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RESERVOIR ASSESSMENT OF THE MAK-BAN GEOTHERMAL FIELD, LUZON, PHILIPPINES

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ABSTRACT

The Mak-Ban geothermal field has been under commercial operation since 1979. The National Power Corporation (NPC) produces bulk electricity from its 330 MW_e geothermal power plant complex with the Philippine Geothermal, Inc. - Union Oil of California (PGI-UNOCAL) as steam field operator. It is one of the major base-load power plants in the Philippines and contributed 10% of the country's total energy requirements from 1980-89. It is also a reliable plant and achieved the best plant factor of 80% for all power generating plants during the same period.

In this report, an attempt is made to assess the extent and nature of the Mak-Ban geothermal field. By using three different reservoir assessment methods, i.e. volumetric, lumped modelling, and in-situ boiling to available field data, the generating capacity of the field for 30 years was estimated and predictions made for the pressure drawdowns for different production rates in the future. According to this assessment, the Mak-Ban reservoir will supply steam for the current installed plant capacity of 330 MW_e for at least 30 years, or up to 2010, as the plant has already been in operation since 1979.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The author was granted a six-month Fellowship at the United Nations University Geothermal Training Programme (UNU-G.T.P.) at Orkustofnun - National Energy Authority, Reykjavik, Iceland beginning April 24th, 1992. The course aimed to provide each fellow with sufficient knowledge and practical expertise to work independently within a select geothermal discipline for application in his institution and home country. It consisted of lectures on exploration, development, production and utilization aspects of geothermal energy, together with seminars and area excursions to different low and high temperature geothermal areas of Iceland. The author also attended the specialized course on reservoir engineering with the following subjects:

- Reservoir engineering/assessment, geothermal modelling (simple, numerical);
- Well testing, analysis, design, and monitoring;
- Well logging, borehole geophysics (thermal conduction, heat flow, temperature logs, pressure logs, lithological logs, miscellaneous logs);
- Reservoir physics, two phase reservoirs and wells, fluid chemistry and utilization;
- Monitoring of geothermal areas, injection and tracer tests, modelling and utilization case histories, etc.;
- Computer program applications, etc.

For the completion of this course, the author is submitting a research report on the Mak-Ban geothermal field in Luzon, Philippines. The National Power Corporation, the author's agency, currently operates a 330 MW_e plant complex in the area. These plants exhibited the best performance of all power generating power plants in the country from 1980-89. It has consistently supplied the electrical requirements of the Luzon grid, the premier island and site of the most extensive power users in the Philippines.

The NPC's energy policy is geared towards the supply of electricity from reliable, readily available, economical and optimal performance of its generating power plants. The Mak-Ban plants have consistently shown these characteristics since they started their operations. The NPC is, therefore, concerned about the present and future performance of these plants. The Mak-Ban reservoir is projected to provide the steam requirements of the plants for its economical life of 25 years. It is foreseen that the good performance of the Mak-Ban reservoir, coupled with a better performance of the power plants, will alleviate and provide the much needed power requirements of the country.

This report describes reservoir analysis of data from the Mak-Ban geothermal field. Based on general information on the field, stored-heat calculations were carried out in order to assess Mak-Ban's generating capacity. Production and pressure drawdown data were used in lumped parameter modelling and the future pressure response of the field was predicted. Finally, some simple calculations were carried out in order to understand the induced boiling in the formation as fluid is withdrawn from the reservoir.

2. GEOTHERMAL OPERATIONS IN THE PHILIPPINES

2.1 Geological framework of geothermal resources

The Philippine Archipelago, together with the island arcs and land masses that border the Pacific Ocean, comprise the Circum-Pacific "ring of fire", so-called because of the active volcanism in the area. Such volcanoes, together with the spatially and causally correlated earthquakes, are manifestations of the convergence of huge blocks or plates of the earth's crust. These crustal plate movements brought by persistent volcanic and seismic activities incessantly shape and alter the islands along structural lines defining the active blocks in the geologic structure of the Philippine Archipelago.

Plate tectonics and attendant volcanism resulted in geothermal areas that produce sufficient heat suitable for commercial exploitation. It is believed that these geothermal energy resources can provide the bulk of the energy requirements of the country and considerably reduce over-dependence on oil and other fossil fuels (Gazo and Datuin, 1990).

2.2 Geothermal energy development

Even before the energy crisis of 1973, the Philippines focused its attention on the development of local and cheaper energy sources (e.g. geothermal energy) needed for economic development and progress. With the successful production of electricity from geothermal steam in Tiwi, Luzon in 1969, the government realized the value of geothermal energy. Since then it has advocated its national policy of developing, exploiting and utilizing its abundant and untapped geothermal resources in the country (Table 1).

The Philippines started its commercial operation of a 3 MW_e geothermal pilot plant at Tongonan Leyte in 1977 and since then has become the second largest geothermal electrical energy producer in the world by 1990 (Table 2). Currently, the National Power Corporation (NPC), a government owned corporation, produces bulk electricity from the Tiwi and Mak-Ban geothermal power plants in Luzon, with the Philippine Geothermal, Inc. - Union Oil of California (PGI-UNOCAL) as steam field operator. NPC also operates the Leyte (Tongonan) and Negros (Palinpinon) geothermal power plants in Visayas, with the Philippine National Oil Company-Energy Development Corporation (PNOC-EDC) - also a government owned agency - as steam field operator (Figure 1).

2.3 Review of geothermal operations

A review of the operational performance of NPC power plants revealed that in 1989, the installed geothermal generating capacity was 888 MW_e or 15% of the country's total installed power plant capacity of 6,000 MW_e. These plants generated 41,400 GWh or 22% of the country's total electricity requirements at a total plant factor of 60% from 1980-89. This amounted to savings of 70 million barrels (700 million US$) of oil consumption (Table 3).

The 330 MW_e Mak-Ban geothermal power plants contributed 10% of the total energy requirements of the country from 1980-89. It is one of the top base-load power plants in the country and has the highest plant factor, 80%. It also accounted for a savings of 31 million barrels (310 million US$) of oil equivalent importations during this period.

TABLE 1: Philippine geothermal energy reserves (Datuin and Roxas, 1990)

Field name	Installed (MW_e)	Proven (MW_e)	Probable (MW_e)	Potential (MW_e)
A. LUZON				
1. Mak-Ban	330	387	440	800
2. Tiwi	330	330	250	250
3. Bac-Man	-	140	80	220
4. Batong-Buhay	-	150	350	350
5. Mt. Pinatubo	-	-	200	300
6. Irosin-Bulusan	-	-	-	30
7. Mt. Labo	-	-	400	1000
8. Daklan	-	-	-	50
9. Buhi-Isarog	-	-	160	-
10. Acupan	-	-	-	34
11. Mt. Natib	-	-	-	160
Sub-total	660	1007	2040	3194
B. VISAYAS				
1. Tongonan	112.5	400	800	1200
2. Palinpinon	115.5	224	283	372
3. Biliran	-	7	283	372
4. Mambucal	-	1	1	-
5. Baslay-Dauin	-	1	20	30
6. Anahawan	-	-	160	160
7. Burauen	-	-	330	330
8. Bato-Lunas	-	-	160	160
Sub-total	228	633	2037	2624
C. MINDANAO				
1. Mt. Apo	-	-	160	160
2. Malindog	-	-	160	160
3. Amacan	-	-	916	350
Sub-total	-	-	1236	350
TOTAL	888	1641	5313	6168
UNDISCOVERED RESERVES				1000-2000
APPROXIMATE TOTAL POTENTIAL				8000

Proven reserves:	Potential MW_e under well head but not yet utilized or proven by reservoir testing.
Probable reserves:	Sites whose geological and geophysical data give assurance that the well will extend beyond the currently tested wells.
Potential reserves:	Identified and tested plus unidentified reserves likely to be discovered by the year 2000.

TABLE 2: Installed geothermal power plant capacities in the world in MW_e (Huttrer, 1990)

Country	Year	
	1980	1990
1. United States	1,444	2,770
2. Philippines	894	888
3. Mexico	425	700
4. Italy	459	545
5. New Zealand	167	283
6. Japan	215	215
7. Indonesia	32	142
8. El Salvador	95	95
9. Nicaragua	35	70
10. Kenya	45	45
11. Iceland	41	45
12. Turkey	21	21
13. China	0	21
14. Soviet Union	11	11
15. France	4	4
16. Portugal (Azores)	3	3
TOTAL	3,891	5,823

TABLE 3: Data on power plant operations in the Philippines, 1980-89 (NPC, 1990)

Plant type / Name	Installed capacity (MW_e)	Rel.instal capacity (%)	Generated electricity (GWh)	Generated electricity (%)	Plant factor (%)
Total Phil.	6007	100	191900	100	40
Oil-Based	2582	49	91500	48	40
Malaya	650	11	2900	15	55
Hydro	2130	29	48500	25	40
Binga	100	2	4500	2	50
Coal	405	7	10500	5	50
Batangas	300	5	9300	5	60
Geothermal	888	15	41400	22	60
Mak-Ban	330	5.5	18800	10	80
Tiwi	330	5.5	18000	10	70
Negros	115.5	2	1900	1	40
Leyte	112.5	2	2700	1	40

Total savings from Mak-Ban geothermal power plants, 1980-89 = 31 million barrels of oil equivalent = 310 million US$(@ 10 US$ / bl of oil)

Plant factor = [(gross gen. cap.)/(rated capacity x days per year x 24 hrs)] x 100)

Typical plant factors (%): Hydro = 30-50 Oil thermal = 75
Diesel = 70 Geothermal = 75
Coal = 70

