RESOURCE ASSESSMENT OF THE MAHANAGDONG GEOTHERMAL PROJECT, LEYTE, CENTRAL PHILIPPINES

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SUMMARY - *An* updated assessment of the Malianagdong Geothermal Project was carried out based on volumetric stored heat calculations. Drilling results are used as basis for refining previous hydrological reservoir models and in constraining reservoir parameters. The paper outlines recommendations for step-out exploratory testing beyond the postulated resource boundaries. The re-assessment indicates ca. 2675 to 4175 MWe-years of stored heat is recoverable as electrical energy. In terms of a 25-year plant life and an 80% load factor tlie equivalent power capacities range from 107 to 167 W e . The result is corroborated by a Monte Carlo simulation of uncertainties in the stored heat calculations which indicates a geothermal reserve ranging from 100 to 180 MWe, with the greatest probability in the range of 130 to 140 MWe. .

1. INTRODUCTION

The Malianagdong Geothermal Project is located within the Greater Tongonan Geothermal Field about 12 km NE of Ormoc City, on the island of Leyte in the Central Philippines (Fig. 1). The project lies along a NW-SE trending Neogene-Quaternary volcanic arc which bisects the island in association with a major sinistral fault, the Philippine Fault (PF) which provides primary and secondary permeability to most geothermal areas found along or close to this structure. Since 1976 eight volcano-related geothermal areas have been studied in Leyte by the Philippine National Oil Company-Energy Development Corporation (PNOC-EDC) at various stages of exploration and development activities. Six of these including Malianagdong , are confined to a 5 km wide x G0 km long pull-apart basin feature of tlie Philippine Fault of Pleistocene age. The other two are found outside of this feature but dong the Philippine Fault.

PNOC-EDC has recently undertaken a' detailed re-assessment of the geothermal resources in Leyte with a view to developing a large block (e.g. 605 MWe) of geothermal power generation in Leyte by tlie year 1997 for export to major load centers on the islands of Cebu and Luzon. Future generation from the Mahanagdong resource will comprise an important component in the Leyte power expansion programme. This paper aims to: 1) present an updated assessment of the resource potential of tlie Malianagdong reservoir; 2) recommend programmes for future study to refine present understanding of tlie reservoir; and 3) assess development of Mahanagdong at a proposed level of 165 MWe against the results of the present resource evaluation.

1.1 PREVIOUS RESOURCE ESTIMATIONS

Several geothermal resource estimations have been carried out at Mahanagdong (KRTA 1982, Ogena 1988, PNOC-EDC 1990). KRTA (1982) estimated a resource potential of 138 MWe based on wells MG-1 and MG-2D. Following the completion of well MG-5D, a similar (137 W e) was arrived at in subsequent assessment (Ogena, 1988). Both reports recommended further delineation drilling to fully characterize the reservoir.

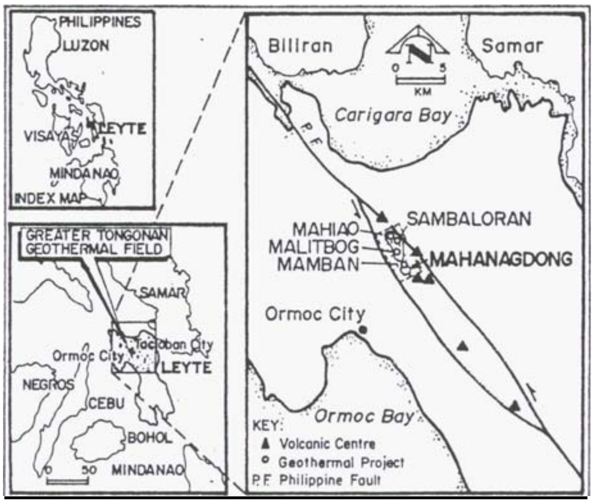

Fig. 1 Location Map, Mahanagdong Geothermal Project.

In 1990, a decision was made to review Mahanagdong data in preparation for the resumption of delineation drilling. An updated assessment incorporating the results of these earlier reviews was later prepared (PNOC-EDC, 1990) which decreased the previous power estimates by KRTA (1982) and Ogena (1988) to a conservative range of 80 to

109 MWe for estimated minimum and maximum resource areas, respectively.

2. DRILLING RESULTS

Five deep exploratory wells were drilled within the Mahanagdong project between 1980 and 1990 (Fig. 2). The first three wells (MG-1, MG-2D and MG-5D) were all sited within the Mahanagdong resistivity anomaly with a strong bias on geophysical information and to a lesser extent on geological and geochemical **data.** Although these wells were all productive and have a total proven capacity of 25 MWe it was deemed necessary to conduct additional surface studies to complement existing **data** prior to nominating further delineation well targets. The result of these studies has been reported by Salonga et al. (1990), Layugan et al., (1990) and Geochemistry Staff (1990). Two further wells, MG-4D and MG-7D, were then drilled in 1990 to further characterize the resource and assess the viability of developing at least 110 MWe from the project. Table 1 summarizes the **data** obtained from the five wells.

