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# TRACER LEAK OFF TESTS AS MEANS OF CHECKING WELL INTEGRITY. APPLICATION TO PARIS BASIN GEOTHERMAL PRODUCTION WELLS

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## ABSTRACT

Exploitation of geothermal district heating systems, located most often in sensitive, densely populated, urban environments require thorough monitoring of well integrity.

The latter is commonly controlled via casing caliper logs and packer leak off tests, provided production equipment, such as submersible pump sets and downhole chemical injection lines, have been previously removed.

Tracers, or fresh water, either injected downhole or squeezed from surface, production equipment in hole, may prove a feasible and cheaper alternative in assessing a reliable damage diagnosis.

The present paper reviews the figures of merit of candidate tracers, radioactive isotopes ($^{131}$I, $^{82}$Br, $^{99m}$Tc), chemical (NaI, $Li^2CO_3$), fluorescent (Rhodamine WT), fresh water, and field implementation protocols, based on selected Paris Basin case studies.

Field achievements led to the selection of combined, short duration, squeeze of Lithium carbonate/fresh water slugs regarded as the most rewarding, routine, and cots effective procedure.

## BACKGROUND AND SCOPE

Surveillance of geothermal district heating wells requires thorough monitoring of casing/tubing integrities, particularly in the Paris suburban areas heated by thirty four doublets (i.e. 68 production and injection wells) operated in a sensitive, densely populated, urban environment.

Several wells have undergone severe casing damage owing to a thermally hostile corrosive fluid and loose cementing, the latter noticed most often in the upper cased sections, leading to casing piercing and leaks whenever exposure to active aquifers vis-à-vis or/and via channeling occur.

Evidence of such damage can be provided by production monitoring and subsequent depletion of discharge rates and wellhead pressures. However, at this stage, the diagnosis may prove ambiguous as it calls for several damage source mechanisms, reservoir plugging and casing scaling among others. Decline in static well head pressures is another, a priori reliable, means for identifying casing leaks, after due substraction of pressure interferences from all possible interacting wells, in deed a delicate exercise. As a result, from these precursory shows remains the problem of assessing whether or not there is a casing piercing/leak and, if such is the case, to locate it precisely.

Direct assessment by casing leak off tests is the most popular method, extensively practiced in the oil and gas and geothermal industry. It requires to kill the well and remove the in hole production equipment (production pump, tubing, pressure control and downhole chemical injection lines) prior to running the pipe string (or coiled tubing)/straddle packer assembly, thus mobilizing a workover facility, either a servicing rig or a coiled tubing unit. It leads however to high operative costs, which add to significant exploitation losses, bearing in mind that rig move in/move out and completion of packer pressurization tests result in most instances in a ca one week interruption of production.

Therefore tracer testing has appealed to geothermal operators as it offer a means of expecting a sound leak diagnosis in less than two calendar days, *production equipment in hole*, thus at reasonable costs.

The rationale behind the method consists of (i) injecting/squeezing, from production well head or via a resident downhole chemical injection line, a given tracer (either radioactive or chemical, fresh water even) volume, and (ii) monitoring the volumes recovered at surface in terms of restituted tracer ratio and resident times, indicative of the leak magnitude and location.

The present paper reviews the tracer selection problematics, field implementation of tracer injection protocols and relevant interpretation of tracer restitution sequences.

Along this line it should be readily emphasized that, in the Paris Basin, all tested wells are over pressured (i.e. eruptive) and equipped with submersible, either electrically (ESP's) or hydraulically, turbine (HTP's) driven pump sets and, last but not least, resident downhole chemical inhibition lines (of the auxiliary injection, type AIT, coiled tubing) [(1)].

The case studies presented and discussed in the forthcoming sections address the following well configurations and tracer injection procedures:

- **case 1** : downhole injection, via the resident AIT, of a radioactive isotope, on a ESP equipped well.
- **case 2** : injection in the turbine energizing tubing (HTP equipped well) of a combined fluorescent chemical tracer sequence.
- **case 3** : squeeze from surface, on a HTP equipped well, of a combined fresh water/fluorescent tracer sequence.
- **case 4** : squeeze from surface (ESP equipped well) of a combined freshwater/chemical tracer sequence.

Case history 3 enabled to identify and quantify a casing leak.

Case histories 1, 2 and 4 concluded to casing/tubing integrities, further confirmed, respective to cases 1 and 4, by similar protocols implemented five and two years later.

Accuracy of the tracer flow back curves and related restitution ratios is discussed in (2).

## TRACER SELECTION

A variety of candidate tracers can be contemplated, namely :

**Fluorescent agents**. Rhodamine WT is preferred as it is chemically neutral, i.e. non adsorbed by exposed pump, casing metal and AIT thermoplastic surfaces. Tracer restitution is easily monitored by means of standard calorimetric recording devices. It's use is however more or less qualitative as compared to chemical and radioactive tracer monitoring/recording techniques, regarded as more rigorous. Fluorescent tracers are best used as a quick look method enabling to appraise tracer restitution sequences (duration, resident times) prior to chemical/radioactive tracers.

**Chemical tracers**. Iodine is the most popular in hydrogeological applications. Lithium is another candidate. Limitations in use depend on the Iodine and Lithium contents in geothermal waters which imply that injected concentrations stand one order of magnitude higher than nascent (geothermal background noise) concentrations, to allow non ambiguous and reliable interpretation of tracer response.

**Radioactive tracers.** Three candidates have been considered, Iodine $^{131}$I isotope, Brome $^{82}$Br isotope and Technetium $^{99m}$Tc radioisotope. Their selection is guided by (i) their lifetimes (periods), which stand at 8 days ($^{131}$I), 1,5 day ($^{82}$Br) and 6 hours ($^{99m}$Tc) respectively, (ii) their supply and availability (for instance $^{82}$Br was no longer available at the time the experiments were carried out), and (iii) environmental regulations and authorizations in force ; in France utilization of $^{131}$I, owing to its fixation on human thyroid, is subjected to (re)injection of the traced fluid in deep seated reservoir formations, after formal approval by an ad hoc commission. Monitoring of tracer response is achieved via a radioactive impulse counter.

**Fresh water.** It is the most simple and, by all means, the cheapest "tracer". It can be reliably utilized as water slugs, in conjunction with chemical tracers, provided there exists a strong physico-chemical contrast, (salinity, temperature, pH) with the geothermal water which happens to be the case in the Paris Basin (presence of a hot, mineralized, geothermal brine). Water conductivity is therefore the recorded parameter.

## TRACER INJECTION PROCEDURES

Depending on the depth of the investigated leak either downhole or surface injection will be implemented.

A deep seated target would be best evidenced by injecting the tracer downhole via the AIT line according to the design shown in fig. 1A. When the well is equipped with an ESP, the master valve is shut and the traced fluid produced in self flowing mode, through the annulus, (see fig. 1B), to avoid any tracer trapping whatsoever in the ESP and production tubing. For a non eruptive well, production would be achieved via the ESP in which case only the cased sections exposed to tracer circulation, i.e. below pump intake, are investigated.

In the absence of a downhole control (or chemical injection) line the tracer can be squeezed from the surface wing valve as depicted in fig. 2, a procedure also eligible to leaks located at shallow depths.

