MULTI-SPECIES MIXING MODELS USED TO DETERMINE THE AMOUNT OF AWIBENGKOK RECHARGE LIQUIDS

Tri Julinawati[1] and Phil Molling[2]

[1]Chevron Geothermal Indonesia, Sentral Senayan II, 26th Floor, Jl. Asia Afrika No. 8, Jakarta 10270, Indonesia

[2]G7geochem, Santa Rosa, CA USA

TJFO@chevron.com; molling@gmail.com

Keywords: *Awibengkok, Salak, mixing model, geochemistry, MIP, brine injection, condensate injection, MR, boiling.*

ABSTRACT

While the initial fluid produced from a liquid-dominated geothermal reservoir is usually pristine reservoir brine, later production often includes a mixture of reservoir and other fluids (e.g., marginal recharge, injected brine and steam condensate). Instead of utilizing conventional mixing models using a single chemical species (i.e., Cl^-) to characterize reservoir mixing processes, a seven-element mixing model was developed and applied to assess the changing composition of the Salak production liquids. The results of these mixing models help constrain the Awibengkok numerical simulations used for resource management. The measured concentrations of seven chemical species (i.e., Cl, B, SO_4, HCO_3, NH_4, Ca and Mg) in the produced fluids of each liquid-producing well can be matched by using up to four end-member fluids in each mixing model. The mixing components (end-members and the liquid composition to be matched) are constrained by the historical produced brine and measured injected brine/condensate compositions and, where available, analyses of downhole samples. As with any mixing calculation, the mixing models rely heavily on the strength of underlying assumptions. For instance, the liquid chemical flash-corrections are dependent on estimated reservoir liquid enthalpies.

These mixing models yield approximate matches of the historical data with varying degrees of accuracy. The semi-quantitative nature of this technique still represents a geochemical interpretation. The matching of produced liquids through 2012 is encouraging and has led to new insights into the flow of fluids in the Awibengkok reservoir. For example, changing ratios of injected brine through time is observed in numerous producers, and several marginal recharge fluids of different origins are required to match the production chemistry. Several eastern Awibengkok wells also have enrichments in some species that require a rapid boiling process as an explanation.

1. INTRODUCTION

The Awibengkok geothermal field, also known as Salak, is located about 60 km south of Jakarta on the island of Java, Indonesia (Figure 1). The original exploration contract area, including the current proven field, lies on the southwestern flank of the Gunung Salak volcano (2,211 m above sea level), for which the contract area was named. A proven area of 18 km^2 and an installed capacity of 377 MWe yields a power density of about 21 MWe/km^2 (Stimac, et al., 2008). The Awibengkok reservoir was initially fully liquid-dominated when it was first developed in 1994, but has since formed a large steam cap in the eastern half of the field. In the Awibengkok development scheme, 46 wells have been used as producers through 2013, and 17 wells have been used as injectors at various times, both for brine and steam condensate. Multiple attempts have been made to quantify the hydraulic connections between injectors and the various producers including tracer tests and Cl matching (Sullera and Horne, 2001; Gunderson et al., 2002). While the initial fluid produced from a liquid-dominated geothermal reservoir is usually pristine reservoir brine, later production often includes a mixture of reservoir and other fluids (e.g. marginal recharge fluids, injected brine, and injected steam condensate). Results of this study determined: (1) which injector may be best connected to a particular producer during each year, (2) the possibility of multiple compositions of marginal recharge fluids with different origins, (3) the maximum amount of original mass-in-place still being produced per well and (4) confirmed a rapid-boiling process in certain eastern Awibengkok wells. The main products/outputs of this type of modeling are histograms showing the proportional mass of each mixing end-member.