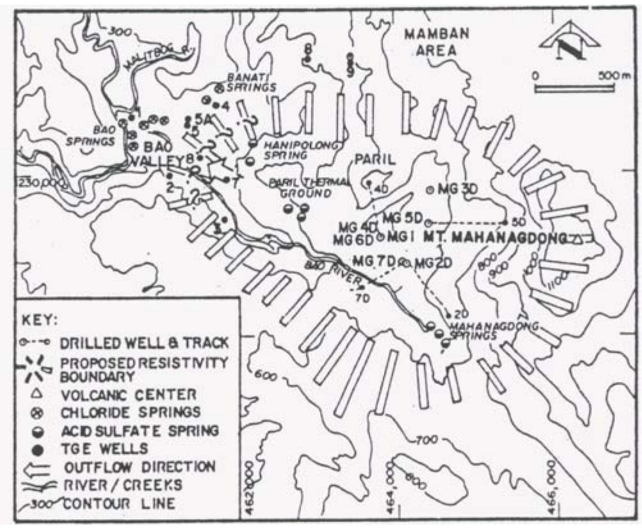

Fig. 2 Wells and Thermal Springs Location Map.

2.1 Subsurface Geology

The subsurface geology of the Mahanagdong wells has been previously described in a number of reports (Palma, 1981; Palma and Hermoso, 1981; Tebar, 1983; Bayrante and Herras, 1990 a,b; Reyes, 1991 a,b, c,). A petrological review was conducted by Reyes et al. (1990). The stratigraphy determined by deep drilling is :

Mahanagdong Volcanics (MV); surface formation of Pleistocene to Recent age consisting of a series of slightly to weakly weathered andesitic lava flows intercalated with breccias derived primarily from Mt. Mahanagdong. The formation thickens to the west attaining 760 m in MG-2D and a minimum thickness of 150 m in MG-5D.

Mamban Formation (MF); slightly to intensely altered water-lain sedimentary formation of Late Miocene to Pliocene age, unconformably underlying the Mahanagdong Volcanics. It consists of andesitic hyaloclastite with thin layers of sedimentary breccias and carbonaceous **sandy and** silty claystone. It contains minor allochthonous, fossiliferous limestone in MG-4D. Maximum thickness is 985 m (in MG-1).

Bao Volcano-Sedimentary Formation (BVSF); intensely altered sedimentary breccias intercalated with lenses of recrystallized limestone and clayey siltstone and sandstone of middle Miocene to Pliocene age. The upper contact is marked by the appearance of shelfal limestone and carbonaceous siltstone to sandstone in the sedimentary breccia. The formation contains clasts of mostly andesites with minor basalt.

Mahiao Sedimentary Complex (MSC); composed of heterolithologic breccias with a matrix of claystone and sandstone of Middle Miocene to (?) Oligocene in age. The formation is considered the local basement in the geothermal field. In most of the wells, transition to this formation is marked by the predominance of microdiorite and diorite clasts which exhibit downward coarsening and paleo alteration. The rock matrix is composed of claystone and sandstones which are dominantly altered to illitic clays and chlorite.

Table 1 ***Summary*** *of Well Data.*

WELL CODE	DATE SPUDDED (MM/DD/YY)	DEPTH (m VD)	TEMP / DEPTH (°C / m)	ENTHALPY (kJ/kg)	INJECTIVITY (L/S-MPa)	FLUID TYPE	COMMENTS
MG-1	07/11/80	2335	280/1200	1358	23.0	NEUTRAL TO SLIGHTLY BASIC ALKALI - CHLORIDE	BOTTOM TEMPERATURE AFFECTED BY DOWNFLOW; COMMERCIAL (12.5 MWe)
MG-2D	01/19/81	2017.7	272/1961	1140	66.0	- DO -	COMMERCIAL (8.7 MWe); CALCITE BLOCKAGE AT 1000 m
MG-5D	12/05/82	2703.7	310/2610	1380	30.0	- DO -	COMMERCIAL (4.2 MWe) HIGH GAS (1.9-4.4 %); BLOCKAGE AT 844
MG-4D	05/01/90	1788.7	233/1059	<800	76.5	- DO -	PRESENTLY NON-COMMERCIAL DUE TO STRONG DOWNFLOW AT 1118 m; FLUID INCLUSION TH> 290°C AT BOTTOM
MG-7D	06/05/90	2248.9	261/1629	1368	157.0	- DO -	COMMERCIAL (13.2 MWe); TEMP. BELOW -1050 NOT MEASURED DUE TO OBSTRUCTION

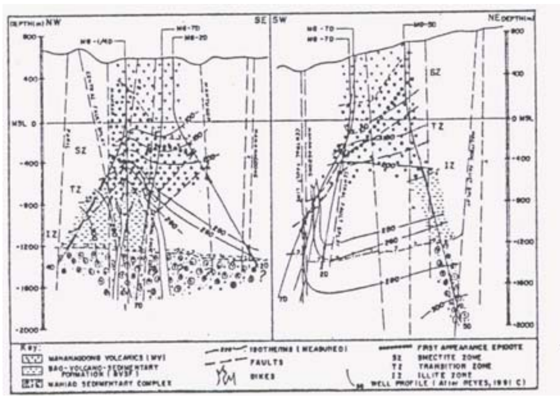

Fig. 3 Distribution of Mineral Zones, Stratigraphy and Isotherms.