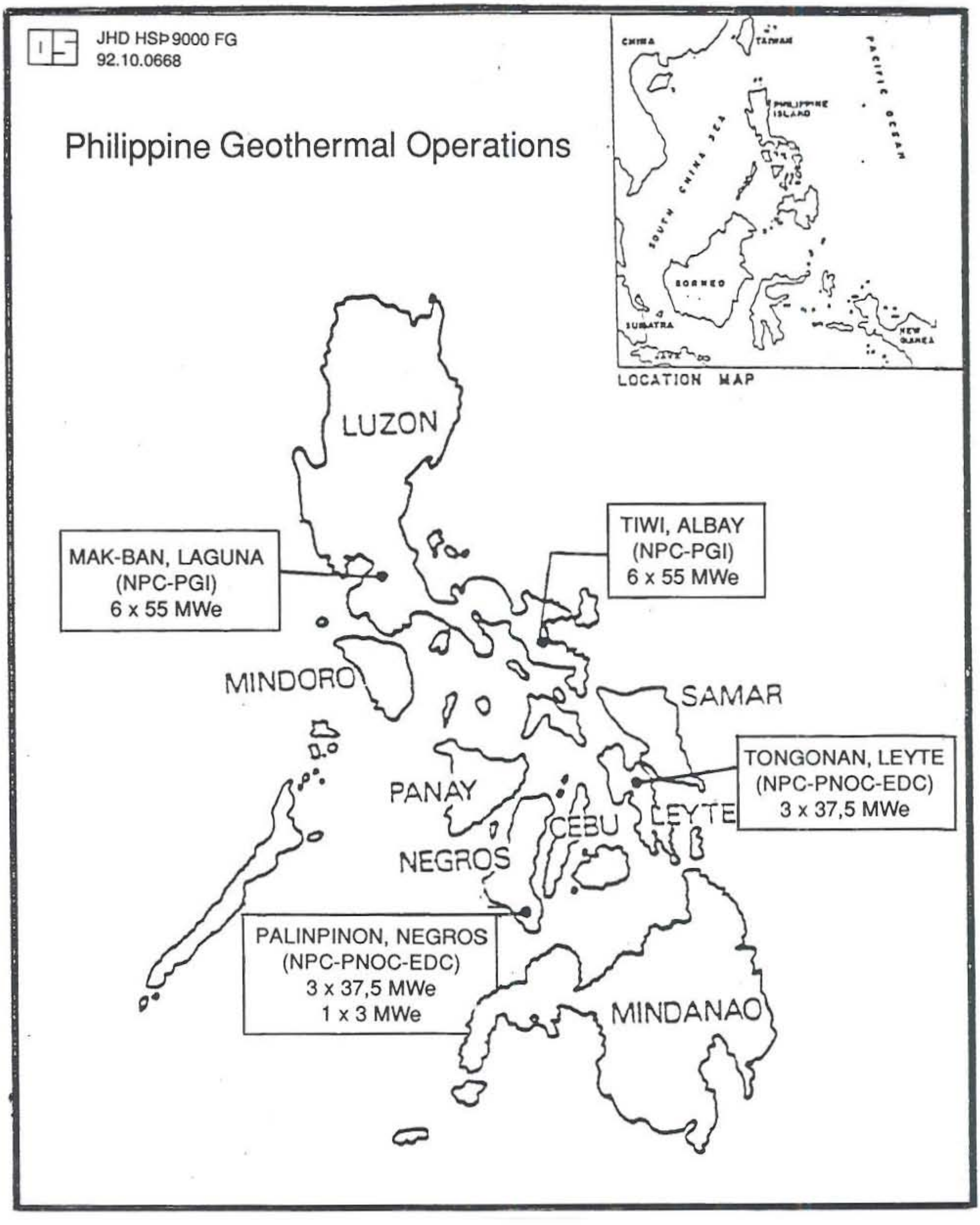

FIGURE 1: Philippine geothermal operations

3. MAK-BAN GEOTHERMAL FIELD

3.1 Background

On September 10, 1971, the NPC entered into a service contract with the PGI-UNOCAL to develop the Tiwi area and serve as steam supplier for its geothermal power plants. In 1973, PGI undertook an addendum to their original Tiwi contract with NPC for concurrent development of the Makiling-Banahaw (Mak-Ban) geothermal area. The expanded scope of the service contract took into consideration the basic similarities in the nature and planned scheme of development for both areas.

This Mak-Ban contract was officially embodied in Presidential Proclamation No. 1111 issued on February 21, 1973. It established as reservation, a parcel of land in the provinces of Laguna, Quezon, and Batangas with an area of 1,620 km^2 for the purpose of developing, exploiting and utilizing geothermal energy.

3.2 Location and main geological features

The Mak-Ban geothermal area is nestled between the two major non-active Makiling-Banahaw volcanoes. It is only 74 kilometres south of Manila (Figure 2). It is characterized by spas, thermal baths and hot springs prevalent near the town of Los Baños located at the northern base of the Makiling Volcano.

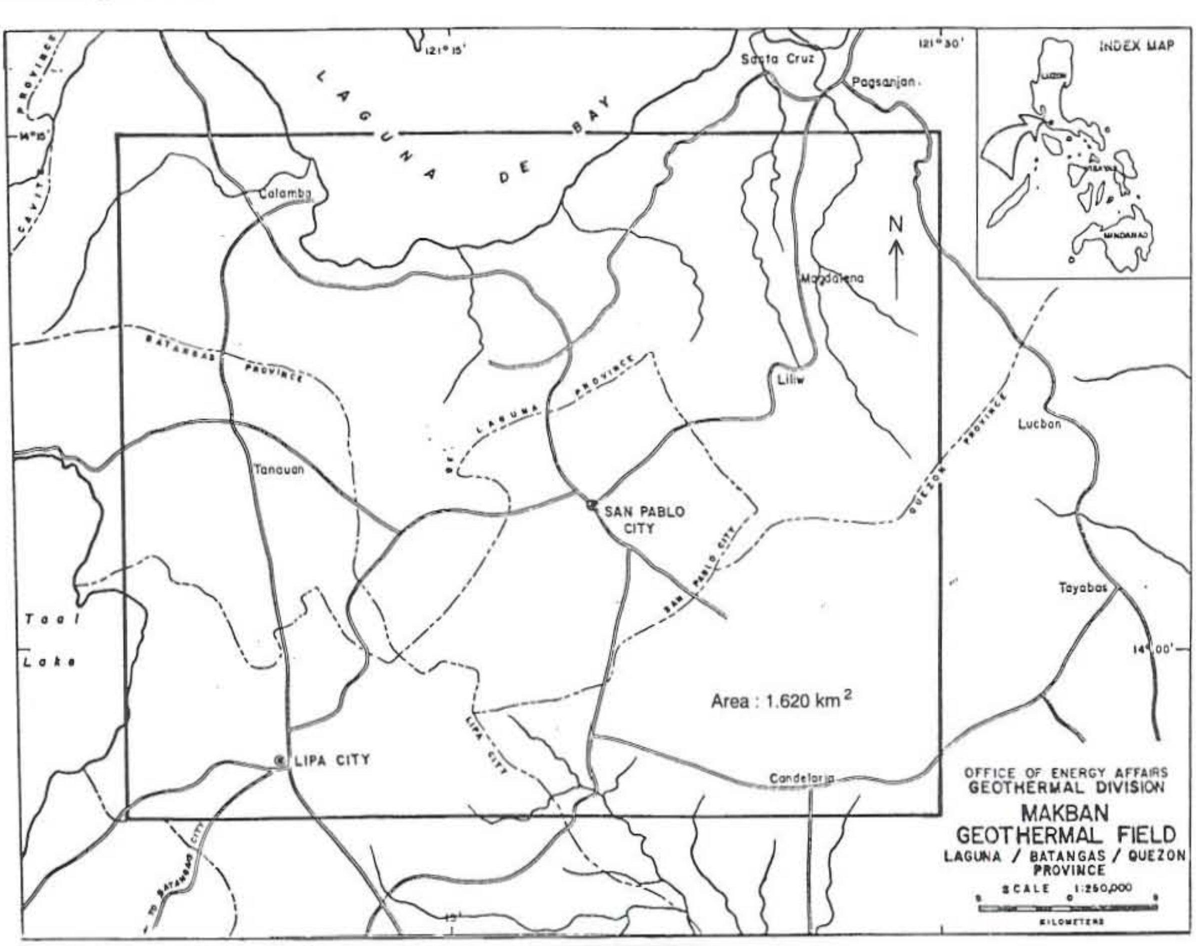

FIGURE 2: Location map of Mak-Ban geothermal field

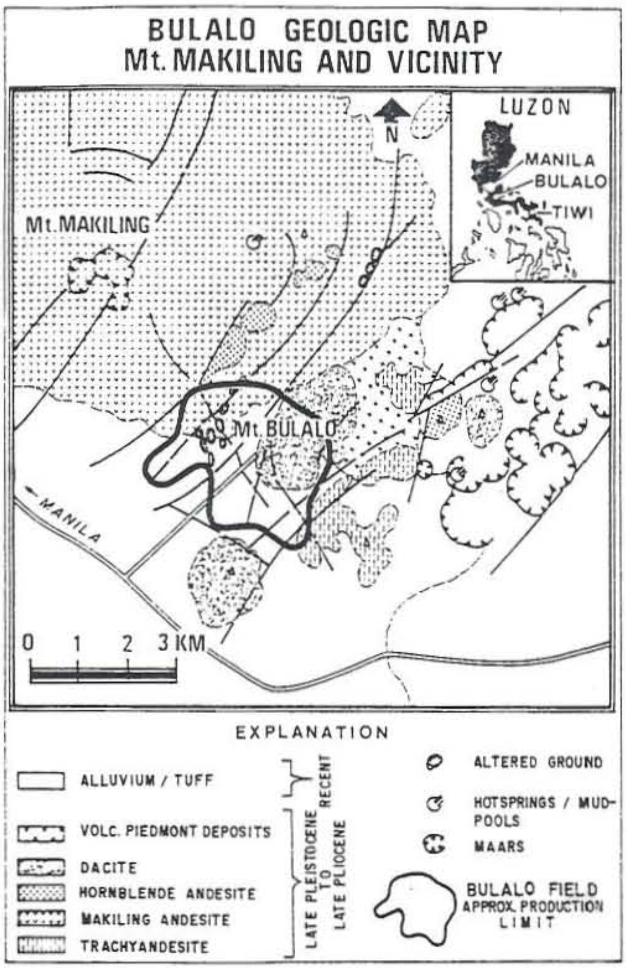

FIGURE 3: Mak-Ban geological map (Benavidez et al., 1988)

3.3 Production

The Mak-Ban (Bulalo) production field consists of 59 production wells and 23 injection wells which are either capable or incapable of commercial production (Figure 4). There are six satellite stations strategically located within the field's production area. Each station has a primary separator, scrubber and a pumping station for reinjection. The designed steam consumption rates for the NPC geothermal power plants range from 225 to 250 kg/s of steam per 100 MW_e produced depending on the operation of steam ejectors or gas compressors (NPC, 1990a).

Surface geology is characterized by deposition of a sub-volcanic basement consisting of andesite flows (trachyandesite, hornblende andesite, and Makiling andesite), alluviums/tuffs, volcanic piedmont deposits, and dacite of Late Pleistocene to Later Pliocene (Figure 3).

The Bulalo field (commonly referred to as the Mak-Ban geothermal field) is the only part of the Mak-Ban geothermal area currently under exploitation. It is located on the southeastern flank of Mt. Makiling, an 800 m high extinct and partially eroded andesitic stratovolcano. This field is directly associated with the Mt. Bulalo dacite dome, a parasitic dome formed about 500,000 years ago.