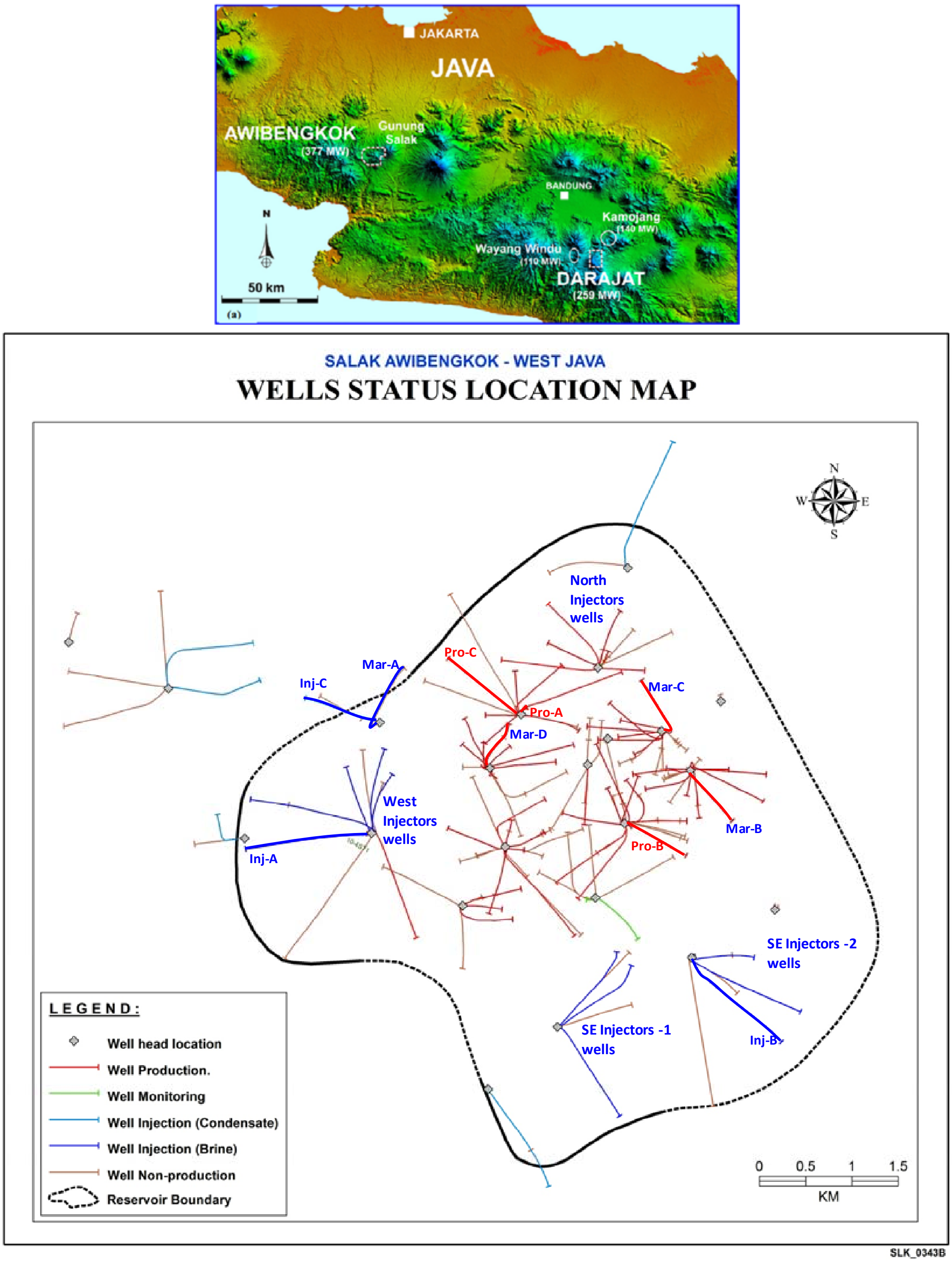


Figure 1: Top - Image of West Java with major cities and volcanic centers. Awibengkok and Darajat contract areas (dashed polygons) and other producing geothermal fields (circles) are also shown. Bottom - Map of the Gunung Salak contract area showing wells mentioned in discussion section (bold trajectory lines).