2. Petrology

A comprehensive petrological evaluation of Mahanagdong has been reported by Reyes (1991). A detailed discussion of the **data** is beyond the scope of the paper. However, some of the significant aspects of the evaluation are given below.

The distribution of alteration mineral zones, stratigraphy, and isotherms is illustrated in Fig. 3. As shown in wells MG-1, MG-4D to the west and MG-7D to the southwest, clay zones extend to temperatures beyond their usual stability ranges. For example, the smectite zone extends beyond 220°C. The fact that the area is very permeable suggests a young age for the present hydrothermal system. Cooling is indicated in MG-2D where the illite zone appears below 230°C. The effect of a cool fluid inflow is likewise illustrated in MG-4D by the depression of isotherms in MG-4D. Conversely, increasing temperatures consistent with fluid inclusion, clay zones and downhole measurements are indicated close to andesite dikes at MG-1. The opposite is indicated at MG-7D since the dike encountered in the well is old and not associated with the postulated heat source driving tlie present system. High temperatures (> 300°C) are indicated to the NW and **NE** (i.e. MG-4D and MG-5D).

2.3 Chemistry Of Mahanagdong Wells

The chemistry of Mahanagdong wells were previously reported by Macambac (1990). The comparative discharge chemistries at full bore and throttled conditions are given in Table 2. Except for MG-5D and MG-4D, the rest of the data are at stable condition. No stable chemistry was attained in MG-5D because of a cycling discharge characteristics (Macambac, 1988) while MG-4D has an aragonite blockage at 424 m.

Apart from MG-4D the discharge fluids from Mahanagdong wells are neutral to slightly alkaline with almost similar Cl_{res} concentrations ranging from 2000 to 3000 mgkg. The SO_{4res} and Mg_{res} concentrations range from 12 to 76 and 0.01 to 0.05 mgkg, respectively, are remarkably similar in the drilled wells.

With the exception of MG-5D, NCG concentration in the Mahanagdong wells are relatively low and uniform, ranging from 0.25 to 0.70% w/w TD. MG-SD has considerably higher NCG levels up to 6.5% w/w TD due to the presence of a high gas feed in tlie well (Table **2**).

Reservoir Chemistry And Sector Trends. An unusually high degree of water encroachment into the reservoir is indicated by high Ca concentrations in the fluid and consequently lower CVCa ratio. The CVCa ratios of the stable wells (MG-1, MG-2D and MG-7D) have fairly small range, 156 to 262, indicative of a lower degree of meteoric water mixing compared to wells MG-5D and MG-4D.

The relatively broad CVCa range in MG-5D (56 to 201) is indicative of cooler fluid encroachment along faults at tlie southeastern sector of the field. This is consistent with fluid inclusion data (Reyes, 1990). MG-4D fluids, although not stable, exhibit the lowest degree of coldwater mixing.

The very narrow range of Cl/B ratio, 20 to 24, (excluding MG-4D), strongly indicates a chemically homogeneous reservoir brine with little variation in reservoir **rock** composition and an absence of widespread illitic clays which might selectively remove B from hydrothermal solution.

Fig. 4 depicts the Cl_{res} against $TSiO_2$ for Mahanagdong wells together with the TGE wells in the Bao valley (see Fig. 2) and alkali-chloride springs in the Bao and Banati area. The data from MG-1, MG-2D, MG-5D and MG-7D are notably clustered, indicative of the homogeneity of the thermal fluids in the Mahanagdong reservoir. Based on this plot two possible dilution paths are suggested: 1) a dilution line L_1 defined by meteoric water at 30°C connecting MG-4D with the rest of the Mahanagdong wells; 2) a dilution line L_2 defined by meteoric water at 30°C and the Bao/Banati springs. The plot also shows two possible cooling processes for Mahanagdong well fluids outflowing towards Bao: 1) a conductive heat loss line L_3 defined by Mahanagdong reservoir fluids towards TGE-5 and Banati springs; 2) boiling line L_4 defined by Mahanagdong fluids outflowing towards TGE-4, TGE-5A and Bao springs. These trends suggest that the chloride springs in the Bao Valley are related to cooling of Mahanagdong fluids by conductive heat losss and boiling processes.

