0	1026
9T	18.7	55.3	74.0	25.3	1239
12T	6.9	40.0	46.9	14.7	1020
13T	10.4	60.1	70.6	14.7	1020
14T	22.0	66.0	88.0	25.0	1231
16T	30.3	85.3	116.2	26.1	1254

Pressure Transient Tests

Again in 1979, CPC completed a large-scale well pressure transient testing program in the Chingshui geothermal field.

Pressure buildups

Well 4T was the first deep well drilled by CPC in Chingshui field. While drilling, a significant mud loss was noted from 750 to 800 m. In October 1976, after 133,000 tons of production, an initial pressure buildup test was conducted at the well. In September 1977, another pressure buildup test was run after 1.1 million tons of production. The tests and interpretation are found in the literature (Shen and Chang, 1979). When well 4T was flowing at 126 tons/day, a measured bottom-hole flowing pressure at 1500 m in the slotted liner was 1372 psia. This information combining with the flowing pressure-temperature vs. depth profile

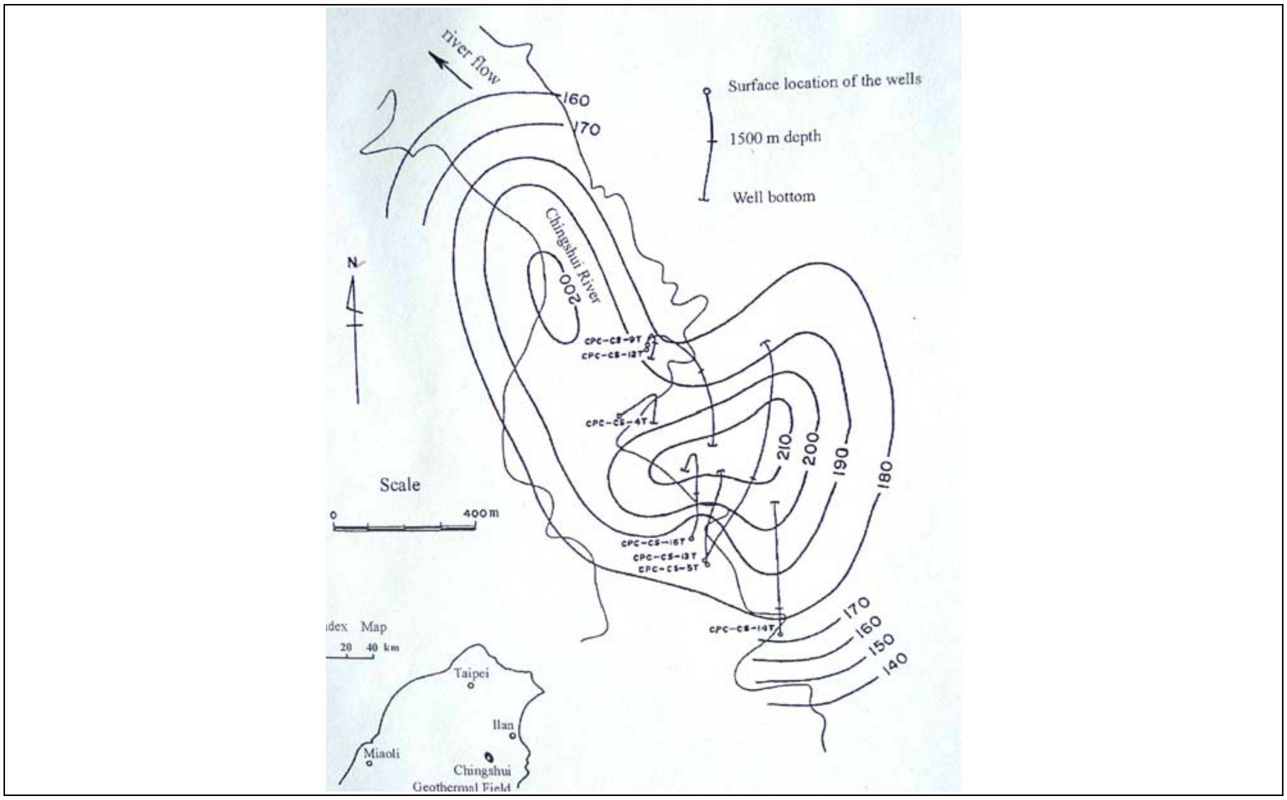

Figure 2   Surface Well Locations in Chingshui Geothermal Field

measured in the well clearly indicates that this geothermal reservoir is liquid-dominant.

