Tracer Injection Evaluation in Kamojang Geothermal Field, West Java, Indonesia

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ABSTRACT

In Kamojang field, reinjection activity has been carried out since 1983. Tracer injection tests were run to determine the interconnection between water reinjection and production wells.

Tracer of radioisotope tritium as tritiated water (HTO) was injected at KMJ-15 in 1983 and 1992 with activity 370 GBq respectively and at KMJ-46 in 2003 with activity 550 GBq . Tritium injected in KMJ-15 was monitored at production wells that lay at surround of reinjection well. By using TRINV and TRCOOL programs developed by Geoscience Division Orkus Tonum - Iceland , simulation of data could be interpreted to determine breakthrough time of water reinjection and cooling effect to the reservoir. The breakthrough time of water reinjection is about 5 to 7 years and mass recovery of all 7 wells of production is about 13.5%. The average of temperature decline rate in reservoir is about 0.21 °C in 10 years.

The tritium that was injected at KMJ-46 in 2003 is already detected at six wells but the breakthrough time has not been reached yet and the monitoring is still underway. The simulation by using the same program is made in spite of the data not being complete yet. Simulation shows that the breakthrough time is faster than the 1992 injection, i.e. 1 to 3 years respectively.

Fig.1. Location map of Kamojang Geothermal Field in Java Island

INTRODUCTION

Kamojang field was the first geothermal field developed in Indonesia and lies in Java Island, about 40 km distance to the southeast of Bandung, the capital of West Java.

The first five exploration wells were drilled in 1926 by the Dutch. But Pertamina, as a Government Company, started to run an exploration study from 1971 to 1974 and continued by drilling ten exploration wells until 1979.

KMJ-6 was one of ten exploration wells that was used to supply a monoblock plant with 250 kW capacity. It is recognized as the first geothermal plant in Indonesia.

Now, in exploitation and production stages, Kamojang Field has 77 wells, included the five Dutch wells and ten exploration wells. The total installed capacity is 140 MWe that is supplied with 1100 t/h steam from 33 production wells and maintained by five reinjection wells. The 140 MWe is divided into three plant units, i.e. Unit I for 30 MWe and Units II and III for 55 MWe each.

The first unit of 30 MWe was installed in 1982 and the next two units of 110 MWe were in 1987. Steam supply for the plants is designed in four pipelines, i.e. PL-401, PL-402, PL-403 and PL404. Each pipeline (PL) gathers the steam from some wells (5 to 12 wells) and the pipelines meet in the header before entering the plant.

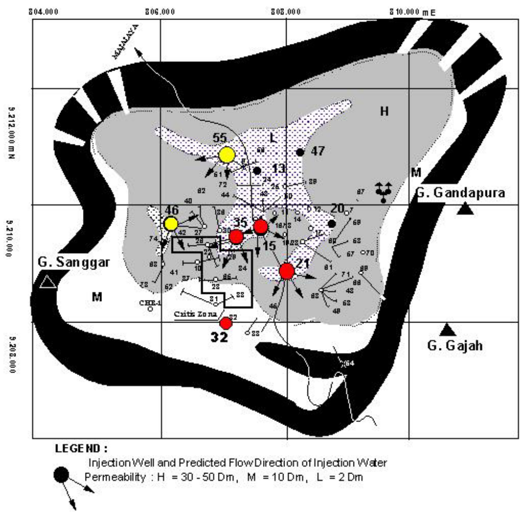

Fig.2. The location of reinjection wells at Kamojang Geothermal Field

Six reinjection wells are used for maintaining the reservoir. KMJ-15 and KMJ-21 are located in the centre of the field. KMJ-35 and KMJ-46 are located in the west reservoir boundary. KMJ-55 and KMJ-32 are located in north and south boundaries of the field respectively. All the reinjection wells are active except KMJ-32 that has been stopped in 2002 because the injection water is running out of the reservoir.

