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GEOTHERMAL WELL TESTING

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ABSTRACT

Geothermal wells are fundamental components in geothermal research and utilization and improved understanding of geothermal systems during the last century coincided with geothermal wells becoming the main instruments of geothermal development. Geothermal wells provide access deep into the systems, not otherwise possible, which enables a multitude of direct testing and measurements of conditions at depth. The testing made possible through wells includes well testing, one of the main tools of geothermal reservoir physics/engineering. Through well testing and consequent pressure transient analysis the main reservoir parameters, such as permeability and storativity, can be estimated along with reservoir boundary conditions, if a test is sufficiently long-lasting. Such estimates consequently provide key information for conceptual model development. Pressure transient analysis is performed on the basis of appropriate reservoir models, often the well-known Theis model, and involves in fact model simulation of the pressure transient data collected. Well tests range from very short step-rate injection or production tests, via longer production (discharge or pumping), pressure build-up and interference tests to long-term (months – years) reservoir testing, often involving several wells. Tracer testing, also a kind of well testing, is the most important tool for the purpose of assessing the danger of production well cooling during long-term reinjection, if combined with comprehensive interpretation and cooling predictions (reinjection modelling).

1. INTRODUCTION

Wells or boreholes are vital components in both geothermal research and utilization, since they provide essential access for both energy extraction and information collection. The breakthrough of increased geothermal utilization and improved understanding of geothermal systems during last century coincided in fact with geothermal wells becoming the main instruments of geothermal development. Wells enable a drastic increase in geothermal energy production, compared to natural out-flow, and provide access deep into the systems, not otherwise possible. As the latter they can provide much more detailed and specific information than the various surface exploration methods, information which is fundamental for conceptual model development and revision (the subject matter of this short course), once they become available.

Geothermal wells play a variable role during both development of a geothermal resource and during their utilization. The main roles are either as temperature gradient, exploration, appraisal, production, step-out, make-up, reinjection or monitoring wells. Wells also play an essential role in all geothermal reservoir physics (or reservoir engineering) research. Such research would be particularly ineffective without the access into geothermal systems wells provide. Geothermal reservoir physics is the scientific discipline that deals with mass and energy transfer in geothermal systems and geothermal wells. It attempts to understand and quantify this flow along with accompanying changes in reservoir conditions, in particular those caused by exploitation, mainly through applying different modelling techniques (Axelsson, 2013). During the exploration stage of a geothermal resource research focuses on analysis of surface exploration data; mainly geological, geophysical and geochemical data (Axelsson and Franzson, 2012). This emphasis changes to reservoir physics research during development and utilization, with geothermal reservoir physics e.g. having the potential to play a key role in geothermal resource management.

The purpose of geothermal reservoir physics is, in fact, twofold: To obtain information on the nature, reservoir properties and physical conditions in a geothermal system and to use this information to predict the response of reservoirs and wells to exploitation. Based on the latter the energy production capacity of a geothermal resource can be assessed. Response predictions also aid in the different aspect of the management of geothermal resources during utilization (Axelsson, 2008). Geothermal reservoir physics emerged as a separate scientific discipline in the 1970s even though some isolated studies of the physics of geothermal systems had been conducted before that in countries like Iceland, New Zealand and the USA (Grant et al., 1982). Geothermal reservoir engineering, as well as geothermal technology in general, draws heavily from the theory of ground water flow and petroleum reservoir engineering, the former having emerged in the 1930's. However, geothermal reservoirs are in general considerably more complex than ground-water systems or petroleum reservoirs. The different aspects of geothermal reservoir physics are e.g. discussed by Bödvarsson and Witherspoon (1989), Grant and Bixley (2011) and Axelsson (2012).

The testing made possible through wells includes well testing, one of the main tools of geothermal reservoir physics. It is more correctly called pressure transient testing because it involves disturbing the pressure state of a reservoir, through mass extraction or injection, and observing the resulting pressure transients. Through well testing and consequent pressure transient analysis the main reservoir parameters can be estimated along with reservoir boundary conditions. Such estimates consequently provide key information for conceptual model development. Pressure transient analysis is performed on the basis of appropriate reservoir models. Well tests range from very short step-rate injection or production tests, via longer production (discharge or pumping), pressure build-up and interference tests to long-term (months – years) reservoir testing, often involving several wells.

Tracer testing, which is also a kind of well testing, yet not pressure transient testing, is the most important tool to study the connections between reinjection wells and production wells and to assess the danger of production well cooling during long-term reinjection, if combined with comprehensive interpretation and cooling predictions (reinjection modelling).

This paper starts out by reviewing the different types of geothermal wells, as background information. After that it discusses the main methods of pressure transient well testing used during geothermal research and development, along with other reservoir research conducted through wells, and consequently the main pressure transient analysis methods. Subsequently the paper discusses briefly the application of tracer testing in reinjection research and their subsequent analysis. The paper is concluded by general conclusions and recommendations.

2. GEOTHERMAL WELLS

2.1 General

Wells or boreholes are vital components in both geothermal research and utilization, since they provide essential access for both energy extraction and information collection, as already mentioned. Deep geothermal drilling didn't really commence on a large scale until the middle of the 20th century even though some geothermal drilling had already started a century before that. Deep (150–200 m) geothermal drilling started in Larderello, Italy, in 1856 (Grant and Bixley, 2011) and the first deep (~970m) geothermal well in Hungary was drilled in Budapest from 1868 to 1878 (Szanyi and Kovács, 2010).

The design, drilling and construction of geothermal wells are discussed in the geothermal literature, e.g. in the proceedings of a short course held by UNU-GTP and LaGeo in San Salvador in March 2012 (see http://www.unugtp.is/page/sc-14/). Sarmiento (2007) discusses drilling practises in The Philippines in particular, where extensive experience has accumulated during the countries extensive geothermal development. Typically the upper parts of a geothermal well are closed off by a series of casings; to stabilize the well, to close off non-geothermal hydrological systems and for safety reasons. The deeper parts of the well are either fully open or cased with a so-called liner, which is not cemented in place but perforated in selected intervals, to allow fluid (water and/or steam) to flow from the reservoir into the well. The most significant difference between geothermal and petroleum wells are the following:

(i) Geothermal wells are most often drilled in hard, igneous rocks, which are more difficult to drill than the sedimentary environment of petroleum wells.
(ii) The open production sections of geothermal wells are quite long in comparison with those of petroleum wells, ranging from a few hundred metres to more than 2 km.
(iii) Yet geothermal wells usually have some discrete in-flow sections (feed-zones, see below).
(iv) Geothermal wells often encounter high temperatures and pressures, sometimes associated with blow-out danger due to explosive boiling.
(v) Water is commonly used as drilling fluid for open sections in contrast with drilling mud most commonly used in petroleum wells to avoid clogging any feed-zones (also reduced pollution danger).
(vi) The drilling of successful geothermal wells often involves large, or even total, circulation losses.
(vii) Geothermal production wells are generally of larger diameter (up to a few tens of cm's) than petroleum wells, because of greater flow-rates involved.

Grant and Bixley (2011) discuss some of these in more detail.

A geothermal well is connected to the geothermal reservoir through feed-zones of the open section or intervals. The feed-zones are either particular open fractures or permeable aquifer layers. In volcanic rocks the feed-zones are often fractures or permeable layers such as interbeds (layers in-between different rock formations) while in sedimentary systems the feed-zones are most commonly associated with a series of thin aquifer layers or thicker permeable formations. Yet fractures can also play a role in sedimentary systems. In some instances a well is connected to a reservoir through a single feed-zone while in other cases several feed-zones may exist in the open section, but often one of these is the dominant one.

Geothermal wells can be classified as one of three principal types:

(a) liquid-phase low-temperature wells, which produce liquid water at well-head (pressure may be higher than atmospheric, however),
(b) two-phase high-temperature wells where the flow from the feed-zone(s) is liquid or two-phase and the wells produce either a two-phase mixture or dry-steam or
(c) dry-steam high-temperature wells where the flow from the feed-zone(s) to the well-head is steam-dominated.

In the liquid-phase and dry-steam wells the inflow is single phase liquid water or steam, respectively, while two-phase wells can be furthermore classified as either liquid or two-phase inflow wells. In multi feed-zone two-phase wells one feed-zone can even be single-phase while another one is two-phase.

In general the productivity of geothermal wells is a complex function of:

(1) well-bore parameters such as diameter, friction factors, feed-zone depth and more,
(2) feed-zone temperature and enthalpy,
(3) feed-zone pressure, which depends directly on reservoir pressure and reservoir permeability,
(4) well-head pressure or depth to water level during production and
(5) temperature conditions around the well.

Most of these parameters can be assumed approximately constant for reservoirs under production, except for the reservoir pressure (3), which varies with time and the overall mass-extraction from the reservoir. The feed-zone temperature and enthalpy may also vary with time in some cases, albeit usually more slowly than reservoir pressure. Axelsson and Steingrímsson (2012) discuss the multidisciplinary research conducted during drilling, testing and monitoring of geothermal wells, research not discussed here.

Finally it should be mentioned that geothermal wells are often stimulated following drilling, either to recover permeability reduced by the drilling operation itself, to enhance lower than expected near-well permeability or to open up connections to permeable structures not directly intersected by the well in question. Axelsson and Thórhallsson (2009) review the main methods of geothermal well stimulation with emphasis on methods applied successfully in Iceland. The methods most commonly used involve applying high-pressure water injection, sometimes through open-hole packers, or intermittent cold water injection with the purpose of thermal shocking. Stimulation operations commonly last a few days while sometimes stimulation operations have been conducted for some months. The stimulation operations often result in well productivity (or injectivity) being improved by a factor of 2-3.

2.2 Types of geothermal wells

The different types of geothermal wells are listed and described briefly below (see Axelsson and Franzson, 2012):

(1) **Temperature gradient wells** are generally both slim and quite shallow, most often only around 50 m in depth, even though in some instances they may reach a few hundred metres depth. Their main purpose is to study shallow temperature conditions (temperature gradient) and estimate heat flow. In contrast with other geothermal wells temperature gradient drilling can in fact be classified as a surface exploration tool.
(2) **Exploration wells** are deeper wells intended to extend into the geothermal system being explored, i.e. to reach a specific target. Their main purpose is to study temperature conditions, permeability and chemical conditions of the target. Exploration wells are either so-called slim wells with diameter < 15 cm, which are drilled for the sole purpose of exploring conditions at the target depth, or exploration wells designed as production wells (full diameter wells). The former can be used to estimate the capacity of production wells later drilled to reach the same target(s). The latter can later be converted to production wells, however, if successful.
(3) **Production wells** are wells drilled with the sole purpose of enabling production of geothermal energy (as hot liquid, two-phase mixture or steam) from a specific target, or a geothermal reservoir. Their design is of paramount importance, e.g. the casing program applied. Production wells are either designed for spontaneous discharge through boiling (high-temperature reservoirs) or for the application of down-hole pumps (lower temperature reservoirs).
(4) **Step-out wells** are either exploration or production wells drilled to investigate the extent, of a geothermal reservoir already confirmed. A step-out well either approaches the edge, or boundary, of a reservoir or is drilled beyond it. A number of step-out wells in different directions may be required if a given reservoir is extensive in area.
(5) **Make-up wells** are production wells drilled inside an already confirmed reservoir, which is being utilized for energy production, to make up for production wells which are either lost

through damage of some kind (collapse, scaling, etc.) or to make up for declining capacity of wells.