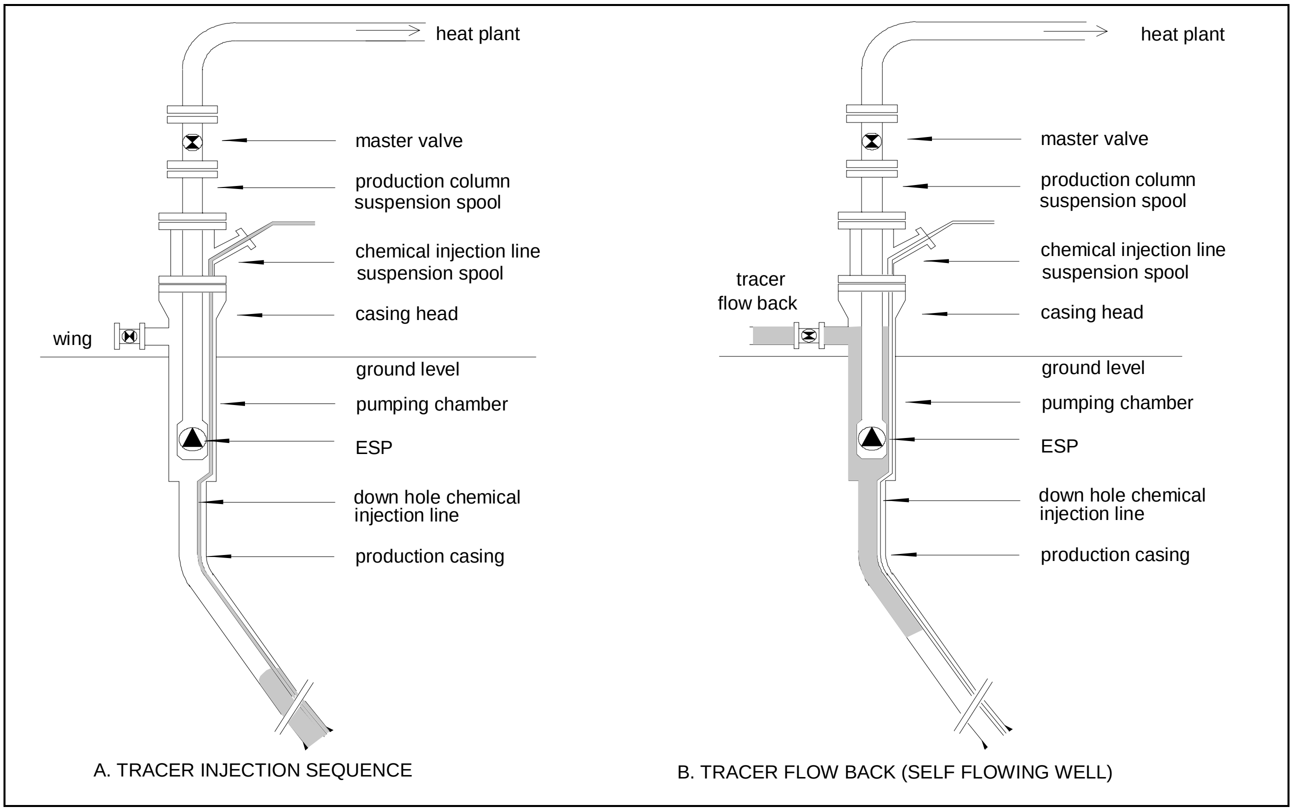


*Figure 1. Tracer injection by means of a resident down hole injection line and restitution (self flowing production) trough 2" casing head wing valve*

Injected tracer quantities must allow to access the depth of the leak and can therefore be as large as the cased well volume. However, whenever the damage is located close to the casing shoe the interpretation may be biased by tracer losses in the underlying geothermal reservoir, which requires special care during the squeezing stage.

The presence of a HTP instead of an ESP somewhat complicates the exercise. Here the pump is driven by a hydraulic turbine fed by a high pressure charge pump and fluid (driving and reservoir produced geothermal water) produced by the annulus. As described in fig. 3 the tracer is injected in the surface part of the energizing loop, getting therefore diluted by the reservoir fluid after passing through the turbine. The energizing loop must therefore be circulated long enough to ensure the whole of the tracer has been evacuated to the heat plant and injection well. In such circumstances preliminary fluorescent tracer tests are recommended in order to define the proper circulation time.

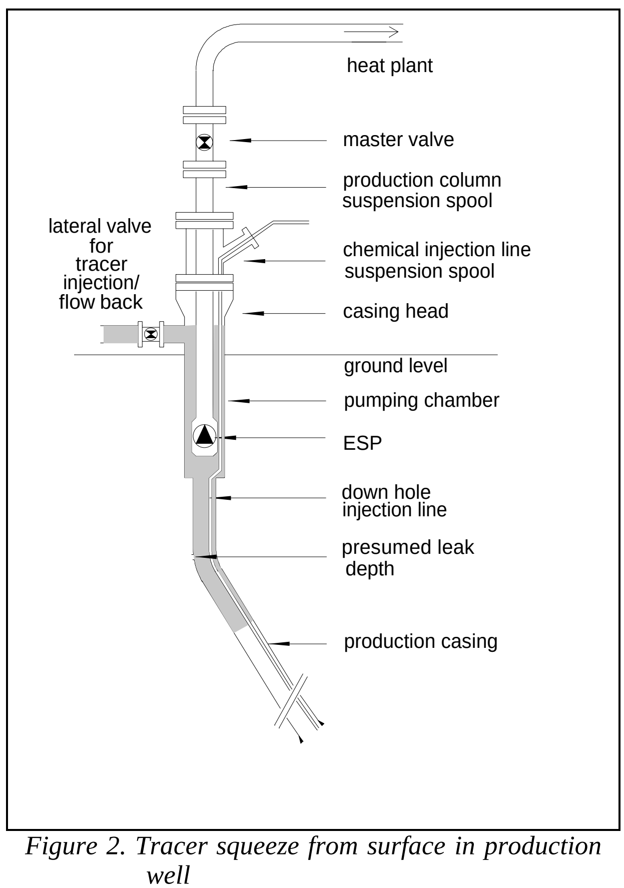


*Figure 2. Tracer squeeze from surface in production well*

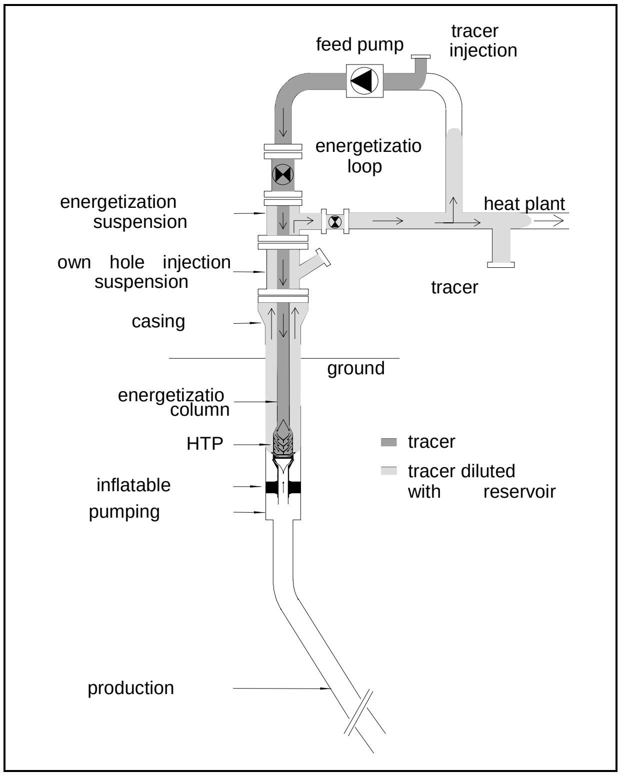


*Figure 3. Tracer injection in a turbopump produced geothermal well*

## TEST INTERPRETATION

### The general chemical tracer case

The experimental tracer concentration vs. time plot shown in fig. 4 is quite illustrative of the ideal tracer restitution curve