Several NE-SW trending regional faults and Makiling ring faults cross the field. These are normal faults towards Mt. Makiling which are intersected by NW-SE trending normal faults towards the south. Surface areas of acid sulphate steaming ground are located along the traces and at intersections of these fault systems. These thermal features reflect the venting of steam and gases from a two-phase zone that overlies Bulalo's deep reservoir brine (Benavidez, et. al., 1988).

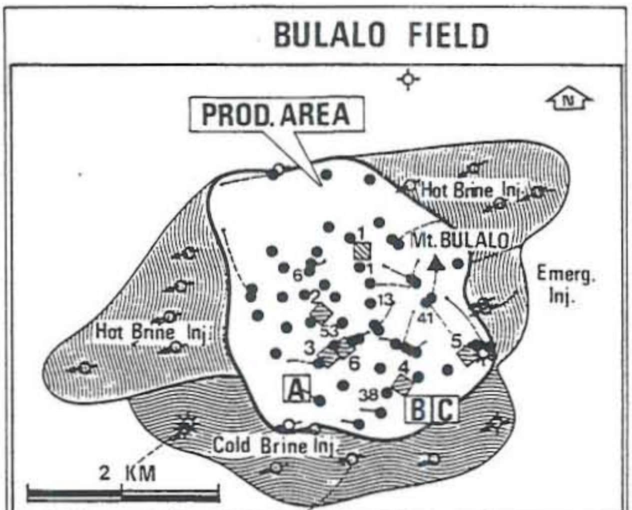

FIGURE 4: The Mak-Ban production field (Benavidez et al., 1988)

The salient features of the Mak-Ban geothermal wells are as follows (NPC, 1990a):

Discovery well - Bulalo 1, 25/11/74
No. of wells by 1990 - 86 (59 producers, 23 injectors, 4 plugged & abandoned)
Deepest well - Bulalo 65, 3,625 m
Shallowest well - Bulalo 64, 656 m
Ave. depth of product. well - 1,940 m
Ave. steam production / well - 7 kg/s
Ave. drilling time / well - 40 days
Ave. well density - 4 wells / km^2
Ave. cost / well - 1.2 million US$
No. of satellite stations - 6
No. of wells per sat. station - 8

4. GEOTHERMAL RESOURCE ASSESSMENT

4.1 Terminology

A geothermal resource base is the total thermal energy in the earth's crust beneath a specified area, referenced to local mean annual temperature (Figure 5). It can be divided into two parts:

"*Accessible geothermal resource base*" down to 3 km depth (the current limit of production drilling);

"*Inaccessible geothermal resource base*" down to 10 km which is unlikely to be tapped by production drilling in the foreseeable future.

The accessible geothermal resource base can also be divided into

"*Useful accessible geothermal resource base*" ("*geothermal resource*"), i.e. the thermal energy that can be extracted at costs competitive with other forms of energy at a specified time under the prevailing technology and favourable economic situation;

Residual accessible geothermal resource base, the thermal energy that is unlikely to be extracted economically and legally at some specified time in the future.

Finally, the geothermal resource can be further divided into

"*An economic geothermal resource*", i.e. the thermal energy that can be extracted economically and legally at cost competitive with other commercial energy sources at the time of determination;

"*A sub-economic geothermal resource*", i.e. the thermal energy that cannot be extracted legally at a cost competitive with other commercial energy sources at the time of determination, but might be extracted economically and legally at some specified time in the future.

Geothermal resource assessment is used for estimation of the geothermal resource base. It can be national, regional or localized in scope and provides a framework for long-term energy policy and strategy decisions. It is dependent on geological, geophysical, technological, economic, legal, environmental and other factors (Muffler and Cataldi, 1978).

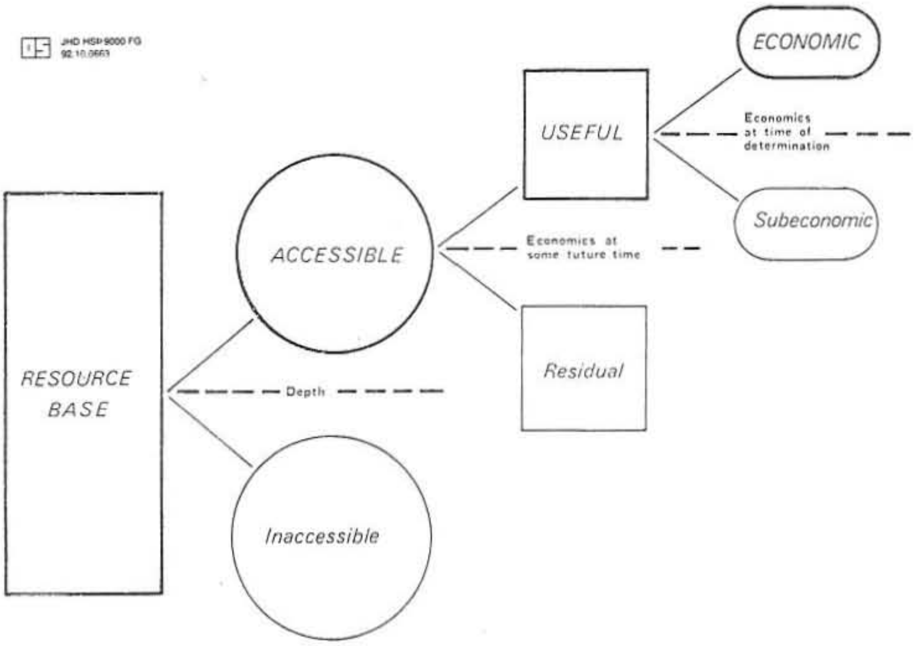

FIGURE 5: Logical subdivisions of the geothermal resource base (Muffler and Cataldi, 1978)

4.2 Volume method

The volume method is considered the most comprehensive, useful, and reliable depiction of the accessible geothermal resource base. It is applicable to virtually any geological environment and the required parameters can be measured or estimated. The inevitable errors can be partly compensated for, while the major uncertainties on recovery factor and resupply of heat are foreseen to be resolved in the future (Muffler and Cataldi, 1978). In the present study, the volume method was chosen to assess the energy content of the Mak-Ban geothermal field.

4.2.1 Computation of geothermal resource base

The total porosity, ϕ_t, is first established and the thermal energy contained in the rock, H_r, and pore fluid, H_f, is then calculated. The geothermal resource base, H_{RB} is obtained from

$$H_{RB} = H_r + H_f = [V\rho_r(1-\phi_t)C_r(T-T_{ref})] + [V\rho_{fT}\phi_t(h_T - h_{T_{ref}})] \tag{1}$$

where

C_r = rock specific heat (kJ/kg°C);
h_T = fluid specific enthalpy at temperature under consideration (kJ/kg);
hT_{ref} = fluid specific enthalpy at reference temperature (kJ/kg);
ρ_r = specific rock density (kg/m^3);
ρ_{fT} = specific fluid density at temperature under consideration (kg/m^3);
T_{ref} = reference temperature (°C);
T = temperature of the volume of rock and water under consideration (°C);
V = reservoir volume (km^3).

In accordance with the terminology of Muffler and Cataldi (1978), the total heat is calculated to 10 km depth for the geothermal resource base, H_{RB}, but only the heat in the uppermost 3 km is considered accessible, H_{acc}.

4.2.2 Computation of useful geothermal resource

The useful geothermal resource, H_R, is only a small fraction of the accessible geothermal resource base, H_{acc}, that can be brought to the surface. It is estimated by applying a geothermal recovery factor, R_g, to the accessible geothermal resource base, such that

$$H_R = R_g H_{acc} \tag{2}$$

In his lectures at the UNU - Geothemal Training Programme in September 1992, Dr. Muffler suggested that for water-dominated geothermal systems, R_g may be plotted linearly against ϕ_t with values ranging from as low as 0% at $\phi_t = 0$, to as high as 25% at $\phi_t = 20$ (Figure 6). The recovery factor will then be given by the linear equation

$$R_g = 1.25\phi_t + 0. \tag{3}$$

From this we can derive the recovery factor for a known total porosity of the geothermal reservoir. The useful geothermal resource is also called the geothermal reserve of the area.

4.2.3 Computation of economic geothermal resource

The next step in the calculations is to estimate how much of the geothermal reserve, H_R, can be converted into a usable energy form in a power plant. The economical geothermal resource is then defined as

$$H_E = kH_R \quad (4)$$

where k is called the efficiency factor.

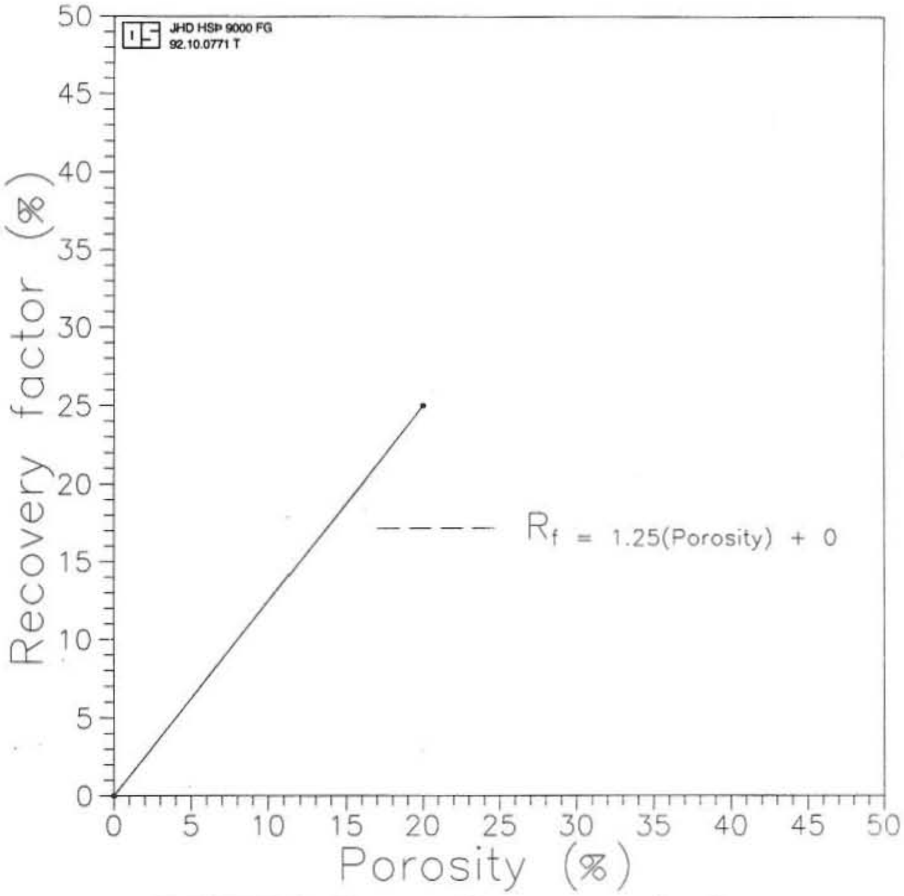

FIGURE 6: Recovery factor vs. porosity plot

The thermal energy of a geothermal resource is either used directly (e.g. space heating) or for electrical generation. Electrical generation is considered the most valuable use of high temperature geothermal resources. In order to estimate the efficiency of these two ways of utilizing geothermal reserves, one has to consider two things: 1) What are the minimum production temperatures, T_{min}, of fluids from the reservoir required for the conversion; which defines how much of the geothermal reserve is available for the specific utilization. 2) What energy losses occur during the conversion (and use). The efficiency factor, k, will then be given as a multiplication of two terms, the available energy fraction from the reserve and the conversion efficiency, η_u.