2. METHODOLOGY

The new liquid mixing-models technique uses multiple species instead of the conventional use of one or two species (i.e., Cl, Cl-B) for matching purposes. This approach quantifies the amounts of various liquids supplying the producing wells using seven species: Cl, B, SO_4, HCO_3, NH_4, Ca and Mg (Table 1). This method is complex and time-consuming in application as it currently uses a manual trial-and-error technique. Sensitivity studies (multiple end-member compositions) and historical trends are used to increase the confidence of the results. The complexity of the matching technique led to the development of a “score” from 1-10 (10 being the best score) to evaluate the best-matching mixture. Points are awarded if the matched amount of chemical species is within the historical data range or within 10% of the range of values for that species for a given year, respectively.

The following assumptions are used in the multi-species mixing method (Table 1):

1. Matching technique requires a match with Cl and then B as a second priority, and then the lowest priority are the remaining species SO_4, HCO_3, NH_4, Ca and Mg.

2. Early-produced mass-in-place (MIP) is used as a reference composition gathered from the baseline chemistry at each production well at presumed initial-state.

3. Brine injectate is always part of the mixed liquid being matched at Salak. Compositions of brine injectate from the year being matched are used wherever possible and can be constrained by tracer test results.

4. Steam condensate injected into well Mar-A is assumed to be the primary source of dilute SO_4- and NH_4-rich fluids mixing into the reservoir even though acid sulfate fluids are present near surface thermal features.

5. There can be differing compositions of dilute marginal recharge (MR) fluids in the field. The MR composition that yields the best score in a mixing model dictates which MR composition will be used, even though the source of the MR may be distal.

Table 1: Unique composition of each end-member fluid and assumptions used for each component.

End-Member Composition (ppm)				Constituent	Score	Assumptions
MIP	Brine	Condensate	MR			
6,860	10,256*	1*	3,650	Cl	3	Conservative
240	376	24*	102	B	2	
7*	28	80*	17	SO_4	1	Affected by boiling
32	25	75*	66*	HCO_3	1	
0.07	0.13	0.03	0.37*	Mg	1	Affected by carbonate precipitation
2.29	46	2*	300*	Ca	1	
4	6	26*	4	NH_4	1	Enriched during boiling

Note: The asterisks (*) denote the marker chemistry that helps make the liquid end-member unique.

The following are generalized governing rules to determine the "best" matches (Table 2):

- Cl is the first species matched, followed by B, because these species are more hydrophilic (i.e., conserved in the liquid) than the others. A "best" match always assumes that Cl and B are matched before any other species.

- A 3rd fluid may be added to make the best matches so that the mixture includes MIP, MR and injected brine. Less frequently, injected condensate is used as the 3rd or 4th component.

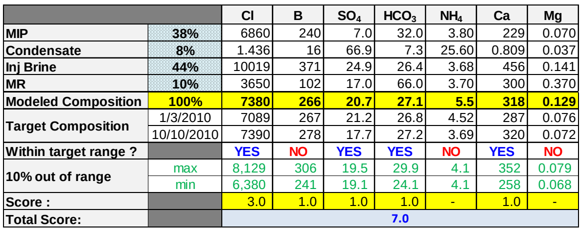
- One half-point (or, in the case of B, 1 of 2 points) is given if the matched value is within 10% of the measured range of values for a given chemical species.

- In cases where a unique best-match can't be reached (i.e., solutions with similar best scores but different fluid distributions), the match closest to previous historical matches will determine which highest-score solution is used.

- If the range of Cl is higher than any end-member fluid and confirmed by high B, then boiling of the mixed liquid is assumed. The matching is suspended and the liquids mixing at a boiling production well are assumed to be the last (i.e., lower) Cl match.

- If Cl to be matched is near the upper limit of the highest Cl end-member and the B range is higher than all fluids, rapid boiling near the well is assumed.

Table 2: The mixing model worksheet of well Pro-A for 2010 shows a chemical matched with a score of 7.