(6) **Reinjection wells** are used to return energy-depleted fluid back into the geothermal system in question or even to inject water of a different origin as supplemental recharge. The location of reinjection wells is variable as reinjection can either be applied inside a production reservoir, on its periphery, above or below it or outside the main production field, depending on conditions and the purpose of the reinjection.

(7) **Monitoring wells** are used to monitor changes in geothermal systems, mainly after utilization starts, mostly pressure and temperature changes. These are in most cases already existing wells, such as exploration wells or abandoned production wells. Active production wells are sometimes used for monitoring purposes (chemical content, temperature and pressure). Carefully designed and comprehensive monitoring is the key to successful management of geothermal resources during utilization.

(8) **Unconventional wells** are either wells of unconventional design or wells drilled into parts of geothermal systems generally not used for energy production. Examples are wells that are deeper than normal, well drilled into magma or wells drilled into supercritical conditions.

The different types of wells play a role during different stages of geothermal research and development, and all types can contribute data used in conceptual model development. Pressure transient testing can e.g. be performed in all well-types while tracer tests are commonly performed between reinjection and production wells. The key to the successful drilling of any type of geothermal well is, furthermore, correct siting and design of the well based on a clear definition and understanding of the drilling target aimed for, founded on all information available at any given time. This is best achieved through a comprehensive and up-to-date conceptual model incorporating, and unifying, the essential physical features of a geothermal system. Geothermal drilling targets and well siting are discussed in a separate presentation at this short course (Axelsson et al., 2013). It may also mbe mentioned that Stefánsson (1992) analyses the success of geothermal development, which depends to a great extent on the success of drilling.

3. RESERVOIR RESEARCH CONDUCTED THROUGH GEOTHERMAL WELLS

3.1 During drilling

The principal research conducted during drilling of geothermal wells is achieved through logging of the wells, often called wireline logging. This involves measuring various contrasting, partly unrelated, parameters for different purposes as a function of depth. Some of these are drilling technology related, others for logging geological parameters and still others for reservoir physics purposes. The following are the main logging methods applied during geothermal well drilling (see Axelsson and Steingrímsson (2012) for more details):

(A) Caliper and cement bond logging aimed at measuring variations in well diameter and assessing the integrity of casing cementing. In addition imaging of casings and other parts of wells by video cameras is increasingly being used.

(B) Geophysical logging (resistivity logs, neutron-neutron logs, gamma-gamma logs, sonic logs and natural gamma ray logs) aimed at estimating different physical properties of the rock formations intersected by the well. This type of logging supplements drill cutting analysis, in particular for depth intervals where drill cuttings aren’t available.

(C) Fracture imaging is increasingly being used to study specific fractures and fracture distributions in wells. The method most often applied is televiewer logging, which provides an extremely valuable addition to other logging methods, and circulation loss analysis, aimed at understanding feed-zones in wells.

(D) Temperature and pressure logging can be viewed as the main reservoir physics logging performed during drilling. In addition spinner logging is often applied to estimate fluid flow in wellbores as well as inflow or outflow through feed-zones.

Pressure transient well testing (the subject of this paper) is usually not applied during drilling. Exceptions include situations when the outcome of a drilling operation needs to be assessed before drilling is completed, which can be done through short-term step-rate injection or production testing, comparable (often shorter, however) to tests normally applied at well completion (see below). The results of such testing are sometimes used to determine whether a drilling operation should be terminated or not.

During the drilling phase of a well temperature and pressure logging has a few different research purposes; firstly to evaluate well conditions regarding the drilling operation itself, secondly to locate feed-zones (inflow or outflow zones) and thirdly to estimate reservoir temperature and pressure. During drilling temperature and pressure are, however, lowered by drilling fluid circulation as well as being often affected by inflow or outflow through feed-zones or internal flow between feed-zones, and it's difficult to estimate reservoir temperature and pressure accurately. Axelsson and Steingrímsson (2012) discuss the methods used for that purpose.

3.2 At well completion

At well completion reservoir physics research kicks in at full force, including well testing, with the main purpose being to assess the result of the drilling operation. If the outcome is deemed satisfactory the drilling operation is stopped, otherwise drilling may be continued to greater depth, or a program of well stimulation may be initiated (see later). The main phases of conventional completion program for a geothermal production well are as follows:

(1) Temperature and pressure logging, sometimes accompanied by spinner logging, to evaluate location and relative importance of feed-zones as well as temperature conditions prior to later phases of the completion test (due to temperature limitations of instruments used).
(2) Geophysical logging and fracture imaging of the production part of the well.
(3) Step-rate well-testing; through injection in high-temperature wells or production in low-temperature wells. Pressure (and sometimes temperature) transients are preferably measured down-hole.
(4) Temperature and pressure logging is normally performed after, sometimes even during step-rate testing. Spinner logging can be beneficial to assess feed-zones.

The purpose of the step-rate well-testing, which is the main reservoir physics research conducted at the end of drilling a well, is to obtain a first estimate of the possible production capacity of a well and to estimate its production characteristics. In the case of high-temperature wells this estimate is only indirect since it's not performed at high-temperature, production conditions. Step-rate well-testing usually lasts from several hours to a few days. The following are the parameters usually estimated on basis of step-rate test data:

(a) Injectivity index, defined as $\boldsymbol{II} = \Delta \boldsymbol{q}/\Delta \boldsymbol{p}$, with $\Delta \boldsymbol{q}$ the change in flow-rate and $\Delta \boldsymbol{p}$ the change in down-hole pressure, usually based on measured values at the end of each step. In the case of low-temperature wells tested through production step testing a comparable index is defined, termed productivity index (***PI***). A productivity index is also estimated during production testing of high-temperature wells. This will be discussed later in the present chapter.
(b) Formation transissivity or permeability-thickness ($\boldsymbol{T}$ or $\boldsymbol{kh}$, respectively), to be discussed in Chapter 4 below.
(c) Formation storage coefficient ($\boldsymbol{S}$) or storativity ($\boldsymbol{s}$), also to be discussed in Chapter 4.
(d) Skin factor of a well and wellbore storage capacity (see Chapter 4).

The injectivity index (as well as the productivity index) is a simple relationship, approximately reflecting the capacity of a well, which is useful for determining whether a well is sufficiently open to be a successful producer and for comparison with other wells. It neglects, however, transient changes and turbulence pressure drop at high flow-rates. For liquid phase low-temperature wells a more accurate productivity relationship can usually be put forward relating mass flow-rate (***q***) and well pressure (***p***):

$$p = p_0 - b(t)q - Cq^2 \tag{1}$$

The pressure can either be measured as down-hole pressure, depth to water-level if pumping from the well is required, or well-head pressure if flow from the well is artesian. The term p_0 represents the initial well pressure before production starts, ***b(t)q*** transient changes in well pressure reflecting transient changes in reservoir pressure (addressed in Chapter 4) and Cq^2 turbulent and frictional pressure changes in the feed-zones next to the well, where flow-velocities are at a maximum, and in the well itself. The term ***b(t)*** depends on the properties of the reservoir in question, such as permeability and storativity. The injectivity/productivity index is, therefore, in fact an approximation of this term. To be exact the term will also include interference (due to production and/or reinjection) from other nearby wells. Figure 1 shows examples of productivity curves (often also called deliverability or output curves) for three liquid-phase low-temperature geothermal wells with vastly variable production characteristics, based on real Icelandic low-temperature examples.

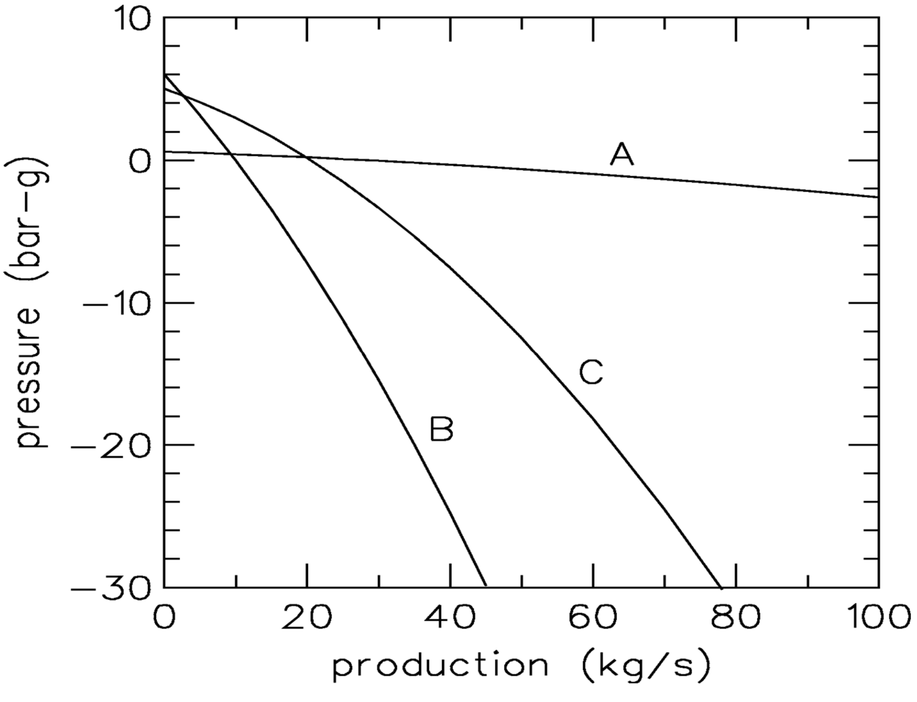

FIGURE 1: Examples of productivity curves (i.e. Equation (1)) for liquid-phase low-temperature geothermal wells with varying characteristics. Based on real Icelandic examples (see Axelsson and Gunnlaugsson, 2000)

It may be mentioned that Rutagarama (2012) presents a good treatise on the role of well-testing in geothermal resource assessment while Sarmiento (2011) discusses completion testing in more detail than done here, based on examples from high-temperature geothermal fields in the Philippines. Pressure transient analysis of step-rate well test data, collected during either injection or production, is discussed in Chapter 4 below and some examples presented.

3.3 Stimulation related testing

Geothermal wells are often stimulated following drilling, either to recover permeability reduced by the drilling operation itself, to enhance lower than expected near-well permeability or to open up connections to permeable structures not directly intersected by the well in question. Axelsson and Thórhallsson (2009) review the main methods of geothermal well stimulation with emphasis on methods applied successfully in Iceland. The methods most commonly used involve applying high-pressure water injection, sometimes through open-hole packers, or intermittent cold water injection with the purpose of thermal shocking. Chemical stimulation (mostly applying acid) methods are also used. Experimental procedures, such as using deflagration to stimulate wells and propellants to maintain stimulation achieved, have also been tested (Axelsson and Steingrímsson, 2012). Stimulation operations commonly last a few days while in some instances stimulation operations have been conducted for some months. The stimulation operations often result in well productivity (or injectivity) being improved by a factor of 2-3.

Emphasis is placed on careful reservoir monitoring during stimulation operations. Seismic monitoring has e.g. provided valuable information in some few cases. Further research and "state of the art" technology are needed to better understand stimulation processes, however, and to improve the outcome of geothermal stimulation operations. The results of stimulation operations are usually assessed through repeated step-rate well-tests (see Section 3.2) and by comparing injectivity (or productivity) indices estimated before, during and after stimulation operations. Changes in skin factor can also be used to evaluate the outcome of such operations.