TRACER TESTS

Tracer tests are used extensively in surface- and groundwater hydrology as well as pollution and nuclear-waste storage studies. Tracer tests involve injecting a chemical tracer into a hydrological system and monitoring its' recovery, through time, at various observation points. The results are, consequently, used to study flow-paths and quantify fluid-flow. Tracer tests are, furthermore, applied in petroleum reservoir engineering. The methods employed in geothermal applications have mostly been adopted from these fields. The main purpose in employing tracer tests in geothermal studies is to predict possible cooling of production wells due to long-term reinjection of colder fluid by studying connections between injection and production wells.

Tracer test design

When designing a tracer test the following aspects must be considered carefully: (1) what tracer to select, (2) the amount of tracer to inject and (3) the sampling plan to follow (sampling points and frequency).

The tracer selected needs to meet a few criteria: (i) It should not be present in the reservoir (or at a constant concentration much lower than the expected tracer concentration); (ii) It should not react with or absorb to the reservoir rocks; (iii) It should be easy (fast/inexpensive) to analyse. The following are the tracers most commonly used in geothermal applications:

1. Radioactive tracers such as iodide-125 (^{125}I), iodide-131 (^{131}I), tritium (^{3}H), etc.
2. Fluorescent dyes such as fluorescein and rhodamine WT.
3. Chemical tracers such as iodide, bromide, etc.

Tritium as a radioactive tracer was chosen for use in the vapor reservoir at Kamojang as an ideal tracer for vapor-dominated systems (also for liquid-dominated systems). The advantagse of tritium tracer are that it is a chemical compound (HTO)similar to water, and is easy and safe to handle even on injection and sampling preparation (because it is a β emitter). Tritium also has a long lifetime with radioactive half life 12.34 years, which is good to observe fluid pathways that have small permeability. In Kamojang field reservoir permeability ranges between 5 to 50 mD and even rock of permeability between reinjection and production at KMJ-15 well has poor permeability that could inhibit direct flowing.

Tracer test execution and calculation

Execution of a tracer test can involve one well-pair or several injection and production wells.

Sampling frequency is case specific, but should in general be quite high initially (a few samples per day), but may be reduced as a test progresses (a few samples per week).

In Kamojang, tritium tracer was tested in three different times in the two reinjection wells KMJ 15 and 46. In KMJ 15, tritium was injected in 1983 and 1992 with activity 370 GBq respectivelly. Monitoring tritium concentration by sampling at production wells (KMJ 11, 14, 17, 18, 26, 27 and 30) was started from 1989 to 2001. For KMJ 46 reinjection well, tritium tracer was innjected in July, 2003 with activity 550 GBq and now is still being monitoring at the production wells KMJ-62, 22, 41, 72, 36, 26, 27 and 31.

The breakthrough time and mass recovery calculation that is based on the monitoring data is calculated by using ICEBOX program, i.e. TRINV and TRCOOL. Mass recovery (%), flow velocity (m/s), dispersion coefficient (m^2/s), concentration maximum time (TU), time breakthrough (sec) and dispersivity (m) are outputs of TRINV program. The TRCOOL is used to predict reservoir temperature decline due to injection.

As there are two injection stage in Kamojang Field, the Curve Expert 1.3 program is used to support the TRINV program in plotting the Gauss distribution curve as simulation curve. Previously we had to make correction of the monitoring data to know the background value and decay factor then obtain the net concentration.

DATA ANALYSIS AND INTERPRETATION

At Kamojang Geothermal Field, the radioactive tracer, i.e. tritium (^{3}H), was injected in 1983 first and then again in 1992 at the same well i.e. KMJ-15. The injection monitoring was started in 1989 in eight production wells, i.e. KMJ-11, 14, 17, 18, 35, 26, 27 and 30.

Monitoring data of tritium concentration since 1989 to 2001 for production wells (KMJ-11, 14, 17, 18, 35, 26, 27 and 30) surrounding of KMJ 15 reinjection well is plotted in form of tritium concentration (tritium units) vs. monitoring time (years) as shown in Figs. 3 and 4. Before plotting, the tritium concentration has been corrected with its decay factor as shown in Table 2.