		Cl	B	SO_4	HCO_3	NH_4	Ca	Mg
MIP	**38%**	6860	240	7.0	32.0	3.80	229	0.070
Condensate	**8%**	1.436	16	66.9	7.3	25.60	0.809	0.037
Inj Brine	**44%**	10019	371	24.9	26.4	3.68	456	0.141
MR	**10%**	3650	102	17.0	66.0	3.70	300	0.370
Modeled Composition	**100%**	**7380**	**266**	**20.7**	**27.1**	**5.5**	**318**	**0.129**
Target Composition	1/3/2010	7089	267	21.2	26.8	4.52	287	0.076
	10/10/2010	7390	278	17.7	27.2	3.69	320	0.072
Within target range ?		YES	NO	YES	YES	NO	YES	NO
10% out of range	max	8,129	306	19.5	29.9	4.1	352	0.079
	min	6,380	241	19.1	24.1	4.1	258	0.068
Score :		3.0	1.0	1.0	1.0	-	1.0	-
Total Score:		7.0						

3. SENSITIVITY STUDY

In an effort to determine which MR end-members should be used to match a specific production well chemistry, a range of MR analyses are tested to see which one yields the best score. Table 3 illustrates the example of a sensitivity study using variable MR and condensate compositions. In this example, a maximum matching score for the 2008 Pro-C chemistry is attempted.

An early MR value collected during a flow test at Mar-A in 1996 is taken to represent a moderately dilute edge field mixture of outflow and groundwater (3,648 ppmw Cl). A 2007 Mar-C MR sample is more dilute (1,241 ppmw reservoir Cl) and was used for comparison. These dilute samples ranged in HCO_3 content from 146 to 333 ppmw, 31-97 ppmw SO_4 and 304 to 389 ppmw B. This suggests a variable composition for the source of MR at Awibengkok and introduces additional uncertainty to the technique. The combination of Mar-A MR and Inj-C condensate gave the best matching score for the Pro-C example (Table 3).

Table 3: Variable end-member MR and condensate mixed matches to provide maximum score for Pro-C wells.

No.	End-Member MR	End-Member Condensate Injection	Score
1	Mar-A (1996)	Inj-C (2008)	6
2	Mar-B (2007)	Inj-C (2008)	4
3	Mar-A (1996)		4.5
4	Mar-B (2007)		4
5	Mar-C (2007)		3
6	Mar-A (1996)	Mar-D (2007)	4
7	Mar-B (2007)	Mar-D (2007)	~4.5
8	Mar-C (2007)	Mar-D (2007)	<4
9		Inj-C (2008)	~4.5
10		Mar-D (2007)	~4.5

4. DISCUSSION

Three examples are used to describe the utility and flexibility of the multi-species mixing-model technique. Pro-A represents a well where, ultimately, four (4) different liquids appear to be mixing in the produced fluid. Pro-B represents a well where the injectate appears to impact the well through time, but the boiling process is required to match the high B. Lastly, well Pro-C represents an example of the mixing-model approach using downhole chemical data. A map of the Awibengkok geothermal field shows where these wells are located (Figure 1).

4.1 Well Pro-A

The historical mass-distribution histogram of the well Pro-A mixing models (Figure 2) shows the relative contribution of the major fluid types. An increasing proportion of MR is observed through time which suggests the continuing influx of MR fluids into the Awibengkok geothermal reservoir. The brine injectate contribution increases during the first few years then levels off during 1998 - 2000. The increase in injectate contribution correlates to the increasing rate of injection in the West Injectors wells at that time (Figure 3). In 2001, less injectate was mixed into the fluids at well Pro-A. This change coincides with the movement of brine injectate to a new deeper injector, Inj-A, located further from Pro-A. This suggests that injecting at Inj-A decreases the impact of injectate on Pro-A. Simultaneously, the decline in injection breakthrough coincides with the increase in the amount of MR seen in well Pro-A fluids. Increased production of injected condensate in Pro-A during 2007-2012 appears to coincide with increased condensate injection rates in well Inj-C (Figure 3).

