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Tracer tests in geothermal resource management: analysis and cooling predictions

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TRACER TESTS IN GEOTHERMAL RESOURCE MANAGEMENT: ANALYSIS AND COOLING PREDICTIONS

by

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1. INTRODUCTION

Geothermal energy is a renewable, environmentally friendly energy-source based on the internal heat of the Earth. It is associated with volcanic activity, hot crust at depth in tectonically active areas or permeable sedimentary layers at great depth. Geothermal energy is now utilised in more than 50 countries, with electricity production in about 20 countries. The energy production potential, or capacity, of geothermal systems is highly variable. It is primarily determined by the pressure decline caused by mass extraction, but also by energy content. Pressure declines continuously with time in systems, which are closed or with limited recharge. The production potential of geothermal systems is, therefore, often limited by lack of water rather than lack of energy. Geothermal resource management involves controlling energy extraction from geothermal systems underground so as to maximise the resulting benefits, without over-exploiting the resource.

When geothermal systems are over-exploited production from the systems has to be reduced, often drastically. Overexploitation mostly occurs for two reasons: Firstly, because of inadequate monitoring, and data collection, understanding of systems is poor and reliable modelling is also not possible. Therefore, the systems respond unexpectedly to long-term production. Secondly, when many users utilise the same resource/system without common management or control (The Geysers in the U.S.A and large sedimentary basins in Europe and China, are examples).

Geothermal reinjection should be considered an essential part of any modern, sustainable, environmentally friendly geothermal utilisation and an important part of the management of geothermal resources. It started out as a method of waste-water disposal for environmental reasons, but is now also being used to counteract pressure draw-down, i.e. as artificial water recharge, and to extract more of thermal energy in reservoir rock (Stefansson, 1997; Axelsson and Gunnlaugsson, 2000). Reinjection will increase production potential considerably in most cases, as has been learned through experience and theoretical studies. Geothermal reinjection started in Ahuachapan, El Salvador, in 1969, The Geysers, California, in 1970 and in Larderello, Italy, in 1974. It is now an integral part of the operation of at least 40 geothermal fields in 17 countries. Without reinjection the mass extraction, and hence electricity production, would only be a small part of what it is now in many of these fields.

The water injected into geothermal reservoirs includes waste-water and condenser-water from power plants, return-water from direct use (space heating, etc.), ground-water and surface-water or even sewage-water. Some operational problems are associated with reinjection, such as an increase in investment and operation costs, cooling of production wells and scaling in surface equipment and injection wells (Stefansson, 1997). Injection into sandstone reservoirs has, furthermore, turned out to be problematic.

The possible cooling of production wells, or thermal breakthrough, has discouraged the use of injection in some geothermal operations although actual thermal breakthroughs, caused by cold water injection, have been observed in a relatively few geothermal fields. In cases where the spacing between injection and production wells is small, and direct flow-paths between the two wells exist, the fear of thermal breakthrough has been justified. Stefansson (1997) reports that actual cooling, attributable to injection, has been observed in Ahuachapan (El Salvador), Palinpinon (Philippines) and Svartsengi (Iceland). The temperature of well AH-5 in Ahuachapan declined by about 30°C due to an injection well located only 150 m away, while the temperature of well SG-6 in Svartsengi declined by about 8°C during 4 years of injection. The temperature decline of well PN-26 in Palinpinon was reviewed by Malate and O'Sullivan (1991). The thermal breakthrough occurred about 18 months after reinjection started. Subsequently, the temperature declined rapidly, dropping by about 50°C in 4 years.

Cooling due to reinjection is minimised by locating injection wells far away from production wells, while the benefit from reinjection is maximised by locating injection wells close to production wells. A proper balance between these two contradicting requirements must be found. Therefore careful testing and research are essential parts of planning injection. Tracer testing, which is used to study flow-paths and quantify fluid-flow in hydrological systems, is probably the most important tool for this purpose. The main purpose of tracer testing in geothermal studies/management is to predict possible cooling of production wells due to long-term reinjection of colder fluid.

Comprehensive interpretation of geothermal tracer test data, and consequent modelling for management purposes (production well cooling predictions), has been rather limited, even though tracer tests have been used extensively. Their interpretation has mostly been qualitative rather than quantitative. This report presents a review of methods that may be used for this purpose. These methods are equally applicable to radioactive and other chemical tracers. The review is focused on software related to tracer test analysis, and reinjection simulation, which is included in the *ICEBOX* software package, which has proven to be very effective (United Nations University Geothermal Training Programme, 1994). These programs are based on simple models, which are able to simulate the relevant data quite accurately. The utilisation of detailed and complex numerical models (such as TOUGH2-models) is seldom warranted, at least as first stage analysis. In the following the basics of tracer testing will be reviewed, including tracer test design and execution (chapter 2), along with the basics of the theory of solute transport in hydrological systems (chapter 3).

The main emphasis is on tracer test interpretation (chapter 3) and cooling predictions (chapter 4) along with field examples (chapter 5).

2. 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 through studying connections between injection and production wells. Their power lies in the fact that the thermal breakthrough time is usually some orders of magnitude (2-3) greater than the tracer breakthrough time, bestowing tracer tests with predictive powers.

2.1 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). These aspects will be discussed below.

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

Radioactive materials are excellent tracers, since their background levels may be expected to be negligible and they are detectable at extremely low concentrations. They are, however, subject to stringent handling, transport and safety restrictions, and their use is forbidden altogether in some places. The procedure for measuring radioactive tracer concentration in samples collected is, furthermore, more complicated and time consuming than the procedure for measuring the concentration of most other kinds of tracers. Because of these drawbacks radioactive tracers are not commonly used in geothermal applications. Yet considerable experience has been gathered in New Zealand (McCabe *et al.*, 1983) and Central America.

When selecting a suitable radioactive tracer their different half-lives must be taken into account. Fig. 1 shows a comparison between the decay rates of iodide-131 and iodide-125, which have half-lives of 8.5 and 60 days, respectively. Note that the initial activity of the two tracers are based on the initial activity commonly used in tracer tests, 2 Ci ($74 \cdot 10^9$ cps) for iodide-131 and 0.5 Ci for iodide-125. The figure shows that after about a month the activity of iodide-125 is still of the order of 0.35 Ci, while the activity of iodide-131 is only of the order of 0.15 Ci. After two months the activity of iodide-125 will be about 0.25 Ci, while the activity of iodide-131 will only be about 0.01 Ci, rendering it almost undetectable. Therefore, iodide-131 is only suitable for tracer tests expected to last less than, or of the order of a month or so. Iodide-125, which is considerably more expensive, will have to be selected for tests that will last more than 1-2 months.

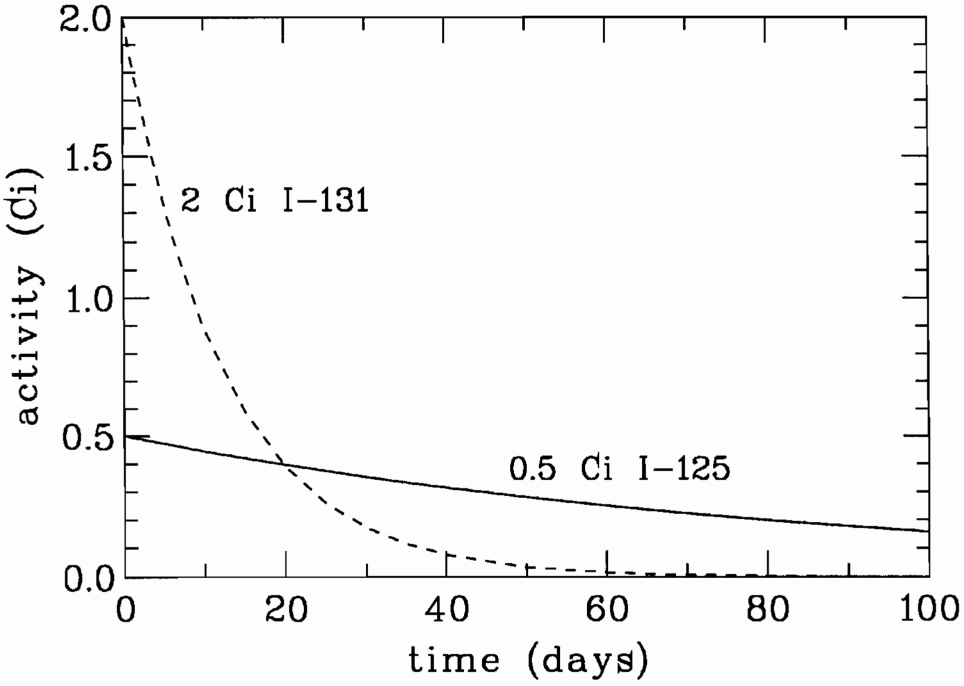

Figure 1. A comparison of the decay of a sample of ^{131}I with an initial activity of 2 Ci and a sample of ^{125}I with an initial activity of 0.5 Ci.

Sodium-fluorescein has been used successfully in a numerous geothermal fields, both low-temperature ones and in higher temperature systems (Axelsson *et al.*, 1995; Rose *et al.*, 1997 and 1999). Fluorescein has the advantage of being absent in natural hydrological systems. Its may also be detected at very low levels of concentration (10-100 ppt). Furthermore, the concentration of fluorescein is measured very easily, it being a fluorescent dye. The main disadvantage in using fluorescein is that it decays at high temperatures. This decay may be presented in a manner similar to that of radioactive isotopes, i.e. through the use of a half-life. According to the detailed study by Adams and Davis (1991) this thermal decay becomes significant above approximately 200°C, where the half-life is almost 2 years. At 220 and 240°C the half-life of fluorescein is 150 and 37 days, respectively, according to Adams and Davis (1991). Above 250°C fluorescein decays too rapidly for it to be usable as a tracer. Fig. 2 shows the relationship between the decay rate of fluorescein and reservoir temperature.