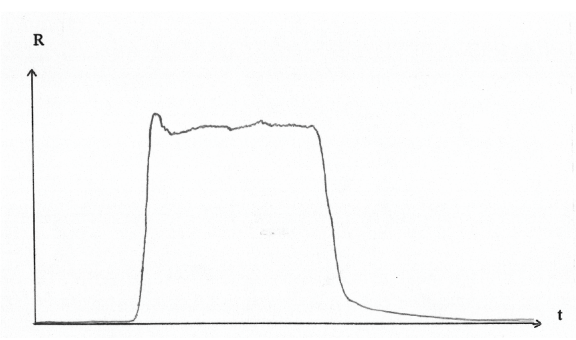


*Figure 4: Experimental tracer restitution curve*

The recovered (restituted) tracer mass, corrected from background noise is calculated by integrating the experimental response over the duration of the test. Hence the restituted mass Mg(g) is given by :

$$(1) \qquad m_R = \int_0^{+\infty} [c(t) - c_0] Q_p(t) dt = \int_{t_0}^{t_C} [c(t) - c_0] Q_p(t) dt$$

with :
$c(t)$ : concentration of the tracer (g/l),
$c_0$ = initial tracer concentration in formation fluid (g/l),
$Q_p(t)$ : instant restitution flowrate (l/h),
$t_0$ : time restitution starts (h),
$t_c$ : time restitution ends (h).

Restitution rate R (%) is given by :

$$(2) \qquad R = \frac{m_R}{m_0}$$

with :
$m_0$ : initial injected mass (g).

The restitution rate must be corrected from measurement (flowrate and concentration determinations), initial mass and integrating errors respectively.

Integration of [concentration x flowrate] vs. time is calculated from concentrations ($c_i$) measured on the n samples and flowrates ($Q_i$) monitored during the experiment at times $t_i$.

An easy way to handle error determination consists of integrating the above formula by two different methods (maximizing and minimizing methods) discussed in Appendix.

### The specific radioactive tracer case

Part ($Q_c$) of the total flow production ($Q_p$) is diverted to a measuring cell, which counts the total number of radioactive impulses ($N_c$) during the whole restitution time ($t_c$ - $t_0$). Background noise ($N_{BN}$) from the total impulses number must then be substracted from the total impulses number. This last figure is corrected from cell volume ($V_c$) down to the total measured volume of fluid circulated through the cell [$Q_c(t_c-t_0)$], and the corresponding total number of impulses in the produced geothermal fluid is adjusted to the flowrate ratio ($Q_p/Q_c$). The number of impulses ($N_2$) corresponding to the total extracted geothermal fluid is therefore :

$$(3) \qquad N_2 = (N_c - N_{BN}) \frac{V_c}{Q_c(t_c - t_0)} \frac{Q_p}{Q_c}$$

This injected tracer needs also to sampled with an aliquot sample (a) taken before injection in order to access the number of impulses generated by the injected tracer mass. The number of impulses ($N_a$) generated by the aliquot is then corrected by subtracting the geothermal background noise ($N_{BN}$) because geothermal water is used for aliquot dilution prior to measurements. This last figure is corrected up to the total volume (A) of injected tracer and the radioactive decay of the injected tracer during the time between injection in the well ($t_0$) and measurement of the aliquot (t), gives the initial number of impulses, ($N_1$) of the injected tracer.

$$N_1 = (N_a - N_{BN}) e^{\left[0.693 \frac{t - t_0}{T}\right]} \left( \frac{A - a}{a} \right) \quad (4)$$

Restitution rate is therefore :

$$R = \frac{N_2}{N_1} \quad (5)$$

with :
$Q_P$ = production flowrate,
$Q_c$ = cell sampling flowrate,
$V_c$ = cell volume,
$N_1$ = number of impulses generated by the tracer injected in the well,

$N_2$ = number of impulses generated by the tracer produced by the well,
$N_c$ = number of impulses generated by the fluid circulated through the measuring cell,
$N_{BN}$ = number of impulses generated by the geothermal fluid (background noise),
$N_a$ = Number of impulses generated by the aliquot,
T = half time of radioactive decay, (radioactive period)
a = aliquot volume,
A = dilution volume of tracer,
$t_0$ = time measuring of the extracted fluid started,
t = time measuring of the aliquot started,
$t_c$ = time experiment in the measuring cell ended

## CASE STUDIES

A series of tests have been conducted on typical Paris Basin geothermal production wells whose features are highlighted in table 1.

### Case 1. Radioactive Tracer Test

The clean up, via casing jetting, of the local geothermal district heating well in 1992 evidenced a piercing of the pumping chamber. After unsuccessful attempts to seal a casing patch over the damaged casing interval, well integrity was reestablished thanks to a remedial cement squeeze. A tracer test was carried out a year later to check the integrity of the cement squeeze.

Iodine isotope $^{131}I$ and Technetium radioisotope $^{99m}Tc$ were selected as a result of their availability, easy operation and, last but not least, the existence of an injection well solving the $^{131}I$ disposal problem. Tests were carried out from 23 to 25 June, 1993, with the assistance of the French Atomic Energy Agency (CEA), Grenoble DAMRI Laboratory [3]

Tracers were injected downhole via the resident AIT aimed at permanent injection of corrosion inhibitors into the geothermal source reservoir.

