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Review of Baseline Geochemical Model and the Impact of Production at the Darajat Geothermal Field, Indonesia

R. Purwantoko Mahagyo, Phil A. Molling and Abu Dawud Hidayaturrobi

Chevron Geothermal Indonesia, Jakarta, Indonesia

G7geochem, Santa Rosa, California

Chevron Geothermal Indonesia, Garut, Indonesia

wantoko@chevron.com

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ABSTRACT

The geochemical-based initial-state conceptual model at the Darajat geothermal reservoir was largely delimited using distribution of non-condensable gas (NCG) chemistry, gas geothermometry and boron. Changes in chemistry to the initial-state distribution due to exploitation are reviewed through 2008.

Chemical constraints of early well fluid samples allow characterization and location of predominant reservoir processes at near initial-state conditions of the Darajat Geothermal Field. Three end-member compositions were determined: (1) Central Upflow (basal recharge); (2) the southern Condensation Cell (active shallow heat pipe); and (3) Eastern and Southern Edge Field (marginal recharge-MR). Best estimates of an upflow NCG geothermometer temperature (liquid/steam equilibrium) is 275-310^{o} C. The upflow is producing between 10-20% equilibrium steam-cap steam and 80% equilibrium steam from flashed liquid from gas grid estimates. Superheat values at initial-state range from 1.0 to 9.0^{o} C. The major chemical distinctions of the different portions of the Darajat Geothermal reservoir are (1) an H_2S-enriched Central Upflow, (2) a CO_2-enriched Condensation Cell, and (3) elevated N_2/Ar signal at the Edge Field wells. This edge field characteristic is corroborated by the meteoric signatures of stable isotopic values for early samples.

Each compositional-type is located within the structural framework of the Darajat Field. The Central Upflow Zone is confined to between Gagak and Cibeureum Faults. The Condensation Cell is located between the Cibeureum and Cipandai Faults. Edge Field fluids ("*air-related*" groundwater) appear to use the Gagak Fault to migrate from the NE edge to the center of the Darajat Field. Similar groundwater fluids appear to mix with the compositions of the Condensate Cell along the Ciakut Fault.

The early boron (B ppmw in steam) contained in the Central Upflow and Edge Field Zones was ~1.0 ppmw. The range of values in the Condensation Cell was higher than both the Central Upflow Zone and Edge Field Zones with a range of B between 1.5 and 5 ppmw. Boron has increased to up to 50 ppmw in the reservoir steam and ~100 ppm in the condensate injectate during the current production stage. This suggests that B is being concentrated (re-cycled) along specific flow paths as the condensate (liquid) injected is boiled and concentrates to many times the reservoir steam values. Continued monitoring of boron is also conducted regularly at surface manifestations for comparative purposes to the shallow reservoir.

NCG in steam (NCG_{stm}) has systematically decreased in production wells until 2001 and was followed by small increases in NCG (wt. %) from 2001 to 2006. In general, the NCG_{stm} in production wells from initial-state and NCG_{stm} values in producing wells in 2006 indicates the NCG_{stm} has decreased. This is not the normal historical trend of NCG_{stm} in steam cap portions of reservoirs. Both at the Geysers and Larderello gas concentrations in steam initially increased with the onset of production (Beall and Box, 1993; D'Amore and Pruess, 1985). The current low NCG_{stm} at Darajat is believed to result from the generation of steam from low gas liquids, such as groundwater, surface water injectate, or condensate injectate.

1. INTRODUCTION

1.1 Background

Presently Indonesia contains numerous large geothermal fields. The reserves from these fields are primarily used for converting geothermal energy to electricity. One of these large geothermal fields is Darajat located in South Central Java. The demand for electricity is outpacing supply in Indonesia and the move toward cleaner energy in the world has created an opportunity for the expansion at the Darajat Geothermal Field.

Darajat is the second largest geothermal development in Indonesia after Awibengkok, also managed by Chevron Geothermal of Indonesia (CGI). Darajat is currently producing 260 MWe from three power plants: Unit 1 at 55 MWe, which is operated by PLN; Unit 2 at 95 MWe unit rated capacity, which is operated by CGI; and Unit 3, a 110 MWe plant that began commercial operations in July 2007 and was constructed and is operated by CGI.

Geochemistry data is essential in monitoring a geothermal reservoir during exploitation. Integration of non-condensable gas (NCG) chemistry, boron (B) and superheat (SH) can be used to determine changes in reservoir performance from the impact of injection or marginal recharge. In addition, SH measurements can add information on the tendency of the reservoir to "*dry-out*".