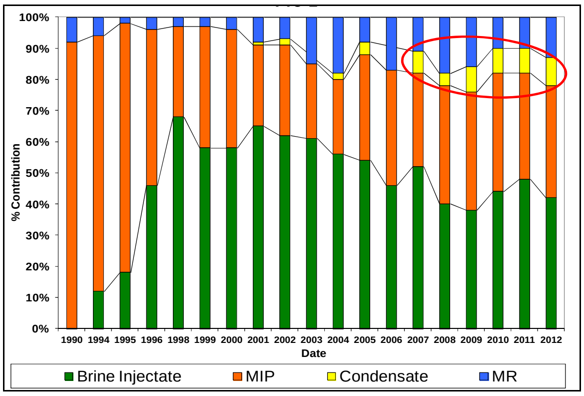


Figure 2: Histogram of well Pro-A mixing model showing the contribution of each fluid type. The red circle shows the increase of Inj-C condensate injectate produced in 2007-2012 (modified from Julinawati, 2011).

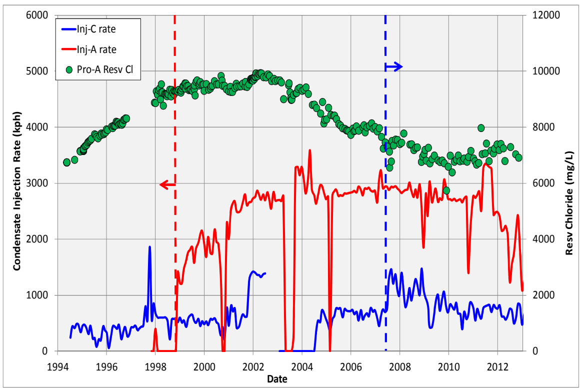


Figure 3: Historical Cl at well Pro-A and injection rates at Inj-C (condensate) and Inj-A (brine). The dashed lines show the beginning of changes in injection rate (purple-Inj-A; blue- Inj-C).

4.2 Well Pro-B

Figure 4 shows the historical mass-distribution of the well Pro-B mixing model which demonstrates the well's production is strongly connected (>50% of the liquid mass) to brine injectors. Pro-B appears to be impacted by both condensate and brine injected from SE Injectors-2 (Figure 5). The lower amounts of Pro-B brine-injectate production from 1999 to 2003 (Figure 4) coincides with the reduction in brine injection rates at SE Injectors-2 wells from 2000 to 2003 which was moved to SE Injectors-1 wells. The increasing trend of brine injectate production after 2003 reflects the continuing impact from SE Injectors-2. The decline of brine and condensate injection in SE Injectors-2 wells begins in 2002 and coincides with the cessation of condensate injection at SE Injectors-2 and SE Injectors-1 wells (Figure 4).

At well Pro-B, boiling was inferred in order to match the B concentrations in 2011-2012. At least 105% (Table 4) of total liquid contribution is needed to match Cl, B and HCO_3 in 2011. This means 5% excess is due to boiling of reservoir liquid. Instead of decreasing with the removal of injectate, the Cl and B become more concentrated due to boiling. The boiling condition is suspected as a result of lowering the injection at SE Injectors-2 wells (Figure 5) thus resulting in lower liquid levels and decreased cooling.

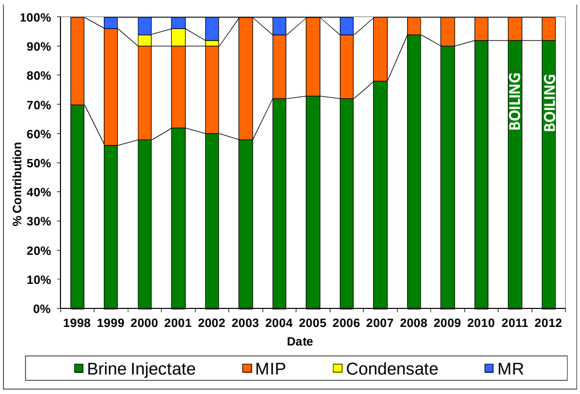


Figure 4: Histogram of the well Pro-B mixing model showing the contribution of each fluid type. The condensate produced in 2000-2002 appears to come from condensate injection at North injectors wells (modified from Julinawati, 2011).

