RESOURCE EVALUATION AND DEVELOPMENT STRATEGY, AWIBENGKOK FIELD

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1. ABSTRACT

The Awibengkok geothermal field, West Java, Indonesia, began generation of 110 MWe in early 1994 and is currently being expanded to 330 MWe. The initial series of five exploration wells delineated a geothermal resource with high temperatures, substantial volume, and relatively benign fluids. Interference testing utilizing the exploration wells was successfully used to measure field permeability. Based on high measured field permeability, large diameter wells were drilled to demonstrate commercial deliverability. A numeric modeling approach recognizing the uncertainty in interference tests and other factors was implemented to determine the production capacity of the reservoir. The numeric model, continuously refined and calibrated to field performance, demonstrates that the field can sustain 330 MWe over the contract life and provides a basis for optimizing reservoir management strategies.

2. INTRODUCTION

The Awibengkok geothermal field is located on the western flank of Mount Salak 60 kilometers south of Jakarta, West Java, Indonesia (Figure 1). Unocal Geothermal of Indonesia (UNOCAL) has explored and operated the field since February of 1982 under a joint operating contract with the Indonesian National Oil Company (PERTAMINA). Steam is sold to the Indonesian Electric Utility (PLN). Units 1&2, comprised of two 55 MWe Ansaldo turbine generators, have operated since early 1994. Plans are to expand the capacity of the field to 330 MWe by early 1998.

3. FIELD HISTORY

3.1 Evaluation

The discovery well was drilled and tested by March, 1983. Well 1-1 encountered an underpressured, saturated liquid geothermal resource and had a production capacity of five MWe through a standard (220 mm) perforated liner. Produced fluids showed the reservoir to be brine with approximately 12,000 ppm TDS. Four additional exploration wells were drilled to delineate about 10 km^2 of resource, with reservoir temperatures ranging from 225°C to 265°C. Reservoir fluid characteristics were homogeneous across the field and average production from these first five wells was 4 MWe. All wells produced from saturated liquid zones. Pressure measurements taken at the feed points in the wells indicated the wells to be connected to a common reservoir. Single well transient testing showed well permeabilities from 4 to 40 d-m.

The first interference test was conducted in 1984 following the completion of the exploration wells. This test utilized all of the exploration wells, 1-1 and 5-1 as production wells, 2-1 as an injection well, and 3-1 and 4-1 as observation wells equipped with helium filled capillary tubing hung opposite the permeable zones. The test showed good connectivity between the wells with rapid pressure response of similar magnitude at both observation wells. Test analysis showed field permeability to be on the order of 150 d-m. No mass rate declines or enthalpy changes were detected at the production wells.

Wellbore simulation (Strobel, 1984) showed that the high permeability could supply much higher rates if larger diameter wellbores were used to minimize feed point to wellhead pressure loss. The first "big hole", well 6-1, was drilled to confirm the calculations in 1985. Well 6-1 tested at a production capacity of 20 MWe and demonstrated the commerciality of the project. Two additional big holes were drilled for confirmation and additional resource delineation. Wells 7-1 and 8-1 were drilled to the west of the exploration wells and encountered higher production temperatures of up to 283°C. Wells 7-1 and 8-1 are currently utilized as production wells and together contribute about 40 MWe.

Additional interference testing with various configurations of production, injection and observation wells showed all the wells except 5-1, and later 9-2, to be very well connected with high permeability. The interference test illustrated in Figure 2 is typical of Awibengkok interference tests. The difference in response between observation wells 3-1 and 5-1 is attributed to a semi sealing permeability barrier between 5-1 and the main area of the reservoir. This interpretation is based on the results of interference tests in various configurations including using 5-1 as a production well. Single well transient tests also indicated the reservoir permeability in the near vicinity of well 5-1 was comparable to the rest of the reservoir.