Because this relationship is known, fluorescein tracer tests in high-temperature geothermal systems may, in principle, be corrected for this decay if the temperature along the flow path between injection and production well is known. It may be mentioned that Adams and Davis (1991) present an example where this relationship is used in an inverse manner, i.e. to deduce the effective temperature of an injection-production flow-path. In a cases where the temperature of the injected water may be of the order of 150°C, which is common, while the reservoir temperature is of the order of 250-300°C, determining the effective flow-path temperature is, however, not straight-forward.

Two laboratory experiments simulating reservoir conditions were carried out concurrent with a reinjection project at Laugaland in N-Iceland, described later, to study the thermal stability of fluorescein (Axelsson *et al*, 2001). The results of these experiments indicate that sodium-fluorescein neither decays at the reservoir temperature in question (95-100°C), nor interacts with the alteration minerals in the basaltic rocks of the reservoir, at the relevant time-scale (several months).

Some new tracers are also being developed and tested, among these various polyaromatic sulfonates (Rose et al., 2001). Some of these have been found to be promising alternatives for fluorescein being thermally more stable. Their decay kinetics indicate that they may be suitable up to temperatures of 310-350°C. It should also be mentioned that all the tracers discussed above are, in fact, liquid-phase tracers while specific vapour-phase tracers have been tested. One of these is plain alcohol, which has proven to be of some use, albeit not stable enough for quantitative analysis. Adams *et al.* (2001) present information on recent advances in the development of such vapour-phase tracers.

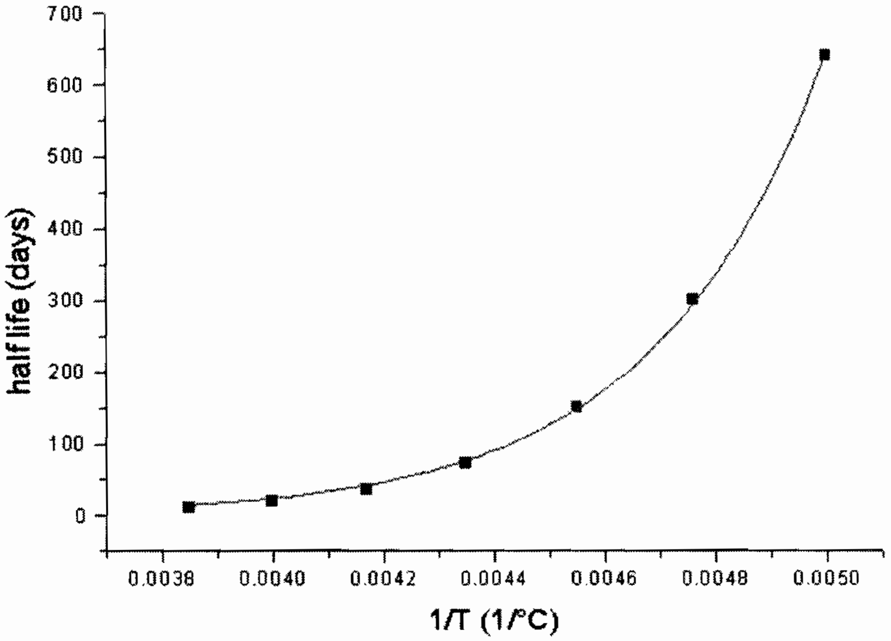

Figure 2. Thermal decay of sodium-fluorescein, presented as half-life versus the inverse of temperature (Adams and Davis, 1991).

After a suitable tracer has been selected the mass of tracer to inject needs to be determined. This is always difficult to determine beforehand, but depends on several factors:

1) Detection limit.
2) Tracer background (if any).
3) Injection rate (q).
4) Production rate (Q) and how many wells are involved.
5) Distances involved.
6) Return rate anticipated (slow/fast).

The required mass may be estimated very roughly through mass-balance calculations, wherein injection- and production rates are taken into account, as well as an expected recovery time-span. This time-span depends on the distances involved, but also on how directly the wells involved are connected. In this respect the activity of radioactive tracers may be treated as fully comparable to mass. In general tracer tests should be designed such that tracer concentrations reach 5-10 times the detection limit. The mass to inject may also be estimated through theoretical calculations, such as using the software *TRCURV*, included in the *ICEBOX* software package. It is based on a flow-channel model, which will be discussed in the following chapter. It may be mentioned that the amount of sodium-fluorescein injected is usually in the range of 10-100 kg, while the mass of potassium-iodide must be an order of magnitude greater (100-1000 kg). The radioactive tracers iodide-125 and iodide-131 are normally injected with an initial activity of 0.5 and 2 Ci, respectively.

2.2 Tracer test execution

Tracer test execution can involve from one well-pair to several injection and production wells. In the latter case several tracers must be used, however. The geothermal reservoir involved should preferably be in a "semi-stable" pressure state prior to test. This is to prevent major transients in the flow-pattern of the reservoir, which would make the data analysis more difficult. In most cases a fixed mass (M) of tracer is injected "instantaneously", i.e. in as short a time as possible, into the injection well(s) in question. Sometimes a fixed concentration is injected for a given period, however. Samples for tracer analysis are most often collected from flowing/discharging wells, while down-hole samples may need to be collected from wells, which are not discharging.

The length of a tracer test depends on local reservoir conditions and distances between wells involved, which control the fluid flow-pattern in the reservoir. They usually last from a few weeks to months or even years. When distances are long and/or fluid flow is slow, tracer tests must be expected to be quite long. The length is preferably not determined beforehand, however, since the rate of return is hard to forecast. Once a sufficiently good data-set has been obtained, a tracer test may be terminated. Tracer tests are often cut short for technical or financial reasons.

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). A sampling program comparable to the one suggested below may quite often be applicable:

Week 1:	2 samples per well per day
Week 2:	1 sample per well per day
Weeks 3-8:	3 samples per well per week
Following weeks:	1 sample per well per week

This program is aimed at detecting any rapid tracer returns during the first few days after injection of the tracer. After the first week a sharp tracer return is not expected because of greater dispersion. Therefore, the sampling frequency may be reduced. Fig. 3 shows this schematically. It may also be mentioned here as a general rule that it is better to collect too many samples than too few. This is because the outcome of a tracer test is never known beforehand. Not all samples need to be analysed, in fact. The sampling frequency is also often affected by technical restrictions such as available manpower, the number of wells being sampled, measurement techniques and other factors. But again a general tendency towards lower sampling frequency, as time progresses, should apply.

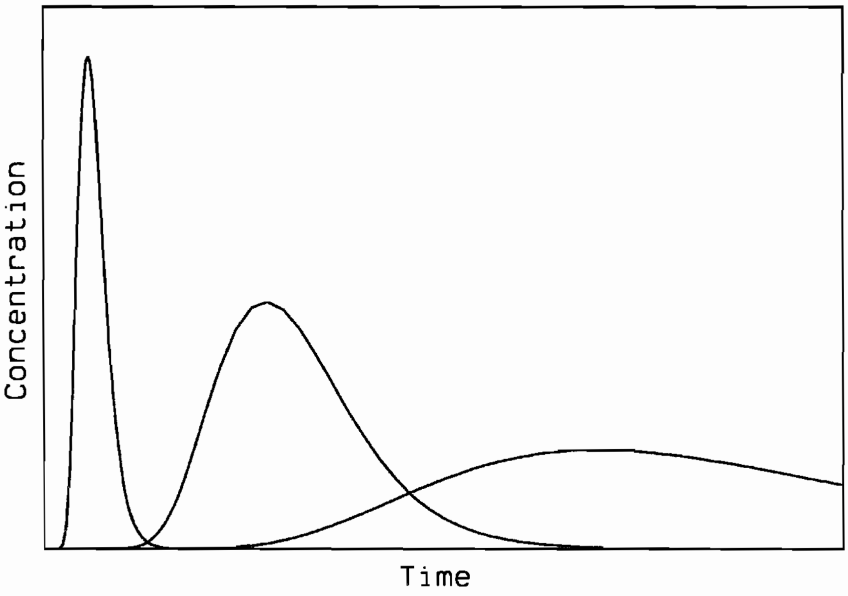

Figure 3. Figure showing typical fast and slow tracer return profiles.

Methods of analysing and interpreting tracer test data are discussed in the following chapter, but some aspects may be observed directly (see Fig. 3). These include (1) the tracer breakthrough-time, which depends on the maximum fluid velocity, (2) the time of concentration maximum, which reflects the average fluid velocity, (3) the width of the tracer pulse, which reflects the flow-path dispersion, and (4) the tracer recovery (mass or percentage) as a function of time.

3. TRACER TEST ANALYSIS AND INTERPRETATION

Interpretation of the tracer test data aims at quantifying the danger of cooling of production wells during long-term reinjection, as already mentioned. Numerous models have been developed, or adopted from groundwater- and nuclear-waste storage studies, for interpreting tracer test data and consequently for predicting thermal breakthrough and temperature decline during long-term reinjection (Pruess and Bodvarsson, 1984; Horne, 1985; Stefansson, 1997). It must be pointed out, however, that while tracer tests provide information on the volume of flow paths connecting injection and production wells, thermal decline is determined by the surface area involved in heat transfer from reservoir rock to the flow paths, which most often are fractures. With some additional information, and/or assumptions, this information can be used to predict the cooling of production wells during long-term (years to decades) reinjection.

The theoretical basis of tracer interpretation models is the theory of solute transport in porous/permeable media, which incorporates transport by advection, mechanical dispersion and molecular diffusion. This will be reviewed very briefly below. A method of tracer test analysis/interpretation, which is conveniently based on the assumption of specific flow channels connecting injection- and production wells, will consequently be presented. The *ICEBOX* software package includes several programs that may be used for tracer test analysis (United Nations University Geothermal Training Programme, 1994). In particular *TRINV*, which is an interactive program for inversion of tracer test data, and *TRCOOL*, which is a program used to predict cooling of production wells during long-term reinjection. A few other programs can be of use in tracer work (*DATE2SEC*, *TRMASS* and *TRCURV*). The use of these programs will be discussed.