Chemical data from all production wells, surface facilities and surface thermal manifestation are all monitored in order to interpret the changes in reservoir processes. Ultimately, these changes in reservoir processes help to better manage the Darajat Geothermal Field.

1.2 Location

The Darajat Geothermal Field is located about 150 km southeast of Jakarta, Indonesia, and 35 km Southeast of Bandung, the capital of West Java (Figure 1). It is located in the Garut Regency of the West Java Province.

The field lies within the Kendang volcanic complex, one of many volcanoes in the volcanic arc that extends from the Northern tip of Sumatra, through Java, and Eastward through the Banda Arc. The Kendang volcanic complex is part of a Quaternary volcanic range, extending from Papandayan volcano in the southwest to the Guntur volcano in the Northeast. The average elevation of the field is between 1750 – 2000 meters above sea level.

Figure 1: Location map of the Darajat Geothermal Field

2. DISCUSSION

This paper reviews the initial-state (baseline) conditions in the reservoir prior to exploitation and then focuses on the changes in chemistry induced by exploitation, particularly the effects of condensate injection (CI) and Marginal Recharge (MR).

At Darajat, B appears to be a good indicator for the migration of liquid condensate-injectate (CI). B is routinely measured in the produced steam (measured in condensed steam samples). Boron has a relatively high solubility, and thus tends to partition into the liquid phase upon condensation. This partitioning of boron into the liquid phase makes boron a very useful natural tracer to track chemical breakthrough of injected steam condensate (*refer to Sugandhi et al., 2009 and Hidayaturrobi et al., 2009 in this volume, for more discussion and details*).

NCG chemistry is also utilized for tracking CI breakthrough and migration of MR into production wells. Both MR and CI contain very low amounts of dissolved bicarbonate. Therefore, boiling of either liquid generates a steam with a low wt. % NCG_{stm}. It is the chemistry of the NCG that distinguishes between the boiling of MR and CI. Relatively higher amounts of N_2 and Ar tend to exist in steam generated from MR, whereas higher H_2S distinguishes steam generated from CI.

Superheated conditions in a geothermal reservoir can exist when steam is heated beyond saturated conditions (at a constant pressure). In other words, saturated steam becomes superheated when the steam comes into contact with a phase that exists at a higher temperature (e.g., reservoir rocks). SH measurements can determine changes in the balance between heat transferred between produced mass (steam) and stored heat in the reservoir rocks. With respect to injection, liquid CI boils at saturated conditions and can mix and lower the superheat of the reservoir steam. Alternatively, the addition of more steam from boiling CI to a fracture can distribute the heat transferred from the rock over more mass and also lower the measured superheat of the produced steam. This phenomenon would typically lower the superheat of the produced steam (assuming a constant reservoir or operating pressure).

Temporal changes in B, NCG, and SH will be discussed at 2 distinct periods: (1) initial-state 1995-1998; (2) current conditions represented by 2008 chemical data.

2.1 Chemical Characteristics at Initial-State

Chemically, the Darajat Geothermal Field can be partitioned into three regions: Condensation Cell, Upflow, and Edge Field (Figure 2). Basically, the initial state geochemical model is similar to the model which is developed in an earlier report by Kingston Morrison (1996) and updated by G7geochem in 2007.

The upflow region (Central Upflow Zone) is located along the Gagak Fault near DRJ-7, -9, -10 where the high-temperature steam is added to the reservoir. Condensation chemical affects have been identified along the southeastern margin of the Darajat reservoir and are typified by chemistry in DRJ-4 and -8. Two zones of boiled MR were indentified in the south-southwest and northeastern portions of the reservoir. These Edge Field zones are represented by the chemistries of DRJ-5 and -19, respectively.

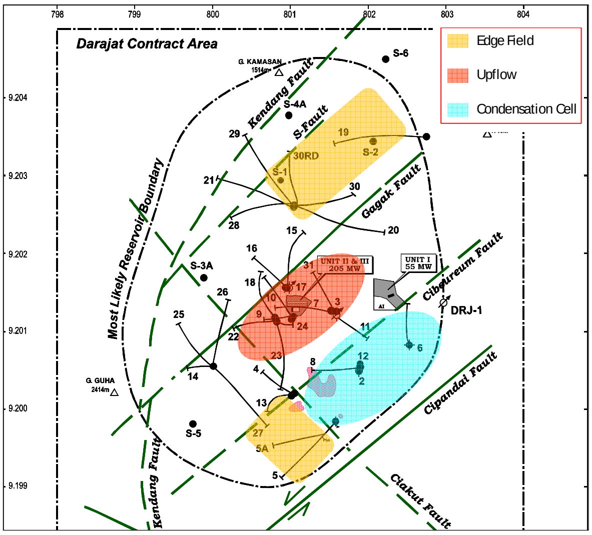

Figure 2: Geochemically-distinct regions of the Darajat field. Red areas are surface thermal areas

2.1.1 Non-Condensable Gas (NCG) Distribution

At initial-state each zone: Upflow, Condensation and Edge Field has a distinctive chemistry. The major differences in NCG chemistry of the three zones are shown in Table 1.