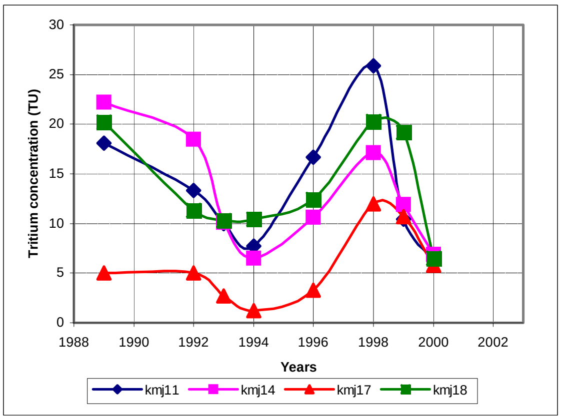

Fig.3. Tritium concentration along monitoring at KMJ-11, 14, 17 and 18 from 1st and 2nd injection

Figure 3 shows that the data from 1989 to 1994 was influenced by the first injection after the time of breakthrough. And the data after 1994 to 2000 comes from the second injection.

Figure 4 shows that the data after 1994 to 2000 comes from the second injection but the data from 1989 to 1994 was not influenced yet by the first injection. This is because those wells (KMJ-26, 27, 30 and 35) are located in the west area and that area had only just started production in 1987.

The third tritium injection was run in 2003 at the well KMJ-46 and the monitoring is still ongoing. In the same manner, concentration of tritium monitoring data for production wells (KMJ-22, 41, 36, 72, 62 etc.) surrounding the reinjection well KMJ 46 is plotted as shown in Fig 5.

Figure 5 shows the data of tritium concentration as the result of the third injection. The rapid appearance tritium at KMJ-27 and KMJ-62 is due to that those wells are closed to KMJ-46 as reinjection well and located in the same cluster. The progress of tritium concentration is still monitoring until now.

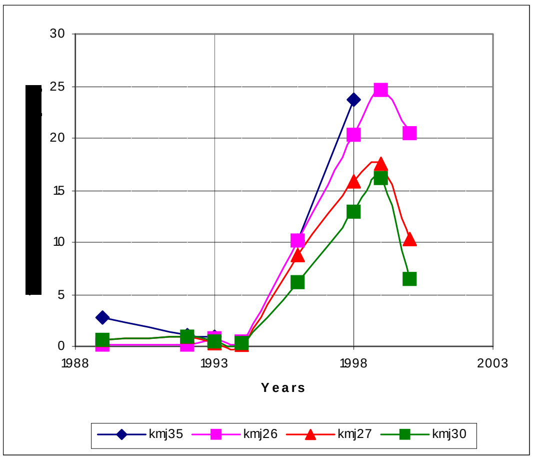

Fig.4. Tritium concentration along monitoring at KMJ-26, 27, 30 and 35 from 1st and 2nd injection

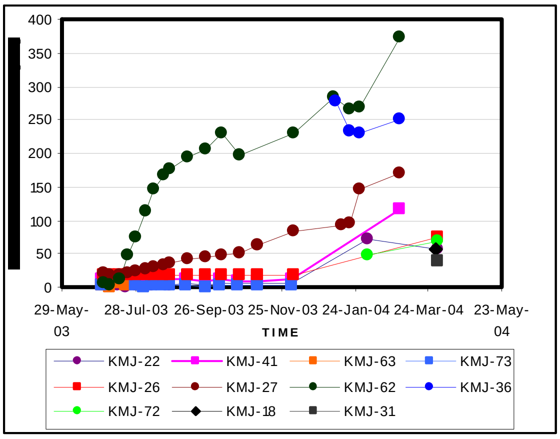

Fig. 5. Tritium concentration along monitoring from 3rd injection

As there are two injection stages, there are two influences to the reservoir. The second injection in 1992 gave influence to the first injection return from 1983 which had not yet reached to background values. So the initial monitoring data needs to be corrected to get the background value and decay factor, then to find the net concentration. Also the Gauss distribution curve is used to define time breakthrough and tritium interference concentration, see Table 1 and Figure 5.