For space heating purposes of geothermal resources, the typical value for T_{min} is 80°C, but 180°C in electrical generation. In space heating the major conversion losses do not occur at the power plant but at the users of the hot water (the customers) as the water still contains some thermal energy as it is rejected after use. Typically 50-90% of the thermal energy delivered by a heating service is put to use in space heating. Conversion losses in electrical generation (rejected heat during the process and mechanical losses in the turbine) are quite high. For a water-dominated high temperature field, only 8-12% of the thermal energy produced from the geothermal reservoir enters the electrical grid as electrical energy.

4.3 UNU-GTP resource assessment (1992)

The geothermal resource base of the Mak-Ban field was calculated down to a depth of 10 km below sea level (b.s.l.) by applying the volume method. Based on available data, the size of the field was estimated as 20 km^2. Subsequently, the field was divided into five sub-areas (blocks) of different sizes (Figure 7).

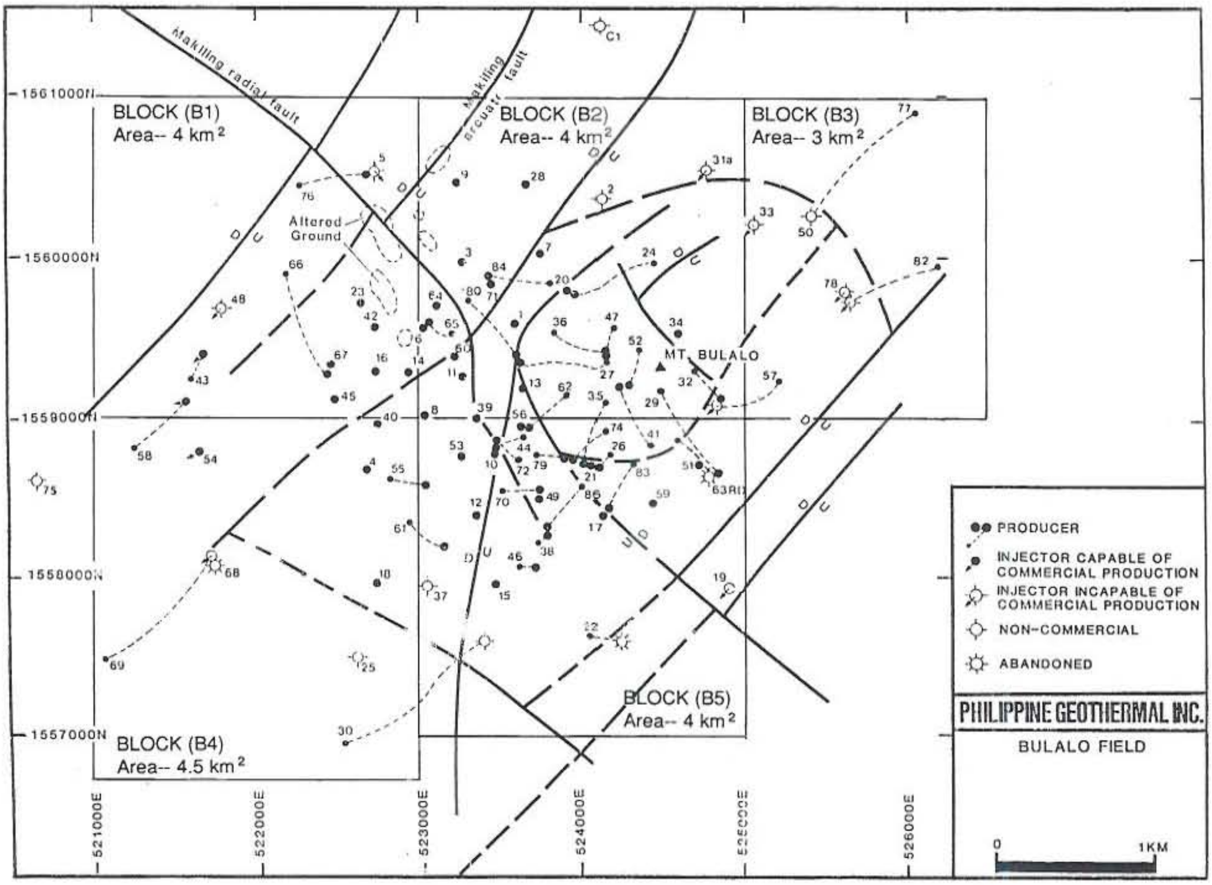

FIGURE 7: Reservoir area used for the reservoir assessment

The sub-areas contain 64 wells that were drilled in the field. Well temperature measurements for each sub-area were plotted against depths to get the reservoir temperature (Figure 8). At 3 km depth b.s.l., the temperature everywhere in the field was assumed to be 350°C and increasing to 850°C at 10 km depth b.s.l.

The useful geothermal resource (the reserve) was calculated from the accessible resource base using recovery factors based on available information on porosity in the reservoir. The economical geothermal resource was calculated for electrical generation only, as this is the utilization in Mak-Ban, assuming minimum production temperature from the reservoir of 180°C and a conversion efficiency of 10% in the generating process. The parameters used in the assessment,

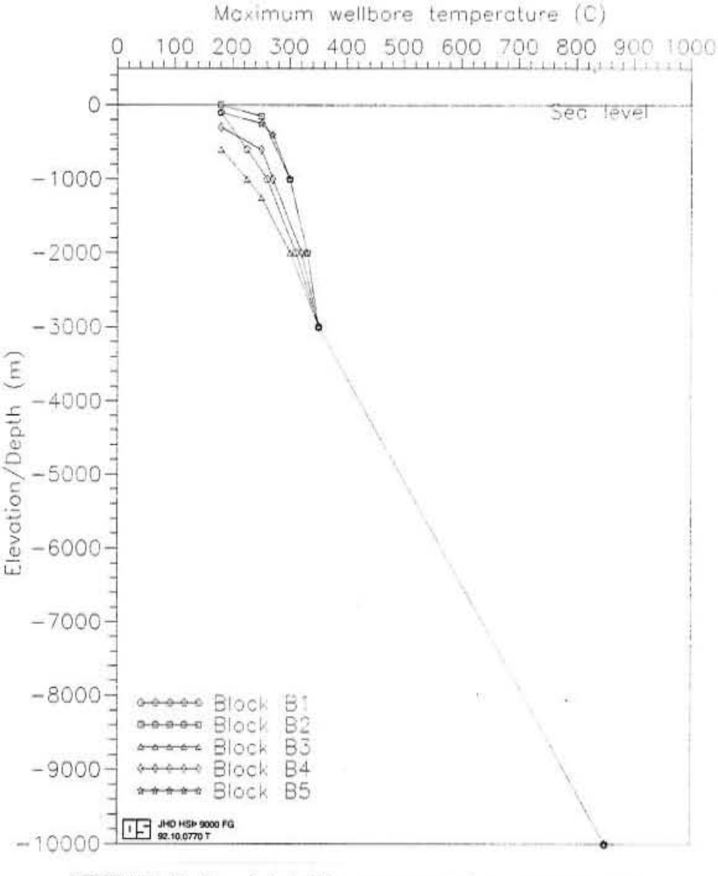

FIGURE 8: Mak-Ban reservoir temperature

together with the main results, are summarized below.

Reservoir area = 20 km^2;
Reservoir thickness = 3 km;
Reservoir volume = 60 km^3;
Reference temperat. = 30°C for thermal heat (mean annual temp. in the Philippines);
= 180°C for electrical generation;
Rock density = 2700 kg/m^3;
Rock specific heat = 1 kJ/kg°C;
Porosity = 15% above 1500 m b.s.l.;
= 11% between 1500 m and 3000 m b.s.l.;
= 0% below 3000 m b.s.l.;
Recovery factor = 19% @ ϕ_t=15%, or 14% @ ϕ_t=11%;
Conversion efficiency = 10% @ 250 kg/s of steam per 100 MW$_e$.

The main results of the study are as follows:

H_{RB} = Geothermal resource base, 600-10000 m = 3,470 x 10^{14} kJ;
H_{acc} = Accessible geothermal resource base, 600-3000 m = 450 x 10^{14} kJ;
or 143 x 10^4 MW$_t$-y;
H_R = Useful geothermal resource base, 600-3000 m = 20 x 10^4 MW$_t$-y;
H_{R180} = Available geothermal resource base for el. gen. = 10 x 10^4 MW$_e$-y;
H_E = Electrical power capacity (econ. resource base) = 10,000 MW$_e$-y.

The UNU-GTP resource assessment shows that of a geothermal resource base of 3,470 x 10^{14} kJ, 13% can be considered accessible, and only 1% is available for electrical generation. The electrical energy generating capacity is estimated at 10,000 MW$_e$-years. Assuming a 30-year life time of a power plant, the generating capacity would be 330 MW$_e$, which is exactly the installed capacity of the Mak-Ban power station today. The UNU-GTP resource assessment, therefore, indicates that the potential capacity of the field is the current installed capacity for 30 years (Table 4 and Figure 9).

TABLE 4: Summary of the UNU-GTP resource assessment for Mak-Ban

Particulars	Temperat. range (°C)	Volume (km^3)	Heat in rock (kJx10^{14})	Fluid mass in place (kg x 10^{12})	Heat in fluid (kJx10^{14})	Tot.resour. heat (kJx10^{14})
H_{RB} *	180-850	195	3404	5	70	3470
H_{acc} *	180-350	60	382	5	70	450

H_R = 63 x 10^{14} kJ or 20 x 10^4 MW$_t$-y; H_{R180} = 100,000 MW$_e$-y; H_E = 10000 MW$_e$-y.