Pressure buildups were also conducted at wells 5T, 13T, 14T, and 16T. An early interpretation concluded that the formation's flow capacity (kh) was in the order of 2.4 to 3 D-m. All wells had a large positive skin factor. There was no apparent reservoir pressure decline after a sustained production of these wells (Chiang et al. 1979).

Interference tests

In November 1979, when well 4T was on production, wellhead pressure responses were observed at wells 4, 5, 9, 12, 13, and 14T. Figures 2 and 3 show surface and bottom-hole well locations, respectively, in Chingshui field. Production rates of well 4T ranged from 80 to 84 tons/hour during the interference test. Some problems due to the release of inert gas to the 2" pipeline hampered the recording of pressure responses at the wellhead of well 13T and probably at well 5T. Pressure drops ranged from 11 to 18 psi were recorded at the wellheads by the end of the 11-day test, which implied these observation wells were responding to well 4T's production. A quantitative interpretation of this interference test from a type-curve matching technique can be found in the literature (Chang and Ramey, 1979).

An average of flow capacity, kh, of 3.7 D-m and a porosity-thickness product of 600 m were concluded. This porosity-thickness product was converted to estimate the producible amount of fluids from the reservoir and the equivalent amount of power to be generated for 35 years (Chiang et al. 1979).

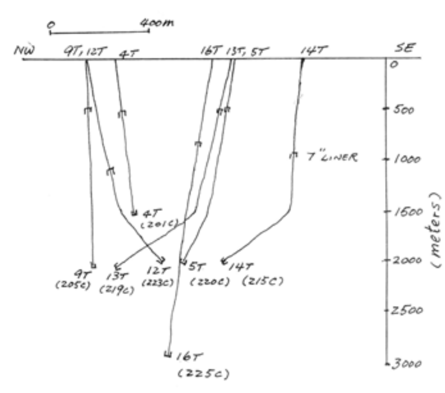

Figure 3   Bottom-hole Well Locations in Chingshui

Interpretation Models and Data Acquisition

The interpretation model applied by CPC to analyze these important pressure transient tests was the line source solution, which assumes a radial flow in a homogeneous porous formation of a constant thickness. In Chingshui field, all the production wells penetrated only one formation: Jentse member. It was difficult to assign a single value of formation thickness in the analysis. A spherical or semi-spherical flow model may be more realistic to interpret the tests.

Recently, a linear flow model has been applied to interpret the Chingshui interference test. Again, a constant formation thickness, h, was assumed. In comparing the results, the permeability-thickness product was much greater, 4 to 10 folds, yielded from the linear model rather than the radial model. But the average porosity-thickness product was 525 m from the linear model interpretation, which is an excellent comparison to the 600 m from the radial model results (Fan et al. 2005).

No production logging (PTS surveys, Mao 2000) was run to determine fluid entries into these long and slotted liners. The resolution of these wellhead pressure gauges might not have been enough to pick up small changes, especially when an inert gas was present and had to be bled off. As implied by different values of the initial wellhead shut-in pressures measured at the observation wells, the interference test may be improved by including initial transient and late transient effects when well 4T was shut in.

PRODUCTION DECLINE

In 1981, a 3 MW power plant was commissioned to operate on an experimental basis. A total of 4.5 MW power generation capacities were then available in Chingshui. Figure 4 presents the production history from the Chinghsui geothermal field. A sharp initial decline can be noted in the curve from 1981 to 1984. The production rates dropped from 300 tons/hr to 95 tons/hr, or an average of over 30% decline per year. Apparently, some efforts had been made to sustain the field production since 1984. However, in 1993, the plant ceased operations when the power output was only 0.18 MW. Scale deposits of calcium carbonates and silica were identified during well workovers. Non-condensable gases in the producing fluids, primarily carbon dioxide, amounted to over 10% by volume. Scaling was identified as the predominant reason for the decline in well productivity. A project has been initiated to resume Chingshui field production (Fan et al. 2005).