3.1 Theory of solute transport

The theory of solute transport in porous and fractured hydrological systems underground is discussed in various publications and textbooks, but the reader is referred to Bear *et al.* (1993) and Javandel *et al.* (1984). The term "solute" indicates a chemical substance dissolved in fluid. The following are the principal modes of transport:

1. By advection and convection, i.e. through movement of the fluid involved.
2. By mechanical dispersion, which is reflected in variations in actual fluid particle velocities.
3. By molecular diffusion, which causes the solute to diffuse from regions of high concentration to regions with lower concentration.

If the transport were only through constant velocity fluid movement, tracer test analysis/interpretation would be simple. But because of the other modes of transport, in particular mechanical dispersion, their analysis/interpretation is much more involved. Fig. 4 illustrates the main causes of mechanical dispersion, which are through:

(a) the effect of pore/fracture walls,
(b) the effect of pore/fracture width, and

(c) the effect of flow-path tortuosity.

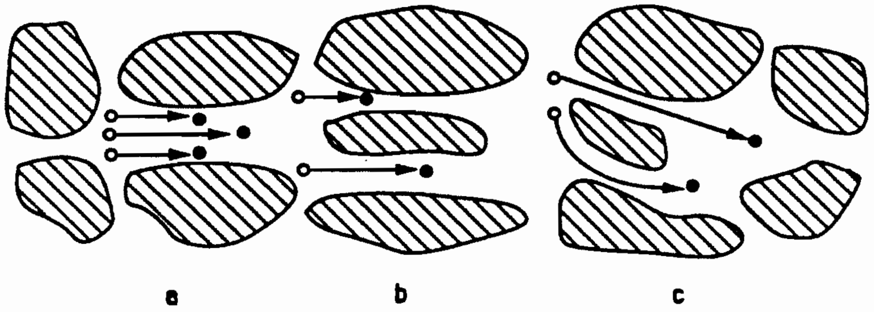

Figure 4. A schematic figure illustrating the causes of mechanical dispersion: (a) the effect of pore/fracture walls, (b) the effect of pore/fracture width and the effect of flow path tortuosity.

The basic equations describing the solute flow are the following:

(1) $$F_x = F_{x,advection} + F_{x,dispersion}$$

where F_x denotes the mass flow rate of the solute (kg/m^{2}s) in the x-direction, and

(2) $$F_{x,advection} = u_x \phi C$$

(3) $$F_{x,dispersion} = -\phi D_x \, \partial C / \partial x$$

Equation (3) is the so-called Fick's law. In addition u_x denotes the fluid particle velocity (m/s), ϕ the material porosity (-), C the solute concentration (kg/m^3) and D_x the so-called dispersion coefficient (m^2/s):

(4) $$D_x = \alpha_x u_x + D^*$$

where α_x is the dispersivity of the material (m) and D^* is the coefficient of molecular diffusion (m^2/s). Comparable equations apply for the y- and z-directions.

The differential equation for solute transport is derived by combining the above flow-equations and the conservation of mass of the solute involved. For a homogeneous, isotropic and saturated medium the differential equation is:

(5) $$\begin{aligned} &\frac{\partial}{\partial x}\left[D_x\frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_y\frac{\partial C}{\partial y}\right] + \frac{\partial}{\partial z}\left[D_z\frac{\partial C}{\partial z}\right] \\ &- \frac{\partial}{\partial x}\left[u_x C\right] - \frac{\partial}{\partial x}\left[u_x C\right] - \frac{\partial}{\partial x}\left[u_x C\right] = \frac{\partial C}{\partial t} \end{aligned}$$

By combining this equation with appropriate boundary- and initial conditions for the material domain being studied, a model is fully defined. Theoretically a mathematical solution should exist for any such problem, but in practice their solutions are often very complicated (Javandel *et al.*, 1984). Such complicated problems may, of course, be solved numerically with the aid of powerful computers. Some simpler analytical solutions are possible after highly simplifying assumptions have been made on geometry, dispersion, etc. One such model, and the associated solution, forms the basis of the method of tracer test analysis/interpretation presented below.

Another example of an analytical solution to equation (5) is available for a model of a homogeneous, infinite, confined hydrological reservoir with constant reservoir thickness b and two-dimensional radial flow. This solution is normally not suitable for analysing tracer test data, but can of use in reinjection studies. Fluid with solute concentration C_0 is injected at a rate Q (m^3/s) since time t = 0 through an injection well at the center of the reservoir, while the initial concentration C = 0. By neglecting molecular diffusion the following approximate solution may be obtained:

$$\frac{C}{C_0} \approx \frac{1}{2} erfc\left[\left(\frac{r_D^{1/2}}{2} - t_D\right)\left(\frac{4}{3}r_D^3\right)^{-1/2}\right] \tag{6}$$

with $r_D = r/\alpha_L$, where r is the radial distance from the injection well, α_L is the longitudinal (radial) dispersivity, $t_D = \dfrac{Qt}{2\pi b\phi\alpha_L^2}$ and *erfc* is the complimentary error function.

3.2 Tracer test interpretation on basis of a one-dimensional flow-channel model

Before radioactive tracer test data is interpreted some steps must be taken to correct and prepare the return data collected. These are:

1) Correct the data for radioactive decay by the following equation:

   $$C_{corr} = C_{meas}\, exp(0.693t/t_{1/2}) \tag{7}$$

   where C is the activity of the tracer (cps), t is the time since the tracer was at full initial activity, $t_{1/2}$ is the half life of the radioactive isotope being used as tracer and *exp* is the exponential function. The half-lives of iodide-131 and iodide-125 are 8.5 and 60 days, respectively.

2) Also correct by multiplying by 1/(sample volume∗measurement efficiency), which results in concentration-, or activity values, in units cps/L or cps/m^3.

3) It should be noted that following these steps radioactive tracer data are fully comparable to mass, one may simply interchange “kg” and “cps”. The return data are then compared with the initial activity (0.5 - 2 Ci, 1 Ci = $37\cdot10^9$cps), just as conventional tracer test data are compared with the mass of tracer injected (kg).

When analysing tracer test data one must keep in mind that some of the tracer recovered through the production wells is injected back into the reservoir. If this is a significant amount it will interfere with the data interpretation and must be corrected for. This is seldom the case, however. Bjornsson *et al.* (1994) present a method for doing such a correction. The program *TRCORRC* in the *ICEBOX*-package may be used for this purpose. In addition, the program *TRCORRQ* may be used to correct for small variations in production- and/or injection rates.

The first step in analysing tracer test data involves estimating the mass (activity) of tracer recovered throughout a test. This is done on the basis of the following equation:

$$m_i(t) = \int_0^t C_i(s)Q_i(s)\,ds \tag{8}$$

where $m_i(t)$ indicates the cumulative mass recovered in production well number i (kg), as a function of time, C_i indicates the tracer concentration (kg/L or kg/kg) and Q_i the production rate of the well in question (L/s or kg/s, respectively). The program *TRMASS* in the *ICEBOX*-package may be used for this purpose. An example of such mass recovery calculations is presented in Fig. 5 below.

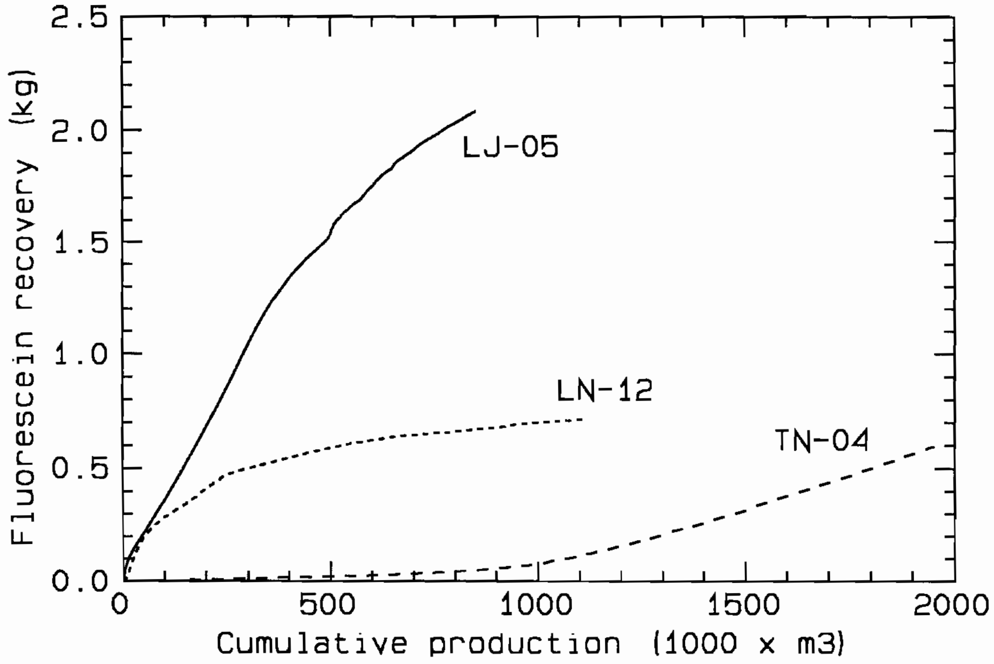

Figure 5. An example of the results of tracer mass recovery calculations from the Laugaland geothermal field in N-Iceland (see chapter 5) during a tracer test during which 10 kg of sodium-fluorescein were injected. It shows the cumulative tracer recovery in three production wells as a function of cumulative production from each well during a two-year period from late 1997 through most of 1999.

A simple one-dimensional flow-channel tracer transport model has turned out to be quite powerful in simulating return data from tracer tests in geothermal systems (Axelsson *et al.*, 1995). It assumes the flow between injection and production wells may be approximated by one-dimensional flow in flow-channels, as shown in Fig. 6. These flow-channels may, in fact, be parts of near-vertical fracture-zones or parts of horizontal interbeds or layers. These channels may be envisioned as being delineated by the boundaries of these structures, on one hand, and flow-field stream-lines, on the other hand. In other cases these channels may be larger volumes involved in the flow between wells. In some cases more than one channel may be assumed to connect an injection and a production well, for example connecting different feed-zones in the wells involved.