Reservoir operating life:
@ 110 MW$_e$ (2 x 55 MW$_e$) - 90 years @ 220 MW$_e$ (4 x 55 MW$_e$) - 45 years
@ 330 MW$_e$ (6 x 55 MW$_e$) - 30 years @ 440 MW$_e$ (8 x 55 MW$_e$) - 20 years

Note: *T_{ref} = 30°C
H_{RB} - geothermal resource base (600-1000 m);
H_{acc} - accessible geothermal resource base (600-3000 m);
H_R - useful resource base;
H_{R180} - available reserve for electrical generation (at T_{ref} = 180°C);
H_E - economical resource base.

4.4 PGI-UNOCAL resource assessment (1983)

A similar reservoir assessment as described above was carried out and published by PGI-UNOCAL in 1983 (Strobel, 1983). In this study, the volumetric method was also used. The base parameters and the assumptions in their calculations were, however, somewhat different from the UNU-GTP assessment. They estimated the size of the field to be only 4-6 km^2, but with a thickness of 3 km, and calculated the energy content down to about -15°C (T_{ref}). No calculations were made for the geothermal resource base down to 10 km. By assuming a 9% recovery factor and 9% efficiency in electricity conversion, they concluded that the reservoir would supply steam for a 330 MW$_e$ power plant for 25 years. The results of their resource assessment study are summarized below:

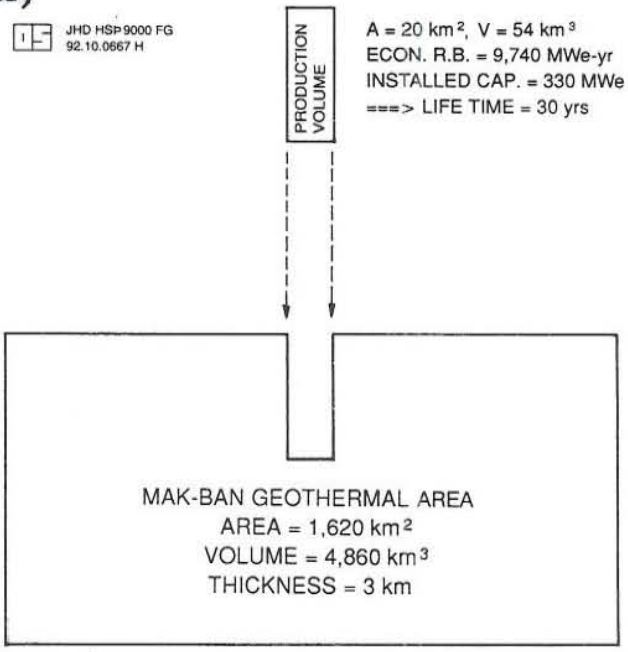

FIGURE 9: Summary of the Mak-Ban resource assessment (UNU-GTP)

Reservoir area = 4
6 km^2;
Reservoir thickness = 3 km;
Reservoir volume = 12-18 km^3;
Temperature range = 250-320°C;
Heat in rock = 100 x 10^{14} kJ;
Fluid mass = 1 x 10^{12} kg;
Fluid heat = 20 x 10^{14} kJ;
Total reservoir heat = 120 x 10^{14} kJ;
Available thermal heat = 40 x 10^4 MW$_t$-y;
Power capacity = 8000 MW$_e$-y.

Reservoir operating life:

@ 110 MW$_e$ (2 x 55 MW$_e$) - 70 years
@ 220 MW$_e$ (4 x 55 MW$_e$) - 40 years
@ 330 MW$_e$ (6 x 55 MW$_e$) - 25 years
@ 440 MW$_e$ (8 x 55 MW$_e$) - 20 years

Although the final results are similar to the UNU-GTP results, these two assessments are quite different. PGI-UNOCAL assumes a much smaller reservoir volume, but also assumes that 9% of the total heat calculated down to -15°C is available for electrical conversion. This assumption leads to a much higher recovery factor than in the UNU-GTP assessment where 16% of the reservoir heat above 180°C is assumed recoverable.

5. SIMPLE MODELLING OF MAK-BAN GEOTHERMAL FIELD

5.1 Need of a model

The optimal production strategy for a geothermal area can be achieved by creating a model with parameters and area measurements that best describe the reservoir. The past, present and future exploitation of the geothermal area must be in compliance with the created model.

Modelling studies are carried out to accurately analyze data from geothermal wells and estimate the generating potential of a system. A good conceptual model represents the current knowledge of the geothermal system and its dynamics. It also serves as a starting point for resource assessment based on analyses of the response of the geothermal reservoir to utilization.

5.2 Lumped parameter model

5.2.1 Theory and methodology

A general lumped network consists of a total of N tanks with mass storage coefficients κ. A tank has the mass storage coefficient κ when it responds to the load of liquid mass m with the pressure $p = m/\kappa$. The tanks are pair-wise connected by up to N(N-1)/2 resistors or conductors of conductivity σ_{ik} ($\sigma_{ii} = 0$). The mass conductivity of a resistor is σ when it transfers $q = \sigma \Delta p$ units of liquid mass per unit time at the impressed pressure differential Δp (Axelsson, 1989). The particular element σ_{ik} connects the i'th and k'th tanks and because of linearity $\sigma_{ik} = \sigma_{ki}$. The network is open in the sense that the i'th tank is connected by a resistor of conductivity σ_i to an external tank which maintains equilibrium pressure of magnitude zero. The network is closed when $\sigma_i = 0$ for $i = 1, 2, ...N$ (Axelsson, 1989).

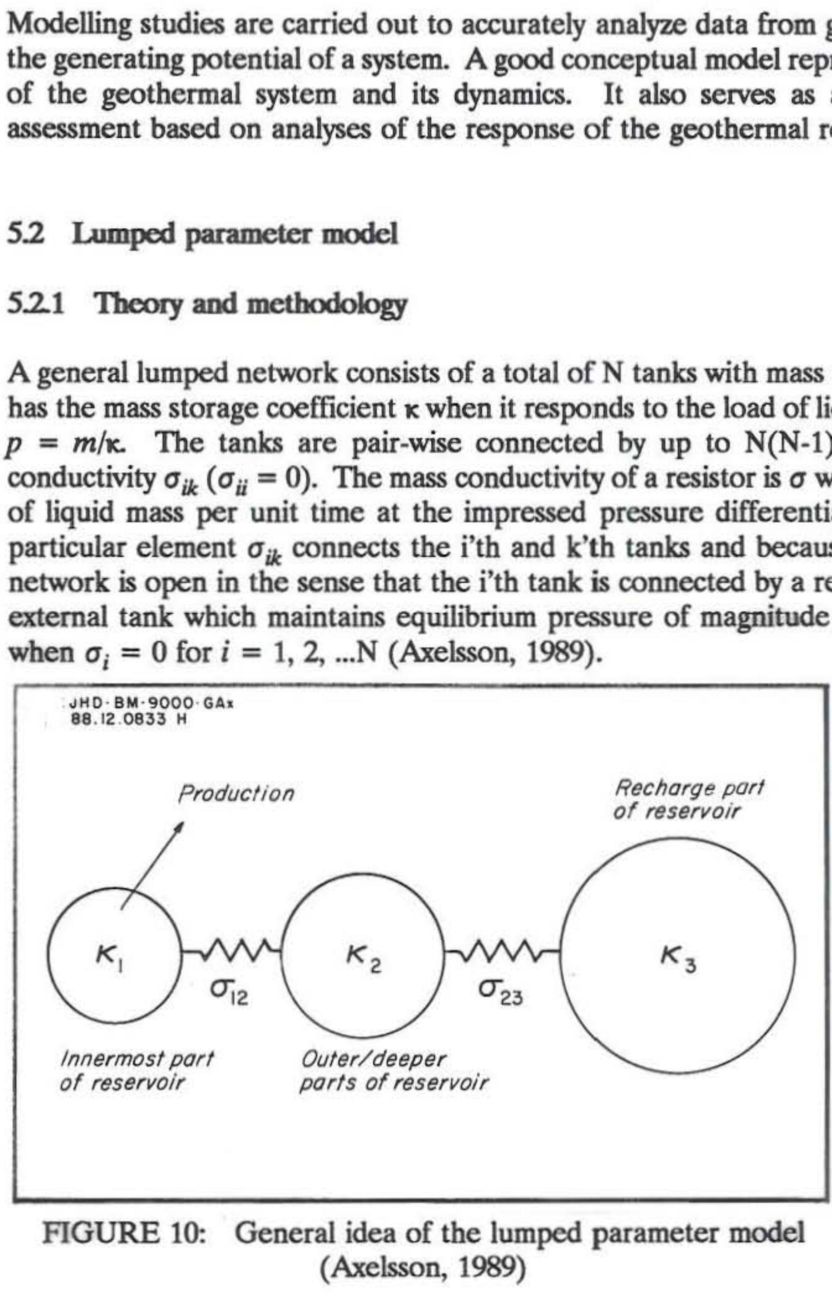

FIGURE 10: General idea of the lumped parameter model (Axelsson, 1989)

To simulate pressure response data from a liquid-dominated geothermal reservoir, an appropriate or best fitting lumped model with parameters, κ and σ, is chosen. Fluids are produced from one of the tanks of the geothermal reservoir. The resulting pressure $p(t)$ is then observed in any given tank of the lumped model (Figure 10).

The capacity or storage in a liquid-dominated geothermal system can result from two types of capacity effects (storage mechanisms) (Axelsson, 1989). It can be controlled by:

a) Liquid/formation compressibility , such that

$$\kappa = V \rho c_t \tag{5}$$

where

V is the volume of that part of the reservoir in question the tank simulates;
ρ is the liquid density;
c_t is the compressibility of the liquid-saturated formation.

The compressibility is given by

$$c_t = \phi c_w + (1-\phi) c_r \tag{6}$$

where

ϕ is the reservoir porosity;
c_w is the compressibility of the water;
c_r the compressibility of the rock matrix.

b) Free-surface mobility, such that

$$\kappa = A\frac{\phi}{g} \tag{7}$$

where

A is the surface area of that part of the reservoir in question that a tank simulates;
ϕ is the reservoir porosity;
g is the acceleration of gravity.

Equations 5, 6 and 7 can be used to compute the total capacity of the main area, κ_1, and the recharge areas, κ_2, of the geothermal system. From these values, we can estimate the total reservoir of the area that may be due to compressibility or free surface mobility.