Table 1. The tritium interference (simulation) concentration

Year	Monitoring time (sec)	Tritium concentration (TU)			
		KMJ -11	KMJ-14	KMJ -17	KMJ -18
1994	3.47 x 10^8	12.1	9.7	1.31	13.74
1996	4.1 x 10^8	4.39	1.37	0.05	6.11
1998	4.73 x 10^8	1.04	0.08	0.005	1.96

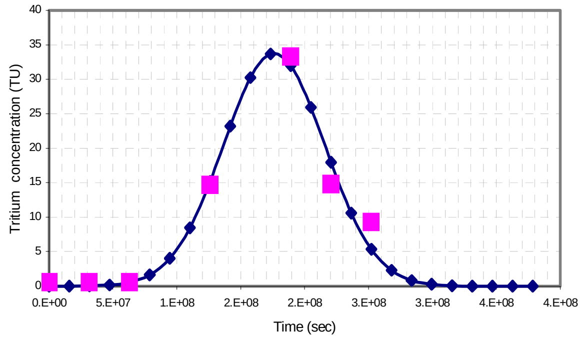

Fig.5. A sample of Gauss distribution curve at KMJ-11

To know the real second injection influence at a production well (reservoir), the interference concentration should be compared with the initial tritium concentration. This shows that well KMJ-11, 14 and 18 were interfering in 1996 and 1998, but in 1994 had no interference because the initial tritium concentration was lower than the interference concentration. But at KMJ-17 there was no interference because the (simulation) concentration in 1994 is higher than the initial concentration, even the interference (simulation) concentrations in 1996 and 1998 are lower than the background value.

Table 2. The net tritium concentration

Well	Tritium concentration (TU)					
	1992	94	96	98	99	00
KMJ -11	0.53	0.53	14.7	33.3	14.8	9.3
KMJ -14	0.53	0.53	0.9	22.7	17.4	9.8
KMJ -17	0.53	0.53	3.5	15.7	15.1	8.3
KMJ -18	0.53	0.53	14.8	27.8	17.8	27.9

The Gauss curve (simulation curve) can be made by using the CurveExpert 1.3 program and data of the net tritium concentration. The simulation result data are imported to TRINV for making simulation model to find time breakthrough and mass recovery. The simulation data, i.e. c (*maximum concentration;* t *(maximum time) and* w *(half-wide of peak)*, are input to TRINV for processing to get output data especially time breakthrough and mass recovery, see Tables 3 and 4.

Table 4 shows that TRINV estimate of time breakthrough at each well is similar to the time of maximum concentration in Table 3. It will be clearer from the fitting curve between TRINV (yellow line) and CurveExpert (red dots) which they are almost fitted, see Figure 6.

Table 3. TRINV input data

Input data	Production wells (KMJ)			
	11	14	17	18
M	3.13 x 10^{12}	3.13 x 10^{12}	3.13 x 10^{12}	3.13 x 10^{12}
Q	20.0	13.4	15.3	28.9
Q	15.0	15.0	15.0	15.0
Rl	998.0	998.0	998.0	998.0
Rr	950	950	950	950
X	838.3	959.1	1030.3	925.0
C	33600	22500	16700	28900
T	1.73 x 10^{8}	1.89 x 10^{8}	2.05 x 10^{8}	1.89 x 10^{8}
W	9.5 x 10^{7}	1.2 x 10^{8}	9.8 x 10^{8}	1.40 x 10^{8}