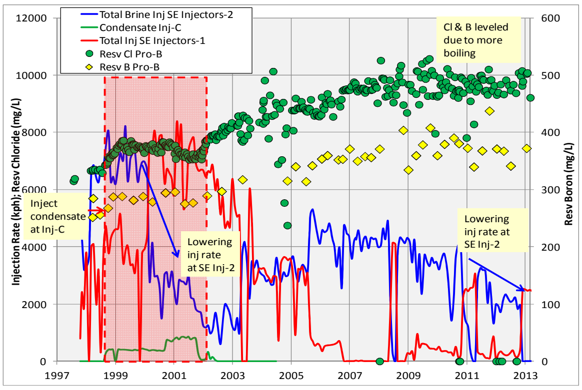


Figure 5: Historical Cl at well Pro-B and total injection rates at SE Injectors-2 wells (brine) and Inj-B (condensate). The red box shows the period of condensate injection at Inj-B while the blue arrows show the period when brine injection rate at SE Injectors-2 wells was lowered.

Table 4: The mixing model worksheet of well Pro-B for 2011 shows a best matched score of 6.5 – 7. It was assumed that there was boiling to match the high B concentration.

		Cl	B	SO_4	HCO_3	NH_4	Ca	Mg
MIP	**15%**	6363	230	7.0	36.0	2.50	209	0.090
Condensate		1.436	16	66.9	7.3	25.60	0.809	0.037
Inj Brine	**90%**	10128	385	15.4	23.6	5.24	460	0.085
MR		1366	58	3.3	123.0	35.81	64	0.090
Modeled Composition	**105%**	**10069**	**381**	**17.0**	**26.6**	**5.09**	**456**	**0.090**
Target Composition	1/23/2011	9886	373	18.3	26.3	3.44	504	0.037
	10/23/2011	10309	438	19.3	26.6	4.71	525	0.037
Within target range ?		**YES**	**YES**	**NO**	**YES**	**NO**	**NO**	**NO**
10% out of range	max	11,340	482	21.2	29.3	5.2	578	0.041
	min	8,897	336	16.5	23.7	3.1	454	0.033
Score :		3.0	2.0	0.5	1.0	-	0.5	-
Total Score:		**7.0**						

4.3 Well Pro-C Downhole Samples

In 2010, flowing downhole chemical samples were collected in well Pro-C at 3,000’, 5,000’ and 6,000’ MD (Figure 6). The samples collected at 3,000’ MD were considered to represent total liquid flow. The two deep samples have high reservoir Cl values of 8,000 and 9,200 ppmw Cl,. However, the duplicate total liquid flow samples contained lower amounts of reservoir Cl (between 5,500 and 7,000 ppmw Cl). This dilution of the deep reservoir liquid produced from the bottom entries is believed to be the result of more dilute liquids being produced in the two shallow entries located at 4,420’ and 3,920’ MD. The results of the multi-species mixing-models at each sample depth are shown in Figure 7. As predicted, the chemistry of the shallowest sample confirms higher concentrations of MR and injected condensate compared to the deeper entries. In fact, the deepest entry produces the most brine injectate, presumably from the West Injectors. Interestingly, there appears to be a higher amount of MR in the deepest entry than in the middle entries.