3.4 During well warm-up and production testing

After the drilling of a geothermal well is completed a well is usually allowed to recover in temperature (heat up) from the cooling caused by drilling fluid circulation and cold water injection. How long depends on local conditions and the development project being followed, but this usually takes a few months. The principal reservoir engineering research conducted during this period is repeated temperature and pressure logging. The temperature data thus collected is used to estimate the undisturbed system temperature, often called formation temperature, as wells usually don't recover completely during the recovery period. Different methods can be used for this estimation, but the method most often applied is the so-called Horner method (see Axelsson and Steingrímsson, 2012). No pressure transient testing is conducted during the warm-up period.

After a well has been allowed to warm up sufficiently it is ripe for output testing. In the case of high-temperature wells this usually involves spontaneous discharge through boiling at depth in the wellbore, which creates the pressure drop necessary to drive the flow of geothermal fluid from the reservoir, through the well, and to the surface (discharge testing). In the case of lower temperature wells either sufficient overpressure in the reservoir, which creates free-flow (artesian) from wells, or pumping, is required for output testing. In many cases high temperature wells need to be discharge stimulated through a variety of methods before discharge can be sustained. Such methods are e.g. discussed by Sarmiento (2011).

Measuring the well discharge of single-phase (liquid water or dry steam) wells is relatively straight-forward whereas measuring the discharge (both mass- and energy-flow) of a two-phase well is much more complex. This involves measuring, or estimating, two out of four key parameters; liquid-flow ($\boldsymbol{q_w}$), steam-flow ($\boldsymbol{q_s}$), total flow ($\boldsymbol{q_{total}}$) or enthalpy of the flow ($\boldsymbol{h_t}$). Once any two have been determined the other parameters can be estimated based on the following equations:

$$X = q_s / q_{total} \tag{2}$$

$$q_{total} = q_w + q_s \tag{3}$$

$$h_t = Xh_s + (1 - X)h_w \tag{4}$$

Here $\boldsymbol{X}$ is the mass-fraction of steam and $\boldsymbol{h_s}$ and $\boldsymbol{h_w}$ enthalpy of water and steam, respectively, at separation conditions on surface.

The following are the main methods used to estimate the output of two-phase wells at surface (see also Grant and Bixley*,* 2011):

(1) Liquid and steam phases are separated (in a separator) and each phase measured separately. Probably the most accurate method but requires the most complex instrumentation.
(2) This method applies to wells with liquid inflow and known feed-zone temperature. Liquid flow is measured after separation and enthalpy of flow estimated on basis of feed-zone temperature.
(3) This method also applies to wells with liquid inflow and known feed-zone temperature. Total flow estimated by the Russel James method and enthalpy of flow on basis feed-zone temperature. The Russel James method is an empirical method, relating total flow and flowing enthalpy, based on measuring the critical lip-pressure at lip of a pipe discharging the two-phase mixture (James, 1970; Grant et al., 1982).
(4) A combination of using the Russel James method on the total flow and consequently measuring the liquid flow-rate after separation.
(5) Using two different chemical tracers to measure the flow-rate of each of the phases in a pipeline (Hirtz et al., 2001). This method is increasingly being used with success, as it doesn't require disruption of power production.

Figure 2 shows an example of discharge test data from the Olkaria Domes field in Kenya. It shows a typical behaviour resulting from the well heating up, actually continuing from the warm-up period after drilling, i.e. enthalpy increases and water flow decreases as the test progresses. In this case the test lasted about a month, but ideally discharge tests should last until an approximate equilibrium is reached, which often may take several months. In some cases equilibrium is not attained. The behaviour of discharging wells is, however, quite variable, depending on the nature of the geothermal reservoir involved and well properties, as e.g. discussed by Bödvarsson and Witherspoon (1989) and Grant and Bixley (2011).

The productivity of geothermal wells is often presented through a simple relationship between mass flow-rate or production (measured as mentioned above) and the corresponding pressure change, either in down-hole or well-head pressure, as a first-order approximation, as already discussed (see discussion on injectivity/productivity above). This relationship is often termed production characteristics or well deliverability (output curve). In general the productivity of geothermal wells is a complex function of well-bore parameters (diameter, friction factors, feed-zone depth, skin factor, etc.), feed-zone temperature and enthalpy, feed-zone pressure, reservoir permeability and storativity, well-head pressure or depth to water level during production and temperature conditions around the well. For two-phase high-temperature wells a simple relationship as given by Equation (1) can't be set up between flow-rate and well-head pressure.

Figure 3 shows examples of productivity curves for two types of two-phase high-temperature geothermal wells with vastly variable production characteristics. It exemplifies a clear distinction between wells with single phase feed-zone inflow, which show typical bell-shaped curves like liquid-phase wells (Figure 1), and wells with two-phase inflow, which show little variation in output with changes in well-head pressure. The possible reasons for the characteristics of the latter wells have been discussed by Stefánsson and Steingrímsson (1980) as well as Bödvarsson and Witherspoon (1989).

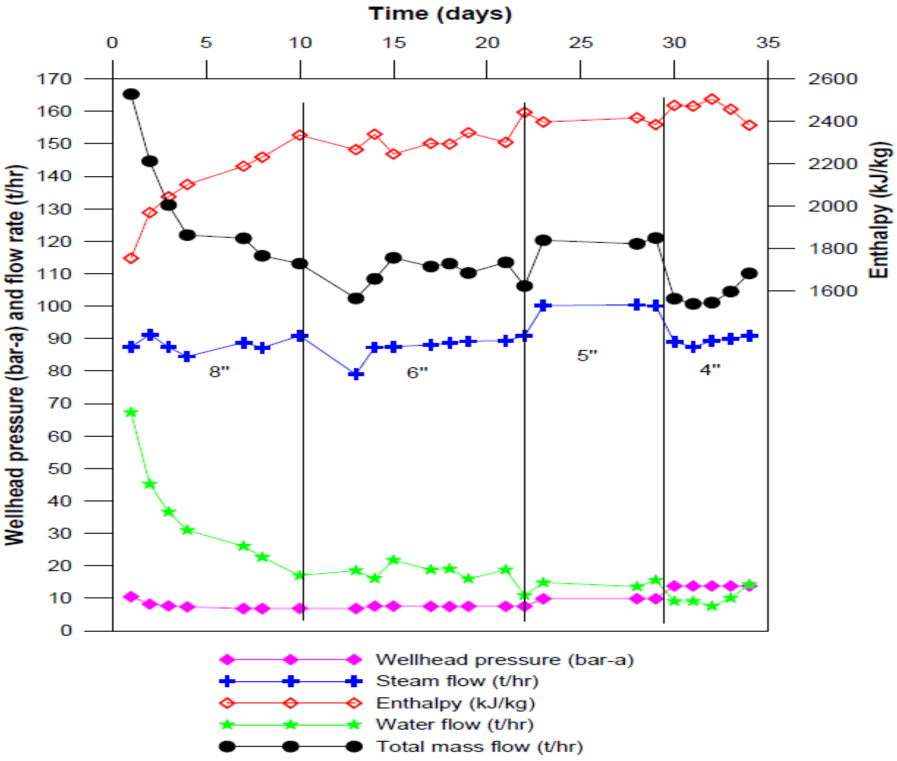

FIGURE 2: Discharge test data from well OW-915A in the Olkaria Domes field in Kenya (Mwarania, 2010)

When analysing data from flowing two-phase wells researchers need to resort to so-called wellbore simulators, i.e. computer software which numerically solves the relevant physical equations to simulate flow-, pressure- and energy conditions in the wells in question. These include mass conservation, pressure changes due to acceleration, friction and gravitation as well as energy conservation. The *HOLA* wellbore simulator is a good example of such software (Björnsson and Bödvarsson, 1987) while several other newer wellbore simulators also exist.

An extremely important part of discharge testing is monitoring of down-hole pressure during testing, either continuously or intermittently. This is not done in nearly all cases, however, as it may be technically difficult and/or quite expensive. If such data are available it is common to define a productivity index (***PI***) simply as the ratio between a change in mass flow-rate and a corresponding change in well pressure, preferably measured at the main feed-zone of a well, as first-stage analysis. For low-temperature, single-phase wells the productivity index is normally quite comparable to the wells injectivity index,

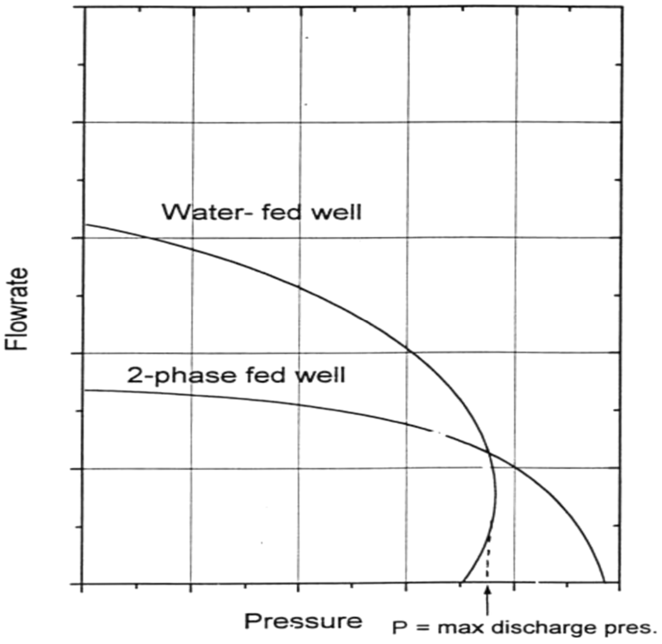

FIGURE 3: General examples of productivity curves for two types of two-phase high-temperature geothermal wells (Axelsson and Steingrímsson, 2012)

if that has been estimated. This is, however, not the case for high-temperature, two-phase wells because of drastically contrasting conditions during injection of colder fluids and high-temperature production. This can be seen clearly in Figure 4 which shows a comparison of productivity and injectivity indices for a number of high-temperature wells worldwide. The figure shows a considerable scatter, at least not a clear one-to-one relationship. A conservative relationship assuming that $\boldsymbol{PI} = \boldsymbol{II}/3$, which has been suggested, is supported by the figure. This is logical in the case of two-phase wells where boiling causes a much greater pressure draw-down than during injection. Yet it seems evident that in the case of highly productive wells the productivity index is considerably larger than the injectivity index (Axelsson and Thórhallsson, 2009).

Conventional pressure transient analysis of down-hole pressure data measured during discharge testing is of course a more accurate method of analysis than the estimation of a productivity index. The analysis methods described in Chapter 4 may be used for this purpose; they are in fact the same methods as used for the analysis of step-rate well-test data.

In addition to simple monitoring of down-hole pressure during discharge testing, supplementary pressure transient testing is sometimes performed. This involves in particular pressure recovery monitoring after discharging wells are shut in and pressure interference monitoring in near-by monitoring wells. Such data add greatly to the reservoir physics analysis of discharge tests. It should be noted, however, that in the case of high-temperature, especially two-phase, reservoirs pressure propagation is very slow so pressure interference may be limited. In lower temperature, liquid-dominated, reservoirs interference testing is extremely valuable.