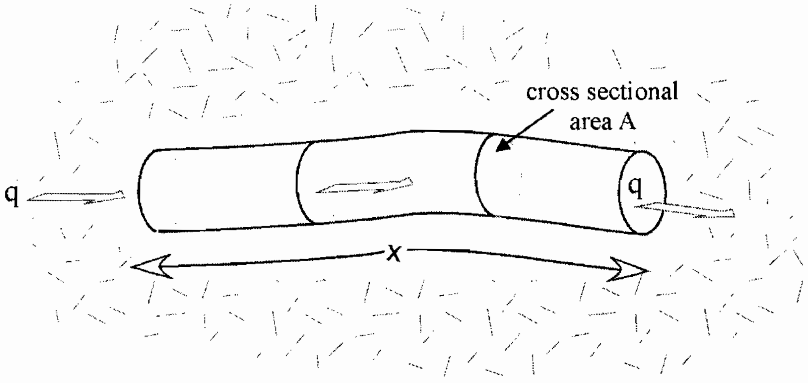

Figure 6. A schematic figure of a flow-channel with one-dimensional flow connecting an injection well and a production well.

In the case of one-dimensional flow, equation (5) simplifies to:

$$D\frac{\partial^2 C}{\partial x^2} = u\frac{\partial C}{\partial x} + \frac{\partial C}{\partial t} \tag{9}$$

where D is the dispersion coefficient (m^2/s), C the tracer concentration in the flow-channel (kg/m^3), x the distance along the flow channel (m) and u the average fluid velocity in the channel (m/s) given by $u = q/\rho A\phi$, with q the injection rate (kg/s), ρ the water density (kg/m^3), A the average cross-sectional area of the flow-cannel (m^2) and ϕ the flow-channel porosity. Molecular diffusion may be neglected such that $D = \alpha_L u$ with α_L the longitudinal dispersivity of the channel (m). Assuming instantaneous injection of a mass M (kg) of tracer at time t = 0 the solution is given by:

$$c(t) = \frac{uM}{Q}\frac{1}{2\sqrt{\pi D t}}e^{-(x-ut)^2/4Dt} \tag{10}$$

Here $c(t)$ is actually the tracer concentration in the production well fluid, Q the production rate (kg/s) and x the distance between the wells involved. Conservation of the tracer according to $c\cdot Q = C\cdot q$, has been assumed. This equation is the basis for the method of tracer test analysis/interpretation presented here, which involves simulating tracer return data with equation (10). Such a simulation yields information on the flow channel cross-sectional area, actually $A\phi$, the dispersivity α_L as well as the mass of tracer recovered through the channel. This mass should of course be equal to, or less than, the mass of tracer injected. In the case of two flow-channels or more, the analysis yields estimates of these parameters for each channel. It should be pointed out that through the estimate for $A\phi$ the flow channel pore space volume, $Ax\phi$, has in fact been estimated.

The tracer interpretation software *TRINV*, included in the *ICEBOX* software package is used for this simulation or interpretation. It is an interactive DOS-mode program, which automatically simulates the data through inversion. The user defines a model with one or more flow-channels and defines a first guess for the model parameters. *TRINV*, consequently, uses non-linear least-squares fitting to simulate the data and obtain the model properties, i.e. the flow channel volumes ($Ax\phi$) and dispersivity (α_L). The software may also be used to plot the results. Chapter 5 below presents some examples of the utilisation of *TRINV*, from geothermal fields in El Salvador and Iceland.

3.3 Discussion

It should be mentioned that the method of analysis presented above should not be looked upon yielding unique solutions, even though it often results in a solutios that are considered to be the most likely ones. Numerous other models have been developed to simulate the transport of contaminats in ground-water systems, and in relation to underground disposal, or storage, of nuclear waste. Many of these models are in fact applicable in the interpretation of tracer tests in geothermal systems. It is often possible to simulate a given data-set by more than one model, therefore, a specific model may not be uniquely validated. The transport of dissolved solids through fractured rocks and the analysis of tracer tests conducted in fractured geothermal systems are, for example, discussed by Horne (1989), Horne and Rodriguez (1983), Robinson and Tester (1984), Grisak and Pickens (1980) and Neretnieks (1983).

In addition to distance between wells and volume of flow-paths, mechanical dispersion is the only factor assumed to control the tracer return curves in the interpretation presented above. Retardation of the tracers by diffusion into the rock matrix is neglected (see Neretnieks, 1983). Through this effect, the chemical used as a tracer diffuses into the rock matrix when the tracer concentration in the flow path is high. As the concentration in the flow-path decreases, the concentration gradient eventually reverses, causing diffusion from the rock-matrix back into the fracture. This will of course affect the shapes of the tracer return curves obtained. In particular, it may cause the flow, through the mode A flow channels discussed above, to be underestimated. Robinson and Tester (1984), on one hand, postulate that matrix diffusion should be negligible in fractured rock. Grisak and Pickens (1980), on the other hand, point out that it may be significant when fracture apertures are small, flow velocities are low and rock porosity is high.

4. COOLING PREDICTIONS

The ultimate goal of tracer testing is to predict thermal breakthrough and temperature decline during long-term reinjection, as already stated. These changes are dependent on the properties of the flow-channel, but they are not uniquely determined by the flow-path volume. This cooling mainly depends on the surface area and porosity of the flow-channel. Therefore, some additional information on the flow-path properties/geometry is needed, preferably based on geological or geophysical information. Predictions may also be calculated for different assumptions as discussed below.

The model presented in Fig. 7 is used to calculated the temperature changes along the flow channel and hence the production well cooling predictions. It simulates a flow-path along a fracture-zone, an interbed or permeable layer. In the model *b* indicates either the width of the fracture-zone or the thickness of the interbed or layer, whereas *h* indicates the height of the flow-path inside the fracture-zone or its' width along the interbed or layer. The flow-channel cross-sectional area is then given by $A = h \cdot b$. To estimate *h* and *b* on basis of the main outcome of the tracer test interpretation, $A\phi$, one must make an assumption on the average flow path porosity, which is often approximately known, and the ratio between *h* and *b*.

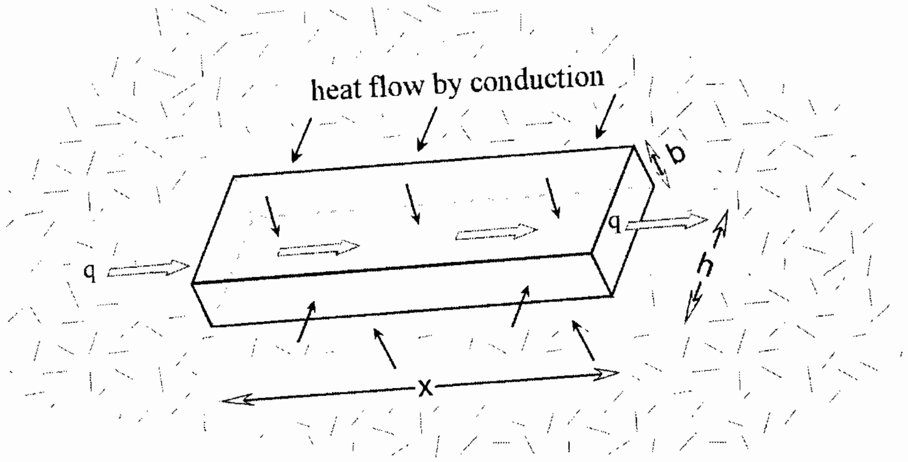

Figure 7. A model of a flow-channel, along a fracture-zone or a horizontal interbed or layer, used to calculate the heating of injected water flowing along the channel, and the eventual cooling of a production well connected to the channel.

The theoretical response of this model is derived through a formulation, which considers a coupling between the heat advected along the flow-channel and the heat conducted from the reservoir rock to the fluid in the channel. Solutions to similar problems are presented by carslaw and Jaeger (1959) and Bodvarsson (1972). The analytical solution for the temperature of the production well fluid is:

$$(11) \qquad T(t) = T_0 - \frac{q}{Q}\left(T_0 - T_i\right)\left[1 - erf\left\{\frac{kxh}{c_w q\sqrt{\kappa\left(t - x/\beta\right)}}\right\}\right]$$

with *T(t)* the production fluid temperature, T_0 the undisturbed reservoir temperature, T_i the injection temperature, *q* and *Q* the rates of injection and production, respectively, *erf* the error-function, *k* the thermal conductivity of the reservoir rock, κ its' thermal diffusivity, x the distance between injection and production wells and

$$(12) \qquad \beta = \frac{qc_w}{\left(\langle\rho c\rangle_f hb\right)}$$

with

$$(13) \qquad \langle \rho c \rangle_f = \rho_w c_w \phi + \rho_r c_r (1-\phi)$$

the volumetric heat capacity of the material in the flow-channel. Here ρ and c are density and heat capacity, respectivly, with the indices w and r standing for "water" and "rock".

The program *TRCOOL* can be used for these calculations, or predictions. It calculates the temperature at time-points given by the user based on information on the flow-channel dimensions and properties provided. When more than one flow-channel is used to interpret the data, the cooling due to each channel must be calculated separately and then added up. Examples of predictions calculated by *TRCOOL*, on the basis of tracer test interpretation, are presented in chapter 5 below.

To deal with the uncertainty in calculating cooling predictions on the basis of tracer test data alone the predictions may be calculated for different assumptions on the flow-channel dimensions and properties. It is recommended that this be at least done for two extremes. First a high porosity, small surface area, pipe-like flow channel, which can be looked upon as a most pessimistic scenario, resulting in rapid cooling predictions. Second a lower porosity, large surface area flow channel, such as a thin fracture-zone or thin horizontal layer, which can be looked upon as a most optimistic scenario, resulting in slow cooling predictions. Field examples of such different cooling model calculations are presented in the following chapter.