Table 1. Initial-state gas chemistry of the main zones in the Darajat Geothermal Field. Red font indicates unique range of chemical constituent.

Chemical Parameter	Upflow (DRJ -7,-9,-10)	Condensation Cell (DRJ -4, -8)	Edge Field (DRJ -5,-19)
NCG (wt. % in stm)	0.5 - 0.7	0.6 - 1.1	1.0 - 1.2
CO_2 (mol. % in NCG)	86.4 - 89.8	87.5 - 95.9	84.8 - 91.6
H_2S (mol. % in NCG)	6.0 - 7.0	2.5 - 6.1	4.0 - 5.0
NH_3 (mol. % in NCG)	0.10 - 0.30	0.03 - 0.06	0.06 - 0.11
CH_4 (mol. % in NCG)	0.30 - 0.60	0.03 - 0.07	0.25 - 0.50
H_2 (mol. % in NCG)	2.5 - 4.0	0.7 - 2.1	2.3 - 3.0
N_2 (mol. % in NCG)	1.3 -1.7	0.8 - 4.1	1.8 - 6.5
Ar (mol. % in NCG)	0.003 - 0.005	0.007 - 0.054	0.030 - 0.080

Wells that produce from the Central Upflow Zone contain the lowest amounts of NCG_{stm} and have the highest amounts of H_2S and NH_3 (mol. %). Lack of condensation or a system gas release could explain this low NCG_{stm} content in the

Upflow area. The Condensation Cell NCG chemistry is unique in that CO_2 is enriched because of the lower amounts of H_2S, NH_3, CH_4 and H_2. The Edge Field wells produce an NCG composition with elevated N_2 and Ar contents.

The enrichment of H_2S and NH_3 in the Upflow zone at initial-state is consistent with the re-boiling of an already boiled liquid. Three possible genetic models are as follows: (1) a liquid that experienced more boiling along a possible outflow path, (2) a liquid which experienced more boiling in a conductively hotter portion of the reservoir or (3) a liquid buffered with sulfide minerals. The high CH_4 content at the Upflow wells (Table 1) can be explained as having the best connection to a high temperature portion of the reservoir. This hypothesis assumes that the Fischer-Tropsch gas-gas reaction buffers CH_4 production. The Upflow wells (DRJ-7, -9, -10) appear to delimit a upflow gas geothermometry temperature of between 275-310^o C on the FT-HSH gas grid (Figure 3). In the case of the Edge Wells, the source of high CH_4 cannot be assumed to be solely from geothermal heat sources (e.g., organic sources) and less confidence in the FT-HSH gas geothermometer temperatures is warranted.

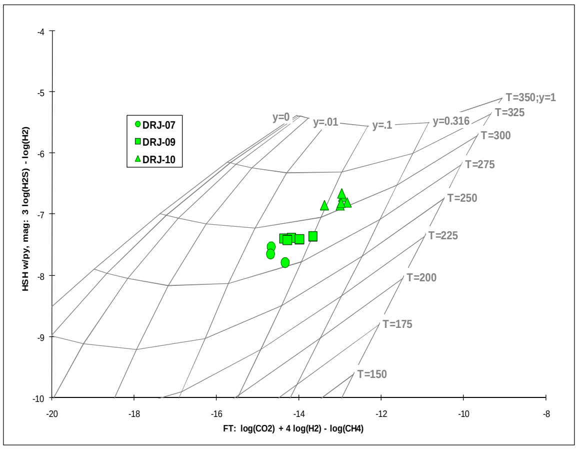

Figure 3: FT-HSH gas grid showing initial-state data of Upflow wells

As an example, the three zones can be graphically distinguished on a N_2-CO_2-Ar ternary plot (Figure 4). The Edge Field wells occupy an area of the plot that is enriched in "*air-related*" processes compared to the other zones. The compositions of DRJ-5, -19 and -20 plots near the AIR composition on the N_2-CO_2-Ar ternary plot. Because DRJ-20 has this groundwater-type signature, it suggests that the Gagak Fault may be a conduit for ground water recharge upon exploitation of the field. The Upflow well NCG compositions occupy an area more enriched in CO_2. The NCG of the Condensation Cell wells appear to be a mixture of the Edge Field and Upflow NCG compositions.