Field set up is shown in fig. 5. Two counting cells were used. A first dynamic cell to deliver a quick look (fairly inaccurate) of the tracer residence/restitution time. An accurate determination of the tracer restitution rate is given by the second counting cell proper. The sampling and counting loop is depicted in fig. 6.

| Case no. | Year completed | Pump type | Tracer type | Objective | Diagnosis |
|---|---|---|---|---|---|
| 1 | 1993 | ESP | RAT | Casing leak | No leak<br>Confirmed by<br>Duplicate test<br>(CT+FWS) 2001 |
| 2 | 1995 | HTP | CT | Energizing tubing leak | No leak |
| 3 | 1997 | HTP | CT+FW | Casing leak | Pumping chamber leak |
| 4 | 1998 | ESP | CT+FW | Casing leak | No leak<br>Confirmed by<br>Duplicate test 2001 |

*Table 1. Test features*

Abbr. ESP : Electrosubmersible pump RAT : Radioactive tracer FW : Fresh water
HTP : Hydraulic turbine pump CT: Chemical tracer

Test n° 2. $^{131}I$ restitution curve is shown in fig. 4

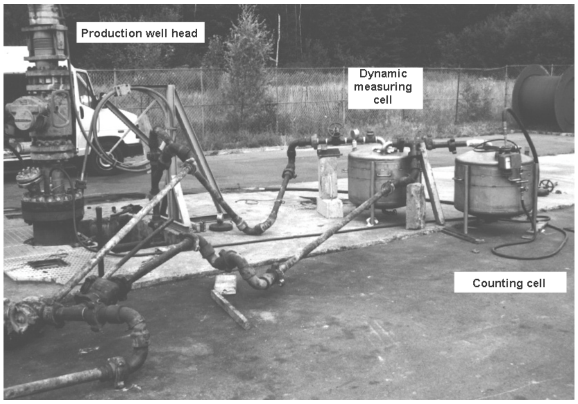

*Figure 5. Field set up*

Three testing sequences were conducted whose results are summarized in table 2. Test n°2 $^{131}I$ restitution curve is shown in fig. 4. The first test was designed to adjust the relevant testing parameters such as injection duration ($t_c$-$t_0$), geothermal (self) production flowrate ($Q_p$) and sampling flowrate ($Q_c$).
This preliminary tests evidenced that:

- the geothermal self production rate ($Q_{p)}$ was of piston type i.e. non dispersive (see fig. 4), which reduces the early estimated monitoring duration by a factor of 3 to 4, and
- the sampling flow rate ($Q_c$) in the counting cell could, as a result, be increased by 3 or 4 times, thus limiting the risk of getting the measuring valves plugged by particulate suspensions in the geothermal fluid. This also contributes to maintaining a constant sampling flowrate which was not the case in the first test.

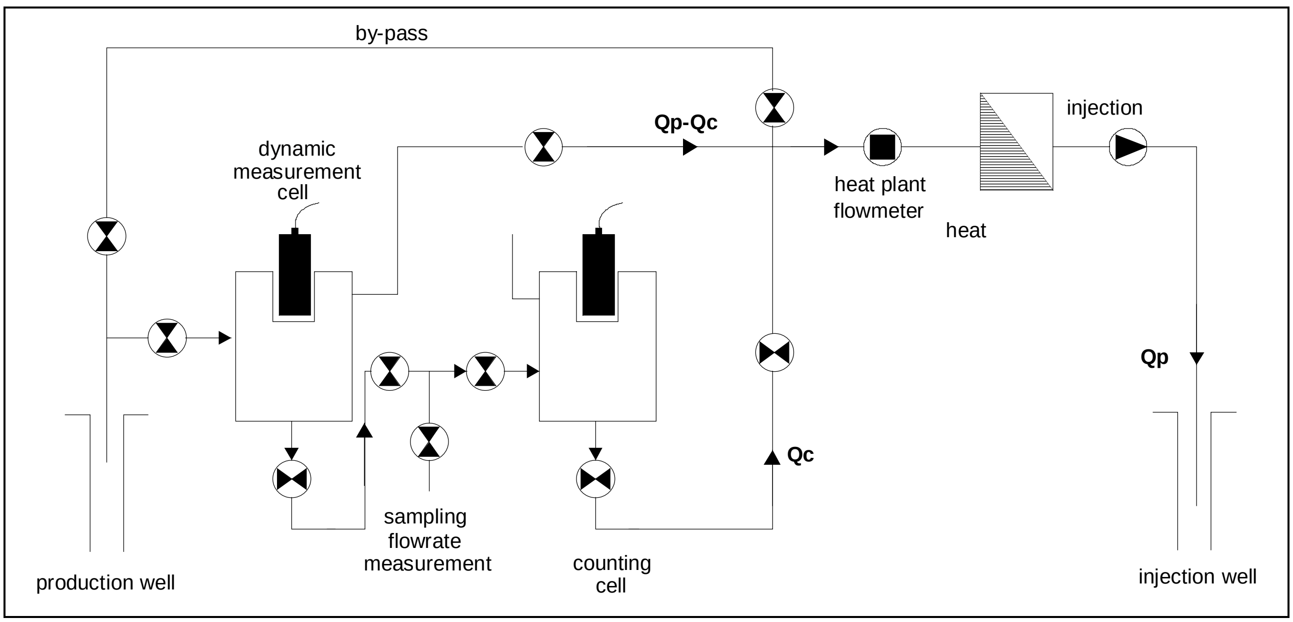

*Figure 6. Experimental monitoring and measurement loop*

| Test number | Symbol | 1 | 2 | 3 |
|---|---|---|---|---|
| Tracer used | | $^{131}I$ | $^{131}I$ | $^{99m}Tc$ |
| Radioactive period (hours) | T | 192 | 192 | 6 |
| Quantity injected | | 74 MBq | 74 MBq | 740 MBq |
| Dilution volume of tracer (l) | A | 1 | 1 | 1 |
| Injection type | | Down hole | Down hole | Down hole |
| Injection rate (l/h) | | 45 | 45 | 45 |
| Aliquot (l) | a | 0.7/1000 | 1/1000 | 2/1000 |
| Cell volume (l) | $V_c$ | 293,2 | 293,2 | 293,2 |
| Well characteristics | | | | |
| Self flowrate (l/mn) | $Q_P$ | 465 | 465 | 465 |
| Well head pressure (bar) | | 6.9-7.0 | 6.9-7.0 | 6.9-7.0 |
| Sampling parameters | | | | |
| Sampling time duration (mn) | $t_c$ | 344 | 294 | 154 |
| Sampling flowrate (l/mn) | $Q_c$ | ≈ 0,400 | 1,00 | 1.2 |
| Total extracted volume (l) | $Q_c t_c$ | 137.6 | 293.2 | 184.8 |
| Radioactivity measurements | | | | |
| Geothermal background noise (impulses) | $N_{BN}$ | 9 873 in 30 mn | 9 873 in 30 mn | 18 000 in 30 mn |
| Output signal (impulses) | $N_c$ | 45 369 in 30 mn | 71 419 in 30 mn | 61 541 in 20 mn |
| Aliquot signal (impulses) | $N_a$ | 63 050 in 30 mn | 95 225 in 30 mn | 73 525 in 3 mn |
| Time duration (mn) | $t-t_0$ | 717 | 52 | 55 |
| Restitution rate | R | 111 % | 111 % | 11,6 % |

*Table 2. Case 1 tracer tests results.*

***Discussion***

The first result is mainly depending on the sampling flowrate ($Q_c$) accuracy. This sampling flowrate was initially set at 0.430 l/mn, but decreased quite significantly during the experiment, down to less than 0.400 l/mn. However, its average value could be estimated at 0.400-0.410 l/mn, resulting in a restitution ratio ranging from 105 ($Q_c$=0.410 l/mn) to 111 % ($Q_c$=0.400 l/mn).

The second result is more accurate thanks to the experimental parameters' adjustment achieved after the first experiment (see above). Hence the error calculation can be estimated as follows:

- number of impulses accuracy : 0.5 %,
- volume measurements accuracy : 1 %,
- sampling flowrate (after degassing of the geothermal water) accuracy : 3 %.