*Table **2** Representative Chemistry of Mahanagdong Wells.*

PARAMETEI.	UNIT USED	MG-1	MG-2D	MG-5D	MG-7D	MG-4D
Ho	kj / kg	1125-1266	982-1196	864-1144	1233-1365	788-830
WHP	MPaa	1.2-2.97	1.21-2.64	0.58-2.19	1.14-3.16	0.10-0.13
pH		5.89-8.60	8.02-8.33	7.43-8.04	7.75-8.06	6.80-8.34
Clwbx	mg/kg	4054-4284	4040-4350	2762-4422	4006-4170	1611-1783
Cl res	mg/kg	2662-2912	2700-3050	1907-2902	2542-2727	1327-1453
SO_4 res	mg/kg	12-16	18-22	14-76	17-20	P4-313
Mg res	mg/kg	0.02-0.04	0.01-0.03	0.04-0.10	0.01-0.05	0.74-2.32
Cl/Ca		218-262	156-179	56-201	173-192	24-42
Cl/B		20-22	20-23	21-24	20-23	25-29
$TSiO_2$	°C	264-270	260-266	253-277	263-275	182-195
TNaKCa	°C	271-279	266-269	241-279	272-282	176-186
CO_2 td	mmoles/100moles	165-285	101-188	282-2735	162-243	56-128
CO_2/H_2S		131-171	68-112	94-525	52-91	110-1113
% NCG	w/w at td	0.51-0.82	0.10-0.30	1.93-4.45	0.37-0.64	0.14-0.68

N.B. 1. MG-1, MG-2D & MG-5D DATA AFTER MACAMBAC (1990)
2. Ho - DISCHARGE ENTHALPY
3. $TSiO_2$ - CORRECTED STEAM LOSS (FOURNIER & POTTER, 1982)
4. TNaKCa - CATION TEMPERATURE (FOURNIER & TRUESDELL, 1973)

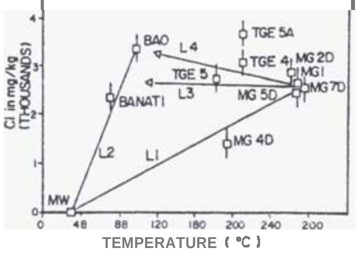

*Fig. **4** Chloride Concentration vs. Temperature Plot (After PNOC-EDC 1991).*

2.4 Well Measurements And Output Test Data

Fig 5 plots the measured temperature of the five wells based on the heat-up surveys and post-discharge downhole measurements. The temperature profile of well MG-4D is limited to only -480 mRSL depth due to a strong downflow persisting below this depth masking the actual downhole temperature in the open section of the bore. Well MG-1's bottom temperature is similarly affected by a downflow from an upper permeable zone, although this is not strong enough to effect a temperature reversal such as seen in MG-4D. It can be surmised from this plot that at a common depth of -1000 mRSL, MG-7D appears to be hotter than MG-1, MG-SD and MG-2D. The temperature at -1050 mRSL in well MG-7D can not be measured due to an obstruction. However, flowing survey data indicates good production at the bottom and no indications of temperature reversal. In addition, calculated temperatures based on $TSiO_2$ (discharge) are high and range from 263 to 275°C. It is thus expected that temperatures of greater than 280°C exist bottomhole (-1640 mRSL). Preliminary field isotherms at levels -1000 and - 1200 mRSL indicate that the highest resource temperatures (> 280°C) lies within the vicinity of wells MG-7D, MG-1 and MG-5D (Fig. 6). The contours are open to the NNE and NW directions..

Well output capacities are tabulated in Table 3. A separation pressure of .80 MPaa and a specific steam consumption rate of 2.2 kg/s-MWe are assumed. Among the four wells discharged at fullbore conditions, well MG-2D has the lowest enthalphy (1140 kj/kg) compared to 1350 kj/kg for wells MG-5D, MG-7D, and MG-1. Wells MG-1, MG-2D and MG-7D deliver high mass flows reflective of their good permeability. MG-SD exhibited a cycling discharge characteristic during early testing although this later stabilized. This is attributed to competition between inter-zonal feeds at different flow conditions.

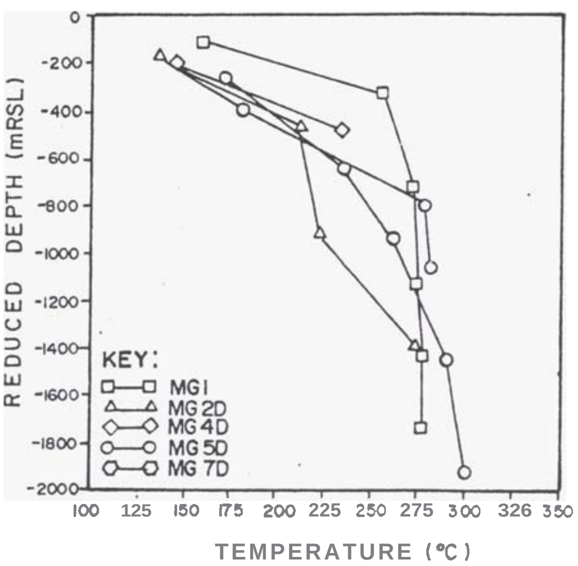

Fig. 5 Measured Temperature of Mahanagdong Wells (After PNOC-EDC 1991).