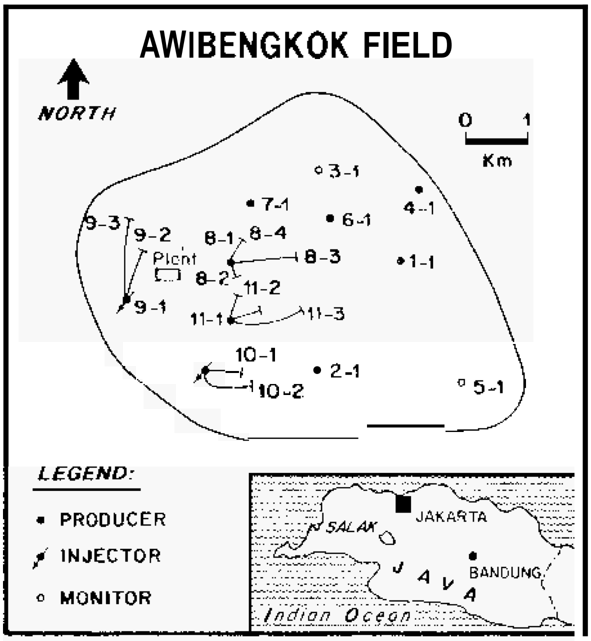

Figure 1 Map of the Awibengkok Field

The interference test shown in Figure 2 also shows two characteristics which are common to all the interference tests performed at Awibengkok. Following the early transient period, both wells show a similar pressure decrease or uniform drawdown rate. There is substantial pressure recovery after shut in, but some pressure depletion following the pressure recovery period.

3.2 Units 1&2 Development

Field testing activities were minimal from 1986 to 1989 while economic assessment and contract negotiations were conducted. Commitment to Units 1&2 (110 MWe) was made in 1989 and drilling activities resumed. The next well drilled was 9-1 which represented a step out of 1.5 km to the west from 8-1 with the objective of finding a suitable area for injection. Initial tests were disappointing in terms of well permeability, but stimulation (acid treatments) resulted in satisfactory injection capacity and the well was eventually production tested at 18 MWe. The second well from the pad, 9-2, was drilled directionally to the north and was also successful as both an injector and a producer. These wells also continued the trend of increasing temperatures to the west with a maximum temperature of 3[illegible]0°C at depth in 9-2.

While some consideration was given to using wells 9-1 and 9-2 as production rather than injection wells, their location topographically downhill from the rest of the field and their deep permeable zones makes them very suitable for injection. Interference testing also revealed that a semi sealing permeability barrier exists between 9-2 and the rest of the wells, similar to that near 5-1. Tracer testing conducted with 9-1 on production and 9-2 on injection confirmed a lack of direct connection between the two wells. Based on this structural feature, well 9-3 was targeted as an offset to 9-2 that also encountered good, deep permeability.

Seven production wells with a total production capacity of 130 MWe are used to supply Units 1&2. All produced brine and steam condensate is reinjected to the reservoir. The production/injection system is divided into two circuits. Brine from wells 7-1, 8-1, 8-2, 8-3 and 8-4 is injected into wells 9-1, 9-2 and 9-3. This circuit accounts for 70% of the production. Brine from production wells 11-1 and 11-2 is injected into wells 10-1 and 10-2. Well 2-1 is used for steam condensate reinjection.

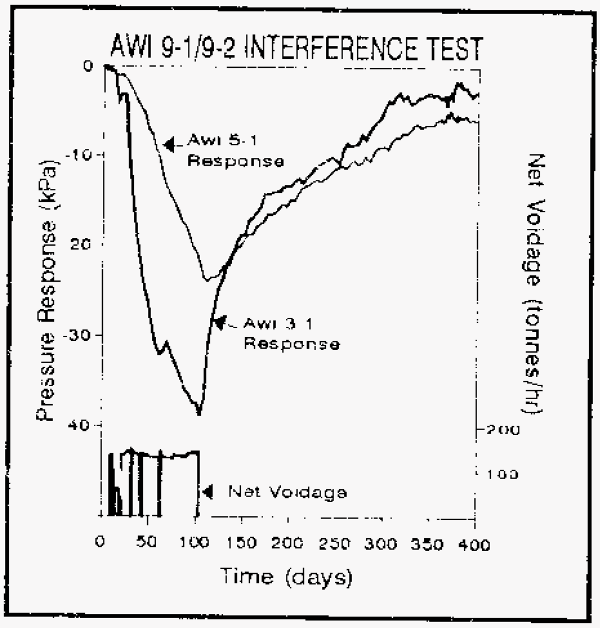

Figure 2: Pressure Response at Wells 3-1 and 5-1 with Well 9-1 on Production

4 AWIBENGKOK RESERVOIR MODELING

4.1 Modeling Strategy

UNOCAL's approach to modeling Awibengkok is one of fully integrating all available data into appropriate conceptual and numerical models while recognizing that uncertainty exists in the early stages of field development. While interference testing provided clear indications of field connectivity and magnitude of permeability, interference testing can over predict mass in place because of uncertainty in system compressibility or undiscovered reservoir heterogeneities. To address this uncertainty and examine field performance under various scenarios, alternate models were constructed (UNOCAL, 1993). A similar approach using multiple models was also utilized by Electroconsult (1986) during their feasibility study of the Awibengkok field for PLN.