The geothermal model can be used to assess the production potential of the reservoir. This is done by using the lumped-parameter model to predict the pressure changes in the reservoir for different cases of future production. The maximum allowable drawdown in the area can be used for estimating the maximum potential of the system.

5.2.2 Simulation results

Lumped-parameter modelling was used to simulate pressure response data with production from Mak-Ban reservoir. Mak-Ban production started in 1977 but increased greatly after 1980. Net mass withdrawal from the reservoir has been closely monitored and excellent production data was made available for this modelling (Figure 11).

The pressure changes resulting from variable production from the field were monitored in three wells, Bulalo-1, Bulalo-6 and Bulalo-10 (Figure 12). Unfortunately, pressure data from these 3 wells and other field measurements were limited. Due to these constraints, lumped

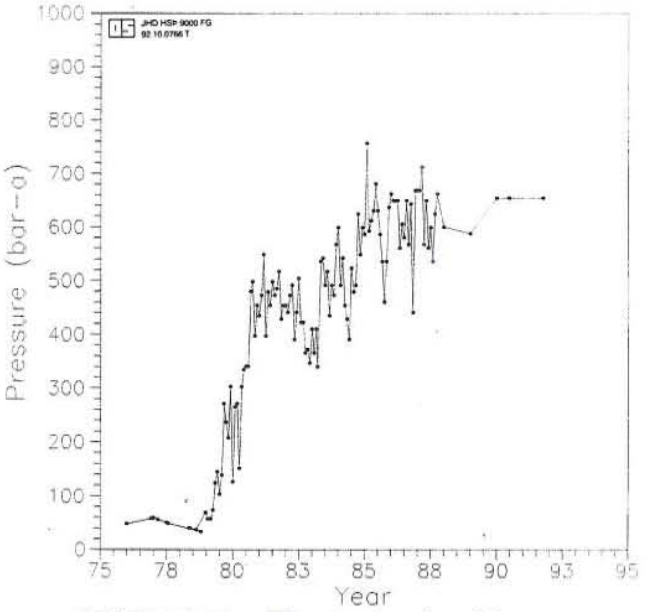

FIGURE 11: The production history of Mak-Ban

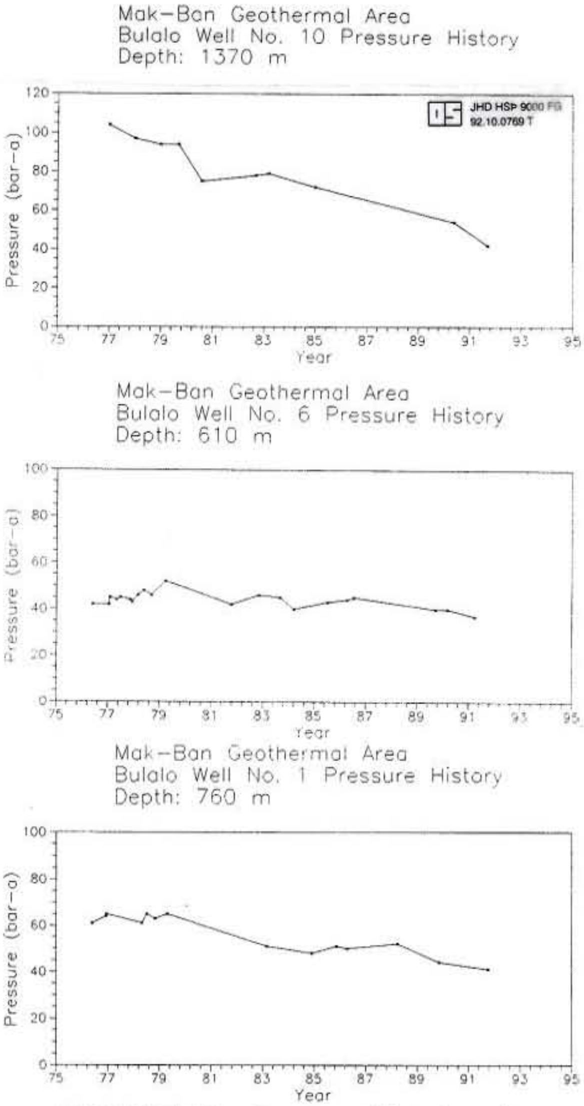

FIGURE 12: Pressure histories of Mak-Ban geothermal wells

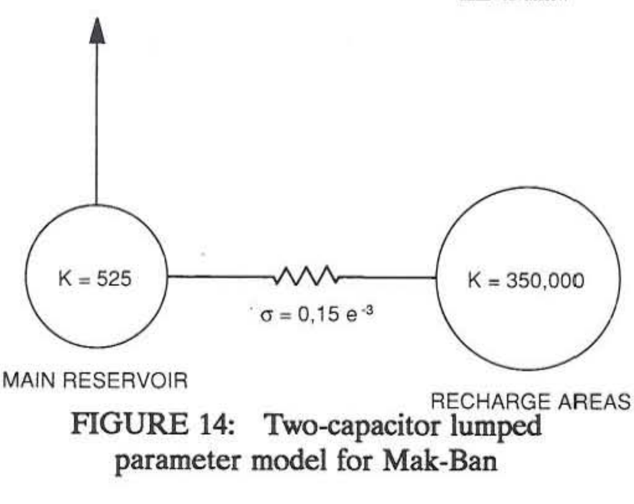

FIGURE 14: Two-capacitor lumped parameter model for Mak-Ban

parameter modelling was found applicable only to data from Bulalo-10. It is the deepest of the three observation wells (reaches 1400 m b.s.l.). It was also considered the best representative of the production process in the Mak-Ban reservoir. It has a major feed zone at 250-500 m b.s.l. and a reservoir temperature of 330°C (Figure 13). The pressure history of well Bulalo-10 shows a pressure drop from about 100 bar-a to 50 bar-a between 1979-1991.

A closed two tank lumped model was used to simulate the pressure response data from Mak-Ban geothermal reservoir. Fluids are produced from the first tank (κ_1) and the pressure is monitored in the same tank. The first tank can be considered as the main production reservoir or well area and the other one acts as the surrounding recharge area of the entire geothermal system. This was considered to be the best possible condition of the reservoir, with a small main production area but a very large recharge area (Figure 14).

The simulation process was carried out automatically by using the LUMPFIT computer program (Axelsson and Arason, 1992). A first guess of the lumped model parameters was made and the parameters were changed by the iterative process until a satisfactory fit was obtained. No previous assumptions were considered on the properties of the reservoir.

5.2.3 Discussion

Based on the results of simulations between observed and calculated pressure levels, we can state that the matches are quite satisfactory, in spite of limited data and the simplicity of the model (Table 5). The good match can be related to the diffusive nature of the pressure response of the geothermal systems.

The best fitting lumped model reveals that the capacities of the main area, κ_1, and the recharge areas, κ_2, are 525 and 350,000 ms^2 (or kg/Pa), respectively. These values clearly reflect the highly variable productivity of the area. It is believed that the high capacity, as well as the high mass conductivity, σ (0.15×10^{-3} ms) reflect the high permeability in the system.

Assume that the reservoir is confined and using the following parameters:

Reservoir temperature, T = 300°C;
Liquid density, ρ_w = 712 kg/m^3;
Water compressibility, c_w = $5\text{x}10^{-9}$ Pa^{-1};
Rock matrix compr., c_r = $0.20\text{x}10^{-10}$ Pa^{-1};
Thickness = 3 km;
Reservoir porosity, ϕ = 10-15%.

Based on this we can estimate a total reservoir size of 210 km^3 (Equation 5), or areal extent of 70 km^2 assuming reservoir thickness of 3 km. If, on the other hand, the reservoir is considered unconfined, the areal extent will be about 30 km^2 (Equation 7). These are larger values than the ones used in the volumetric assessment, especially the reservoir size determined for the confined model.

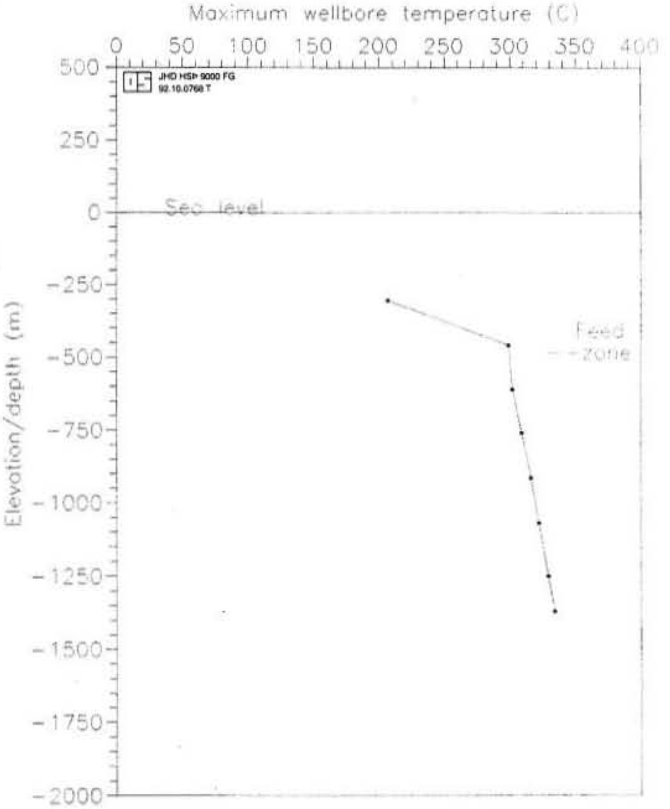

FIGURE 13: Bulalo well no. 10, temperature vs. depth plot

TABLE 5: Calculated pressures at different production rates in Mak-Ban

Time (year)	Observed pressure (bar-a)	Calculated pressure (bar-a)	Actual production (kg/s)
1977.0	104	100	59
1978.0	97	101	42
1979.0	94	100	69
1980.7	75	76	479
1983.3	79	78	334
1990.4	54	55	654
1991.7	42	54	654

5.2.4 Future predictions

The lumped-fit model was used to predict reservoir pressures for different net production rates in Mak-Ban field (Table 6). Future productions were set at 800 kg/s, 650 kg/s, and 500 kg/s and reservoir pressures calculated up to year 2005. It should be noted that the designed steam consumption rates for NPC geothermal power plants are about 230 kg/s of steam per 100 MW$_e$ at a turbine inlet pressure of 10 bar-a, and with geothermal brine being reinjected to the reservoir. The three net production scenarios used in the future prediction would mean a generating capacity of the field at about 400, 330 and 250 MW$_e$, respectively, with the present reinjection.