The differences between the three regions can also be shown using chemical distribution maps. The initial-state distribution of NCG_{stm} shows the high gas contents of the Condensation Cell (Figure 5). Note that data quality control issues prevented the use of DRJ-2 and -12 chemistry in Table 1.

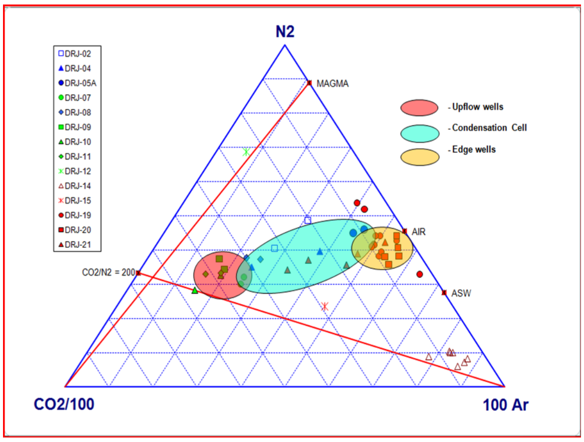

Figure 4: N_2-CO_2-Ar ternary plot of Darajat wells using initial-state data

The Edge Field wells DRJ-5 and -13 presumably have lower NCG than the Condensation Cell wells south of the Cibeureum Fault. It is hypothesized this is a result of dilution from boiling of MR that has a lower NCG content. The Condensation Cell well DRJ-4 is assumed to be low in NCG even though its chemistry is aligned with condensation processes primarily because of its location close to the Ciakut Fault (leakage). The remainder of the Darajat reservoir NCG north of the Cibeureum Fault is typically between 0.5 and 1.0.

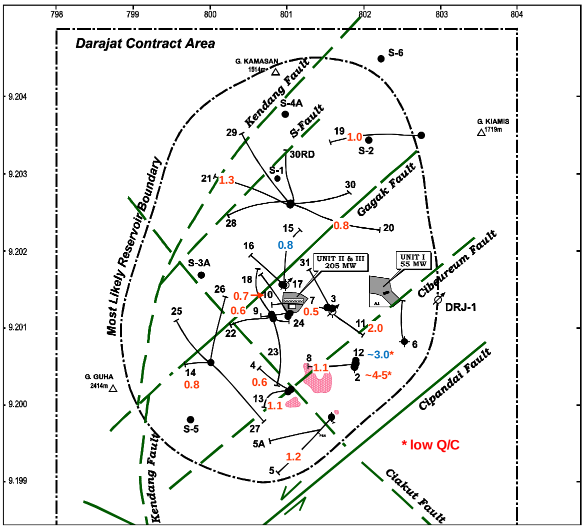

Figure 5: Distribution map of NCG at initial state

2.1.2 Boron Distribution

In the initial-state condition, B content (ppmw in steam) has a fieldwide range value about 0 - 7 ppmw (Figure 6). The Central Upflow Zone has a range of B content about 0 - 1 ppmw. The range of B content in steam for the Condensation Cell wells is larger: 1 to 7 ppmw. This larger range is to be expected as pockets of high NCG, vigorously boiling and natural liquid condensate exist in the shallow portions of the Darajat reservoir where condensation processes are more likely.

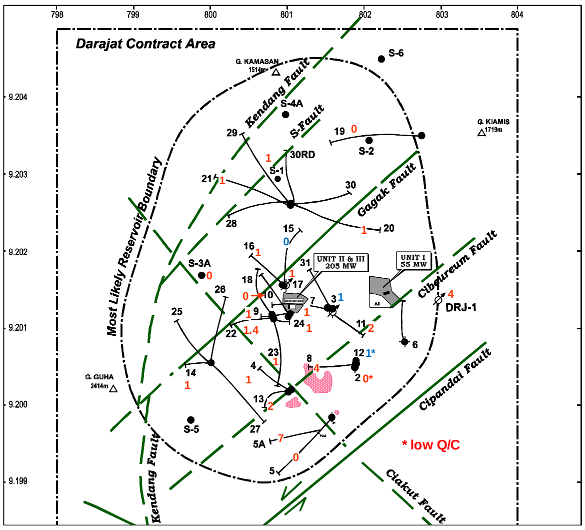

Figure 6: Distribution map of B in steam at initial-state condition. The B values from 1995 to 1998 were used depending on when the well was initially drilled

2.1.3 Superheat Distribution

In the early years 1996-1998, the Darajat Geothermal Field was superheated by approximately 5^o C with a range between 1^o - 9^o C. It is assumed these values were enhanced due to the extraction of mass to supply Unit 1. The distribution of early maximum-recorded superheat values (^{o} C) are shown in Figure 7. It can be argued that saturated conditions existed at initial-state, except possibly for wells that were extracting from beneath thermal features or wells associated with the Condensation Cell (e.g., DRJ-5, -8 and -13). Condensation requires the existence of two-phase conditions or saturation. This existence of condensation phenomenon would reduce the likelihood that any superheat existed at the initial-state.