M : *tracer activity (TU)*

Q : *production rate (kg/sec)*

q : *injection rate (kg/sec)*

rl : *injection water density (kg/m3)*

rr : *reservoir fluid density (kg/m3)*

x : *flowpath distance between reinjection production well (m)*

c : *maximum concentration (TU)*

t : *maximum time (sec)*

w : *half-wide of peak (sec)*

Table 4. TRINV output data

Output data	Production wells			
	KMJ-11	KMJ-14	KMJ-17	KMJ-18
Mr	2.20	1.25	0.86	4.04
U	$4.72x10^{-6}$	$4.90x10^{-6}$	$4.92x10^{-6}$	$4.67x10^{-6}$
D	$1.06x10^{-4\ -4}$	$1.67x10^{-4}$	$1.03x10^{-4}$	2.07x10
C	33.65	22.51	16.73	28.93
T	$1.735x10^{8}$	$1.892x10^{8}$	$2.05x10^{8}$	$1.892x10^{8}$
M	22.37	34.00	20.93	44.28

Mr : *mass recovery (%)*

u : *flow velocity (m/s)*

D : *dispersion coefficient*

c : *maximum tritium concentration (TU)*

t : *time breakthrough (sec)*

m : *dispersivity*

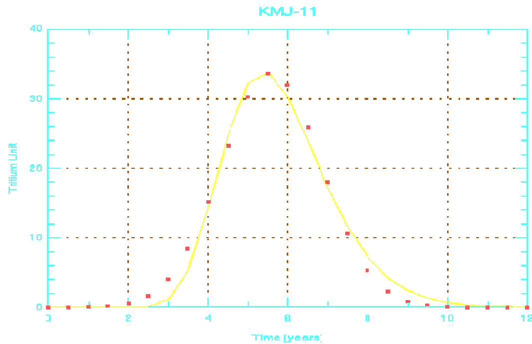

Fig.6. The fitting curve between TRINV and CurveExpert at KMJ-11

Table 5. TRINV input data

Input data	Production wells		
	KMJ-26	KMJ-27	KMJ-30
M	3.13 x 10^{12}	3.13 x 10^{12}	3.13 x 10^{12}
Q	16.3	19.4	5.5
q	15	15	15
rl	998	998	998
rr	950	950	950
x	1141.3	1272.4	1023.3
c	34100	24000	20800
t	2.21 x 10^{8}	2.05 x 10^{8}	2.05 x 10^{8}
w	1.4 x 10^{8}	1.26 x 10^{8}	1. 1 x 10^{8}

Table 6. TRINV output data

Output data	Production wells		
	KMJ-26	KMJ-27	KMJ-30
Mr	2.69	2.03	0.43
u	$4.98x10^{-6}$	$6.0x10^{-6}$	$4.86x10^{-6}$
D	$2.0x10^{-4}$	$2.54x10^{-4}$	$1.027x10^{-4}$
c	34.11	24.04	19.30
t	$2.21x0^{8}$	$2.05x10^{8}$	$2.1x10^{8}$
m	40.29	42.35	26.09

The breakthrough time of KMJ-11 is fastest, i.e. approximately 5.5 years, because this flowpath distance is the nearest at about 838 m.

The breakthrough times of KMJ-26, 27 and 30 which are located in the western area, see Tables 5 and 6, are longer than the wells that are located in the eastern area and the mass recovery is lower as well. This is due to the fact that reinjection well KMJ-15 is closer to KMJ-11, 14, 17 and 18 located in the eastern area.

Although the data is not complete yet, the TRINV simulation in the third tritium injection in 2003 is made in four models of the maximum tritium concentration because the peak of curve (that show the maximum concentration) has not been reached yet. The simulation uses the well KMJ-27 and KMJ-62 because those wells have significant increases of tritium concentration, see Tables 7 and 8.