TABLE 6: Predicted pressures for different production rates at Mak-Ban

Time (year)	Pressure (bar-a) 800 (kg/s)	650 (kg/s)	500 (kg/s)
1991.7	54	54	54
1991.8	49	54	60
1992.0	45	54	64
1992.5	44	54	64
1993.0	44	54	64
1994.0	43	53	64
1995.0	42	53	63
2000.0	39	50	61
2005.0	35	47	59
2010.0	31	44	56
2015.0	28	41	54
2020.0	24	38	52
2025.0	20	35	50
2030.0		32	47
2035.0		29	45
2040.0		26	43
2045.0		23	41
2050.0		20	38
2055.0			36
2060.0			34
2065.0			32
2070.0			29
2075.0			27
2080.0			25
2085.0			23
2090.0			20
Average drawdown per year	.90	.60	.30

For a production of 800 kg/s, pressure will drop from 54 bar-a in 1991 to 45 bar-a in 1992 (Figure 15). Pressure will continue to drop to 35 bar-a in 2005 and the overall pressure decline during 1992-2005 is 0.90 bar/y.

For a production of 650 kg/s (the current production rate), pressure will decline gradually from 54 bar-a in 1991 to 47 bar-a in 2005. The overall pressure decline is predicted to be 0.60 bar/y. At this production rate, the reservoir will be able to sustain and deliver the production requirements of the current installed capacity of 330 MW_e in the field. This is considered the most viable production rate for the field.

If the production is decreased to 550 kg/s, the pressure will increase from 54 bar-a to 64 bar-a in a year (pressure build-up) and then decline gradually to 60 bar-a in 1995 at an overall pressure decline of 0.30 bar/y. At this net production rate, the power plant would be operated at a lower capacity than installed unless reinjection would be increased by 150 kg/s.

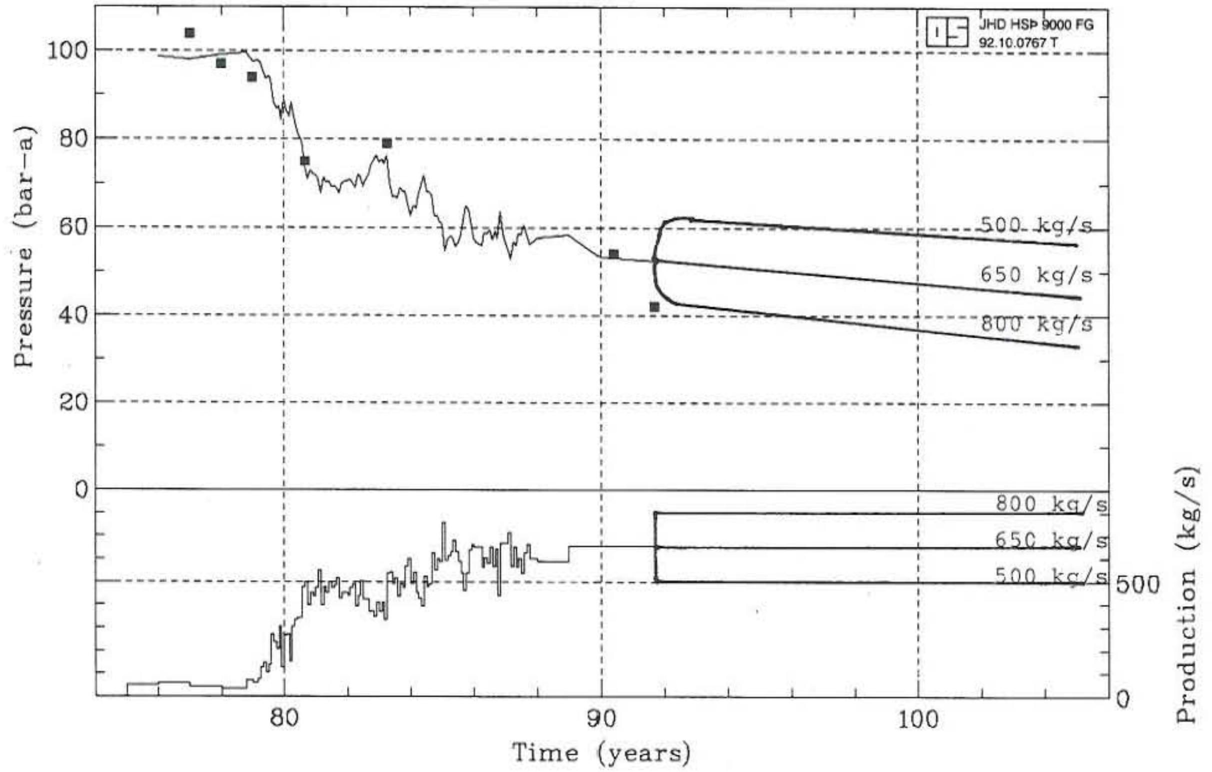

FIGURE 15: Simulations of predicted pressure drawdowns for different production rates

The lifetime of the Mak-Ban field was estimated by using the lumped-fit model and variable net production from the field assuming that the reservoir pressure could be lowered to 20 bar-a. For a production of 800 kg/s (400 MW_e), drawdown to this pressure will be reached in 35 years (or in the year 2025), for 650 kg/s (330 MW_e) it will be 60 years (or in the year 2050), and for 500 kg/s (250 MW_e) it will be 100 years (or in the year 2090).

5.3 Lumped Model - availability of steam from an initially liquid-saturated reservoir

5.3.1 Methodology and assumptions

Production testing, reservoir and geoscientific studies were conducted by PGI-UNOCAL to develop a conceptual model of an initially liquid-dominated Mak-Ban reservoir (Figure 16). This reservoir model indicates a thermal upflow rising vertically from depths of about 3 km b.s.l. or greater. The upflow migrates through intensely altered and fractured andesitic flows, tuffs, and volcaniclastics along permeable fault zones. This geothermal liquid encounters lower pressures, boils and forms a two-phase zone in the upper part of the reservoir (Benavidez, et al., 1988).

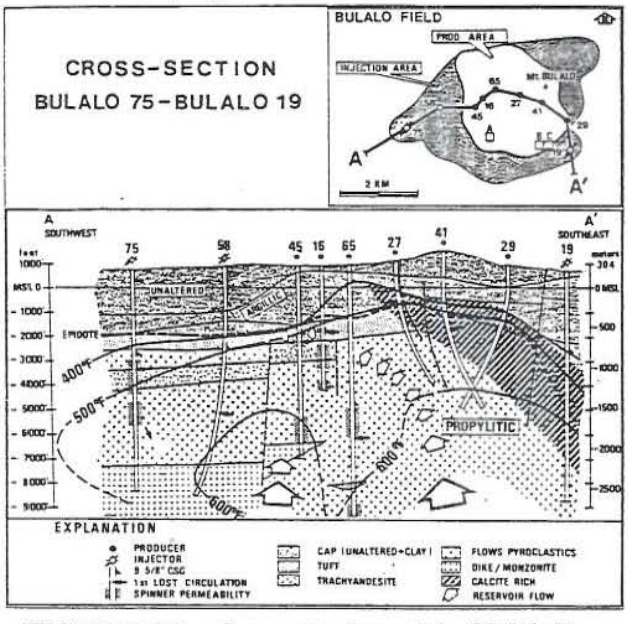

FIGURE 16: Conceptual model of Mak-Ban, PGI-UNOCAL (Benavidez et al., 1988)

During exploitation of such a field, the two phase zone will expand downwards as reservoir pressures decline (pressure drawdown). Pressures and temperatures in the two phase zone, are of course, related to each other through the boiling point relations for water. As the pressure is lowered (drawdown), boiling of the liquid water in the rock pores will lower the temperatures and maintain boiling conditions in the zone. The liquid saturation in the two-phase zone will, therefore, decrease and vapour saturation rise during the exploitation of the field. Most of the steam generated by this in-situ boiling will flow out of the pores and into the fracture network as the specific volume of steam is much higher than that of liquid water.

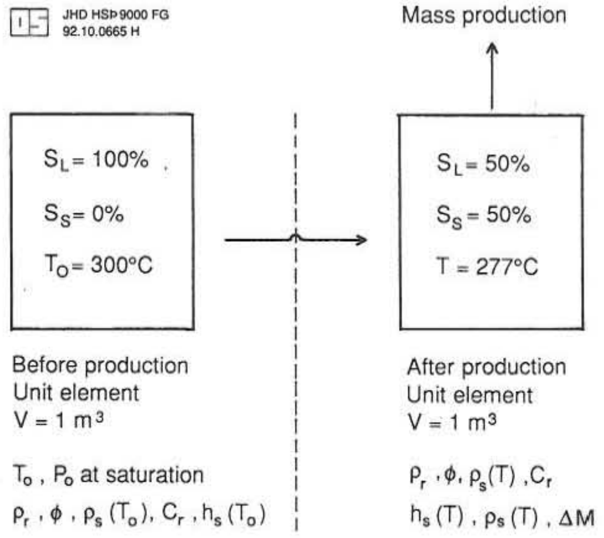

FIGURE 17: Lumped model, available steam for an initially liquid-saturated reservoir

A simple lumped model was used in order to describe in-situ boiling in a reservoir and to determine the amount of steam generated by the process. The model computes the volumetric fraction of steam, S_s in 1 m^3 of rock which has undergone a drop in temperature from the initial saturation value of temperature, T_o, to the new saturation value of temperature, T (Bjornsson, 1992). In order to decrease the temperature, some fluid of mass, m, is produced (Figure 17). Calculations are performed in decreasing steps of T, and after each step the values of T, S_s, and m are computed by using the mass and energy conservation equations.

Mass conservation:

$$V\phi\,\rho_w(T_o) = V\phi\,[S_s\rho_s(T)+(1-S_s)\,\rho_w(T)]+\Delta m \qquad (8)$$

Energy conservation:

$$V[(1-\phi)C_r\rho_r(T_o)+\phi\rho_w(T_o)h_w(T_o)]$$

$$= V[(1-\phi)C_r\rho_r(T)+\phi[S_s\rho_s(T)h_s(T)+(1-S_s)\,\rho_w(T)h_w(T)]]+h_s(T)\,\Delta m \qquad (9)$$

By equating 7 and 8, we can solve for S_s such that

$$S_s = \frac{(1-\phi)/\phi[C_r\rho_r(T-T_o)]+\rho_w(T_o)\,[h_w(T_o)-h_s(T)]}{\rho_w(T)\,[h_s(T)-h_w(T)]}+1 \qquad (10)$$

By substituting Equation 10 in 8, we can calculate Δ_m in some steps of T (T_o, T_o-ΔT, T_o-$2\Delta T$, ...). For comparison, the values of saturation volume steam fraction and mass production for different porosities at every 5°C drop in reservoir temperature are plotted in Figure 18 and Figure 19, respectively.