5. FIELD EXAMPLES

Finally, two case histories involving tracer test interpretation along the lines outlined above, and consequent cooling predictions, will be presented as field examples. These are from the Ahuachapan high-temperature geothermal field in El Salvador and the Laugaland low-temperature field in N-Iceland. The former example involved utilisation of a radioactive tracer while sodium-fluorescein was utilised in the latter. It should be emphasised that the interpretation methods are independent of the tracer used, as already mentioned. It should also be mentioned that in the Ahuachapan case emphasis was placed on evaluating the uncertainty in cooling prediction arising from the fact that tracer tests interpretation only yields information on flow path volumes. The data analysis was more elaborate in the Laugaland case, since the data were much more detailed. In the Laugaland case the increase in energy production enabled through long-term reinjection was, furthermore, estimated. This is important for management purposes and provides the basis for an analysis of the economics of future reinjection at Laugland. The Laugalnd case has been described in detail by Axelsson *et al.* (2000 and 2001).

5.1 Tracer test in Ahuachapan, El Salvador, September/October 2001.

The Ahuachapan geothermal field in El Salvador has been utilised for electricity production for more than three decades (Quijano, 1994). Ahuachapan was the first geothermal field were reinjection was attempted, as mentioned above, yet reinjection was discontinued in the field in the early 1980's. Reinjection inside the geothermal field is now being reconsidered to counteract a substantial pressure draw-down and increase the production potential of the field. Therefore, a reinjection- and tracer-test was conducted in the field in September/October 2001. The test involved injection of about 100 kg/s of sparated water from nearby production well separators, into well AH-33A.

For the associated tracer test the radioactive tracer ^{131}I was injected into the well on September 27, 2001. The initial activity of the tracer was 1.77 Ci. The recovery of the tracer was monitored in several nearby wells for a few weeks. Some recovery (~2% in 2 weeks) was noted in a few wells, namely wells AH-4bis, AH-19 and AH-22. These wells are all along the so-called Buenavista-fault, which is believed to play a big role in the hydrology of the Ahuachapan system. No recovery was noted in any other wells, except for a minor recovery in well AH-20.

The data from wells AH-4bis, AH-19 and AH-22, for the first two weeks, is presented in figures 8 – 10. After two weeks the activity of ^{131}I has decreased to about 25% of the initial activity. The data were prepared and corrected as described above, and consequently simulated through using the tracer interpretation software *TRINV*. The simulated recovery is also presented in figures 8 – 10. It should be noted that a relatively few samples were collected. The initial sampling frequency was, in particular, not sufficiently high. Two samples per day during the first few days would have been more adequate. Therefore, the data analysis/interpretation presented her can neither be considered very accurate nor detailed.

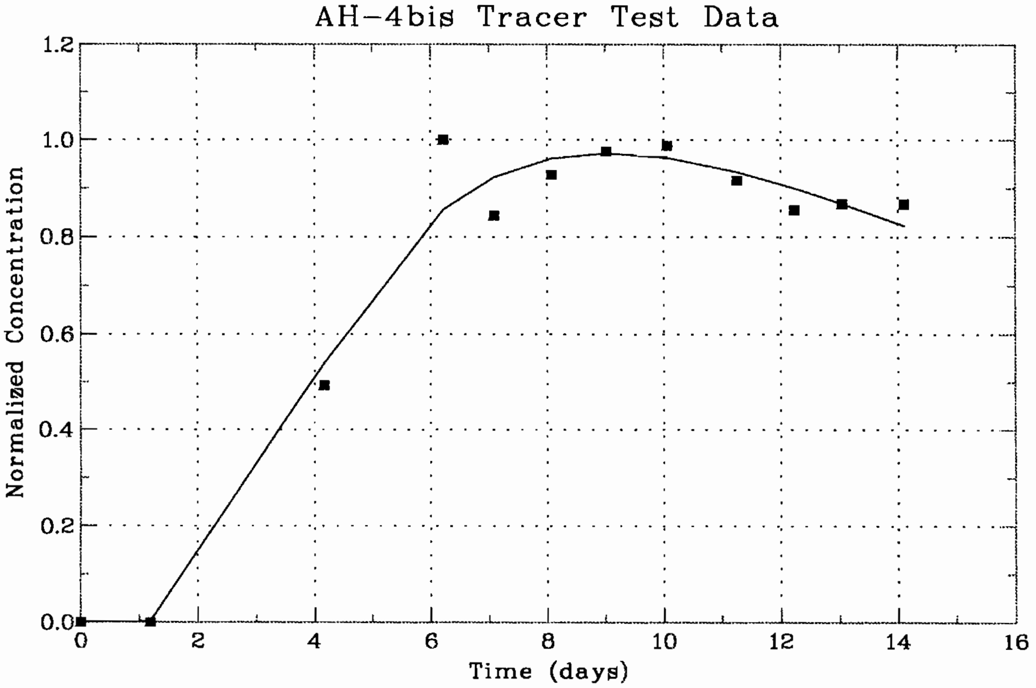

Figure 8. Observed (boxes) and simulated (solid line) tracer recovery in well AH-4bis in Ahuachapan.

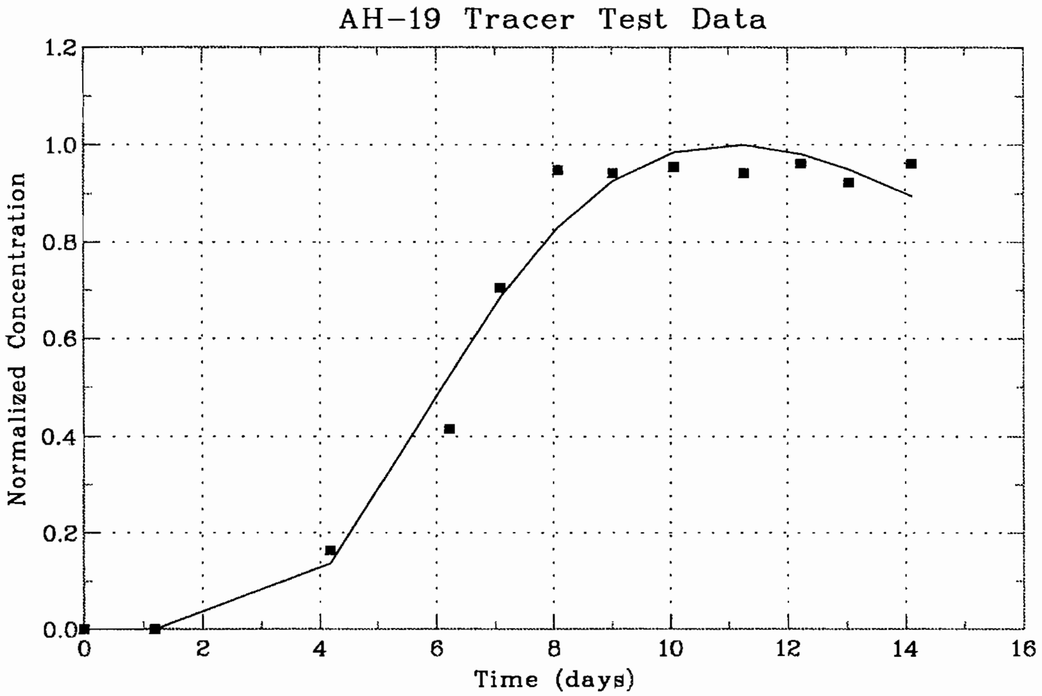

Figure 9. Observed (boxes) and simulated (solid line) tracer recovery in well AH-19 in Ahuachapan.

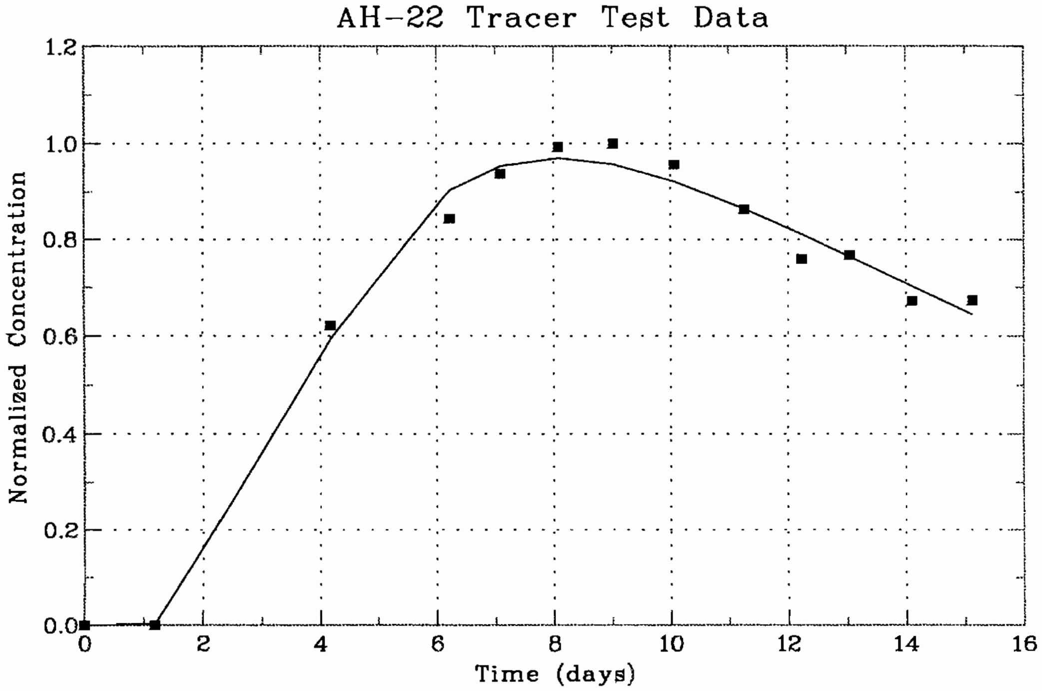

Figure 10. Observed (boxes) and simulated (solid line) tracer recovery in well AH-22 in Ahuachapan.