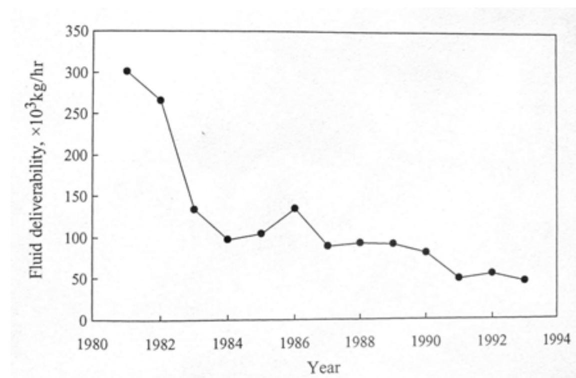

Figure 4 Chingshui Field Production Rates

WELL PRODUCTIVITY MODELS

The effectiveness of a fracture to support well productivity depends upon the fracture length, 2xf, fracture width, w, fracture height, hf, fracture permeability to flowing fluid, kf, and the fracture position in the reservoir.

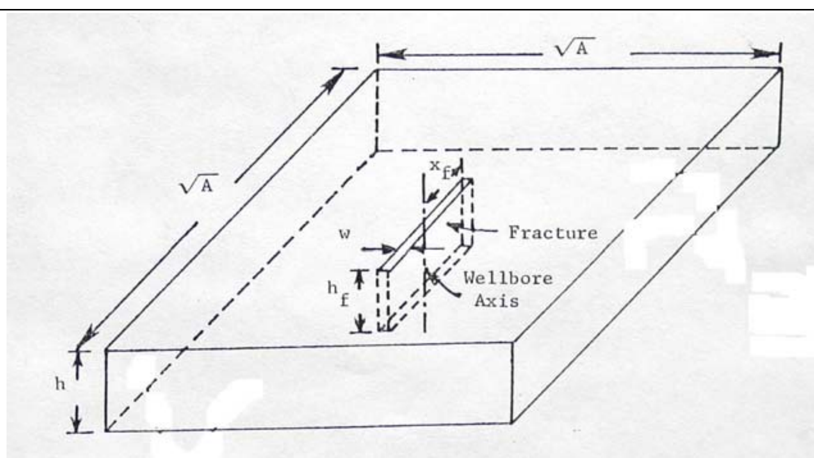

Figure 5 The Schematic Diagram of A Vertically-Fractured Well

Figure 5 schematically shows a vertically fractured well in the center of a squared drainage. If the fracture partially penetrates the well, the model is three-dimensional. If full penetration is assumed, it becomes a two-dimensional problem. In 1946, Muskat presented a solution: By assuming the fracture conductivity is infinite, the effective well radius, rw', is equal to one-half of the half-fracture length, xf, or

$$rw' = 1/2\ xf \qquad (1)$$

This equation was further proved in the pressure transient studies (Gringarten et al. 1974) and in this study.

The productivity of a well penetrated by a finite-conductivity fracture can be studied in the laboratory by using a potentiometric model or numerically using a finite-element model.

A Potentiometric Model

Figure 6 shows the instrumentation used in the laboratory for potentionmetric model measurements. An electrolytic tank was used to represent one-half of the well drainage area. The fracture dimension and fracture permeability were varied (Mao 1977).

A dimensionless effective well radius, rw'D is defined as:

$$Rw'D = rw' / xf \qquad (2)$$

And a dimensionless flow capacity ratio is defined as:

$$CR = (kf\ w) / (k\ xf) \qquad (3)$$

where k is the formation permeability. CR can be described as a ratio of the fracture's capacity to carry fluids into the well versus the formation's capacity to carry fluids into this fracture.

Figure 7 presents a plot of rwD' vs. CR from the potentiometric model studies in terms of dimensionless parameters, in which a single curve can represent a wide range of fracture lengths and fracture permeability. In cases of large CR, rw'D is exactly equal to 1/2. This curve may be used for the design and evaluation of Chingshui well stimulation treatments.

As a matter of interest, this model was applied to study the effects of plugging in fractures near a wellbore as shown in Figure 8, where FE is flow efficiency and sf is a fracture pseudo skin factor.