These parameters lead to a global error on the restitution rate of 9 %, which ranges therefore, say between 102 and 120 %. The error on the produced flowrate (heat plant flowmeter) can therefore be estimated to at least 2 %, since no additional radioactive impulses can be generated from the produced flow. A better estimate of the error on the produced flowrate would be 3-4 %, which matches the usual electromagnetic flowmeter precision.

The second experiment, realized in optimum conditions (steady flowrates) shows undoubtedly that no leak is to be expected in the pumping chamber (neither elsewhere in the well).
The third experiment exhibits a very low restitution rate (12 %) with same errors, i.e. ranging between 3 and 9 %, despite reliable experimental conditions (steady flowrates). Explanation lies in the fact that the tracer used ($^{99m}Tc$) is obviously interacting with and trapped (adsorption) by the geothermal medium and exposed materials. 99 mTc is therefore readily discarded for tracer leak off tests on Paris Basin geothermal wells.

**<u>Case 2. Chemical Tracer Test. HTP Equipped Well</u>**

Doublet monitoring showed in 1995 a 1.5 bar drop in well head static pressure, not induced by surrounding well interferences, thus suggesting a possible casing leak located between the HTP packer and surface.
In order to investigate this damage an ad-hoc test was designed to trace the water circulating between the charge (feed) pump and the hydraulic turbine. Testing was undertaken in July 1995 with the assistance of CEA/DAMRI [(4)].

($^{131}I$) was discarded because of the risks induced by small leaks noticed on the surface loop.

As a consequence a combination of fluorescent (Rhodamine WT) and chemical (Sodium Iodure NaI) was selected instead, as there are of routine use in hydrogeological tracing experiments and do not interact neither with the geothermal fluid nor with the exposed equipment.

Tracers were injected through the HTP energizing circuit at charge pump intake (see fig.3) and the geothermal discharge rate set at a fairly high level (ca 155 $m^3/h$) to create a strong pressure contrast (high gradient) with the receiving aquifer and reliably assess the leak, if ever, and its magnitude. As the circulation transit time through the energizing circuit is short (1 to 2 min) for the aforementioned discharge rate, duration of the tracer injection sequence must be long enough (several hours) to capture the whole plateau of the restitution curve and allow a reliable integration of the signal and derivation of the restitution ratio.

Since a fraction (ca 125 $m^3/h$) of the total produced flow (ca 280 $m^3/h$) is recirculated through the turbopomp the net geothermal production standing at ca 155 $m^3/h$, circulation and sampling times ought to be designed so as to allow the whole of the injected tracer to leave the energizing loop (see fig. 3).

One hundred liters of a tracer solution (114 g of Rhodamine WT and 224 g of NaI) were injected at 30 l/h upstream from charge pump intake (see fig. 3). Because of a leak, a second injection (32.5 l at an average 25 l/h rate) was completed after rinsing the tracer preparation tank. Rhodamine WT concentration (Fluorescent units) measured on site, enabled to determine the tail of the tracer restitution curve.

The Rhodamine response (instant measurements corrected from background noise) is depicted in fig.7A. The curve, somewhat chaotic, reflects two injection pump stops at 95 and 135 min respectively. Oscillations following injection resuming relate to the restart of the pump stepwise. The peak noticed at 180 min is caused by the reinjection of the surface leak, and the secondary peaks correspond to the tank rinsing cycles.

Fig. 7B illustrates the evaluation of Rhodamine concentrations measured, in fluorescent units (FU), on samples. Rhodamine contents are derived straightforwardly as FUs volumes. Whenever needed the Rhodamine mass can be calculated from the fluorimeter calibration curve (see fig. 8).

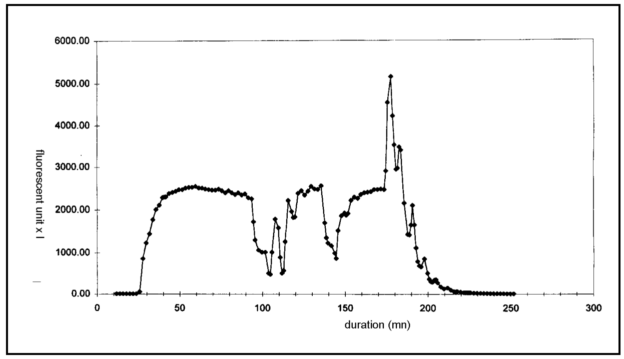


*Figure 7A. Rhodamine restitution curve (instant measurements*

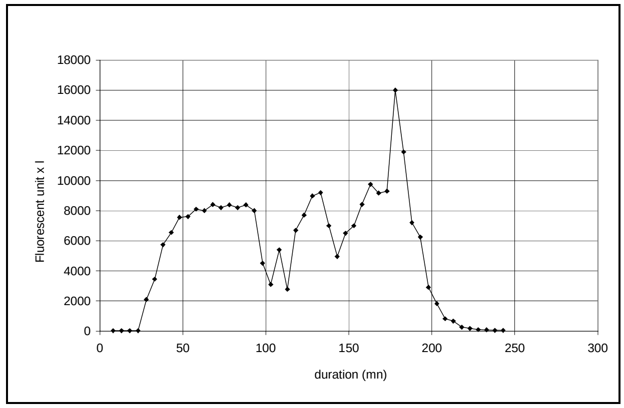


*Figure 7B. Rhodamine samplings results.*

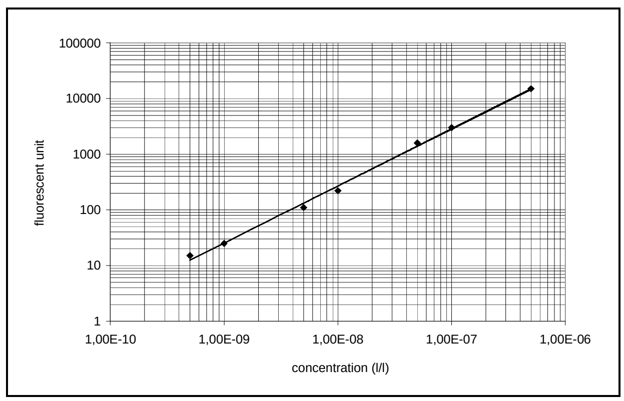


*Figure 8. Fluorimeter calibration curve*

Iodine measurements are biased by nascent Iodine dissolved in the geothermal fluid. This is exemplified in fig. 9A which clearly shows that amount of injected Iodine were unable to defeat the resident background noise. Nevertheless, thanks to adjustments to the Rhodamine restitution curve, the background noise could be estimated at 4200 ppb + 200 pbb thus leading to the corrected restitution curve plotted in fig. 9B. whose integration delivers the tracer restitution ratio.