The principal results of the interpretation, along with basic information on the wells involved, are presented in Table 1 below. Only one flow channel was required for the simulation for each well-pair more detailed analysis was not warranted by the data. The main results are the flow channel volume (actually pore space volume as discussed previously) and flow ratio. The dispersivity values also appear reasonable. Small volumes and dispersivities indicate that well AH-33A is rather directly connected to wells AH-4bis, AH-19 and AH-22. Flow velocities are rather high, or up to 60 m/day. Yet a small fraction of the injected water is recovered through each of these wells, thus predicted temperature declines are not very great. Well AH-19 appears to be not as directly connected as the other two wells (perhaps further away from the Buenavista-fault).

Table 1. Model parameters used to simulate ^{131}I recovery for the production wells AH-4bis, AH-19 and AH-22 and reinjection well AH-33A (injection rate 100 kg/s) along with information on distances between wells and water/steam flow rates. Flow channel volume = pore space volume (volume x porosity) in flow-channel. Flow ratio = fraction of injected water recovered through each well.

Well	Distance, x (m)	Water flow rate (kg/s)	Steam flow rate (kg/s)	Flow channel volume, $xA\phi$ (m^3)	Dispersivity, α_L (m)	Flow ratio (%)
AH-4bis	800	64	31	6300	240	4.9
AH-19	300	40	7	5300	40	4.0
AH-22	600	20	7	4200	150	3.9

The results in Table 1 were, consequently, used to calculate cooling predictions for the three production wells. The cooling of production wells is not uniquely determined by the flow-path volume, it also depends on the surface area and porosity of the flow channels involved, as discussed above. A large flow channel surface area leads to slow cooling and vice versa. To study the uncertainty arising because of this, cooling predictions for wells AH-4bis, AH-19 and AH-22, during long-term reinjection, were calculated for three different assumptions/models. The software *TRCOOL* was used for this purpose. The following models were considered:

(a) A high porosity, small surface area, pipe-like flow channel. This can be looked upon as the most pessimistic case, resulting in rapid cooling predictions.

(b) A low porosity, large volume flow channel. It simulates dispersion throughout a large volume or fracture network.

(c) A high porosity, large surface area flow channel, such as a thin fracture-zone or thin horizontal layer. This is the most optimistic case, resulting in slow cooling predictions.

Detailed information on the models is presented below, where x indicates the distance between wells, b the flow channel width or thickness, H its' height or extent and ϕ its' porosity:

Case (a)	AH-4bis:	x = 800m, b = 3.1m, H = 12.5m, $\phi = 20\%$
	AH-19:	x = 300m, b = 4.7m, H = 18.8m, $\phi = 20\%$
	AH-22:	x = 600m, b = 3.0m, H = 11.8m, $\phi = 20\%$
Case (b)	AH-4bis:	x = 800m, b = 14.0m, H = 56m, $\phi = 1\%$
	AH-19:	x = 300m, b = 21.0m, H = 84m, $\phi = 1\%$
	AH-22:	x = 600m, b = 13.2m, H = 53m, $\phi = 1\%$
Case (c)	AH-4bis:	x = 800m, b = 0.3m, H = 130m, $\phi = 20\%$
	AH-19:	x = 300m, b = 0.5m, H = 176m, $\phi = 20\%$
	AH-22:	x = 600m, b = 0.3m, H = 117m, $\phi = 20\%$

The results of the cooling predictions are presented in figures 11 – 13.

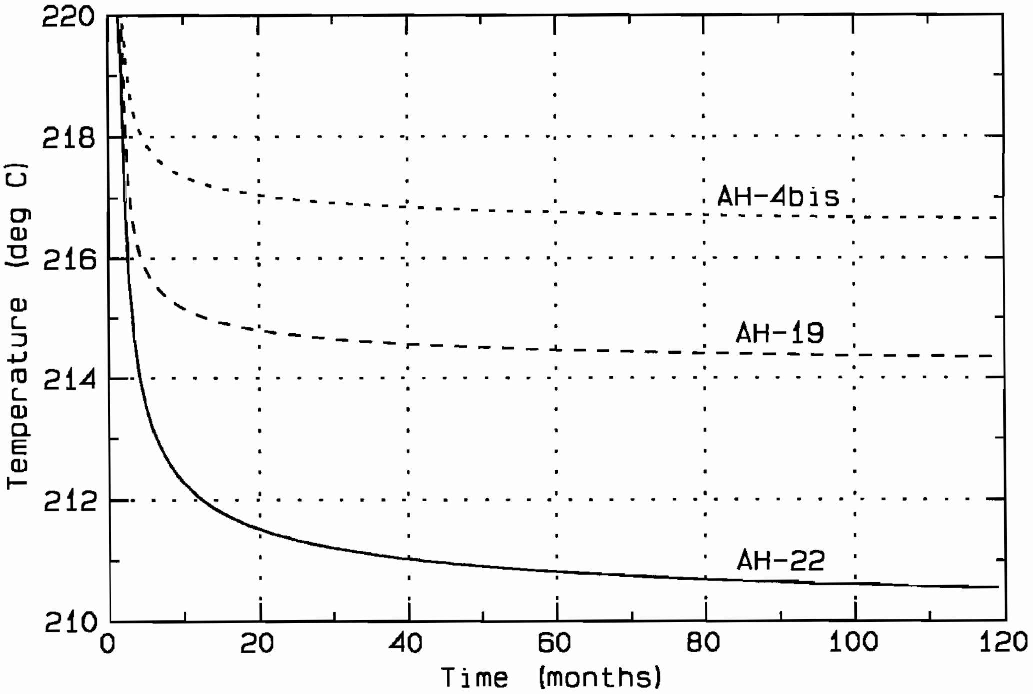

Figure 11. Cooling predictions calculated for wells AH-4bis, AH-19 and AH-22 in Ahuachapan, during reinjection into well AH-33A, for a small surface-area flow channel, the most pessimistic scenario.

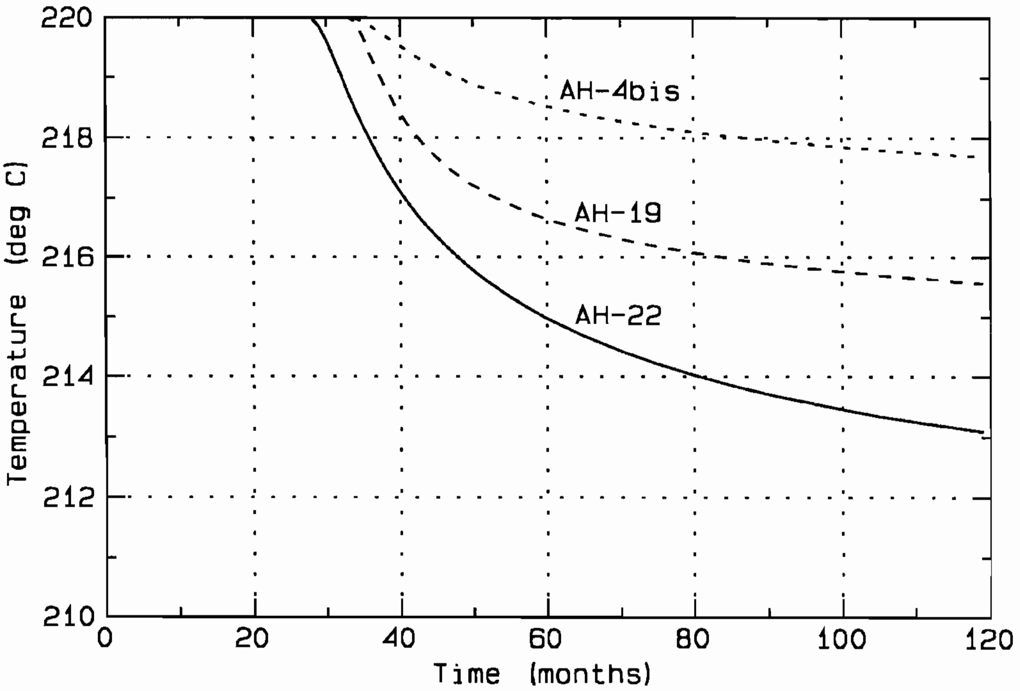

Figure 12. Cooling predictions calculated for wells AH-4bis, AH-19 and AH-22 in Ahuachapan, during reinjection into well AH-33A, for a large volume flow channel scenario.

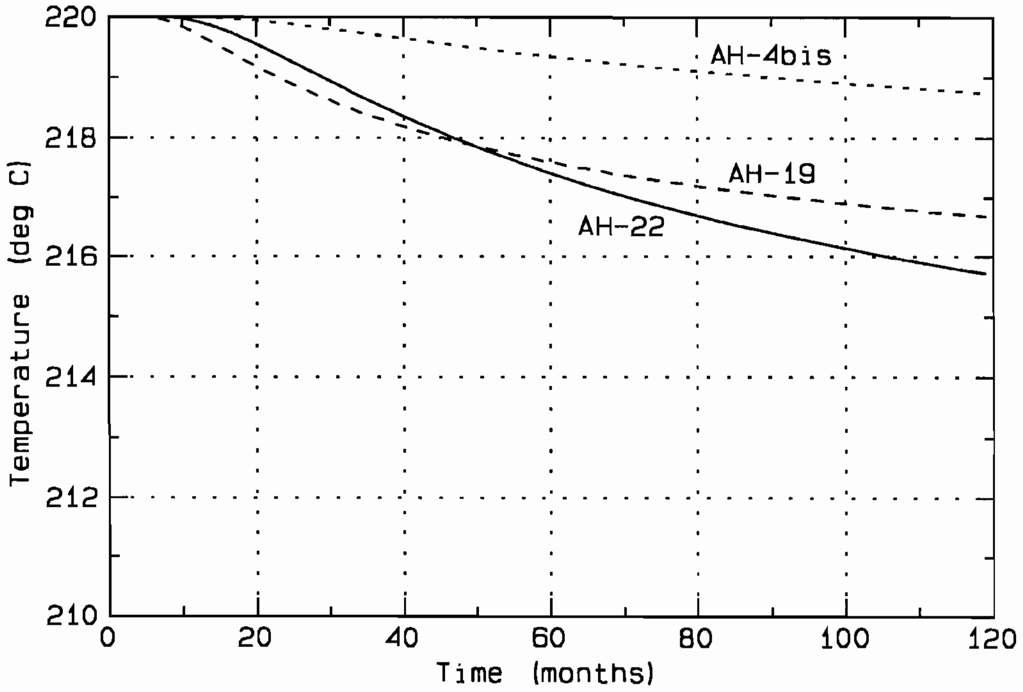

Figure 13. Cooling predictions calculated for wells AH-4bis, AH-19 and AH-22 in Ahuachapan, during reinjection into well AH-33A, for a large surface-area flow channel, the most optimistic scenario.