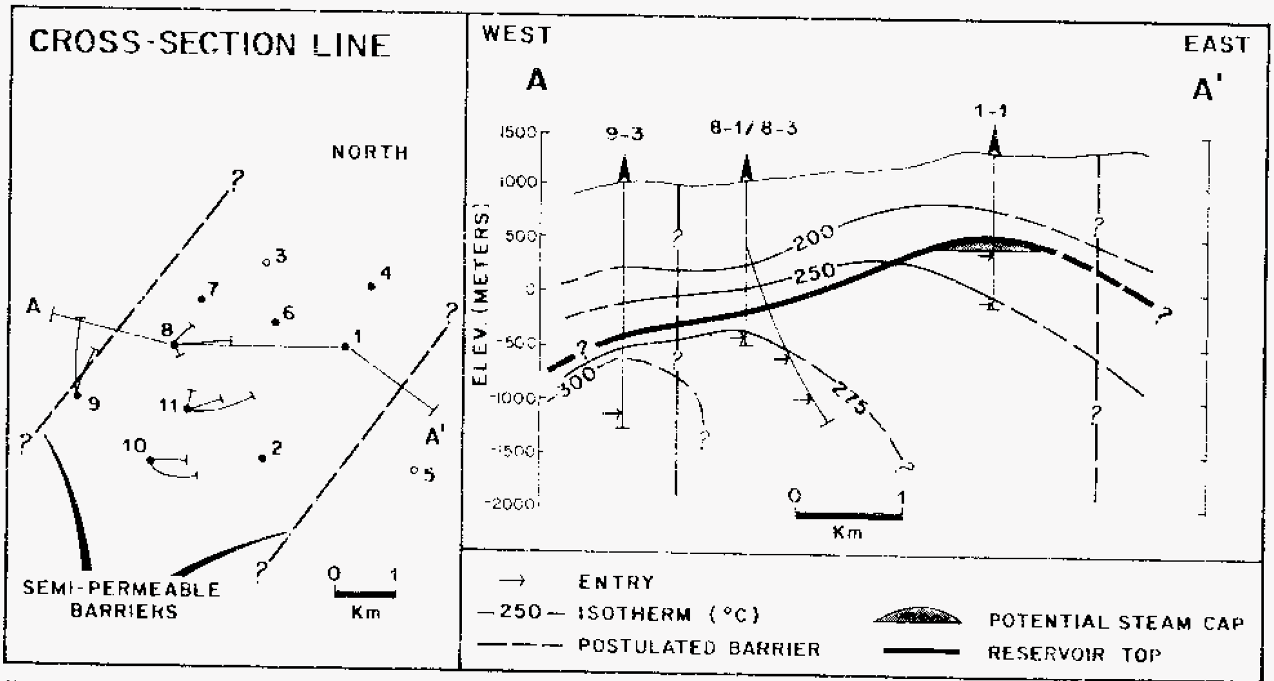

Figure 3: Cross Section of Awibengkok Reservoir

4.2 Conceptual Reservoir Model

Although alternate numerical models have been constructed to deal with uncertainty in the pre-production stage, these models all share certain attributes based on one conceptual model. Since all production has been saturated liquid, the bulk of the reservoir is liquid dominated. This does not preclude the possibility of steam existing above the shallowest entry in the field. To date the shallowest entry was encountered in well 1-1 at 520 m above sea level. This entry has pressure and temperature very close to the boiling point curve. Figure 3 shows a cross section of the field and an indication of where a native steam cap could exist. The formation (or expansion) of a steam cap upon exploitation is a characteristic common to all models. Several feed zones have been encountered deeper than 1200 m below sea level, establishing the thickness used in each of the alternate models.

The high measured permeability and uniform pressure drawdown observed during interference testing are indications of a well fractured system, and the high productivity of wells confirms this. Measured pressure at the feed points define a single pressure gradient and geochemistry shows homogeneity across the field, both indications of high permeability.