In the case of DRJ-24, the less than 1 ppmw B probably represents the proximity of the deep entries to the nearby DRJ-3 liquid injectate that provides steam at saturated temperatures. Low SH values in the Condensation Cell wells could be associated with local pockets of natural condensate and/or proximity of producing entries to migrating liquid MR.

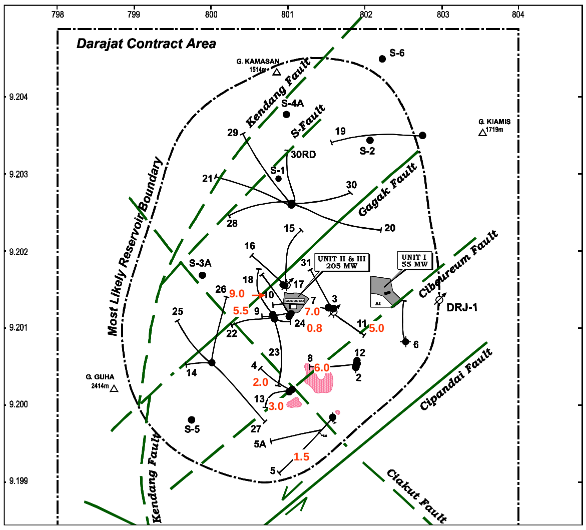

Figure 7: Distribution map of superheat at early production conditions (1996-98)

2.2 Chemical Changes in Exploitation Stage

Darajat has a long exploration and development history. Initial exploration drilling was conducted in the late 1970's. The exploration and development began in 1987 for Unit 1. The second phase of development began in 1996 continued by makeup wells in 2007. Currently, a total of 37 wells have been drilled at the project through March 2008, with 3 of them utilized as injector wells. Unit I (55 MW) came on line in 1994, Unit II (95 MW) came on line in 2000 and Unit III (110 MW) came on line in 2007.

Chemical changes are a result of both extraction of steam and, primarily, injection of steam condensate. Extraction of mass from the reservoir lowers the pressure in the reservoir and may increase the drive for groundwater (MR) to migrate into the reservoir. As the extraction rate increased, a commensurate amount of "*cooling tower*" steam condensate was injected back into the Darajat reservoir (Figure 8).

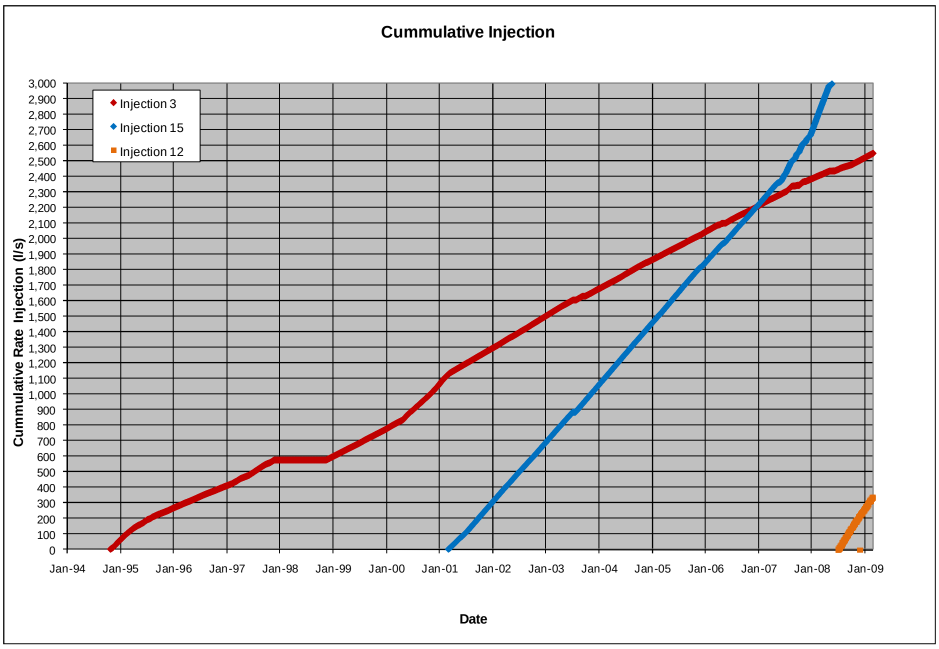

Figure 8: Historical cumulative injection rates for the Darajat injectors

Currently Darajat has 3 injection wells that are located in the production area (Upflow) and Condensation Cell. Basically DRJ-15 is injecting production wells at the Northern part of Darajat field, DRJ-3 for central part (Upflow Region) and DRJ-12 for Southern part (Condensation Cell).