3.5 Long term monitoring

Management of geothermal resources relies on adequate knowledge on the corresponding geothermal system and the monitoring of their response to long-term utilization is therefore essential (Monterrosa and Axelsson, 2013; Axelsson, 2008). Production response monitoring provides in fact some of the most important data on the nature and characteristics of geothermal systems, information which is also indispensable for the development of geothermal conceptual models. It is, in particular, essential for the revision of conceptual models previously developed on the basis of exploration and well data. If the understanding of a geothermal system is adequate, monitoring will enable changes in the reservoir to be seen in advance. Timely warning is thus obtained of undesirable changes such as decreasing generating capacity due to declining reservoir pressure or steam-flow, insufficient injection capacity or possible operational problems such as scaling in wells and surface equipment or corrosion. The importance of a proper monitoring program for any geothermal reservoir being utilised can thus never be over-emphasised. In addition utilization and monitoring can be viewed as really long-term reservoir testing, i.e. a continuation of the production testing discussed above, even though that type of testing is not performed under controlled conditions. Long-term pressure transients monitored during years of utilization, together with data on the mass extraction (always variable) causing it, constitutes, in particular, long-term pressure transient testing.

Monitoring the physical changes in a geothermal reservoir during exploitation is in principle simple and involves measuring the (1) mass and heat transport, (2) pressure, and (3) energy content (temperature in most situations). This is complicated in practise, however (Axelsson and Gunnlaugsson, 2000). Measurements must be made at high-temperatures and pressures and reservoir access for measurements is generally limited to a few wells, and the relevant parameters can’t be measured directly throughout the remaining reservoir volume. Monterrosa and Axelsson (2013) and Axelsson and Steingrímsson (2012) discuss response monitoring in more detail, including the parameters that need to be measured, as well as presenting several relevant examples. It should be mentioned that such physical monitoring data are essential for calibration of models of geothermal systems used to assess their production capacity and for long-term management purposes.

In addition to monitoring physical changes the chemical content of produced water and/or steam also needs to be monitored. Finally repeated indirect monitoring, which involves monitoring the changes occurring at depth in geothermal systems through various surface observations (mainly geophysical surveying, e.g. combined surface deformation and micro-gravity monitoring), can provide valuable additional information, such as on changes in the mass balance of a geothermal system (Axelsson and Steingrímsson, 2012; Axelsson, 2008).

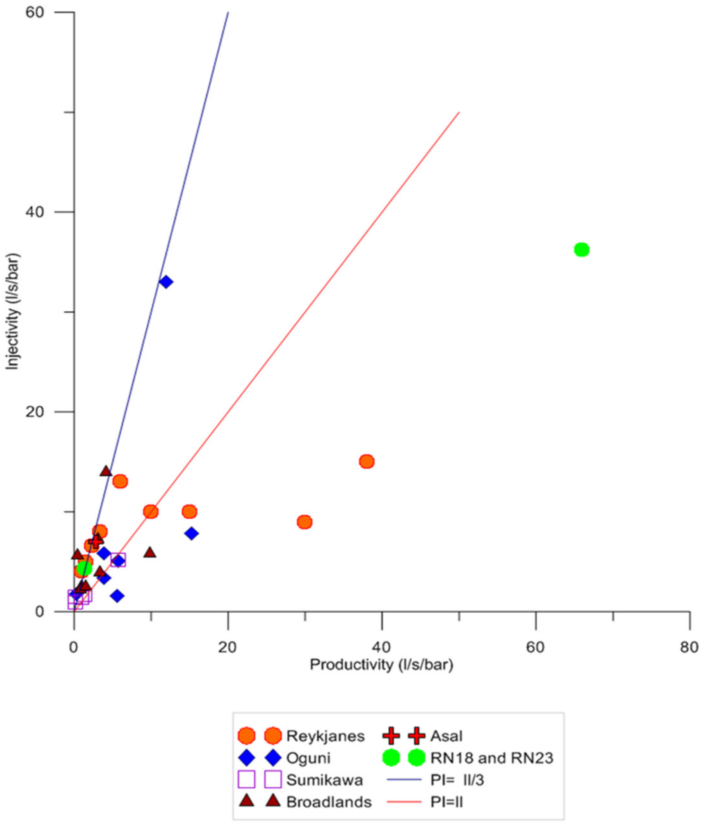

FIGURE 4: The relationship between productivity and injectivity indices for several high-temperature geothermal wells worldwide (Rutagarama, 2012). The red line represents ***PI*** **=** ***II*** while the blue line represents ***PI*** **=** ***II***/3

3.6 For reinjection wells

In the case of reinjection wells, either drilled specifically as such or other types of wells converted into reinjection wells, much of the same reservoir physics research is conducted as described above. The main difference is that reinjection wells don't need to be discharge tested so a step-rate injection test suffices. After well completion injection testing needs to be continued for a long period, usually several months. During this long-term injection testing tracer test are often conducted to study the connection between the designated reinjection well and near-by production wells, with the danger of cooling of the production wells in mind. Tracer testing in geothermal operations is discussed in Chapter 5 below, while a more detailed discussion of other aspects of reinjection well testing and research is presented by Axelsson (2012b). It may be specifically mentioned, however, that the injectivity of reinjection wells sometimes continues to increase during long-term injection, most likely due to thermal stimulation.

4. PRESSURE TRANSIENT ANALYSIS

Pressure transient analysis of pressure transient well-test data is performed to estimate the principal hydrological parameters of the geothermal system around the well(s) being studied. It actually constitutes modelling, or simulation of the pressure transient data by the calculated pressure changes in a relevant model, driven by a given mass extraction from a production well or injection into a reinjection well. Geothermal pressure transient analysis is discussed in detail by Bödvarsson and Witherspoon (1989) and Grant and Bixley (2011).

The main reservoir and well parameters estimated through pressure transient analysis are the following (see also section 3.2):

(a) Formation transissivity or permeability-thickness defined as $T = kh/\mu$ (or $kh\rho/\upsilon$) and kh, respectively, with k the formation permeability, h the reservoir thickness, μ and υ the dynamic and kinematic viscosity of the fluid, respectively, and ρ the fluid density.
(b) Formation storage coefficient defined as $S = sh$ (or shg), with s the storativity of the geothermal reservoir involved, h its thickness again and g the acceleration of gravity. The storativity (with units kg/(m^{3}Pa)) describes the storage capacity per unit reservoir volume and depends on rock and fluid/steam compressibility, free surface mobility or phase change activity (two-phase storativity).
(c) Skin factor of the well, which describes an additional pressure drop next to a well due to so-called wellbore damage, often caused by clogging of formation pore-space by drilling mud. A negative skin factor, however, reflects a well with stimulated near-well permeability.
(d) Wellbore storage capacity, which simply depends on wellbore volume and the well-fluid compressibility.

Axelsson (2012a) as well as Grant and Bixley (2011) discusses permeability and storage capacity in detail. The permeability of the reservoir rock reflects the flow resistance of the flow paths in the rock (fractures and pores) and is the reservoir property that most greatly influences the reservoir response to production. The reservoir fluid-flow may in most cases be described by Darcy's law, which relates the underground fluid-flow with the pressure gradient and permeability. Storage describes the ability of a reservoir to store fluid or release it in response to an increase or lowering of pressure. The storativity gives the mass of fluid that is stored (released) by a unit volume of a reservoir as a result of a unit pressure increase (decrease). Even though storativity is a function of reservoir porosity different kinds of reservoirs have different storage mechanisms:

i. The storativity of confined liquid dominated reservoirs (i.e. not connected to shallower hydrological systems) is controlled by water and rock compressibility.
ii. The storativity of unconfined (free-surface) liquid dominated reservoirs is controlled by free-surface lowering, in the long-term.
iii. The storativity of dry-steam reservoirs (rare in reality) is controlled by the compressibility of dry steam, which is much larger than the compressibility of liquid water.
iv. The storativity of two-phase (boiling) reservoirs depends only weakly on porosity, but is controlled by the phase change resulting from the pressure change. When pressure increases some steam condenses allowing the rock to store more fluid. In addition the heat released during the process heats up the rock surrounding the pores and fractures of the rock. Note that two-phase storativity doesn't depend on compressibility at all.

It should be noted that storativity varies by several orders of magnitude between different kinds of reservoirs, compressibility-storativity (i) being the smallest and two-phase storativity (iv) being the greatest.

The basic differential equation, which is used in geothermal reservoir physics to evaluate the mass-transfer in models of geothermal reservoirs as well as estimate reservoir pressure changes, is the so-called *pressure diffusion equation*. It is derived by combining the conservation of mass (involves storativity) and Darcy's law for the mass flow, which in fact replaces the force balance equation in fluid mechanics. This results in:

$$s\frac{\partial p}{\partial t} = \nabla \cdot \left(\frac{k}{\upsilon} \nabla p \right) - f(x,y,z,t) \tag{5}$$

with ***p*** the reservoir pressure, $\boldsymbol{\upsilon}$ the kinematic viscosity of the reservoir fluid and ***f*** a mass source density simulating mass extraction from wells as well as injection into reinjection wells. By defining the geometry of a problem, and prescribing boundary- and initial conditions, a mathematical problem has been fully defined (i.e. a model). Theoretically a solution to the problem will exists, which can be used to calculate pressure changes and flow in the model, e.g. for pressure transient test analysis.

The pressure diffusion equation discussed shows what role each of the key parameters, permeability and storativity, play in overall pressure variations and fluid flow. In general it can be stated that permeability controls how great pressure changes are and that storativity controls how fast pressure changes occur and spread.

It should be kept in mind that permeability and porosity of geothermal reservoirs is both associated with the rock matrix of the system as well as the fissures and fractures intersecting it. Overall permeability in geothermal systems is usually dominated by fracture permeability with the fracture permeability commonly being of the order of 1 mD (milli-Darcy) to 1 D (Darcy) while matrix permeability is much lower or 1 μD (micro-Darcy) to 1 mD. Yet fracture porosity is usually of the order of 0.1 – 1% while matrix porosity may be of the order of 5 – 30% (highest in sedimentary systems). Therefore, fissures and fractures control the flow in most geothermal systems while matrix porosity controls their storage capacity. It should also be mentioned that in more complex situations permeability can be anisotropic and needs to be represented by a tensor in equation (5).

The pressure diffusion equation is in fact a parabolic differential equation of exactly the same mathematical form as the heat diffusion (conduction) equation. Therefore, the same mathematical methods may be used to solve these equations (see e.g. Carslaw and Jaeger, 1959). Pressure diffusion is, however, an extremely fast process compared to heat conduction. Strictly speaking, Darcy's law, and consequently the pressure diffusion equation, apply only to porous media such as sedimentary rocks. Yet in most cases fractured reservoirs behave hydraulically as equivalent porous media. This is because how fast the pressure diffusion process is and how rapidly pressure changes diffuse throughout a reservoir. The fractured nature is only relevant on a much smaller spatial and temporal scale. The fractured nature of most geothermal reservoirs can't be neglected when dealing with heat transfer, however (see Chapter 5).

Various solutions to the pressure diffusion equation, for corresponding models, provide the basis for the different tools of geothermal reservoir physics, or engineering. This includes models used to interpret well-test data such as the well-known Theis model (see later). Many such models actually originate from ground-water hydrology or petroleum reservoir engineering, where Darcy's law and the pressure diffusion equation are also applicable.

The permeability-thickness and storage coefficient are estimated through an analysis of pressure transients measured during different kinds of well-tests, ranging from very short step-rate injection or production tests, via longer production (discharge or pumping), pressure build-up and interference tests to long-term (months – years) reservoir testing, often involving several wells. In the case of completion well-tests (Section 3.2) pressure transient analysis is a more accurate analysis than involved in the simple estimation of an injectivity/productivity index. The same analysis methods (actually models) can also be used to analyse data from the longer transient well tests.