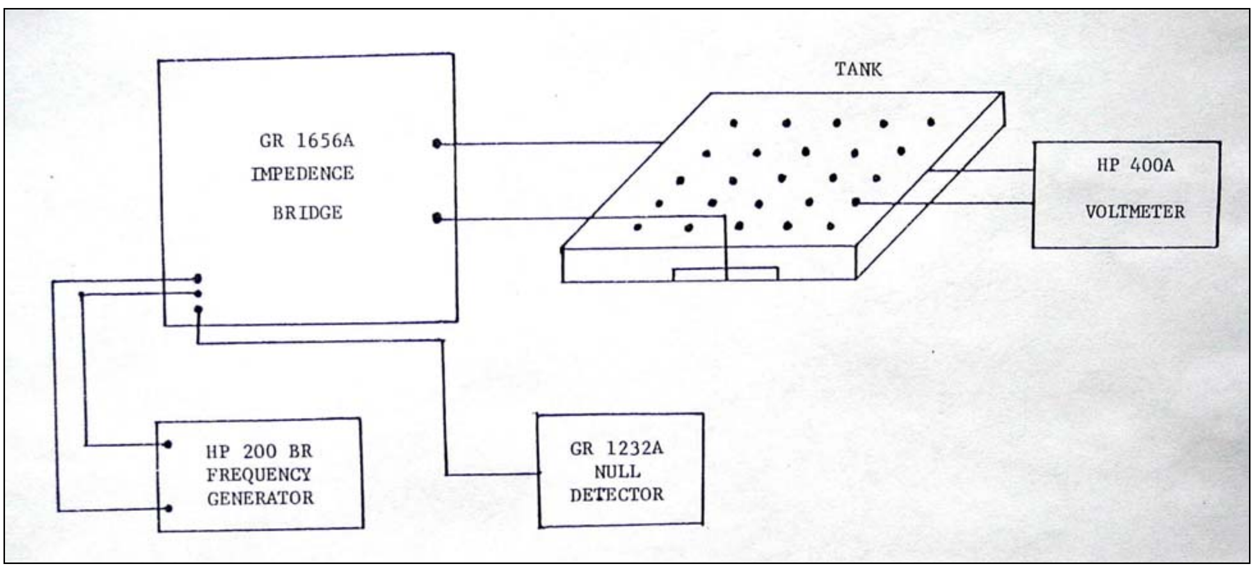

Figure 6 The Potentiometric Model Instrumentation

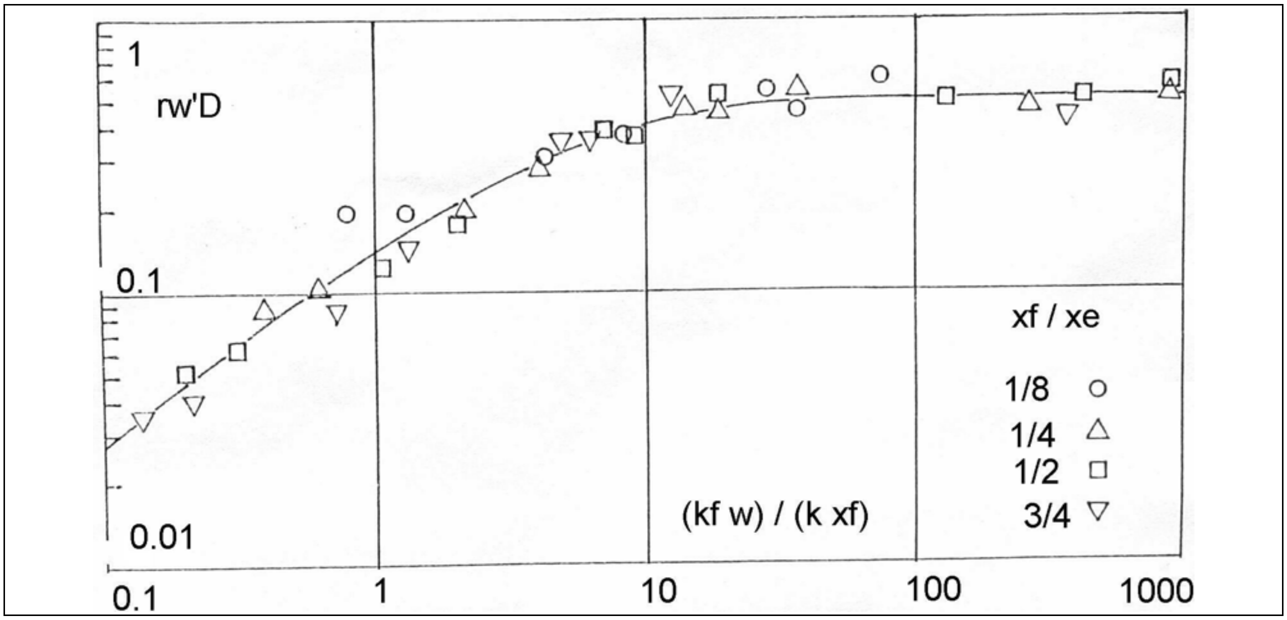

Figure 7 Dimensionless Effective Well Radius vs. Flow Capacity Ratio from Potentiometric Studies