Table 7. The result of TRINV simulation at KMJ-27 (Status : December 2003)

Par	Model			
	1	2	3	4
C	120	150	110	250
t (month)	33	37	40	42
X	673	673	673	673
U	7.23E-6	6.45E-6	5.96E-6	5.68E-6
D	4.13E-4	3.68E-4	3.41E-4	3.25E-4
A	133.27	209.42	179.49	449.74
M	57.15	57.15	57.15	57.15
Mr	4.67	6.55	5.19	12.39

Table 8. The result of TRINV simulation at KMJ-62 (status : December 2003)

Par	Model			
	1	2	3	4
C	400	600	800	1000
t (month)	7	9	10	11.67
X	236	236	236	236
U	1.19E-5	9.29E-6	8.36E-6	7.17E-6
D	2.39E-4	1.86E-4	1.68E-4	1.44E-4
A	57	141.34	232.66	395.84
M	20.04	20.04	20.04	20.04
Mr	3.3	6.37	9.44	13.76

If the simulation model is fit to the real data later, so the breakthrough time of tritium in the third injection is faster than the second injection in 1992. It can be interpreted that reservoir condition in the surroundings of reinjection well KMJ-46 is more permeable than at KMJ-15. This condition corresponds to the permeability distribution map, see Figure 2.

Reservoir cooling is predicted by using the TRINV program, i.e. one of the components of the ICEBOX package. The data input are parameters that correlate with reservoir rock properties, injection water and production wells. Those parameters were taken from previously observations, see Tables 9 and 10, in which the parameters of fracture or flowpath thickness (b) and height (H) are given in the range of 0.1 – 0.001 m dan 400 - 1000 m.

Table 9. TRCOOL data input of reservoir rock properties and injection water

Data input	Unit
Thermal conductivity (*k*)	2.5 W/m^{o}C
Specific heat capacity of rock (C)	800 – 1000 J/kg^{o}C
Rock density (R)	2500 – 2650 kg/m^3
Porosity (p)	5 – 10 %
Reinjection water flowrate (q)	15 kg/detik
Specific heat capacity of reinjection water (c)	4179 J/kg^{o}C
Reinjection water density (r)	990 kg/m^3
Reinjection water temperature (t)	40 ^{o}C

Table 10. TRCOOL data input of production wells

Wells	Q	X	T1	T2
11	20	838.3	244.2	234.6
14	13.5	959.1	230.5	214.4
17	15.3	1030.3	234.6	231.9
18	28.9	925.5	244.2	230.3
26	16.3	1141.3	244	231.8
27	19.4	1272.4	243	232.1
30	5.5	1023.3	231.5	230.3

Q : Production rate (kg/detik)

X : Pathway distnace (m)

T1 : Initial temp. reservoir in 1989 (°C)

T2 : Reservoir temperature in 1998 (°C)

Table 11. The best fitting result of cooling prediction

Par	Wells (KMJ)			
	11	14	17	18
Ti	244.2	230.5	234.6	244.2
t	40	40	40	40
Q	20	13.5	15.3	28.9
Q	15	15	15	15
K	2.5	2.5	2.5	2.5
C	800	800	875	800
R	2600	2600	2650	2600
C	4179	4179	4179	4179
R	990	990	990	990
X	838.3	959.5	1030	925.5
B	0.01	0.01	0.01	0.01
H	732.5	609	733	540
P	10	5	10	10
Ta	234.6	214.4	231.9	230.3
Ts1	234.7	214.4	231.7	230.3
Ts2	211.9	178.5	214.7	211.2

Par	Wells (KMJ)		
	26	27	30
Ti	244,0	243.0	231.5
T	40	40	40
Q	16,3	19.4	5.5
Q	15	15	15
K	2.5	2.5	2.8
C	800	800	1000
R	2600	2600	2650
C	4179	4179	4179
R	990	990	990
X	1141	1272	1033
B	0.01	0.01	0.01
H	530	470	800
P	10	10	5
Ta	231.8	232.1	230.3
Ts1	231.6	232.3	230.2
Ts2	203.1	208.3	208.3