The analysis (or modelling) methods most often applied in the geothermal industry have been inherited from groundwater science (they have also been adopted by petroleum reservoir engineering). These classical methods will not be discussed in detail here but instead the reader is referred to the works by Bödvarsson and Witherspoon (1989) and Grant and Bixley (2011). The foundation of the methods is the

Theis model, a sketch of which is presented in Figure 5, along with sketches of a few variants of the basic model. The Theis model comprises a model of a very extensive isotropic, homogeneous and horizontal permeable layer of constant thickness, confined at the top and bottom, with two-dimensional, horizontal flow towards a producing well extending through the layer.

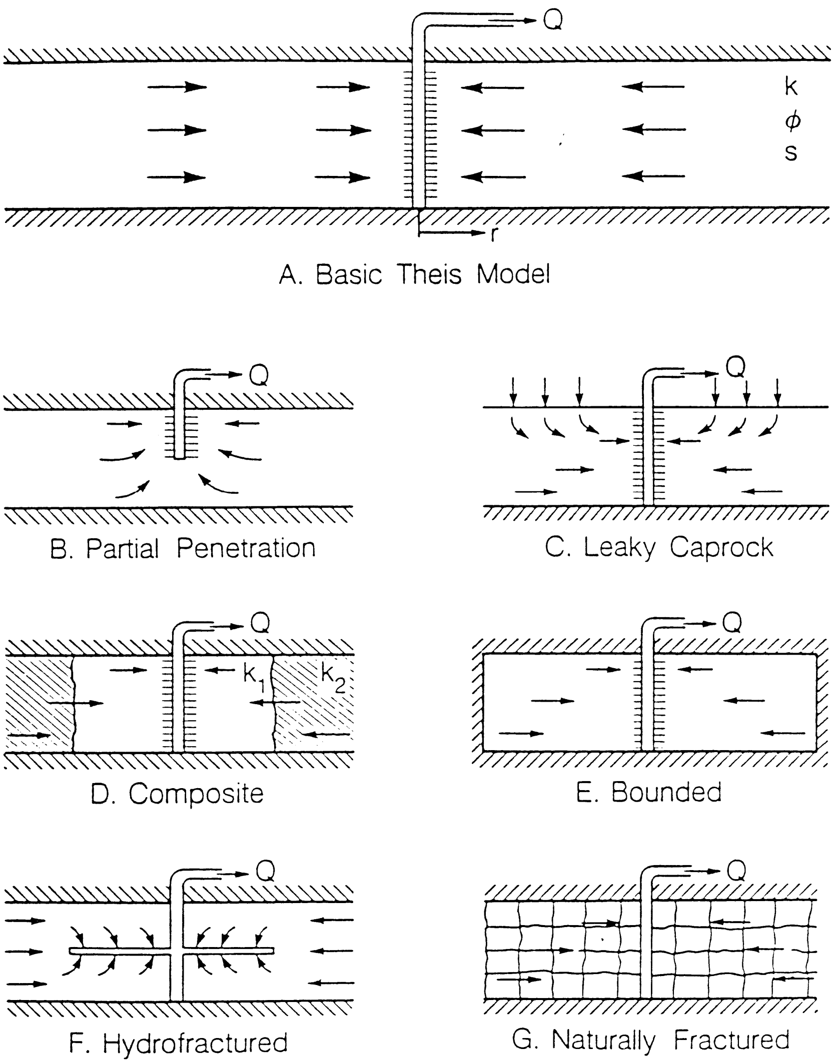

FIGURE 5: A sketch of the basic Theis-model (top) used to analyse pressure transient well-test data along with several variants of the basic model (Bödvarsson and Whiterspoon, 1989)

Well-test data are analysed on basis of the Theis model, and its variants, by fitting the pressure response of the model to observed pressure response data. Consequently the parameters of the model provide an estimate of the parameters of the reservoir being tested. Historically this fitting has been done by using semi-logarithmic plots or the type-curve method. The former method is still used as it is quite simple and effective, in spite of simplifying assumptions; Figure 6 shows the calculated responses of the Theis model and its variants in Figure 5, on a semi-logarithmic plot. The type-curve method has been replaced by more modern, computerized fitting, which today is often applied through an inverse approach, automatically yielding best fitting reservoir parameter estimates. The WellTester software (Júlíusson et al., 2008) has e.g. been used extensively to analyse well-test data from geothermal fields in Iceland, as well as from a variety of other geothermal fields worldwide. Various other well-test analysis software are available, both open-source and commercially.

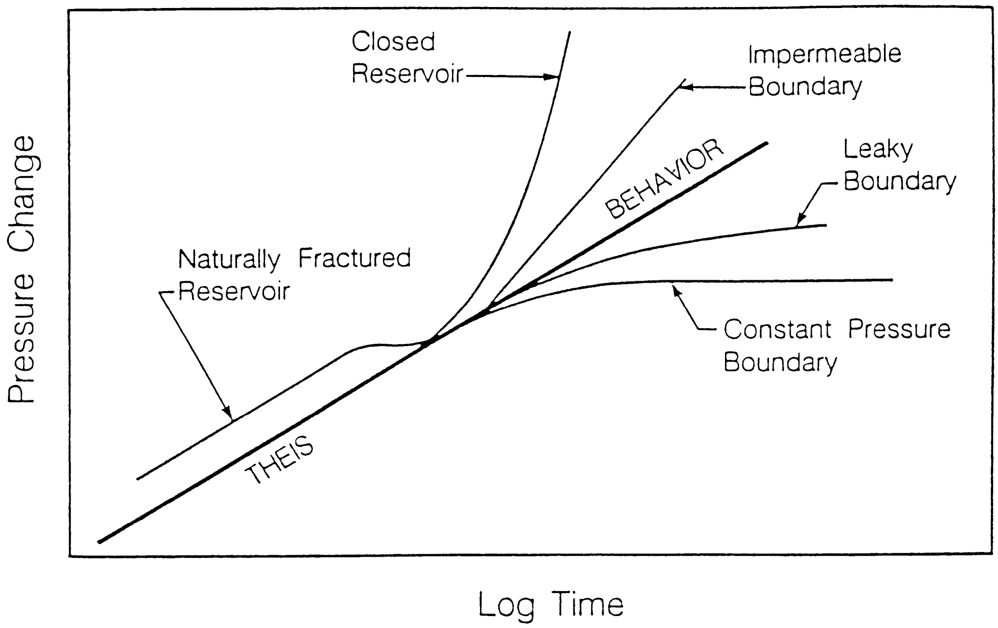

FIGURE 6: Responses of the models in Figure 5 plotted on a semi-logarithmic plot (linear pressure change vs. logarithmic time) demonstrating the linear behaviour, which is the basis of the semi-logarithmic analysis method (Bödvarsson and Whiterspoon, 1989)

Figure 7 shows one of the first examples of the results of computerized fitting of step-rate injection data, from a well drilled into the Krafla volcanic geothermal system in Iceland. It may be mentioned that today combined fitting of the pressure transients and their derivative (derivative analysis) is increasingly being used. Figures 8 and 9 present the results of such an analysis for a high-temperature geothermal production well in the Hengill geothermal region of SW-Iceland, with Figure 8 presenting the pressure transient data collected during a step-rate injection test and Figure 9 a comparison between the corresponding observed and simulated data for one of the steps.

Figures 10 – 12 present two other examples of the analysis, or simulation, of pressure transient data, both involving interference tests during which mass is produced from a certain production well and the resulting pressure transients (interference) observed in a separate monitoring well. Such tests provide the most accurate estimates of the permeability-thickness and storage coefficient, as the analysis of single well pressure transient data doesn't yield unique estimates of the storage coefficient, in addition to the fact that interference tests are generally longer than completion well-tests, providing estimates of reservoir parameters over considerably larger reservoir volumes than the latter. Figures 10 and 11 present data collected during an interference test conducted in the Kawerau geothermal field in New Zealand and Figure 12 presents an interference test example from the Oguni geothermal field in Japan.

The same applies to longer term well-testing, such as discharge testing, as to interference testing (see above). Their analysis also yields estimates of permeability-thickness and storage coefficient, estimates which should be representative for larger reservoir volumes than estimates based on step-rate well-test data, because of the much longer time scale involved. In addition discharge testing is performed at reservoir temperature conditions instead of lower temperature conditions, with an associated viscosity ambiguity, as during step-rate testing.

It should also be stressed that the analysis method for geothermal well-test data reviewed above (Theis model) is based on particular, simplifying assumptions, which are not always applicable. This applies e.g. to the assumption of two-dimensional flow, while three-dimensional flow may be important in many geothermal situations. Therefore, the results of geothermal well-test analyses should be viewed with the model applied in mind. In other words the results are actually model-dependent.

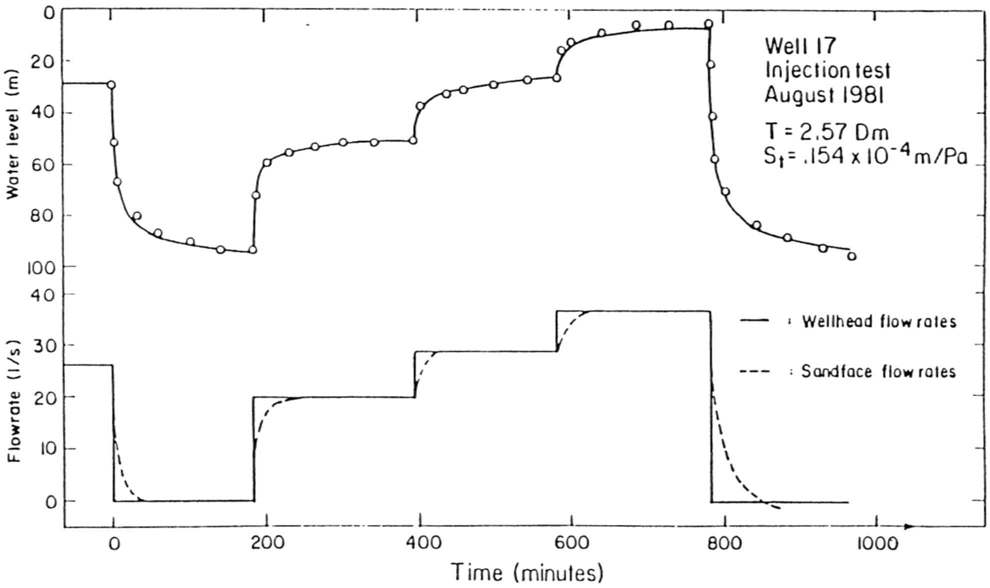

FIGURE 7: An early example of the results of computerized simulation of step-rate injection test data by a Theis-model response (Bödvarsson et al., 1984). Data from a high-temperature production well in the Krafla volcanic geothermal system in N-Iceland

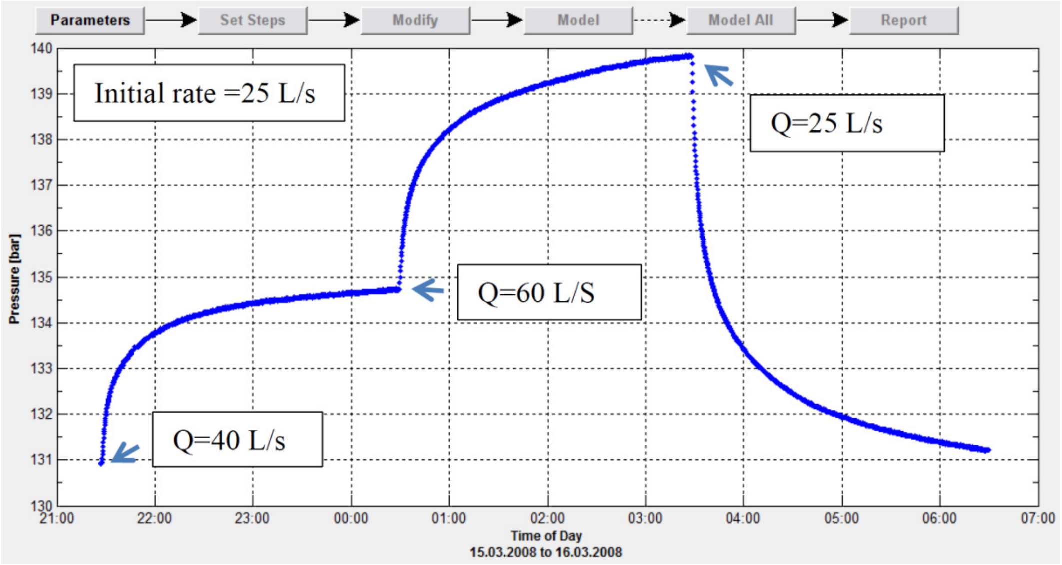

FIGURE 8: Pressure transients measured at 1750 m depth in well HE-41 in the Hengill geothermal region in SW-Iceland during a three-step injection test conducted at the end of drilling (Syed, 2011)

Finally it should be noted that in addition to the conventional reservoir analysis performed on the well data discussed above, the pressure transient data are extremely valuable for the calibration of different kinds of dynamic reservoir models (see Axelsson, 2013), i.e. numerical reservoir models. The simulation of pressure and mass output data by such models is, in effect, pressure transient analysis.