The two system heterogeneities, modeled as semi sealing faults, are also incorporated into all models and are expected to heavily impact field management strategy. Currently, over 50% of the brine from Units 1&2 is injected across the fault near 9-2 into wells 9-2 and 9-3.

Overall the conceptual model for Awibengkok is similar to the model described for Wairakei (Grant et al, 1982). Awibengkok is a high permeability system which will initially produce from saturated liquid zones but will eventually depend upon production from steam or two phase zones in the shallow regions of the reservoir to sustain long term performance.

4.3 Confined Numerical Model

The model defined by the volume of reservoir delineated by the wells drilled to date is designated the "confined" model. The porosity for this model is based on field measurements, which show decreasing porosity with depth. Thus, the confined model

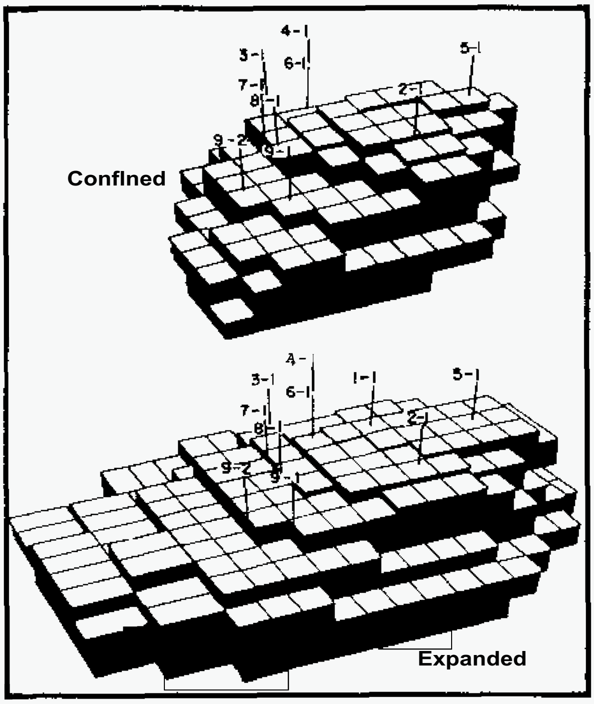

Figure 4 Expanded and Confined Models

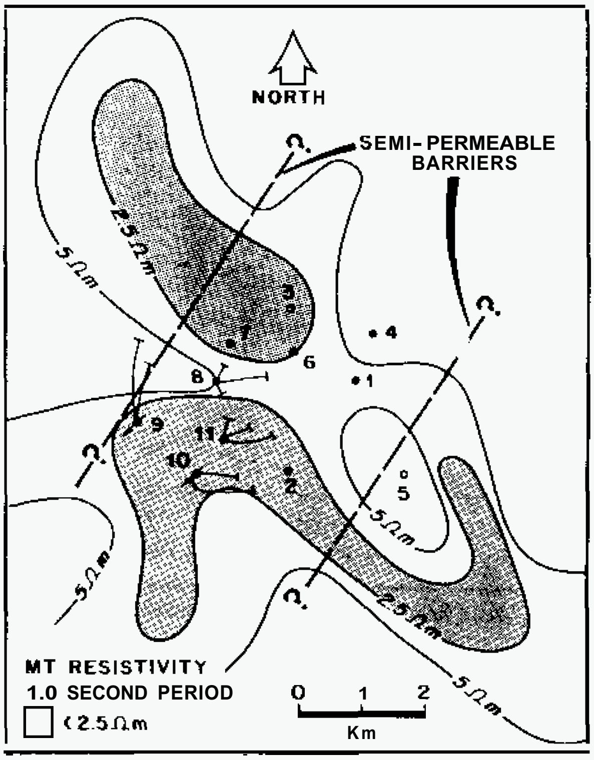

Figure 5 Geophysical Anomaly and Semi-sealing Permeability Barriers

represents best estimates of mass in place for parameters measured rather than inferred by interference testing. The mass in place for this model is 1.7 trillion kg.

4.4 Expanded Numerical Models

The numerical model resulting from rigorous incorporation of field limits delineated by drilling results contains insufficient mass to reproduce the transient response of the interference tests. Based on the pressure response observed during interference tests, alternate "expanded" models were constructed as larger but closed systems (Figure 4). Recognizing that system compressibility could be influenced by the presence of a steam cap in the undrilled portion of the reservoir, the expanded model was constructed to look at upper limits for mass in place. The calibration process to the interference data also provides an indication of where additional mass must be added, potentially useful data for field expansion.