Ti	Initial reservoir temp (°C)	r	Reinjection water density (kg/m^3)
T	Reinjection water temp (°C)	x	Pathway distance (m)
Q	Production flowrate (kg/sec)	b	The width of fracture zone (m)
Q	Reinjection flowrate (kg/sec)	H	The height of fracture zone (m)
K	Thermal conductivity (W/m°C)	p	Porosity (%)
C	Rock specific heat capacity (J/kg°C)	Ta	Actual reservoir temperature (°C)
R	Rock density (kg/m^3)	Ts1	Simulation reservoir temperature (°C) in 1998
C	Specific heat capacity of reinjection water (J/kg^{o}C)	Ts2	Simulation reservoir temperature (°C) in 2009

Cooling prediction model is done by taking the best fitting to each well parameter. Values of p, q, c, r and t parameters are made by trial and error but *k*, C and R are considered to be fixed parameters. The best fitting simulation is taken from the real temperature decline between 1989 and 1998. The result of the best fitting cooling prediction from TRCOOL is shown in Table 11.

Figures 7 and 8 show that the wells that are located in the eastern and western areas have significant temperature decline at the 48th month. KMJ-14 has the highest decline in the eastern area, about 52°C in 20 years and KMJ-26 has the highest decline in the western area, about 40°C in 20 years as well (until 2009).

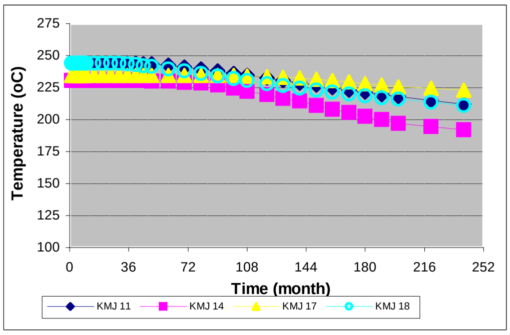

Fig. 7. Reservoir cooling prediction at KMJ-11, 14, 17 and 18

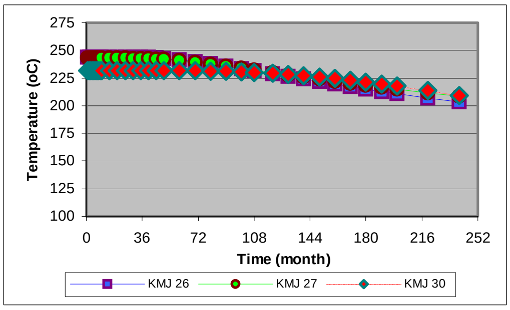

Fig. 8. Reservoir cooling prediction at KMJ-26, 27 and 30

Table 12. The result of reservoir cooling simulation with variation injection flowrate

Well	Q Kg/sec	Ti (°C)	T in 2009 (°C)	Delta T (°C)
KMJ-11	5	244.2	243.99	0.21
	10		238.15	6.05
	15		212.24	31.96
	20		212.24	31.96
KMJ-14	5	230.5	230.48	0.02
	10		220.44	10.06
	15		178.50	52.00
	20		126.17	104.33
KMJ-17	5	234.6	234.60	0
	10		232.16	2.44
	15		214.70	19.90
	20		173.13	61.47
KMJ-18	5	244.2	244.12	0.08
	10		235.38	8. 82
	15		211.20	33
	20		181.61	62.59
KMJ-26	5	244	243.99	0.01
	10		236.10	7.90
	15		203.10	40.90
	20		155.66	88.34
KMJ-27	5	243	242.99	0.01
	10		231.02	11.98
	15		208.30	34.70
	20		162.30	80.70
KMJ-30	5	231.5	231.50	0
	10		231.02	0.48
	15		208.20	23.30
	20		141.39	90.11

By using simulation over various reinjection flowrates, i.e. 5, 10, 15 and 20 kg/sec, it was seen that the temperature decline started in the 9th year. The effective flowrate injection is less than 10 kg/sec. The maximum temperature decline at that flowrate is 12°C in the 20th year, with average 7°C. But the decline temperature was seen to be higher by increasing the injection flowrate, even reaching 50°C at injection flowrate of 15 kg/sec and 100°C at 20 kg/sec, see Figure 9 and Table 8.