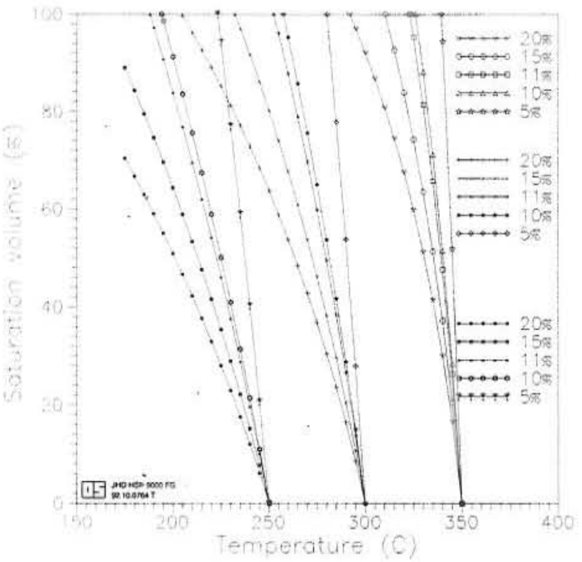

FIGURE 18: Volume saturation fraction at different porosities

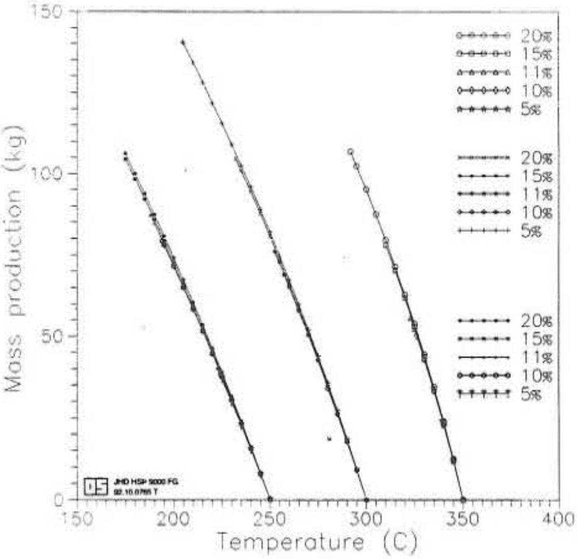

FIGURE 19: Mass production at different porosities

5.3.2 Application to Mak-Ban

The following parameters were used in modelling the in-situ boiling in the Mak-Ban geothermal field and determining the amount of steam produced from the pores in the two- phase zone:

Initial reservoir temperature range, T = 250-350°C
Porosity range, ϕ = 5-15%
Heat capacity of rock, C_r = 1,000 J/kg/°C
Rock density, ρ_r = 2,700 kg/m^3

It was assumed that steam saturation goes initially from 0% to 50% after production. At the initial Mak-Ban reservoir temperature of 300°C and porosity of 12.5%, the maximum allowable steam saturation volume of 50% will be attained when the temperature has dropped to 277°C. This corresponds to a mass production, Δ_m, of 40 kg of steam from each m^3 of reservoir rock in the two-phase zone. (Figure 20 and Table 7).

The initial size of the two-phase zone in Mak-Ban is estimated to be about 5 km^3. The total amount of steam produced from this volume due to in-situ boiling could therefore amount to 200 x 10^9 kg. At a production rate of 250 kg/s of steam per 100 MW$_e$, we can then estimate the generating capacity of the two-phase zone for the following schemes:

@ 110 MW$_e$ plant installation -23 years
@ 220 MW$_e$ plant installation -11 years
@ 330 MW$_e$ plant installation - 8 years
@ 440 MW$_e$ plant installation - 6 years

Based on the above figures, we can see that the initial two-phase zone is not large enough to sustain the economical plant life of 25 years for an installed capacity of 330 MW$_e$.

In supplying steam for a 330 MW$_e$ power plant for 30 years, the two-phase zone has to expand in size to about 16 km^3, which is about 25% of the estimated reservoir size in the volumetric assessment (Figure 21).

TABLE 7: Steam saturation volume and mass production at different porosities in Mak-Ban for each m^3 of reservoir rock in the two-phase zone

Temp. (°C)	ϕ = 10% Sat. vol. (%)	ϕ = 10% Mass prod. (kg)	ϕ = 12.5% Sat. vol. (%)	ϕ = 12.5% Mass prod. (kg)	ϕ = 15% Sat. vol. (kg)	ϕ = 15% Mass prod. (kg)
300	0	0	0	0	0	0
295	15	9	12	9	11	9
290	29	18	24	18	20	18
285	42	26	34	27	30	27
280	54	35	44	35	38	35
275	65	43	54	43	46	43
270	76	50	63	51	54	51
265	86	58	71	58	61	59
260	95	65	79	66	68	66
257	100	69				
255			86	73	74	74
250			93	80	80	81
245			100	87	86	88
240					92	94
235					97	101
232					100	105

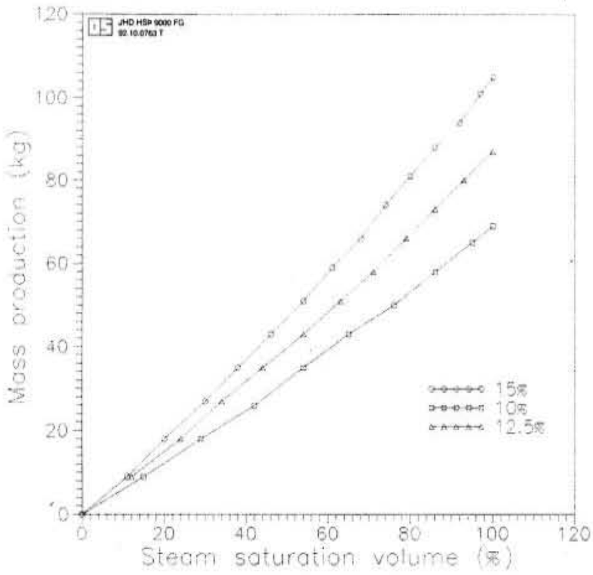

FIGURE 20: Steam saturation volume vs. mass production at different porosities

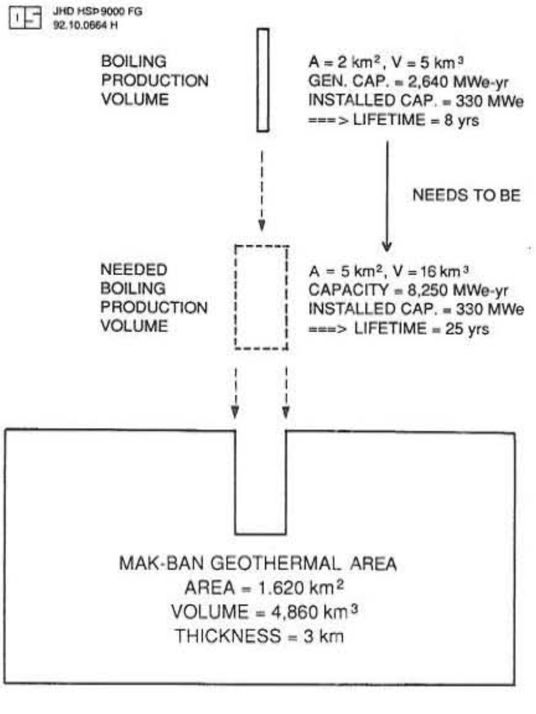

FIGURE 21: Summary of the lumped model for the in-situ boiling at Mak-Ban

6. CONCLUSIONS

Three different assessment methods have been applied to the Mak-Ban geothermal field in order to estimate its power generating capacity. The methods, i.e. the volumetric assessment, lumped-parameter modelling of production versus pressure drawdown data and finally lumped modelling of in-situ boiling in the reservoir, all give similar results. The main conclusions of the study are as follows:

1. The generating capacity of the Mak-Ban field is of the order of 300-400 MW_e for 30 years, according to the volumetric assessment and lumped modelling of production data from the field. A somewhat lower generating capacity is obtained from the in-situ boiling assessment but this depends highly on the estimation of the size of the two-phase zone within the reservoir.

2. The lumped parameter modelling shows that it is the pressure drawdown in the reservoir that limits the generating capacity. Increased reinjection of fluids into the reservoir is, therefore, recommended for prolonging the lifetime of the resource.

3. More detailed monitoring should be conducted in the field as available data (especially drawdown rates) are very limited. It is believed that more high quality production data from the field area will result in a more precise model of the reservoir and a more accurate assessment of the generating capacity of the field.

The current installed plant capacity of Mak-Ban is 330 MW_e. The results of the reservoir assessment described in this report do not justify increased net mass withdrawal (mass produced - mass reinjected) from the field. Additional installation of generating units in Mak-Ban is, therefore, not recommended unless reinjection is increased so that net production rate is maintained at a similar value as today (650 kg/s) although production is increased.

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Takk... salamat...

NOMENCLATURE

A - surface area of reservoir part the tank simulates;
c_t - compressibility of liquid-saturated formation;
c_r - compressibility of rock matrix;
c_w - compressibility of water;
C_r - rock specific heat;
C_v - volumetric specific heat;
g - acceleration of gravity;
H_{acc} - accessible geothermal resource base;
H_E - economical geothermal resource base;
H_f - thermal energy contained in the pore fluids;
H_r - thermal energy contained in the rock phases;
H_R - useful geothermal resource;
H_{RB} - geothermal resource base;
H_{R180} - available geothermal reserve for electrical generation (at $T_{ref} = 180°C$);
h_s - steam enthalpy;
h_T - fluid specific enthalpy at temperature under consideration;
h_{Tref} - fluid specific enthalpy at reference temperature;
h_w - water enthalpy;
k - efficiency factor;
m - liquid mass produced;
N - number of tanks;
p - pressure;
R_g - geothermal recovery factor;
S_s - volumetric fraction of steam;
T - temperature;
T_{min} - minimum production temperature of fluid;
T_o - initial saturation temperature;
T_r - reservoir temperature for the volume of rock and water under consideration;
T_{ref} - reference temperature;
V - reservoir volume.

Greek symbols:

Δp - pressure differential;
η_u - conversion efficiency or utilization factor;
κ - mass storage/capacity coefficient;
ϕ - reservoir porosity;
ϕ_t - total porosity;
ρ_{fT} - specific fluid density at temperature under consideration (kg/m^3);
ρ_r - specific density of rock (kg/m^3);
ρ_s - specific density of steam;
ρ_w - specific density of water;
σ - mass conductivity.

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