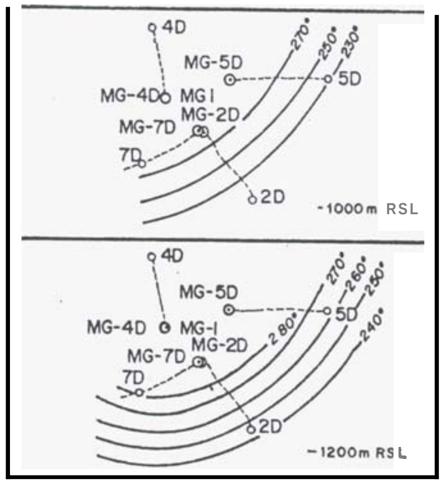

Fig. 6 Mahanagdong Isothermal Contours (After PNOC-EDC 1991).

Table 3 Mahanagdong Well Output (After PNOC-EDC 1991).

WELL	WHP (MPag)	H (kj/kg)	MF (kg/s)	WF (kg/s)	SF (kg/s)	MWe
MG-1	1.1	1358	90	62.0	28.0	12.5
MG-2D	1.1	1140	94	74.8	19.2	8.7
MG-5D	0.8	1350	30	20.8	9.2	4.2
MG-7D	1.0	1368	100	69.0	31.0	13.2
		TOTAL	314	226.6	87.4	38.6

H. E.
1. COMPUTATION EASED ON 2.2 /s SPECIFIC STEAM CONSUMPTION RATE
2. OUTPUT AT 0.8 MPa abs SEPAF TION PRESSURE

3. CONCEPTUAL HYDROGEOLOGICAL MODEL

A proposed conceptual hydrogeological model for Mahanagdong reservoir is depicted in Fig. 7. This is based on a multi-disciplinary analysis of all data. The model is akin to volcano-related, liquid-dominated systems developed in terrains of high relief as proposed by Henley and Ellis (1983) and Hochstein (1985).

Deep drilling in the project has tapped a high temperature geothermal resource characterized by single-phase, neutral to slightly alkaline fluids.

A true "upflow" in the resource is not well developed but thermal plumes are identified close to MG-1, MG-7D and MG-5D (Reyes, 1990). These upwelling fluids are principally chanelled by fault structures. Other structures like the Central Fault Splay and Mamban Faults are known to channel cool dilute fluids (temperature 160-170°C) downward to 1200 m as seen in MG-4D. Lithological permeability control is minor except within the Mamban Formation where aquifers are found between -500 to -700 mRSL.

The thermal plumes are characterized by high measured temperature >280°C (although fluid inclusion data suggest temperature of up to 320°C) at depths of -1000 to -1200 **mRSL.** Mahanagdong fluids are less mineralized than typical Tongonan wells and contain an estimated reservoir chloride of 2000 to 3000 mg/kg.

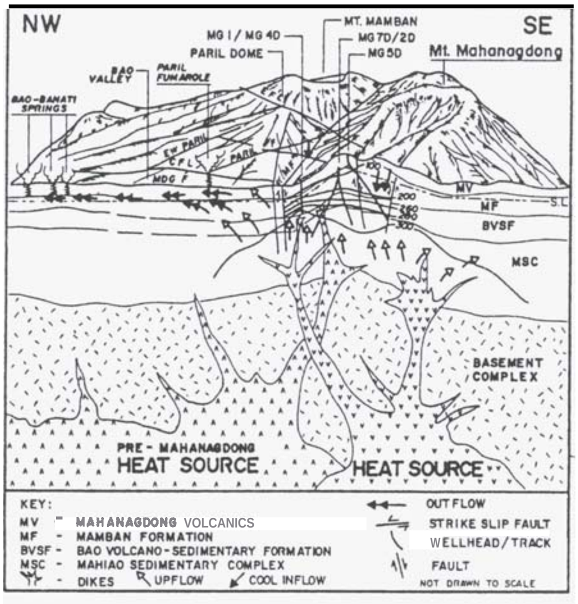

Fig. 7 Conceptual Hydrological Reservoir Model.

The heat source for the system is postulated here to be mainly associated with Mt. Mahanagdong to the immediate northeast of the prospect with a localized thermal upwelling west of the area within the breached crater, and presumably at Paril further to the west as evinced by temperature trends, fluid inclusion data and alteration mineralogy (PNOC-EDC, 1990).