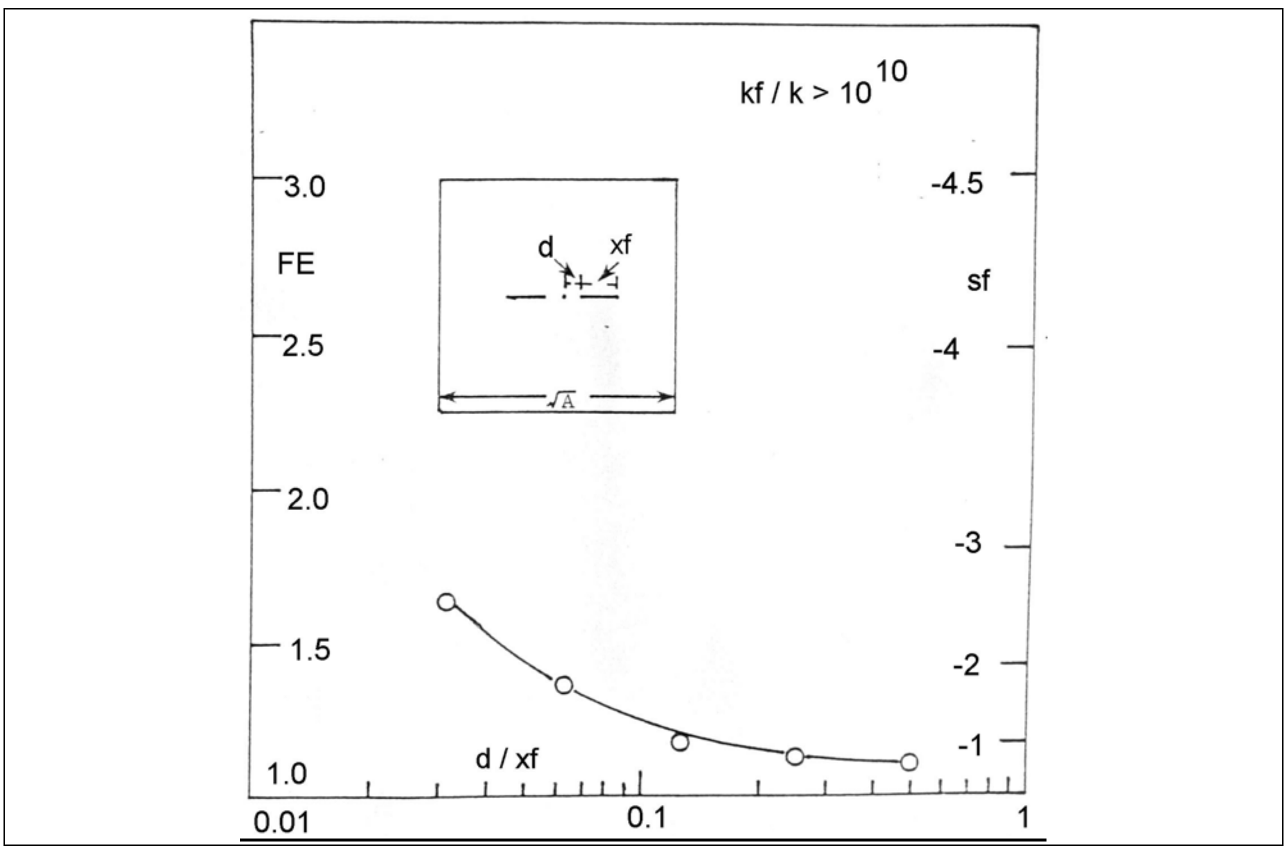

Figure 8 The Effects of Plugging in Fractures near the Wellbore

A Finite-Element Model

A numerical finite-element model was built to compare results. Its physical dimensions and finite-element distribution are shown in Figure 9. Results from the model runs are presented in Figure 10, an excellent comparison with Figure 7 (Mao 1977).