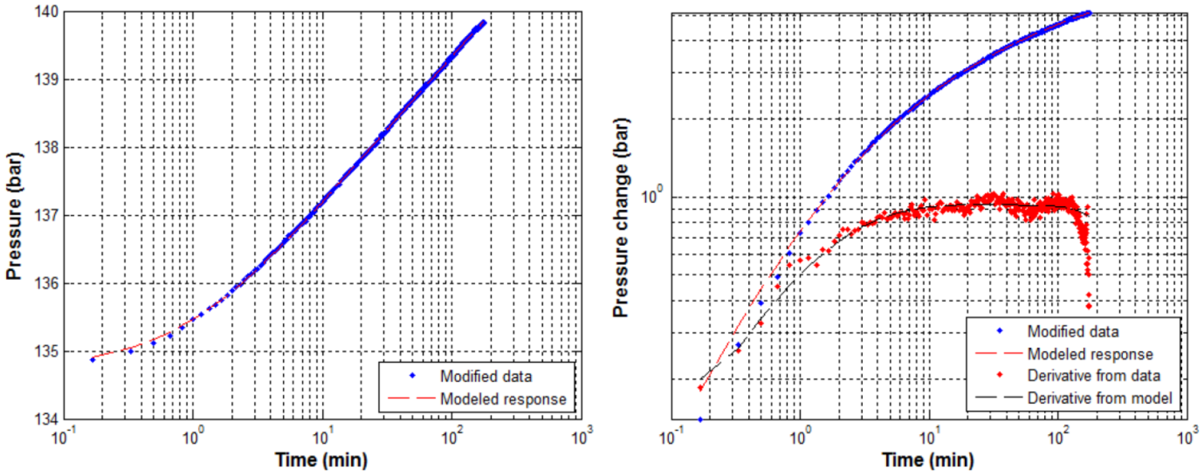

FIGURE 9: Pressure transient data from well HE-41, from the second step of Figure 8, simulated by the WellTester software (see text) and the response of a Theis model variant with a constant pressure boundary (Syed, 2011). The left hand side shows the observed and simulated pressure on a log-linear (semi-logarithmic) scale while the right hand side shows both the observed and simulated pressure, as well as the pressure derivative on a log-log scale. The simulation yields the following parameter estimates: ***kh*** = 1.8×10^{-12} m^2 (1.8 Dm), ***sh*** = 3.6×10^{-5} kg/(Pa·m^2) and skin-factor = -3.5

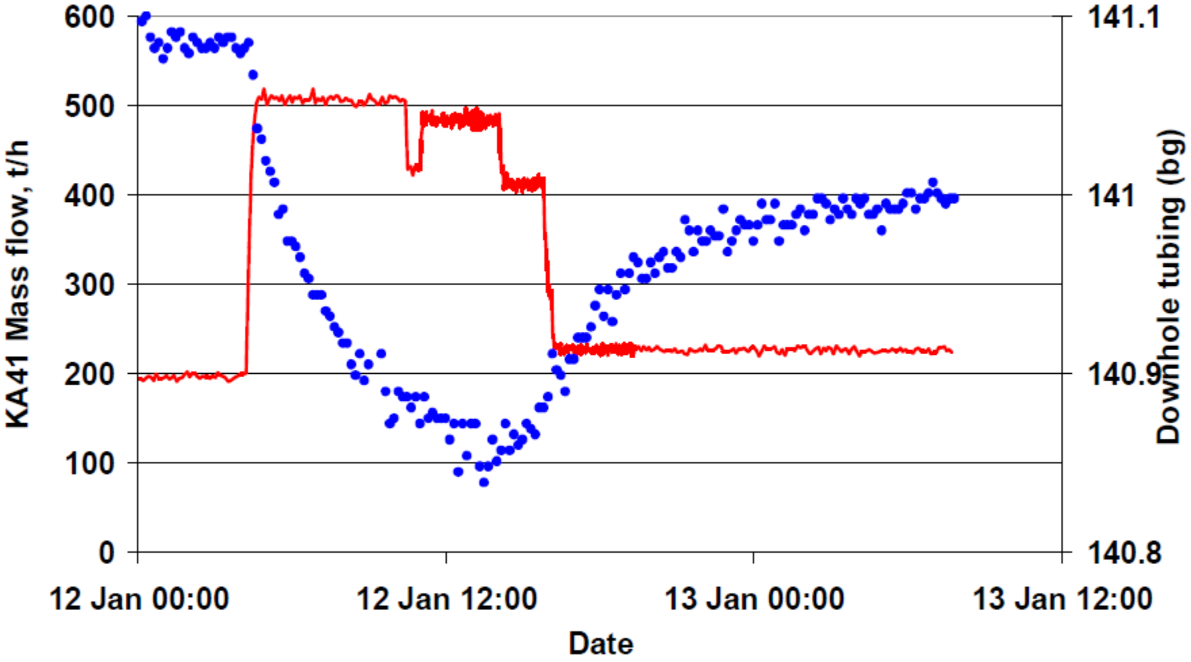

FIGURE 10: Pressure interference test data from the Kawerau geothermal field in New Zealand involving wells KA-41 (production) and KA-6 (pressure observation), see analysis in Figure 11 (Grant and Wilson, 2007)

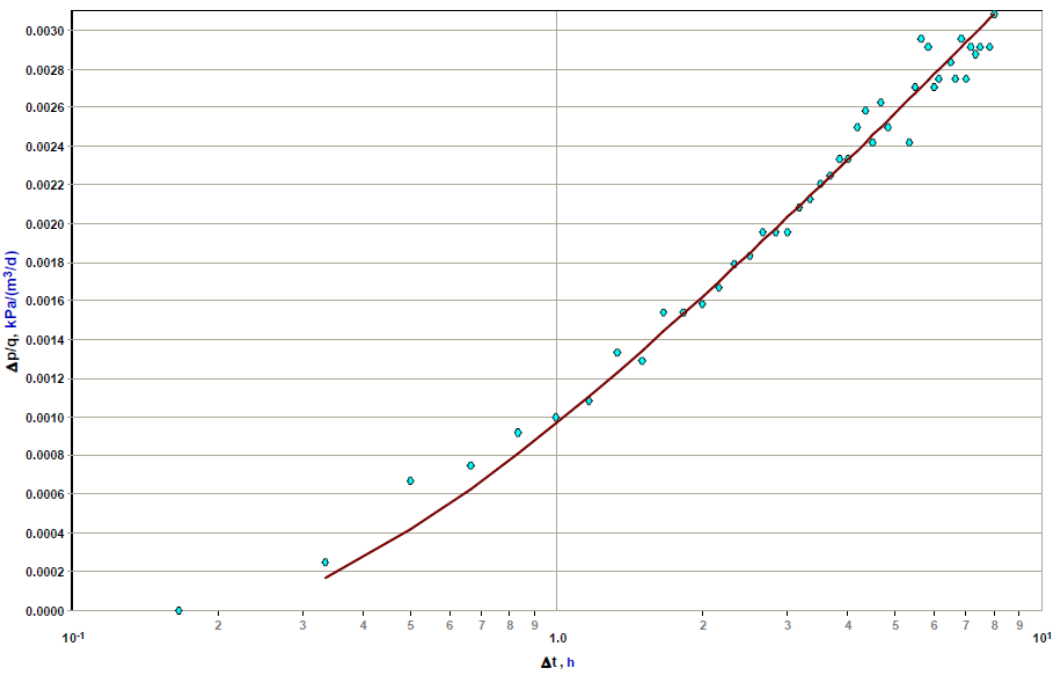

FIGURE 11: Simulation of the pressure response in well KA-6 (see Figure 10) based on the Theis model (Grant and Wilson, 2007). The simulation yields the following parameter estimate: ***kh*** ~ 100×10^{-12} m^2 (~100 Dm) but estimates for the storage coefficient are not reported

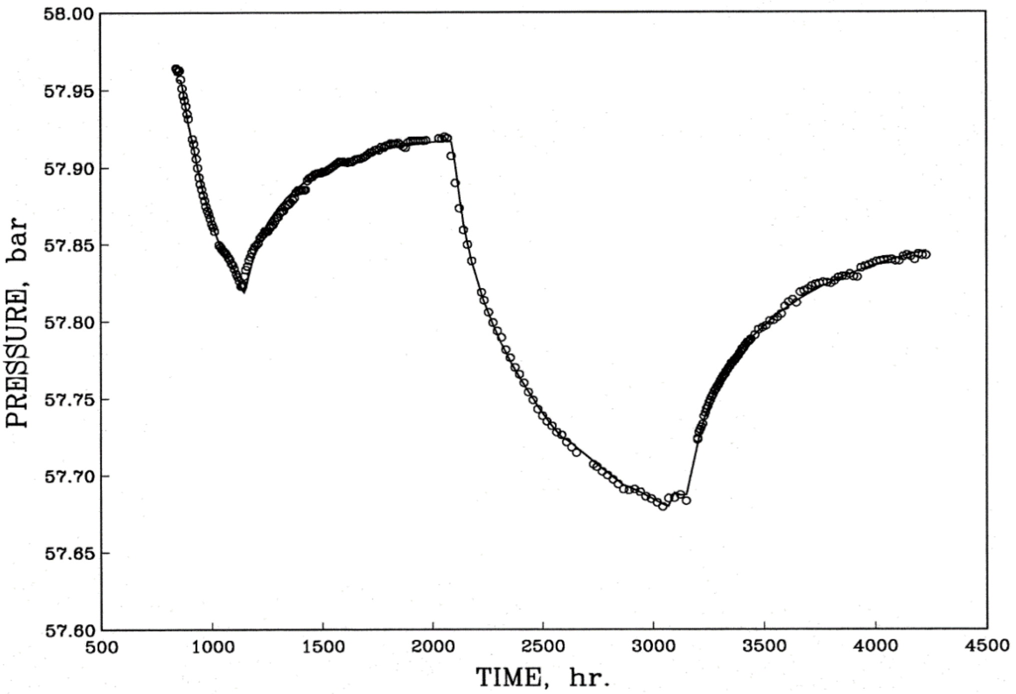

FIGURE 12: Comparison of measured pressure transients (symbols) in slim hole GH-4 in the Oguni geothermal field in Japan with computed response (line), using a Theis model variant with a no-flow boundary, due to production from wells GH-20 and GH-11 (Garg and Nakanishi, 2000). The simulation yields the following parameter estimates: ***kh*** = 150×10^{-12} m^2 (150 Dm) and ***sh*** = 1.6×10^{-3} kg/(Pa·m^2)

5. TRACER TESTING AND ANALYSIS

5.1 General

Tracer testing has become a highly important tool in geothermal research, development and resource management, with its role being most significant in reinjection studies. This is because tracer tests provide information on the nature and properties of connections, or flow-paths, between reinjection and production wells, connections that control the danger and rate of cooling of the production wells during long-term reinjection of colder fluid. Enabling such cooling predictions is actually what distinguishes tracer tests in geothermal applications (studies and management) from tracer tests in ground water hydrology and related disciplines. This information is understandably also important for conceptual model development and revision, when available. This chapter reviews geothermal tracer testing by discussing its general role, by introducing an efficient method of tracer test interpretation and for predicting production well cooling, by presenting a few examples as well as by introducing recent developments and advances in geothermal tracer testing (see also Axelsson, 2012).