Less dense hot fluids rise from depth up faults transecting heterolithologic sedimentary breccias, limestone, siltstone, sandstone, andesitic hyaloclastite, associated tephras and epiclastic sediments. Boiling conditions are noted at about -1000 to -200 relative to sea level due to declining pressures in the upflows. However, at shallower depths (386-537 m), exsolved gases, particularly H_2S, react with the perched water table and produce strong localized acid sulfate alteration assemblages comprised of alunite + natroalunite + kaolinite + opal + cristobalite + pyrite. In some cases, steam-heated features are developed at the surface (e.g. tlie Mahanagdong and Paril fumaroles and hotsprings).

In some parts of the Mahanagdong reservoir tlie thermal upflows are affected by cool inflows of low salinity meteoric waters (e.g. MG-1, MG-4D). These cause considerable perturbation in well bore temperature profiles through strong inter-zonal flows. The source of this cold fluid is yet to be confirmed, however it is thought that it may be derived from surface recharge occurring in the Mamban plateau area to the northeast of the project.

There is a strongly developed lateral outflow from the Mahanagdong field to the northwest of Bao valley. This appears to be largely controlled by the West Fault Splay and the Mahanagdong Faults and *to* a lesser extent inter-formational contacts. This outflow structure is reflected in the geophysical, petrological and fluid inclusion and isotopic data from Bao and Banati area (Reyes, 1990; Layugan et al.,1990; Isidro and Solana., 1991).

4. CURRENT MAHANAGDONG STORED HEAT ESTIMATE

For purposes of initial commitments for power development planning the geothermal resource at Mahanagdong has been sized on the basis of an assessment of volumetric stored heat (Muffler and Cataldi, 1979). This involves the calculation **of** the thermal energy contained in a given volume of rock and water and the estimation of how much of this energy can be recovered. In all cases considered for determining the most probable reserve, the eastern boundary has been fixed using the postulated resistivity boundary. This boundary coincides with an extrapolated line connecting 500 m horizontal drainage radii for tlie easterly directed wells (i.e. MG-2D and MG-5D). Different cases and assumptions used in defining reserve extents in the westerly directions are described below.

Table **4** summarizes the assumed parameters used for the stored heat and power capacity calculations.

Table 4 Summary of Assumed Parameter for Stored Heat and Power Capacity Calculations

I. VOLUMETRIC STORED HEAT

TOTAL HEAT IN PLACE
= DIFFERENCE IN HEAT CONTENT IN ROCK + DIFFERENCE IN HEAT CONTENT IN WATER

$H = V \times (T_{RES} - T_{BASE}) \times ([(1-\phi) \times C_{PR} \times \rho_R] + [\phi \times C_{PW} \times \rho_W])$

WHERE,		ASSUMPTIONS:
V	= VOLUME OF ROCK	FOR DISCUSSION
T_{RES}	= RESERVOIR TEMPATURE	260°C
T_{BASE}	= RWECT TEMPERATURE	180°C
ϕ	= POROSITY	.06
C_{PR}	= SPECIFIC HEAT OF ROCK	0.9 KJ/KG-°C
ρ_R	= DENSITY OF ROCK	2660 KG/M³
C_{PR}	= SPECIFIC HEAT OF LIQUID	CALCULATED FROM T_{RES} AT 260°C
ρ_W	= DENSITY OF LIQUID	CALCULATED FROM
HT	= THERMAL ENERGY (KJ=KWT-SEC=MWT-YR)	

II. ELECTRICAL POWER CAPACITY

$PC = \frac{[H_T \times Rf \times CEf]}{[Lf \times PL]}$

MERE,		ASSUMPTIONS:
Rf	= RECOVERY FACTOR	20%
CEf	= CONVERSION EFFICENCY	12% AT 260°C
Lf	= LOAD FACTOR	80%
PL	= RANT LIFE	25 YEARS
PC	= POWER CAPACITY (MWe)	

4.1 Reservoir Lateral Extent And Boundaries

Fig. 8 illustrates the minimum and maximum resource areas used in the estimation of power potential.

Minimum Area. Two cases are considered in outlining the minimum productive reserve . The first case, assumes a horizontal drainage radius of 250 m for both MG-4D and MG-7D. The area of influence near MG-4D is defined by that point in the well with a temperature of > 220°C projected vertically. This excludes the area affected by low-temperature downflow. Thus, the "smallest or conservative area" covers about 6.3 km^2. The second case (optimistic minimum) similarly considers a 250 m drainage radius for both MG-4D and MG-7D but assumes that the downflow below the production casing shoe at MG-4D can be effectively sealed-off. In addition, a bottom temperature of at least 260°C is assumed at the bottom of the well as indicated by fluid inclusion results. The resource area obtained using this assumption totals 6.8 km^2.

Best Estimate of Reserve Area. The "best estimate" considers **a** lateral extension of 250 m west of the "bigger" minimum area. The basis for this assumption is tlie significantly low resistivity anomaly (< 20 ohm-m) being a likely indicator of either hot mineralized fluids and/or clay alteration resulting from the interaction of thermal fluids with country rock and thus possible acceptable production temperature. This resource area totals 7.8 km^2.