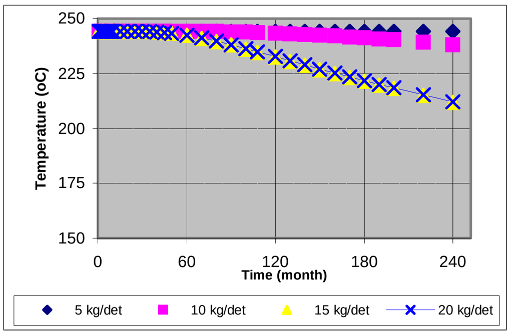

Fig. 9. Reservoir cooling prediction by variation injection flowrate at KMJ-11

The cooling prediction by TRCOOL used simulation in variation reinjection flowrate as well, i.e. 5, 10, 15 and 20 kg/sec, see Table 13.

Table 13. TRCOOL data input at KMJ-27 and KMJ-62

Par	Well	
	KMJ-27	KMJ-62
q	5, 10, 15 and 20	5, 10, 15 and 20
Ti	232.1	237.56
t	40	40
Q	19.4	19.4
k	2.5	2.5
C	800	800
R	2600	2600
c	4179	4179
r	990	990
x	673	236
b	0.01	0.01
H	470	500
p	10	10

The result of simulation showed that the effective injection flowrate is less than 15 kg/sec in the well KMJ-27 but in KMJ-62 is less than 10 kg/sec, see Figures 10 and 11.

CONCLUSION

The second tritium injection in a poor permeable zone, i.e KMJ-15, resulted in a long breakthrough time, i.e. 5.5 to 7 years and a maximum mass recovery of 4%.

If the simulation result corresponds with the real data, the tritium breakthrough time in the third injection is faster than in the second injection because the third tritium injection is in a medium permeable zone. In the 2nd simulation model at KMJ-27, the tritium breakthrough time is 37 months (3 years respectively) at the maximum tritium concentration 150 TU, while the real tritium concentration is 170 TU on

May 2004. The tritium breakthrough time in the 1st model at KMJ-62 is only 7 months at 400 TU concentration, while the real tritium concentration is 372 TU on May 2004. This result will be completed with the data that still being monitored.

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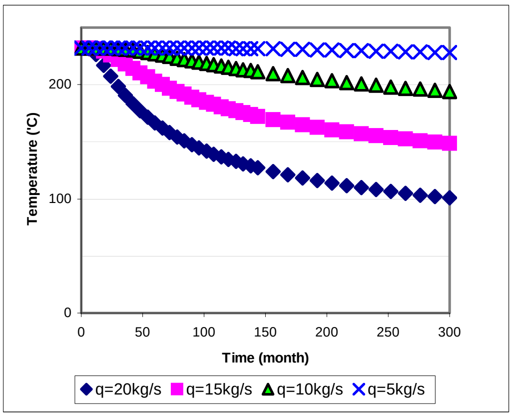

Fig. 10. Cooling prediction curve at KMJ-27

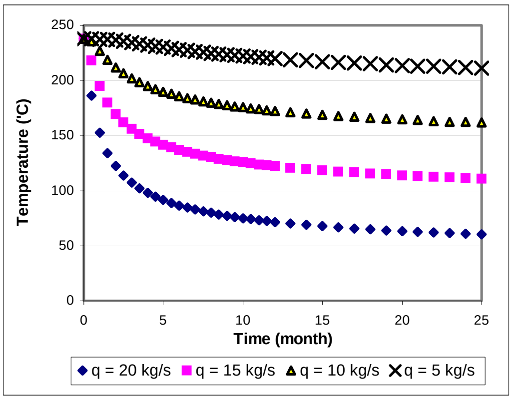

Fig. 11. Cooling prediction curve at KMJ-62