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 extensively in petroleum reservoir engineering. The methods employed in geothermal applications have mostly been adopted from these fields.

Tracer testing has multiple applications in geothermal research and management:

1) The main purpose in conventional geothermal development is to study connections between injection and production wells as part of reinjection research and management. The results are consequently used to predict the possible cooling of production wells due to long-term reinjection of colder fluid.
2) In EGS-system development tracer testing has a comparable purpose even though it's rather aimed at evaluating the energy extraction efficiency and longevity of such operations through studying the nature of connections between reinjection and production wells.
3) For general hydrological studies of subsurface flow, such as flow under undisturbed conditions and regional flow.
4) For flow rate measurements in pipelines carrying two-phase water mixtures.

The power of tracer tests in reinjection studies lies in the fact that the thermal breakthrough time (onset of cooling) is usually several orders of magnitude (2–4) greater than the tracer breakthrough time, bestowing tracer tests with a predictive power. This is actually what distinguishes tracer tests in geothermal applications (see 1) and 2) above) from tracer tests in ground water hydrology and related disciplines. Numerous references on tracer tests in geothermal research and development can be found through the web-page of the International Geothermal Association (http://www.geothermal-energy.org), i.e. at World Geothermal Congresses held every 5 years. The reader is also referred to a special issue of the international journal Geothermics devoted to tracer tests (Adams, 2001) and a paper by Axelsson et al. (2005).

Geothermal tracer tests are mostly conducted through wells and can involve (i) a single well injection-backflow test, (ii) a test involving one well-pair (injection and production) as well as (iii) several injection and production wells. In the last setup several tracers must be used, however. The geothermal reservoir involved should preferably be in a "semi-stable" pressure state prior to a 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 of tracer is injected "instantaneously", i.e. in as short a time as possible, into the injection well(s) in question. Samples for tracer analysis are most often collected from producing wells, while down-hole samples may need to be collected from non-discharging wells. The duration of a tracer test is of course site specific and hard to pinpoint beforehand. The same applies to sampling plans, even though an inverse link between required sampling frequency and time passed can often be assumed (Axelsson et al., 2005).

The tracer selected needs to meet a few basic criteria: It should (a) not be present in the reservoir (or at a concentration much lower than the expected tracer concentration), (b) not react with or absorb to reservoir rocks (see however discussion on reactive tracers below), (c) be thermally stable at reservoir conditions, (d) be relatively inexpensive, (e) be easy (fast/inexpensive) to analyse and (f) be environmentally benign. In addition the tracer selected must adhere to prevailing phase (steam or water) conditions. The following are the principal tracers used in geothermal applications (not a complete list):

Liquid-phase tracers:

- Halides such as iodide (I) or bromide (Br);
- Radioactive tracers such as the isotopes iodide-125 (^{125}I) and iodide-131 (^{131}I);
- Fluorescent dyes such as fluorescein and rhodamine;
- Aromatic acids such as benzoic acid;
- Naphthalene sulfonates.

Steam-phase tracers:

- Fluorinated hydrocarbons such as R-134a and R-23;
- Sulphur hexafluoride (SF_6).

Two-phase tracers:

- Tritium (^3H);
- Alcohols such as methanol, ethanol and n-propanol.

Sodium-fluorescein has been used successfully in numerous geothermal fields, both low- and high-temperature ones (Axelsson et al., 2005). It meets most of the criteria listed above and, in particular, can be detected at very low levels of concentration (10-100 ppt). In contrast the detection limit of halides is several orders of magnitude higher.

The main disadvantage in using fluorescein is that it decays at high temperatures, a decay which becomes significant above 200°C. Therefore new tracers with higher temperature-tolerance, but comparable detection limits, have been introduced, in particular several polyaromatic sulfonates (Rose et al., 2001). These are increasingly being used in geothermal applications. Having several comparable tracers also enables the execution of multi-well tracer tests. Rose et al. (2001) present the temperature-tolerance of several of these compounds, which in some cases exceeds 300°C.

Radioactive materials are also excellent tracers since they are detectable at extremely low concentration (Axelsson et al., 2005). Their use is limited by stringent transport, handling and safety restrictions, however. When selecting a suitable radioactive tracer their different half-lives must be taken into account. Iodide-125 and iodide-131 have half-lives of 60 and 8.5 days, respectively, for example.

It should be mentioned that for flow-rate measurements in two-phase pipelines (Hirtz et al., 2001) fluorescein or benzoic acid are commonly used for the liquid phase. Naphthalene sulfonates are also promising as such. Steam-phase measurements are commonly done using SF_6 or a suitable alcohol.

Special techniques, of differing complexity, have been developed for sampling and analysing geothermal tracers. A discussion of these is beyond the scope of this paper, however.
Figures 13 – 15 show three examples of the results of tracer tests conducted in geothermal systems of quite contrasting nature, also presented by Axelsson (2012). These are just presented as concise examples, without specific field details. Two more examples, with interpretation results, are presented below.

Figure 13 shows the tracer recovery during an unusually long tracer test conducted in the Hofsstadir low-temperature (reservoir temperature 85-90°C) geothermal system in W-Iceland already mentioned twice in this paper. The test involved tracer injection into an operating reinjection well about 1200 m from the production well. The relatively slow recovery indicates that reinjection induced cooling will be limited. This awaits confirmation through comprehensive interpretation and modelling.

Figure 14 shows the tracer recovery during a tracer test conducted in the Krafla high-temperature (reservoir temperature 200-400°C) geothermal system in N-Iceland. The test involved tracer injection into a temporary reinjection well about 200 m from a production well. The relatively rapid recovery was interpreted as indicating a considerable danger of cooling of the production well. Therefore the reinjection well was abandoned as such.

The third example involves tracer tests conducted at the Soultz EGS site in N-France during stimulation and testing between 2000 and 2005 (Sanjuan et al., 2006). The tests involved 4 wells ranging in depth from 3600 to 5300 m. A few different tracers very used, including fluorescein and some naphthalene sulfonates. Figure 15 shows the recovery during the test between wells GPK-3 and GPK-2 separated by 650 m, in which fluorescein was successfully used. It showed the most direct connection in the system.

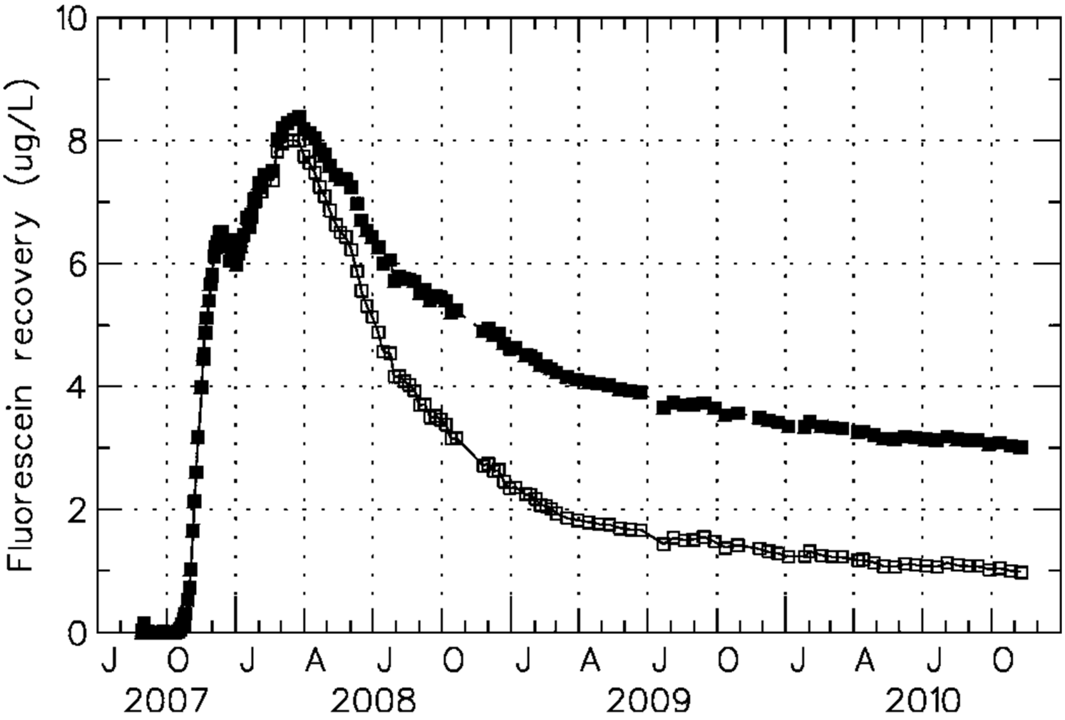

FIGURE 13: Fluorescein recovery in production well HO-1 in the Hofsstadir low-temperature system in W-Iceland, following the injection of 10 kg of the tracer into reinjection well HO-2 (from Axelsson, 2011). The test lasted 3.5 years. The lower curve shows the recovery corrected for the tracer being reinjected (recirculated) after production from HO-1. About 70% of the tracer was recovered during the test