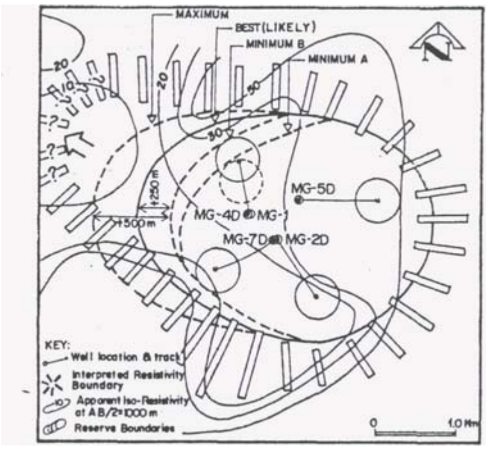

Fig. 8 Mahanagdong Resource Areas and Boundaries (After PNOC-EDC 1991).

Maximum Area. The maximum area assumes an extension of 500 m to the west of the "best estimate" boundary. This western extension includes the low resistivity which is open to the NW. The elongation similarly follows tlie trend of postulated outflow direction towards Bao Valley. The total resource area using this assumption is about 9.8 km^2.

Reservoir Thickness (Vertical Boundary). **A** minimum economic resource temperature of 220°C is assumed for the upper vertical temperature limit of the reservoir. This vertical limit lies at about 550 mRSL in all the wells except MG-2D where a temperature of 210°C was extrapolated to a similar depth. The lower reservoir limit is based on tlie maximum drillable depth using PNOC-EDC Rig # 10 capacity (3500 mVD, -2800 mRSL). It thus assumes an isothermal extension of 800 m beyond the bottom of MG-5D, the deepest well drilled so far (depth 2700 mVD or -1900 mRSL). Using an average elevation of 700 m for Mahanagdong production pad, the reservoir thickness used is therefore 2250 m.

4.2 Recovery Factor

The recovery factor being used in most PNOC geothermal resource assessment follows the method of Cataldi (1979) which considers recovery as a linear function of porosity. For Mahanagdong, the factor used incorporates both the porosity measurement results of Bayrante (1991) and numerical simulation studies of Tongonan 1 field. This appears to give realistic results which can be validated in latter testing results and analysis of reservoir performance.

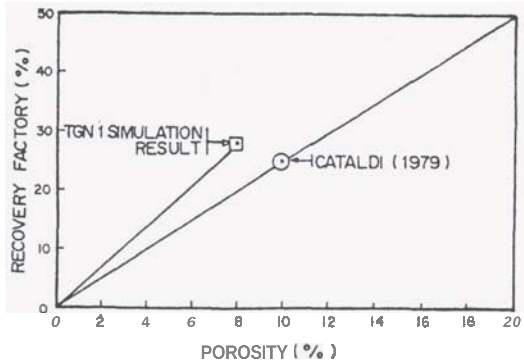

Fig. 9 Recovery vs. Porosity (After ***PNOC-EDC*** *1991).*

Recent simulation studies of the Tongonan 1 reservoir which assumed a porosity of 8% showed **a good** pressure/temperature match with reservoir measurements during the first seven years of commercial exploitation. The simulation results using the mass and heat extraction data to generate 112.5 MWe for 25 years yielded a recovery factor of 28% at full reinjection and 32% without reinjection. In the case of Tongonan 1, these recoveries are higher than values obtained from the Cataldi plot. Since the results are based on historical data and the fact that Mahanagdong lies within the same tectonic setting as Tongonan 1, we used the actual plot in interpolating the recovery factor for the project. Therefore, at an average measured porosity of 6%, a recovery of 20% is used **as** basis for calculating the recoverable heat which can be extracted. (**Fig.** 9).

4.3 Conversion Efficiency

For a resource temperature of 260°C, a conversion efficiency of 12% was used (Bodvarsson, 1974 and Nathenson, 1975).

4.4 Rock Density

A rock density of 2600 kg/m^3 was used for tlie computation. This is based on actual **dry** density core analysis of selected samples (Bayrante, 1991).

4.5 Reservoir Fluid Temperature

The reservoir fluid temperature was derived from the average of the upper vertical temperature limit of 220°C and the maximum bottom vertical temperature limit of **>** 280°C. This is about 260°C.

5. STORED HEAT CALCULATION RESULTS

Table 5 lists the calculated minimum, likely and maximum volumetric stored heat for tlie project. The computed volumetric heat ranges from 107 MWe (minimum) to 167 MWe (maximum). Tlie best value indicates a potential of 133 MWe. All calculation assumes a 25-year plant life and an 80% plant load factor.

Table 5 Mahanagdong Stored Heat-Power Capacity Estimates (After PNOC-EDC 1991).