Condensate injectate contains a negligible amount of dissolved NCG. However, through time the condensing of reservoir steam increases the relative amounts of $SO4^{=}$ (for example compared to HCO_3^-) and actual amount of B. In turn, both relative amounts of H_2S and B increases in steam boiled from CI. Marginal recharge (MR) also appears to have minimal amounts of dissolved NCG chemical constituents. However, liquid MR appears to have a "*remnant*" surface chemical signature as the N_2 and Ar increase in southern production wells as MR enters the Darajat reservoir and is boiled.

2.2.1 Non-Condensable Gas (NCG) Distribution

NCG in steam has systematically decreased in production wells from initial-state until present (data was taken in November 2008). Table 2 shows that the NCG decrease happens in two reservoir regions: Central Upflow and Condensation Cell. A dramatic decrease of about 80%-90% of the initial-state in NCG_{stm} has occurred in the Central Upflow Zone. In the Condensation Cell, a decrease of about 35%-45% of the original amount of NCG_{stm} has occurred. Edge Field wells have increased by about 60%.

The decreases in NCG_{stm} of the Central Upflow in DRJ wells can be explained as more and more steam is produced from boiling CI. This conclusion is confirmed by the relative increases in relative amounts of H_2S, NH_3 and H_2. Although H_2 is considered a very volatile gas species, the increased SO_4 dissolved in the CI buffers increased amounts of H_2 as H_2S is recycled in the reservoir. The decrease in NCG_{stm} of the Condensation Cell wells is most likely caused by the combination of boiling both CI and MR. Relative minor changes in NCG chemistry has occurred with the exception of marked lower amounts of N_2 and Ar. The decrease in N_2 and Ar may reflect the increasing contribution of steam from boiled CI added to the steam boiled from MR. On the other hand, the Edge Field wells increase in NCG_{stm} appears to be a result of increased amounts of condensation probably caused by continued migration of MR into the reservoir. This hypothesis is supported by the observation that all NCG chemical species have lowered since initial-state conditions, increasing the CO_2 content from ~ 89 to ~94 mol. % (compare Table 1 to Table 2).

Table 2. Current-State Gas Chemistry of Regions.

Chemical Parameter	Upflow (DRJ -7,-9,-10)	Condensation Cell (DRJ -4, -8)	Edge Field (DRJ -5,-19)
NCG (wt. % in stm)	0.0 - 0.1	0.4 - 0.6	2.4 - 3.6
CO_2 (mol. % in NCG)	80.4 - 88.8	92.5 - 95.5	91.7 - 96.0
H_2S (mol. % in NCG)	7.0 - 12.7	2.9 - 4.0	2.6 - 3.8
NH_3 (mol. % in NCG)	0.24 - 0.42	0.04 - 0.06	0.01 - 0.05
CH_4 (mol. % in NCG)	0.11 - 0.19	0.03 - 0.04	0.03 - 0.26
H_2 (mol. % in NCG)	3.6 - 4.4	0.9 - 2.6	1.0 - 3.2
N_2 (mol. % in NCG)	0.2 -1.9	0.6 - 0.8	0.4 - 0.9
Ar (mol. % in NCG)	0.003 - 0.020	0.004 - 0.005	0.000 - 0.060

The detail of current NCG content for every production well can be seen in Figure 9.