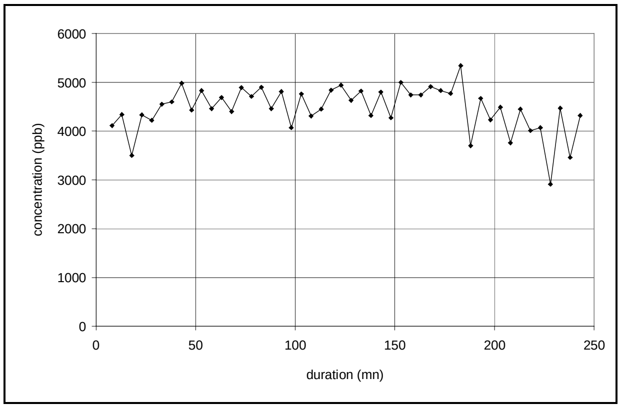


*Figure 9A. total Iodine (non corrected) concentration in geothermal production flow.*

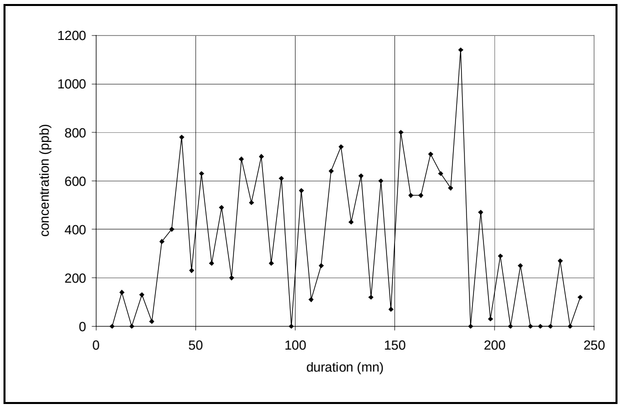


*Figure 9B. Iodine concentration corrected from background noise.*

***Discussion***

Results relating to Rhodamine WT and NaI are displayed in table 3.

It is quite clear that, owing to the strong Iodine background noise from the geothermal fluid, only can the Rhodamine WT corrected curve allow a fairly reliable assessment of restitution ratios which, in the present case, allow to discard the existence of any pumping chamber leak whatsoever. This conclusion could be confirmed later, when static well head pressure recovered its previous value.

It became also pretty obvious that, unless significantly higher Iodine quantities be injected to counter background noise, a substitute neutral candidate tracer should be selected.

| **Tracer** | **Rhodamine WT Absolute figures** | **Precision** | **Na $I^-$** | **Precision** |
|---|---|---|---|---|
| Injected mass $m_0$ | 2.8 $10^9$ FUxl | 1.3 % | 229.6 g | 1.3 % |
| Restitution function integration | | | | |
| minimum | 1.18 $10^6$ FU x mn | 4 % | 47.5 $10^{-3}$ g/l x mn | 5 % |
| maximum | 1.39 $10^6$ FU x mn | 4 % | 120.0 $10^{-3}$ g/l x mn | 5 % |
| Geothermal flowrate ($m^3$/h) | 154 (*) | 4 % | 154 (*) | 4 % |
| Restituted mass M minimum | 1.18 $10^6$ x 154 $10^3$ /60 = 3.03 $10^9$ FUxl | 8 % | 47.5 $10^{-3}$ x 154 $10^3$ /60 = 121.9 g | 9 % |
| Restituted mass M maximum | 1.39 $10^6$ x 154 $10^3$ /60 = 3.57 $10^9$ FUxl | 8 % | 120.0 $10^{-3}$ x 154 $10^3$ /60 = 308.0 g | 9 % |
| **Global restitution ratio R (%)** | **99 - 136** | | **42.8 – 144.4** | |

*Table 3. Case 2 tracer test results.*

**<u>Case 3. Fresh Water/Fluorescein Tracer Test</u>**

Since severe production losses had been noticed on the geothermal, district heating, production well a test was designed to assess whether it could be caused by a casing piercing likely to be located at the HTP packer anchoring depth (101 m).

The simple test design (5) consisted of pumping first a ca 62 $m^3$ volume of freshwater the tail of which is traced with 60 g of Fluorescein. This volume corresponds to a net cased hole depth of ca 825 m.

The self flowing sequence which followed evidenced a flowed back volume of fresh water estimated at ca 5 $m^3$, based on water conductivity recording. Furthermore no return of Fluorescein was observed.

Therefore a leak depth comprised between 80 and 115 m could be inferred.

A more accurate spotting of the leak depth was implemented reconducting a similar protocol. 10 $m^3$ of fresh water were placed into the wellbore, filling the upper 165 m.

The flowback sequence, whose results are illustrated in fig. 10 led to a non ambiguous diagnosis. Only $5m^3$ of fresh water (out of the former 10 $m^3$ injected) were recovered, allowing to locate the leak at a depth of 100 m, as initially suspected (see fig. 10).

These convincing and simple experiments were definitively useful guidelines in designing future, combined chemically traced/fresh water, leak off tests.

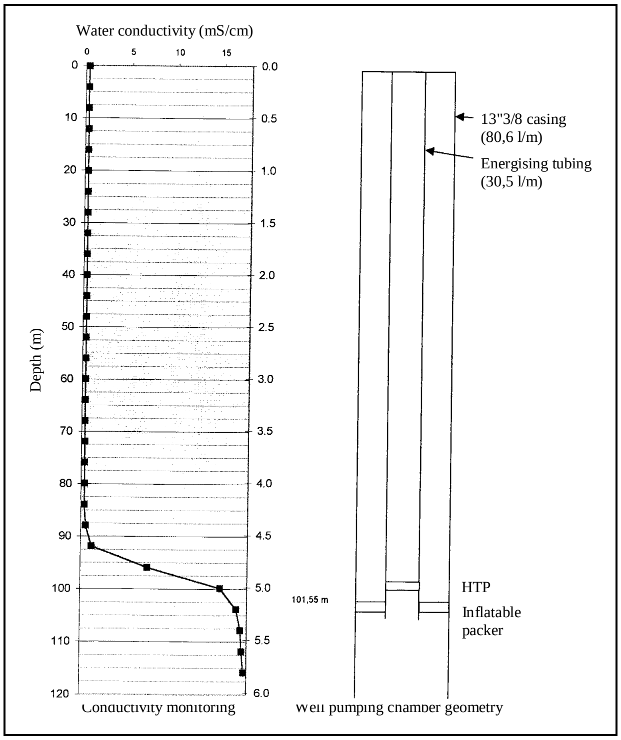


*Figure 10. Case study 3. Water conductivity monitoring and volume/depth assessments (source CFG)*

**Case 4. Squeeze From Surface Of A Combined Chemical Tracer/Fresh Water Sequence**

The test was designed in order to investigate whether a casing piercing identified, on a damaged well, at a depth of ca 460 m, was leaking or not [(6)].

In so doing, and based on experience acquired on early tracer experiments, the following rationale was adopted. Chose a chemical tracer quasi inert with respect to the geothermal fluid and pumped in alternance with fresh water slugs at volumes equal to the well capacity above the casing piercing.

Lithium carbonate ($Li^2$ $CO_3$) proved the best candidate as (i) nascent Li concentrations in formation waters are low (< 2 mg/l), thus minimizing background noise, and (ii) laboratory determination on samples are easier and faster to perform (atomic absorption) than is the case with anions such Iodine I.