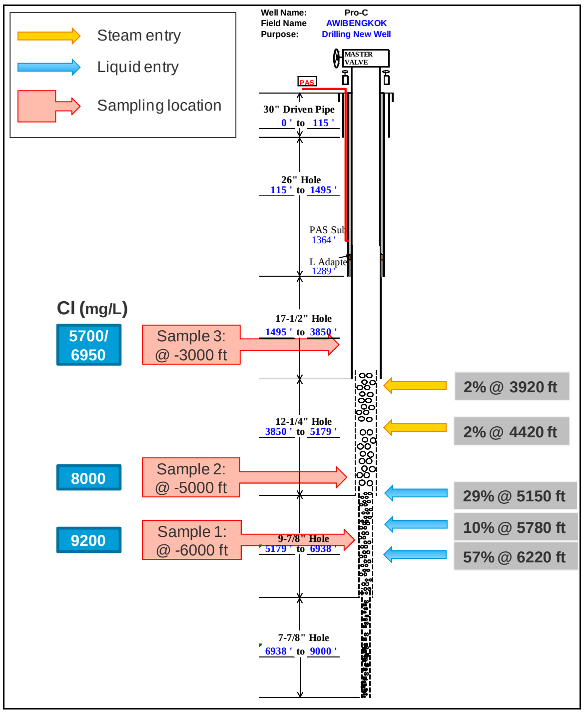
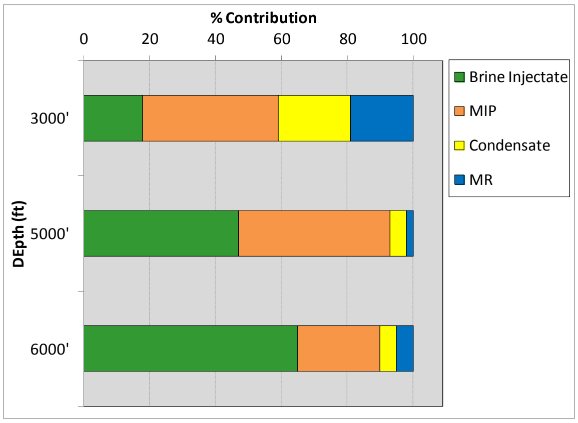


Figure 6: Pro-C well schematic shows the sampling points under flowing conditions and the Cl concentration for each point. The more dilute Cl samples from inside the casing indicate that the two shallow entries (red arrows) must be producing more dilute liquids.



Model Name			2009	2010	2010 DHS		
					3000'	5000'	6000'
Most-likely	**Pro-C**	MIP	20	35	41	46	25
		Condensate	10	15	22	5	5
		Brine Injectate	55	30	18	47	65
		MR	15	20	19	2	5
	Score >>>>>>>>>>>>>>		6.5	6	7	7	7

DHS

Figure 7: Well Pro-C mixing model for downhole samples. The shallowest sample shows more contribution from MR and condensate injectate fluids. The deepest sample has a higher contribution of brine injectate.

CONCLUSIONS

The value of the multi-species mixing-models technique is the refinement of the conceptual models for each well that produces liquid. Chloride dilution can now be explained using multiple dilute fluids with chemically distinct chemistries. This semi-quantitative technique can be integrated with injection tracer test results and natural tracers such as tritium to document the historical changes of liquid production. These more accurate histories will allow better forecasting of the impacts of recharging liquids in terms of cooling and production rates when input into numerical models.

As with any other technique, this approach relies on the strength of the inherent assumptions, specifically confidence in the end-member compositions. Although the current technique is established on spreadsheets and is laborious, plans exist to automate this technique soon.

ACKNOWLEDGEMENT

We thank Chevron Geothermal Salak (CGS) & Pertamina Geothermal Energy (PGE) for granting permission to publish this work, and are especially to Doddy Astra for support us to make this paper. We would like to acknowledgement Eugene Sunio as initial writer in the pilot project, and also to Glenn Golla, Rich Gunderson and Aquardi Suminar for their helpful reviews.

REFERENCES

Gunderson. R., M. Parini, and L. Sirad-Azwar, 2002, Fluorescein and Naphthalene Sulfonate Liquid Tracer Results at the Awibengkok Geothennal Field, West Java, Indonesia, In Proceedings, 27th Workshop on Geothennal Reservoir Engineering, Stanford University, Stanford, CA, Jan. 28-30, 2002.

Julinawati, T., E.G. Sunio and P. Molling, 2011. Multi-Species Mixing Modeling for Matching Salak Production Liquid Chemistry, Indonesia Geothermal Association, December 2011.

Stimac, J., G. Nordquist, A. Suminar, and L. Sirad-Azwar, 2008. An Overview of the Awibengkok Geothermal System, Indonesia, Geothermics, Volume 37, Issue 3, pp. 300-331, June 2008.

Sullera, M. and R. Horne, 2001. Inferring Injection Returns from Cl Monitoring Data: Geothermics, v. 30, pp 591-616.