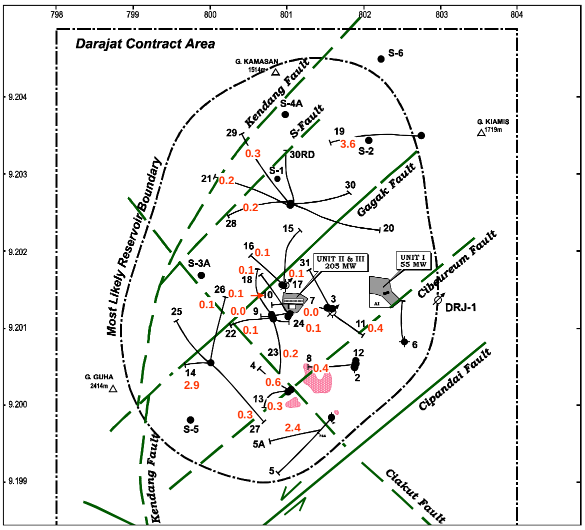

Figure 9: Distribution map of NCG in 2008

2.2.2 Boron Distribution

During the exploitation stage, boron has systematically increased since initial-state both in steam and condensate (Figure 10). Theoretically, the distribution of boron between vapor and liquid is described by the following equations in Glover (1988):

$$1/K_D = B_l / B_v = 10\text{^} [3.0506 - 0.00669\, t], \quad \text{for range } 150 - 320^{o}\,C$$

where,

t = *Separation temperature* (^{o}C)
K_D = *Ratio of the Boron concentration in the steam to that in the water*
B_l = *Concentration of Boron in Liquid*
B_v = *Concentration of Boron in Vapor*

For example at reservoir temperature of 250^{o} C, the log B value of boron is ~1.4 (or a liquid with 100 ppmw boron will generate a steam with ~4.0 ppm boron). With this theoretical background, the evolution of boron (B) in steam gives insight into the migration and boiling history of injectate at the Darajat Geothermal Field.

In 2008, the distribution of boron in steam (B_v) ranges between 2 and 55 ppmw (Figure 10). The range of boron (B_l) injected in liquid CI is between 20 and 92 ppmw in the three injectors (DRJ-3, -12, and -15). This marked increase in both steam and injectate is a result of the re-cycling of B at Darajat. A more detailed review of B re-cycling at Darajat is presented in this volume (Hidayaturrobi et al., 2010).

The different content of B_v in steam is presumed to reflect the concentration of B_l in the CI being boiled nearby the producing well. For example, the 7 ppmw B_v produced in DRJ-7 is result of boiling a liquid (i.e., CI) with ~170 ppmw B_l. The nearby injector, DRJ-3, is injecting a liquid with 92 ppmw B_l suggesting minimal boiling. The 55 ppmw B_v in the DRJ-13 well is estimated to be generated from boiling liquid CI with a B_l concentration of at least 1370 ppmw assuming a reservoir temperature of 250^{o} C (refer to example calculation above). This calculated concentration is ~15 times the DRJ-3 injectate source of B_l. The concentration factor in boiled CI could be higher if some or all of source of CI is from DRJ-12 or if the steam generated from boiled injectate mixes with more dilute insitu steam.

Alternatively, a 100% flash of injectate could generate the high values B_v observed in 2008.

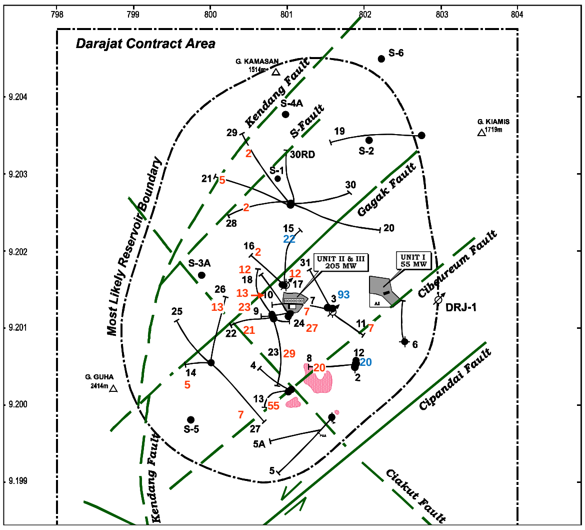

Figure 10: Distribution map of boron in both steam and CI in 2008

However, it is presumed that this phenomenon is currently of minor importance due to prolonged injection of over 13 years. High amounts of flashed CI are more likely to have occurred during the early stages of development.

Historical review of the B_v of producing wells compared to the contents of B_l is suggested to track the rate at which liquid CI boils along the flowpath(s) between injector and producer. Boiling rates of CI are probably affected by power plant operating pressures, reservoir superheat, injection rates and reservoir pressure.

2.2.3 Superheat Distribution

Historical superheat values have fluctuated over the 13 years of production at Darajat. Superheat (SH) measured at the surface is a convenient method to monitor the superheat conditions in the reservoir because surface measurements are collected more frequently. A comparison of B_v and the infrequently-measured downhole superheat is reviewed in this volume in Hidayaturrobi et al. (2010). Changes in wellhead pressures can affect superheat measurements. For this reason, the 2008 SH distribution map (Figure 10) shows values from a period when operations were conducted at normal conditions. Later in 2008, most wells were operated at higher wellhead pressures and surface superheats were lowered by ~50%. Higher extraction rates would have the tendency to increase superheat as reservoir pressures decline and "*dry-out*" expands whereas higher amounts of production of saturated steam from CI would lower the superheat values measured.