AREA (km²)	THICKNESS (m)	Tr (°C)	0 (%)	RF (%)	C.E. (%)	POWER (MWe)	POWER DENSITY MWe/km²
A. MINIMUM							
a) 6.3	2250	260	6	20	12	107	17.0
b) 6.8	2250	260	6	20	12	116	17.0
8. BEST (LIKELY)							
7.8	2250	260	6	20	12	133	17.0
C. MAXIMUM							
9.8	2250	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

N.B.
ASSUMPTIONS:
ECONOMIC RANT LIFE = 25 YEARS
RANT LOAD FACTOR = 80%

5.1 Monte Carlo Analysis

The effect of variation in key reservoir parameters on stored heat calculations is assessed using a Monte Carlo method (Mesquite et al., 1991). This allows for an assessment of the upper and the lower limits of the size of tlie resource together with the most probable size of the resource.

The various inputs to this analysis is summarized in Table 6. Most likely estimates are given together with estimated probability distributions, and minimum and maximum values for different input parameters such as porosity, reservoir thickness, average temperature, conversion efficiency, reservoir area, and recovery factor. The result of the analysis shows a frequency distribution peak at a power capacity of 130 to 140 MWe but still with a broad range from 100 to 180 MWe because of tlie inherent uncertainties in the reserve areas considered (Fig. 10 and 11).

Table 6 Mahanagdong Monte Carlo Analysis Best Estimate and Probability Distribution Input (After PNOC-EDC 1991).

INPUT	BEST GUESS	PROBABILITY DISTRIBUTION TYPE	MN.	MAX.	STANDARD DEVIATION
Area (km²)	7.8	Triangular	6.3	9.8	
Thickness m	2250	Triangular	1800	2700	
Rock Density kg/m³	2670	Constant	2537	2804	
Porosity	0.06	Log Normal			0.12
Recovery Factor	0.20	Triangular	0.15	0.28	
Rock Spec. Heat kj/kg-°C	0.9	Constant	a855	0.945	
Temperature °C	260	Normal			10
Fluid Density kg/m³	783.6	Steam Table			
Conversion Efficiency	012	Triangular	-0.01	c0.02	
Fluid Specific kj/kg-°C	4.8	Steam Table			
Plant Life (years)	25	Triangular	20	30	
Load Factor	0.9	Triangular	0.8	1.0	
Reinjection Temp. °C	180	Triangular			

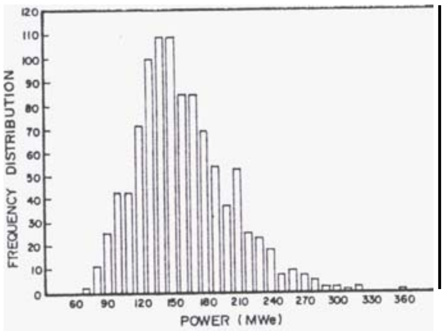

Fig. 10 Monte Carlo Frequency Distribution of Mahanagdong Power Capacity Estimate (After PNOC-EDC 1991).

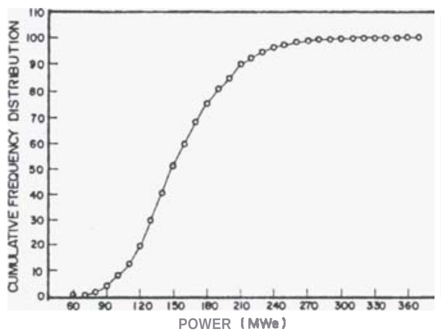

Fig. 11 Monte Carlo Cumulative Frequency of Mahanagdong Power Capacity Estimate (After PNOC-EDC 1991).

6. DISCUSSION

Tlie volumetric stored heat calculation indicates that there is approximately 2675 to 4175 MWe years of stored heat available from tlie Mahanagdong resource, of which 110 MWe can be accessed from the existing pads for the next 25 years.

The Monte Carlo analysis of the estimated power reserve supports an initial development of 110 MWe. Of this target, 38.6 MWe has already been proven at the well head with 5 wells. In addition, a broad range of 100 to 180 MWe capacity has been identified.

A 165-MWe development has been recently proposed for Mahanagdong to augment the 605 MWe development target for Leyte **A.** Before committing to this level of development further delineation testing is necessary to address uncertainties in the reserve areas considered, permeability distribution and recharge potential estimates which affect recovery factor. In particular, further delineation tests are needed towards the west, east, and northeast as step-outs from tlie identified and assumed reserve boundaries. No numerical simulation results are yet available and long-term prediction of the most likely reservoir response is therefore unknown. This is crucial for future reservoir management program and field exploitation and in the overall development strategy.

7. CONCLUSIONS

1. the updated resource assessment indicates that there is approximately 2675 to 4175 MWe-years of stored heat, from which 2750 MWe-years or 110 MWe may be accessed for 25 years from the existing pads.

2. the present data strongly favour an initial 110 MWe development however, further development plans beyond this require step-out exploratory testing beyond the postulated reservoir boundaries.

3. considering the inherent constraints and limitations of the volumetric stored heat calculation method, the present assessment of the project is believed to be conservative.

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