UNOCAL utilizes automated history matching coupled to numerical simulation to determine magnitude of variables which cannot be directly measured. By allowing the porosity to vary in the areas of the reservoir across the semi sealing permeability barriers, the matching process can place mass as needed to match the interference data. The best matches were consistently obtained when significant amounts of mass were placed in the area of the reservoir to the northwest across the permeability barrier associated with 9-2. These data together with the increasing temperature to the west at depth and geophysical anomaly (Figure 5) provide substantial evidence for extension of the Awibengkok reservoir to the northwest (Noor, et al, 1992).

Since the expanded models require mass of unknown temperature outside of the volume defined by drilling, alternate expanded models were constructed. The difference between the two expanded models is the temperature of the fluid outside the drilled area. These two expanded models each match the interference test results and predict similar pressure responses of the reservoir to commercial exploitation. Defining which model

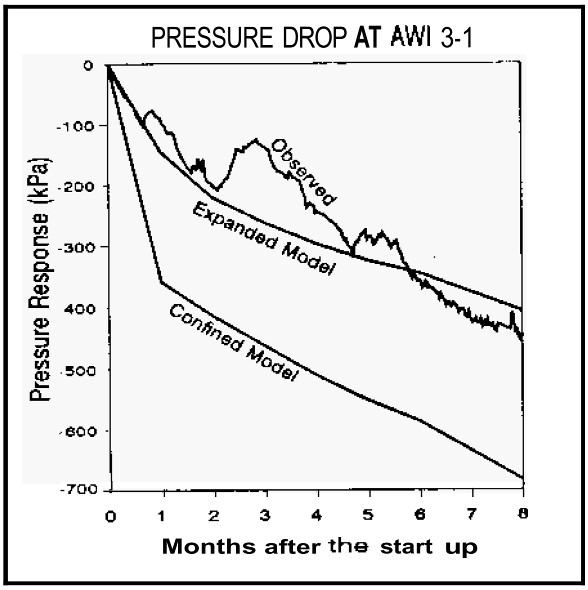

Figure 6: Field Response to 110 MWe Production Load

is more appropriate will be difficult until additional delineatior wells are drilled or long term field performance is available. Both of the expanded models contain substantially more mass in place than the confined model, approximately 5 trillion kg

4.5 Model Performance

To assess performance over ttie life of the project, a load of 330 MWe was applied to the confined and both of the expanded models. Make up wells were added until the steam production capacity of new wells was less than 30 tonnes/hr, a criteria based on economics. The area for drilling make up wells was limited to the "confined" reservoir. probably a conservative assumption

Numerical simulation showed that the confined model required the fewest number otrnakc up wells to sustain 330 MWe This model forms the largest steam cap, allowing high enthalpy production and minimizing declining production due to injection breakthrough.

The expanded model featuring warm fluids around the defined reservoir also sustains 330 MWe for the life of the project, but requires more make up wells since there is less steam cap to exploit. The expanded model featuring cooler fluids sustains 330 MWe fur 20 years, but does suffer some decline late in the field Life if the make up well criteria are adhered to

5. FLELD PERFORMANCE

Figure 6 shows the pressure response at well 3-1 predicted by the confined and expanded models and tlic actual response of the system induced by Units 1&2 start tip The predicted responses were based on 110 MWe starting up and running at constant rate. The early time portion of the observed start up response is affected by several well openings and shut tns associated with start up activities. The later time, post transient observed data is between the two predicted responses with a drawdown rate of 360 kPa/yr versus 34U kPa/yr for the expanded model and 560 kPa/yr for the confined model Recent numerical model calibration has required some reduction in total mass in ttic expanded models to match pressure response to production commercial rates, bur very minor changes in most of the model

6. DEVELOPMENT STRATEGY

Regardless which of the alternate models is used to predict field performance, one feature common to all models is the formation of a steam cap in the shallow region of the reservoir as illusrr-ated in the cross section in Figure 3 The rate of steam cap formation is proportional tu rhe reservoir pressure drop? with the confined model providing the larger steam cap. Post start up response has provided more confidence in the ability to project pressure trends, and exploitable steam cap formation Is expected to be relatively slow. It is expected that the steam-bnne interface will be discreet because of the high reservoir permeability. Most expansion production wells are planned in the area of expected steam cap formation Since predicting where feed points will be enwuntered in undrilled wells is difficult. expansion plans are based on initially saturated liquid production