As of the February 2008, the superheats of production wells (DRJ-4, -8, -11 and -13) near the Cibeureum Fault and associated with the shallow Condensation Cell have the highest SH values (8-14^o C). "*Dry-out*" of the shallow portion of the reservoir and/or possible scaling effects is thought to be responsible for the higher SH. The current SH of the Central Upflow Zone wells (located between the Cibeureum and Gagak Faults) range from 1^o to 5^o C. The low SH values of DRJ-14 and DRJ-27 are expected because of the short period of production in the area. The very low SH (0.8^o C) of DRJ-24 is best explained by proximity of liquid CI from DRJ-3 in the large deep production entries in DRJ-24. Similarly, DRJ-09 and -17 are believed to be more influenced by CI from DRJ-3 and -15, respectively. Initial-state SH values of >5^o C were estimated for the Central Upflow zone (Figure 6), but under lower extraction rates. Therefore, the SH in 2008 would be expected to be higher under the higher extraction rates. The dampening of SH in the Central Upflow is primarily caused by the production of saturated steam form boiled CI. The wells north of the Gagak Fault are generally lower in SH (0.3^o to 3.1^o C) than the Central Upflow Zone because of the shorter exploitation time (similar to DRJ-14 and -27).

Comparison of early (initial-state) and current (Feb 2008) SH distribution maps (Figures 7 and 11) appear to confirm that infield injection has and continues to dampen the ability of the Darajat Geothermal Reservoir to superheat. Continued low superheats coupled with lowering B_v could indicate a cooling of reservoir fractures and possible condensation of high enthalpy reservoir steam.

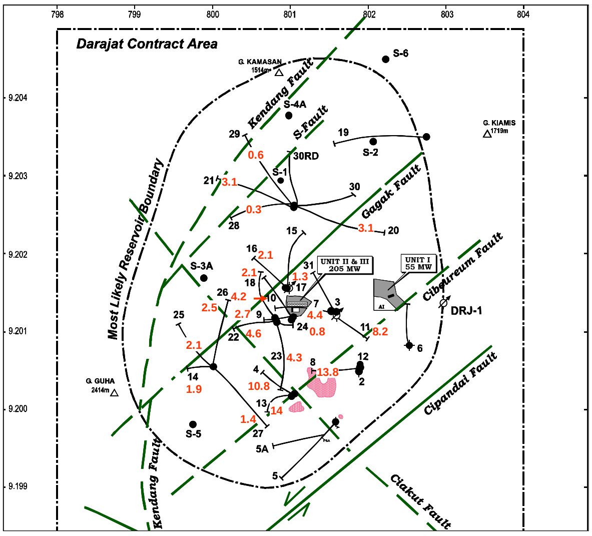

Figure 11: Distribution map of superheat in 2008

2.2.4 Summary of Chemical Changes 1996 to 2008

Review of chemical changes of NCG, B_v and SH can track the effects of infield injection at Darajat.

1. Migration and boiling of liquid from injectors to production wells can be monitored by historical B_v contents.
2. Lower NCG_{stm} and increases in H_2S, H_2 and NH_3 can identify the chemical breakthrough of steam generated from boiling injectate.
3. Lower than expected SH values under high extraction rates (Units I, II and III) confirms the chemical effects from in-field injection at Darajat

In the Condensation Cell, the decrease in NCG_{stm} is most likely caused by the combination of boiling both CI and MR both of which have lower NCG contents. This is shown by minor changes in NCG chemistry even though N_2 and Ar have lower values than initial-state. The increasing contribution of steam boiled from CI probably causes the decrease of N_2 and Ar in the Condensation Cell even though the "surface-related" MR is also being produced. The Central Upflow Zone has depressed NCG_{stm} values because of the large contribution of steam from boiled CI. The increased NCG_{stm} in Edge Field wells probably is caused by continued migration of MR into the reservoir and subsequent condensation of steam.

Fluctuations in B_v depend on the B_l content and the degree of boiling of CI before steam separation in the reservoir.

The boiling of CI in the Darajat reservoir is complex. Factors controlling boiling of liquid in the reservoir are injection rate, fracture temperature, saturation state, reservoir pressure (e.g., extraction rate, entry depth) and operating conditions.

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