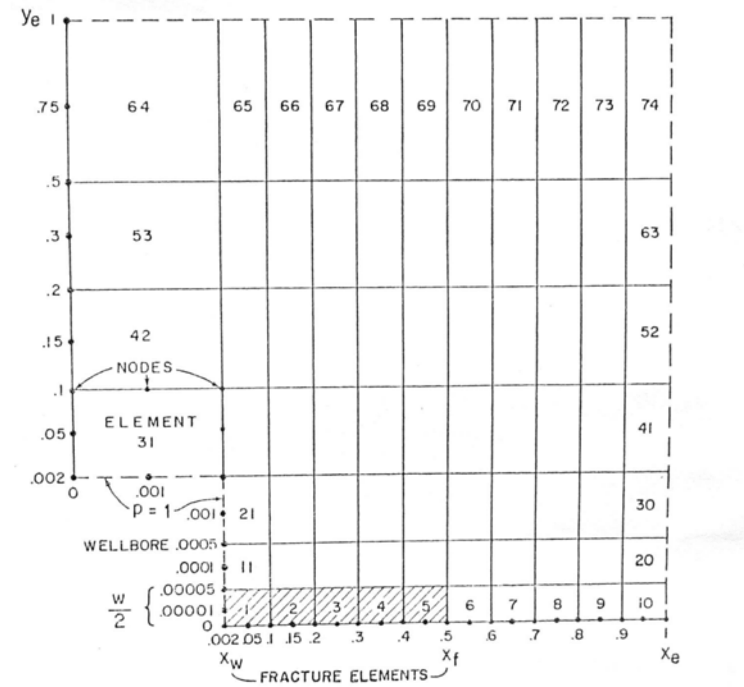

Figure 9   The Finite-Element Model Dimensions and Element Distribution

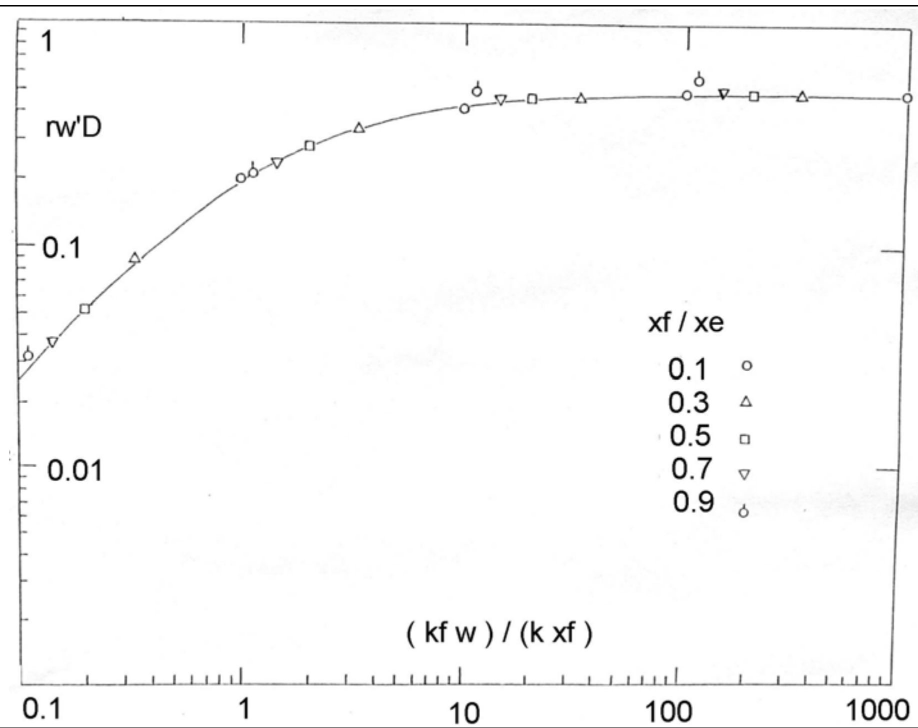

Figure 10   Dimensionless Effective Well Radius vs. Flow Capacity Ratio from Finite-Element Studies

CONCLUDING REMARKS

It is important to review the entire reservoir and well performance information in Chiangshui geothermal field. New tools and techniques can be identified for the design, execution, and evaluation of a program in order to resume and sustain the field production rate. Investigations from a potentiometric model and a finite-element model can demonstrate the effectiveness of well productivity penetrated by finite-conductivity fractures in geothermal reservoirs.

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