Taking advantage of the sharp resistivity contrast with the geothermal fluid, a hot saline brine, fresh water offers, via continuous monitoring of electrical conductivity, an additional means for assessing restitution ratios and, eventually, casing leaks. Furthermore integration of fresh water volumes addresses flowrates.

The injection sequence (via the 2"wing valve) into the annulus is illustrated in fig. 11. It starts with the pumping of one unit volume (ca 15 $m^3$) of, fresh water diluted, $Li^2$ $CO_3$, followed by the injection of an equal volume of fresh water. The well is then self produced via the annulus and 2" wing valve to recover the fresh and traced water slugs (each $15m^3$ in volume) and ultimately underlying geothermal water.

Field set up is described in fig. 12 (injection production phases).

Injection and (self-flowing) production rates are controlled by a flowmeter gauge and volumetric measurements on the 1.5 $m^3$ tanks. Both injection and production rates were set at 15 $m^3$/h the latter by means of a throttle valve.

Sampling intervals varied from 2.5 to 5 min as shown in fig. 14, which displays the conductivity, $Li^+$ concentration, flowrate and temperature vs. time plots.

Fig. 14 evidences an almost ideal piston type Lithium response, with minimum dispersion at the sharp water/fresh water interface (hardly 10 minutes) enabling reliable material balance calculations. Temperature transients, as already suspected in case study 3, cannot, owing to heat conduction, be exploited for any volume calculation whatsoever.

Hence masses and volumes of fresh and Li traced water, based on water conductivity an $Li^+$ concentration, led to reliable assessments of relevant restitution ratios, summarized in table 4.

From the measuring accuracy close to 100 % mean restitution ratio is derived thus conclusive as to the absence of detectable casing leaks, a diagnosis confirmed two years later thanks to a replicate test.

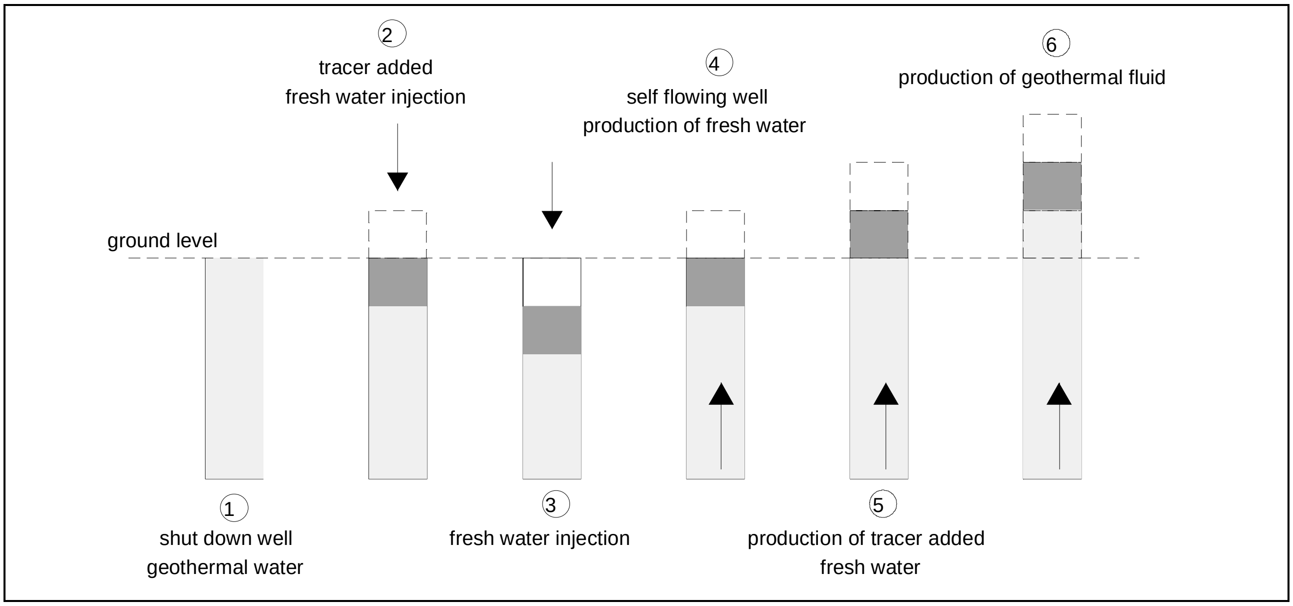


*Figure 11. Case 3. Injection/flow back sequence.*

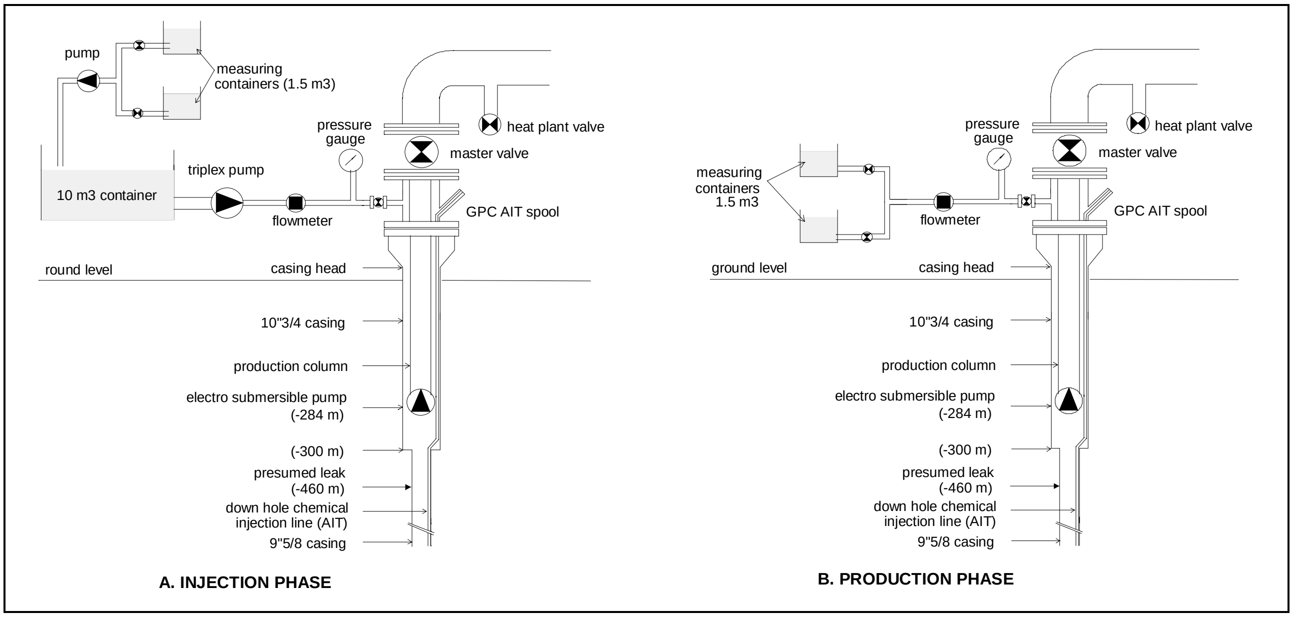


*Figure 12. Experimental set up. Injection and flow back sequences.*

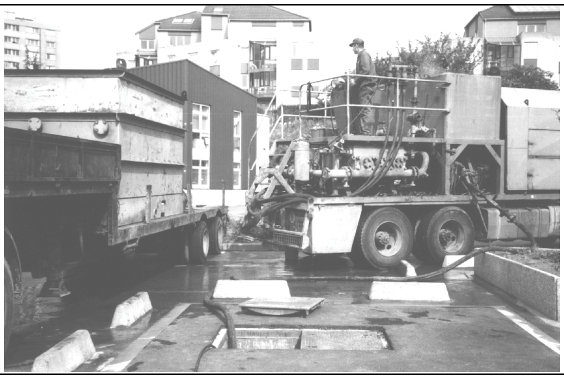

*Figure 13A: Field set up. Triplex pump with small tanks ($1.5m^3$) and mixing tank ($10\ m^3$).*