The most pessimistic prediction model is considered very unlikely on geological grounds, but the results show that some cooling is predicted for wells AH-4bis, AH-19 and AH-22 as a result of long-term reinjection into AH-33A. The greatest cooling is predicted for AH-22, or 4-10°C in 10 years. This will cause some decline in the steam flow-rate for the well (roughly estimated 10-25%). Yet reinjection inside Ahuachapan production field will be beneficial because of pressure recovery, but it must be adequately managed and planned.

2.2 Tracer test at Laugaland, N-Iceland

The Laugaland geothermal field has been utilized for space heating in the town of Akureyri in Central N-Iceland since the late 1970's. The field is characterised by a principal fracture zone surrounded by low permeability rocks, limited recharge and great pressure draw-down. Therefore, reinjection has been considered a possible method of increasing the production potential of the field for a long time. Reinjection at Laugaland was initiated in September 1997 and has been continuous since then. The first two years were devoted to quite intensive research into the feasibility of long-term reinjection. This included extensive tracer testing. A total of more than 1400 tracer samples were collected and analysed from production wells at Laugaland and in near-by areas, in conjunction with the tracer tests.

Three tracer tests were carried out between wells at Laugaland, during the two-year research period. The purpose of these tests was to study the connections between injection- and production wells in order to enable predictions of the possible decline in production temperature due to long-term reinjection. The tests were conducted at different conditions, i.e. for different injection rates and for different wells in use, both injection- and production wells. Two different tracers were used, sodium-fluorescein and potassium-iodide. Here, the results of the first fluorescein test will be reviewed.

The tracer return data collected at Laugaland indicates that the injected water travels throughout the bedrock in the area by two modes:

A. First through direct, small volume flow paths, such as channels along fractures or interbeds. These flow channels may even be looked upon as kinds of pipes containing porous material.

B. Second by dispersion and mixing throughout a large part of the volume of the geothermal reservoir.

The Laugaland tracer test analysis was aimed at determining the volumes involved in the mode A transport, while the mode B transport was not expected to pose any danger of premature thermal breakthrough. As an example Fig. 14 shows tracer test data for the well pair LJ-08/LN-12 from September – November 1997, simulated by the software *TRINV.* Three separate flow channels were used in the simulation, which are assumed to connect the different feed-zones of the injection- and production wells. The properties of the channels are presented in Table 2.

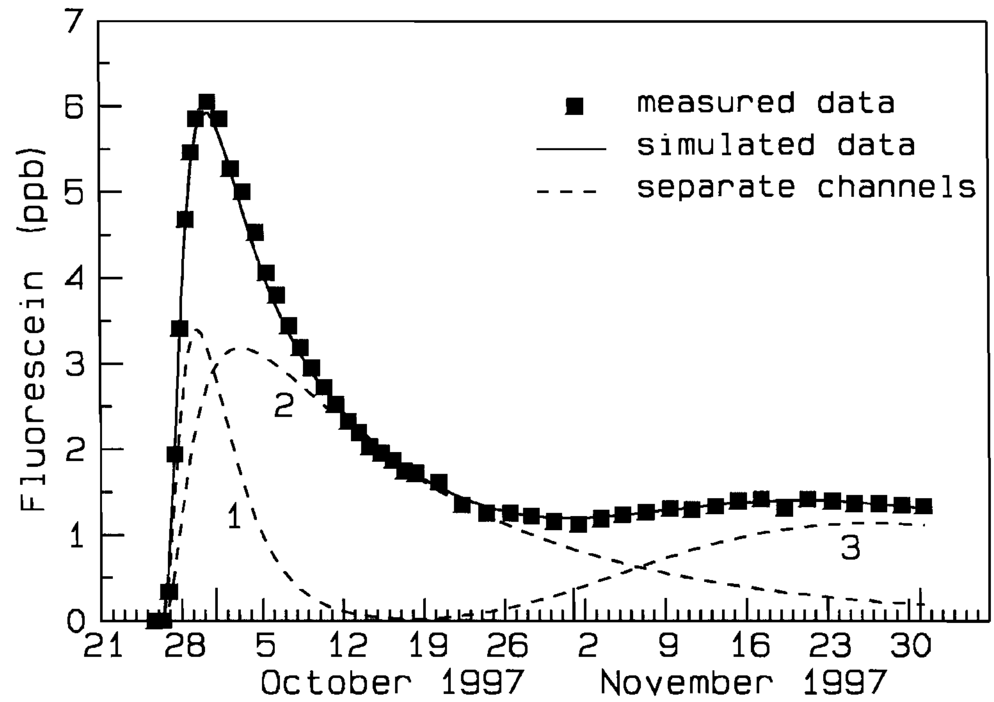

Figure 14. Observed and simulated fluorescein recovery in well LN-12 during the first tracer test. Reinjection into well LJ-08 and production from well LN-12.

Table 2. Model parameters used to simulate fluorescein recovery for the well pair LJ-08/LN-12 at Laugaland. The parameter u denotes the mean flow velocity, A the cross-sectional area, ϕ the porosity and α_L the longitudinal dispersivity of the flow-channel. The variable M_i denotes the calculated mass recovery of tracer through the corresponding channel, until infinite time, while M denotes the total mass of tracer injected.

Channel length, x (m)	u (m/s)	$A\phi$ (m^2)	α_L (m)	M_i/M (kg/kg)
300	7.3×10^{-4}	0.098	61	0.0087
500	4.8×10^{-4}	0.53	264	0.0304
1000	1.7×10^{-4}	1.08	62	0.0229
Total				0.0620

The results in Table 2 indicate that only about 6% of the injected water travels through these channels from injection- to production well. Most of the injected water, therefore, appears to disperse and diffuse throughout the reservoir volume (mode B). The volumes of the channels also appear to be quite small. If one assumes an average porosity of 7% (Bjornsson *et al.*, 1994), the sum of the volumes of the three channels equals only 20,000 m^3. The results in Table 2 are the principal results of the analysis of the Laugaland tracer test data and form the basis for cooling predictions presented later.

The observed fluorescein recovery in well TN-4 in the Ytri-Tjarnir field, which is a separate geothermal field located about 2 km north of Laugaland, was also analysed on basis of the flow-channel model (Fig. 15). Only a single flow-channel was required. The fluorescein background, which appears to be of the order of 50 ng/L, was subtracted from the data prior to the analysis. This background may be the remnants of an older tracer test. The results of the analysis yield a mean flow velocity of $u = 3.5 \times 10^{-5}$ m/s, which equals about 90 m/month, a flow-channel cross-sectional area of $A = 360$ m^2 (assuming a porosity of $\phi = 7\%$), and a dispersivity of $\alpha_L = 97$ m. In addition the calculated relative mass recovery of the fluorescein through this flow-channel, until infinite time, M_i/M, equals 7.2%.

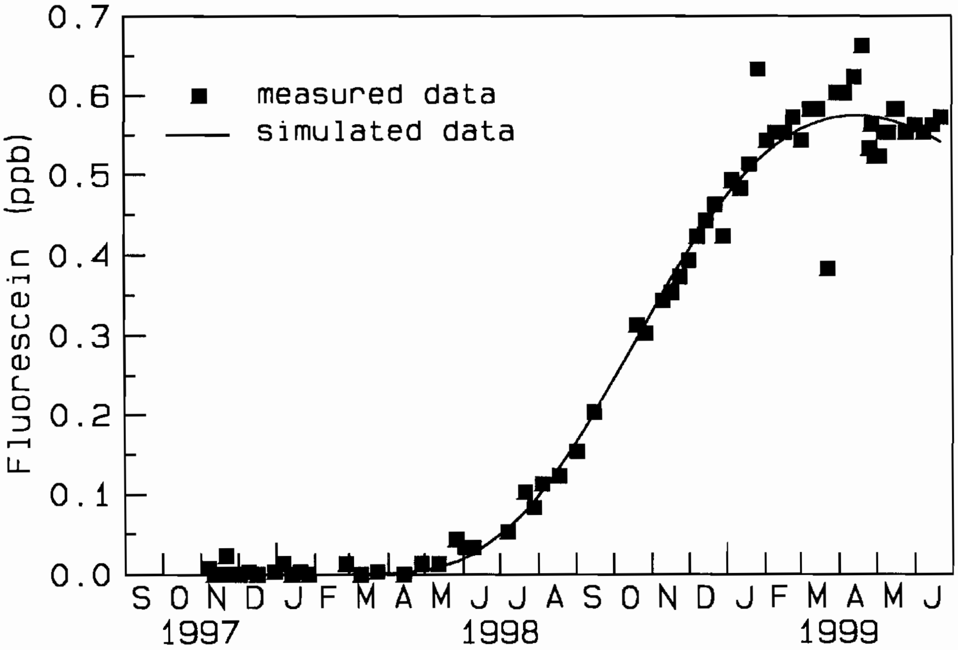

Figure 15. Observed and simulated fluorescein recovery in well TN-04 at Ytri-Tjarnir, 1.8 km north of Laugaland.