Reservoir simulation also indicates that the brine injection - 10,000tons/hour at expansion to 330 MWe - must be deep and towards the edge of the reservoir to minimize injection breakthrough Placing injection deeper than production is consistent with experience in other fields (Home, 1986) as well as with numerical studies on this topic (Pruess and Bodvarsson, 1984). This strategy was reinforced by the results of the first post commercial production tracer test The tracer injection well was 10-1 which currently accepts about 1000 tons/hr of brine from 11-1 and 11-2 production wells The permeability was encountered relatively shallow in well 10-1 at 400 m below sea level while some of the production feed zones in wells 11-1 and 11-2 are as deep as 800 in below sea level.

The tracer returns illustrated in Figure 7 demonstrate the undesired results when injection exit points are located above production feed zones even though the lateral sepal-ation is on the order of 1000 m Well 10-1, which has exceptionally high permeability and is capable of producing 30 MWe, will be converted to a production well as part of the field expansion to 330 MWe Figure 8 shows the general areas for injection arid production for rhe expansion of the field to 330 Mwe Calculations show that 22 new production wells and 11 new injection wells will be needed at planned start up by early 1998

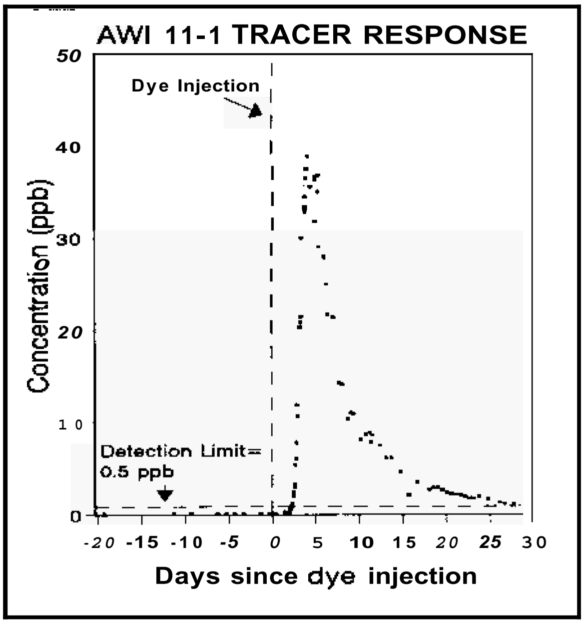

Figure 7: Tracer Response at 11-1 from Injection at 10-1

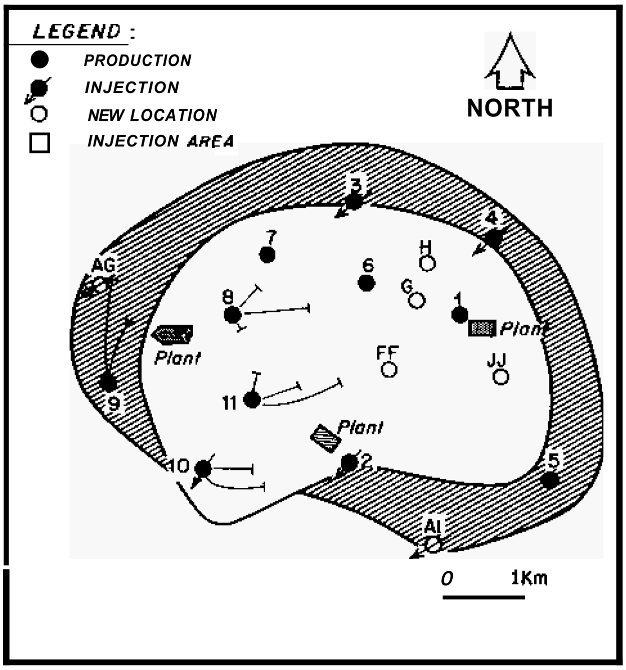

Figure 8 Awibengkok Expansion to 330 MWe

7. SUMMARY

The reservoir evaluation effort at Awibengkok established the feasibility of tlic project in terms of resource quantity and contributed to the commerciality of the project through optimization of wrll design The reservoir management effort utilizes a continuously evolving niodcl based on reservoir performance to optimize additional development These processes and strategies as applied at Awibengkok have greatly benefitted from industry experience world wide, especially from the development of liquid dominated geothermal reservoirs

8. ACKNOWLEDGMENTS

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