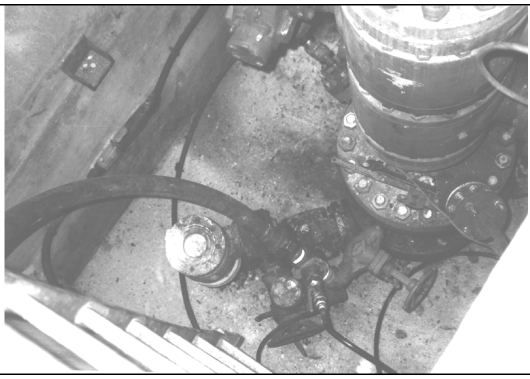

*Figure 13B. Well head with injection/production via 2" wing valve*

| Tracer | **Conductivity** | **Precision** | **Lithium** | **Precision** |
|---|---|---|---|---|
| Injected mass ($m_0$) or volume ($V_0$)<br>Geothermal flowrate<br>Tracer concentration/measurement in restituted water | 30 $m^3$<br>15 $m^3/h$ | 2 %<br>2 %<br>0.2 % | 375 g<br>15 $m^3/h$ | 0.8 %<br>2 %<br>1.3 % |
| Restitution function integration<br>minimum<br>maximum | <br>29.375 $m^3$<br>30.000 $m^3$ | | <br>360.98 g<br>380.83 g | |
| **Global restitution ratio R (%)** | **93.72 – 104.2** | | **92.16 – 105.65** | |

*Table 4. Case 3 tracer test results.*

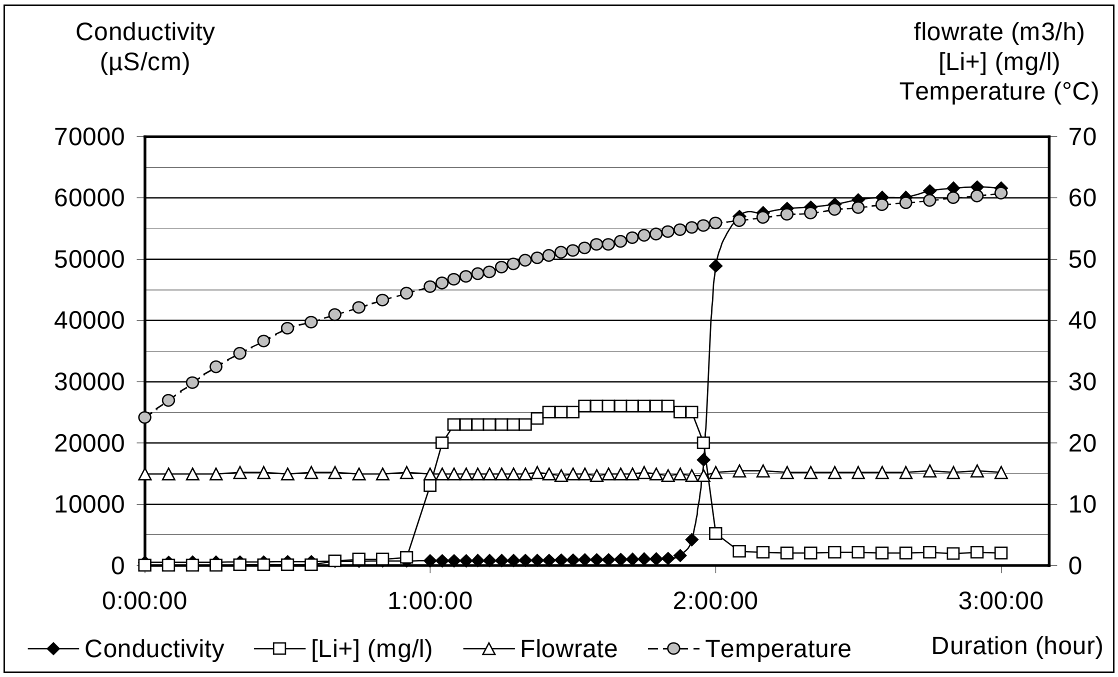


*Figure 14. Case 3 restitution results.*

## CONCLUSIONS

Tracer tests carried out on Paris Basin geothermal district heating wells aimed at identifying casing leaks *production equipment in hole*. These tests were conclusive. Tracer testing proved a viable alternative to conventional packer leak off tests in assessing casing integrity, owing to easier and faster field implementation and cheaper operative costs.

This stated, tracer choice remains the key segment in test design.

Radioactive tracers secure the best accuracy thanks to continuous radioactive impulse-counting thus avoiding any integration whatsoever of the tracer restitution curve. However tracer selection in geothermal applications was limited to two candidates, $^{131}I$ and $^{82}Br$ respectively, both subjected to a number of limitations. $^{82}Br$ is not easily supplied and $^{131}I$ requires special care in handling and disposal due to its human contamination risks. Use of radioactive tracers requires elsewhere due authorization by a competent Authority and the assistance of a specialized, authorized, laboratory which add to delays and costs.

Chemical tracers must be compatible in the sense no chemical nor physical interaction with the formation fluid and exposed equipment materials occurs which would definitely bias signal processing. Along this line a high signal to noise ratio is mandatory i.e. the selected element must avoid conflicting with the same, nascent, element in the formation water for obvious background noise considerations and also to keep the injected tracer amounts to a minimum. This aspect could be evidenced in case study n° 2 with the Iodine tracer.

In this respect Lithium, injected as, fresh water diluted, $Li^2CO_3$ proved the best candidate so far.
Reliability of chemical tracing in assessing, via the integration of the restitution curve, tracer material balance and leak occurrence, is strongly dependant on the tracer sampling rate during well flowback and, last but not least, measurement accuracy.
Adequate sampling and equipment calibration achieve an overall 5 % accuracy of the material balance exercise.

Neither should fresh water be overlooked as long as there exists a sharp resistivity contrast with the geothermal fluid, which was the case here as it addressed a hot saline brine. Furthermore continuous resistivity recording enables to by pass the constraining integration procedure inherent to chemical tracers.

Case study n° 4 led to the design of an optimum testing protocol combining sequential injection of, chemically traced and fresh, water slugs, thus allowing reliable, redundant, interpretation.
It has been shown (case study n° 3) that chemical tracing could match the depth of the leak damage. It can address also the calculation of leaking rates, and be extended ultimately to multiple leak configurations via relevant inversion methods. [(7)]

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