This is quite an interesting result. Firstly, because it confirms a direct connection between Laugaland and Ytri-Tjarnir, which previously had been ruled out. Secondly, because it provides some quantitative information on this connection. The connection appears to be direct because of relatively low dispersivity (compared to the 1800 m distance between the fields) and small flow-channel volume. If, on one hand, one assumes the flow-channel to be along an interbed or a fracture-zone, of a few metres thickness, then its average width, or height, is of the order of 100 m. If, on the other hand, the flow-channel is more like a pipe, then its diameter would be of the order of only 20 m.

The purpose of the tracer tests at Laugaland was to try to quantify the danger of premature thermal breakthrough and rapid cooling of production wells at Laugland during reinjection. The results of the interpretation of the tracer return data were, therefore, used to predict the temperature decline of the production wells, during long-term reinjection into well LJ-08, for a few different reinjection scenarios. These are cases of 10, 15 and 20 L/s average yearly reinjection. Some short-term variations in injection rate are, of course expected, but are discounted in the calculations. According to the estimated long-term benefit from reinjection, these cases should result in increases in the potential production from the field of about 7, 10 and 13 L/s, respectively. Only mode A cooling is considered at this stage and *TRCOOL* is the software used in calculating the predictions. These are based on the same flow-channel model as the tracer test analysis and the results in Table 2.

The cooling of the water travelling through the flow channels, or more correctly the heating-up of this water, depends on the surface area of the channels rather then their volume, as already discussed. Therefore, some assumptions must be made about the geometry of the channels. Here, the geometry that results in the most conservative predictions was selected, i.e. the geometry with the smallest surface area for a given flow-path volume. This is the case where the width and height of a flow-channel are equal. Fig. 16 presents the results of the calculations for well LN-12, assuming an average production of 40 L/s for the well.

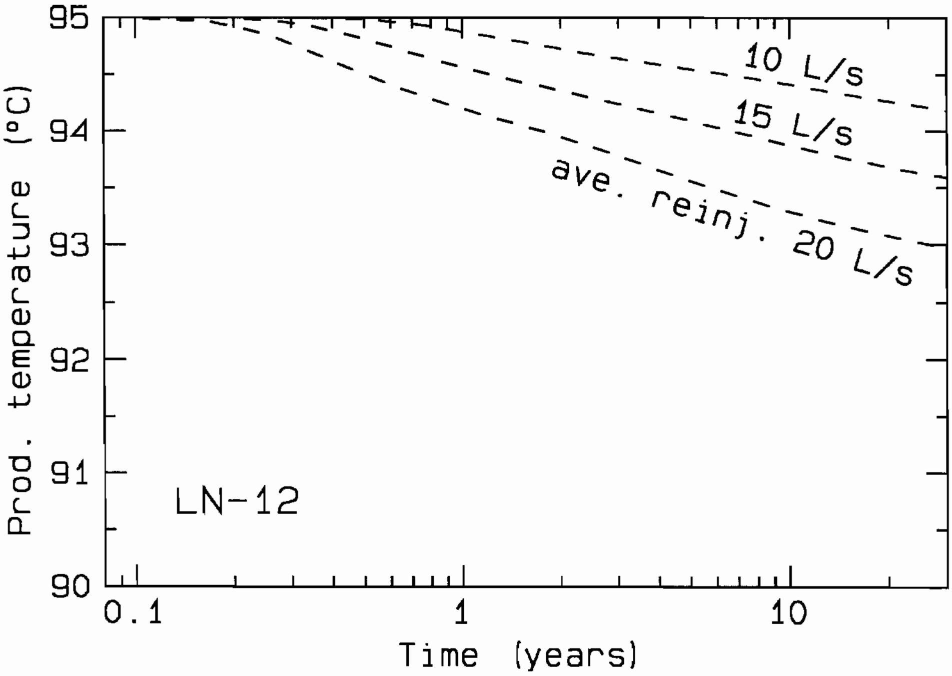

Figure 16. Estimated decline in the temperature of well LN-12 for three cases of average long-term reinjection into well LJ-08, due to flow through the three channels simulated in Fig. 14.

These predictions indicate that the temperature of the water pumped from well LN-12 will decline between 1 and 2°C in 30 years, depending on the rate of reinjection. It is likely that an average reinjection rate of 15 L/s can be maintained, which will cause a temperature decline of only 1.5°C for well LN-12.

Since the cooling predictions (Fig. 16) indicated that some cooling would take place already during the first two years of reinjection, the possibility arose to compare predicted and observed cooling directly. Unfortunately, some measurement discrepancies and other variations mask possible minor changes in the temperature of the production wells at Laugaland due to the reinjection. Yet, it can be stated that two years of reinjection at Laugaland did not cause a temperature decline greater than about 0.5°C. This is, in fact, less than the predicted temperature decline for well LN-12 presented in Fig. 16 above (0.7°C in 2 years).

To estimate the increase in energy production enabled through long-term reinjection into well LJ-08, the possible increase in mass extraction estimated and the predicted temperature changes are simply combined. The final result is presented in Fig. 17, which shows the estimated cumulative additional energy production for well LN-12 during the whole 30-year period being considered. It is considered likely that an average long-term reinjection rate of about 15 L/s can be maintained at Laugaland. The maximum rate will be 21 L/s during the winter-time, when the return water supply is sufficient. During the summer-time, the reinjection rate may, however, decrease down to 10 L/s. Therefore, the above results indicate that future reinjection will enable an increase in energy production amounting to roughly 2 GWh_{th}/month or 24 GWh_{th}/year. This may be compared to the average yearly energy production from Laugaland during the last ten years, which has amounted to about 100 GWh_{th}/year. For this reinjection/production scenario the cumulative energy production, during the 30 year period considered, could reach more than 700 GWh_{th}. These results provide the basis for an analysis of the economics of future reinjection at Laugaland.

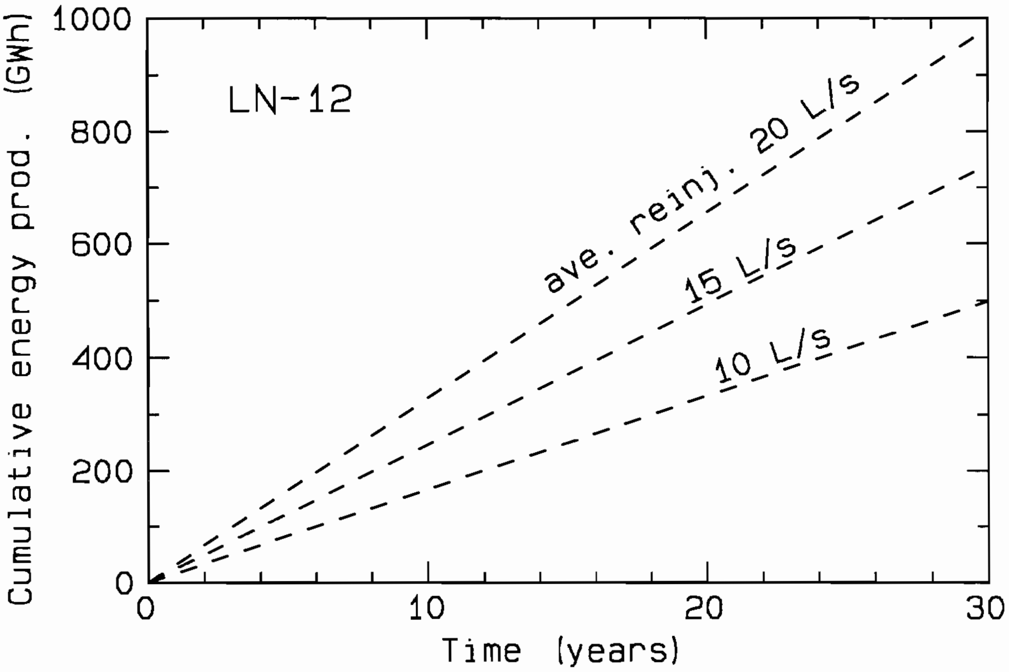

Figure 17. Estimated cumulative increase in energy production for 30 years of reinjection into well LJ-08. Calculated for three cases of average injection and assuming production from well LN-12.

6. CONCLUDING REMARKS AND RECOMMENDATIONS

A simple and efficient method of tracer test analysis/interpretation has been presented, which is based on the assumption of specific flow channels connecting injection and production wells in geothermal systems. It has been used successfully in a number of geothermal fields world-wide. Computer software, named *TRINV*, which is based on the method, uses an automatic inversion technique to simulate tracer return data. It is part of the *ICEBOX* software package (United Nations University Geothermal Training Programme, 1994). The results of the interpretation are consequently used for predicting thermal breakthrough and temperature decline during long-term reinjection in geothermal systems.

It is important to keep in mind, however, that while tracer tests provide information on the volume of flow paths connecting injection and production wells, thermal decline is determined by the surface area involved in heat transfer from reservoir rock to the flow paths, which most often are fractures. To deal with the resulting uncertainty geological information must be taken into account and predictions may be calculated for different assumptions on the flow-channel dimensions and properties. It is recommended that this be at least done for two extreme cases, one resulting in conservative predictions and the other in optimistic predictions.

To summarise, the main steps in tracer test interpretation using the *ICEBOX* software package are the following:

1. Write raw data into data file (ASCII): *date, time, concentration.*
2. Subtract background.
3. Correct for radioactive decay, sample volume and measurement efficiency.
4. Correct for reinjection of tracer, if needed (*TRCORRC*).
5. Change date and time to seconds (*DATE2SEC*).
6. Calculate tracer recovery (*TRMASS*).
7. Interpret data with *TRINV* and get information on flow-channel volume ($Ax\phi$) and dispersivity (α_L).
8. Predict production well cooling (*TRCOOL*).

It is also important to keep in mind that the results of the method of analysis presented here should not be considered unique solutions. Other interpretation models should be considered in may cases, such as models incorporating retention mechanisms like matrix diffusion. The highly complex flow mechanism within the bedrock in many areas needs more detailed analysis/interpretation than possible through the methods presented here.

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