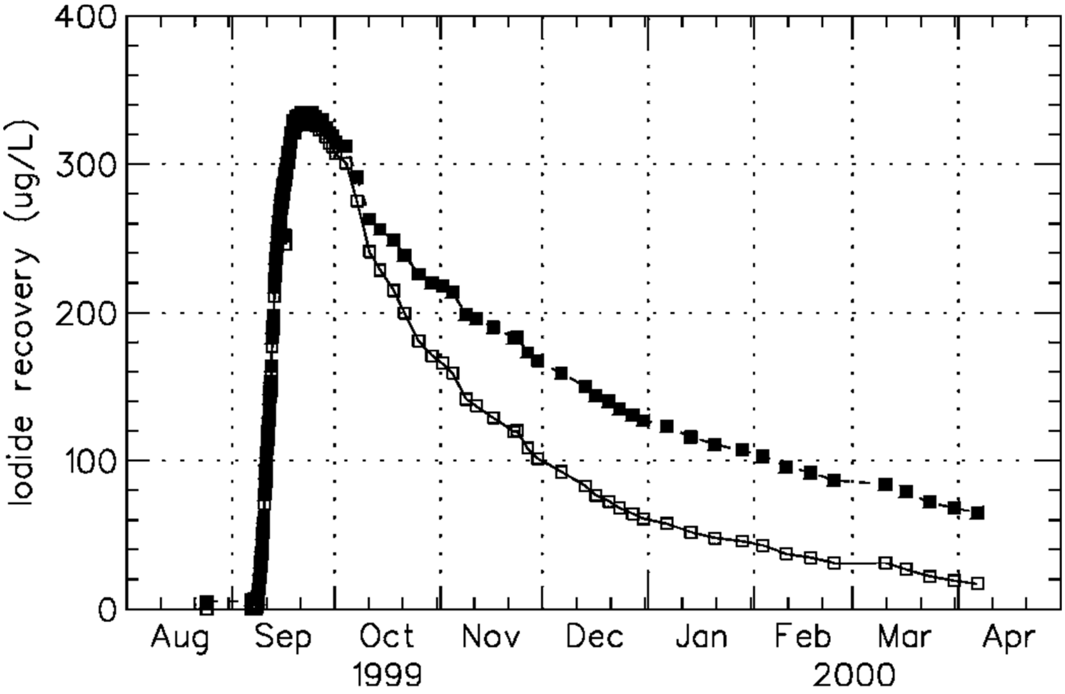

FIGURE 14: Iodide recovery in production well K-21 in the Krafla high-temperature system in N-Iceland, following the injection of 200 kg of KI into well K-22 (from Axelsson, 2011). The test lasted 7 months. The lower curve shows the recovery corrected for the tracer being reinjected (recirculated) after production. About 30% of the tracer was recovered during the test)

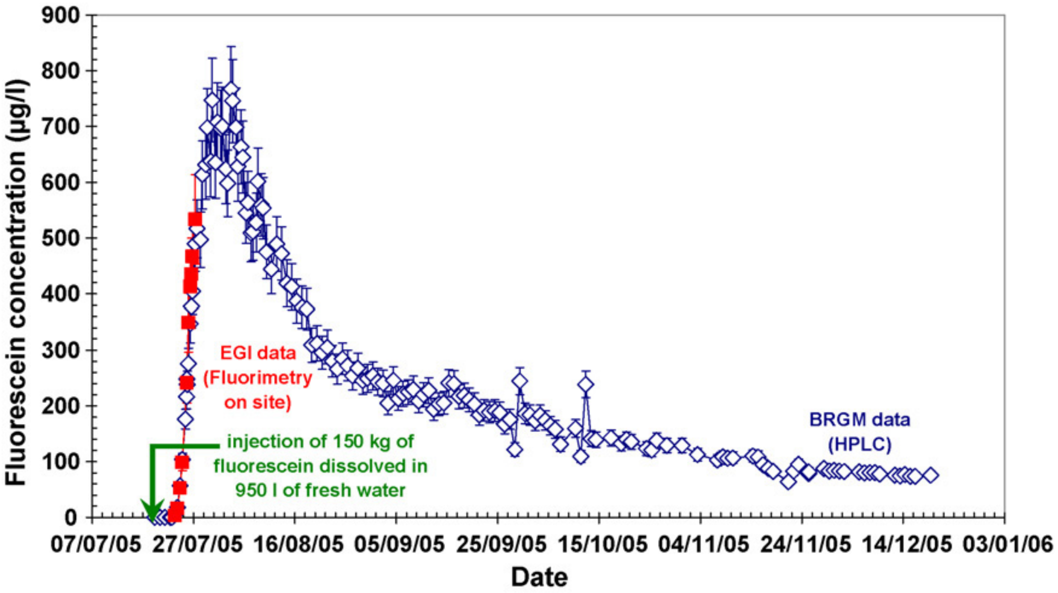

FIGURE 15: Flourescein recovery in well GPK-2 at the Soultz EGS-site in N-France, following the injection of 150 kg of fluorescein into well GPK-3 (figure from Sanjuan et al., 2006). The test lasted 5 months. About 24% of the tracer was recovered during the test

The above are examples of geothermal tracer test data without any quantitative interpretation. Below a specific interpretation method will be presented along with two interpretation examples.

5.2 Interpretation method and examples

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. Axelsson et al. (2005) present a simple and efficient method that may be used for this purpose. It is based on simple models, which are able to simulate the relevant data quite accurately. They are powerful during first stage analysis, when the utilization of detailed and complex numerical models is not warranted. The more complex models become applicable when a greater variety of data become available that may be collectively interpreted.

The method of tracer test interpretation referred to is conveniently based on the assumption of specific flow channels connecting injection and production wells. It has been used to analyse tracer test data from quite a number of geothermal systems in e.g. Iceland, El Salvador, the Philippines, Indonesia and China and consequently to calculate cooling predictions (Axelsson et al., 2005). It has proven to be very effective. This method is based on simple models, which are nevertheless able to simulate the relevant data quite accurately.

The tracer transport model involved assumes the flow between injection and production wells may be approximated by one-dimensional flow in flow-channels. These flow-channels may, in fact, be parts of near-vertical fracture-zones or parts of horizontal interbeds or layers. The 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.

The interpretation method involves simulating tracer return data, such as presented above, on basis of equations presented by Axelsson et al. (2005). The simulation yields information on the flow channel cross-sectional area and dispersivity as well as the mass of tracer recovered through a given channel (equal to, or less than, the mass of tracer injected). In the case of two or more flow-channels the analysis yields estimates of these parameters for each channel. Through the estimates of flow channel cross-sectional area(s) the flow channel pore space volume(s) has (have) in fact been estimated. The tracer interpretation software *TRINV*, included in the *ICEBOX* geothermal software package, can be used for this simulation (Axelsson et al., 2005).

It should be emphasised that this method does not yield unique solutions and that many other models have been developed to simulate the transport of contaminants in ground-water systems, and in relation to underground disposal, or storage, of nuclear waste. Many of these models are in fact applicable for the interpretation of geothermal tracer tests. It is often possible to simulate a given data-set by more than one model; therefore a specific model may not be uniquely validated.

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 method presented above. Retardation of tracers by diffusion from the flow-paths into the rock matrix is neglected. It is likely to be negligible in fractured rock except when fracture apertures are small, flow velocities are low and rock porosity is high.

The main goal of geothermal tracer testing is to predict thermal breakthrough and temperature decline during long-term reinjection, or the efficiency of thermal energy extraction in EGS operations, as already stated. This is dependent on the properties of the flow-channel(s) involved, but not uniquely determined by the flow-path pore-space volume (Axelsson et al., 2005). The heat transfer (cooling/heating) mainly depends on the surface area and porosity of the flow-channel(s). Therefore, some additional information on the flow-path properties/geometry is needed, i.e. geological or geophysical in nature (see also later discussion of recent advances).

To deal with this uncertainty heat-transfer predictions may be calculated for different assumptions on flow-channel dimensions, at least for two extremes. First for a small surface area, or pipe-like, flow channel, which can be considered a pessimistic model with minimal heat transfer. Second a large surface area flow channel, such as a thin fracture-zone or thin horizontal layer, which can be considered an optimistic model with effective heat transfer. Additional data, in particular data on actual temperature changes, or data on chemical variations, if available may be used to constrain cooling predictions.

Figures 16 – 18 present examples of the results of geothermal tracer test analysis using the interpretation method discussed above. The results are only presented briefly here with some numerical findings presented in figure captions. More details can be found in the references cited. Figure 16 shows the fluorescein recovery through a production well in the Laugaland low-temperature geothermal system (reservoir temperature 90-100°C) in N-Iceland, conducted in 1997, simulated by the method presented above (Axelsson et al., 2001). This was during initial reinjection testing in the field, since then reinjection has been part of the management of the system. Figure 17 shows production temperature predictions calculated by a pessimistic model based on the tracer recovery simulation presented in Figure 16. They show that the long-term cooling of the well in question should be minimal, in particular in view of the considerable increase in productivity of the Laugaland system when reinjection is applied (Axelsson et al., 2001).

The final interpretation example is from the Los Azufres high-temperature geothermal system (reservoir temperature ~280°C) in the state of Michoacán in Mexico. It involves interpretation of a tracer test conducted in late 2006 (Figure 18) in which SF_6 was used due to the fact that a steam zone has developed in the system and that production wells involved (NE-part of the field) produce mostly steam (Molina-Martínez and Axelsson, 2011). Cooling predictions based on the interpretation indicate that well AZ-5 may cool as much as 14°C during 30 years of 8 kg/s reinjection into AZ-64 (compared with 21 kg/s production from AZ-5), cooling which is probably not acceptable.

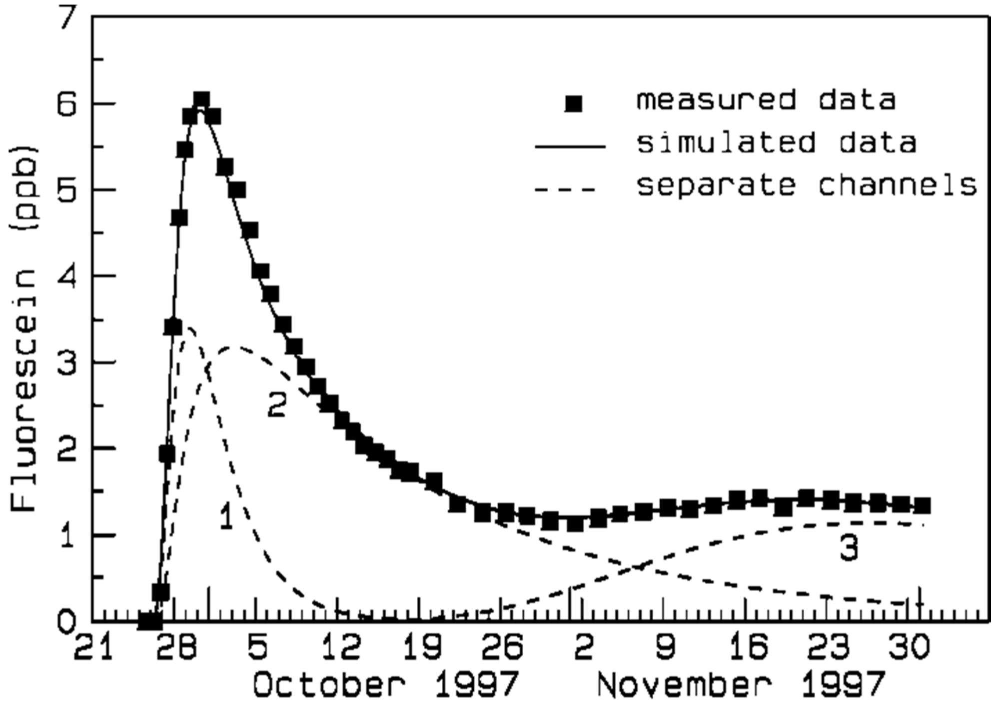

FIGURE 16: Observed and simulated (three flow channels) fluorescein recovery in well LN-12 at Laugaland in N-Iceland during a tracer test in 1997 (figure from Axelsson et al., 2001). Spent geothermal fluid was reinjection into well LJ-08 and production was from well LN-12 about 300 m away. According to the simulation only about 6% of the tracer injected is recovered through this well and the combined flow-channel volume is estimated as 20,000 m^3, assuming 7% porosity

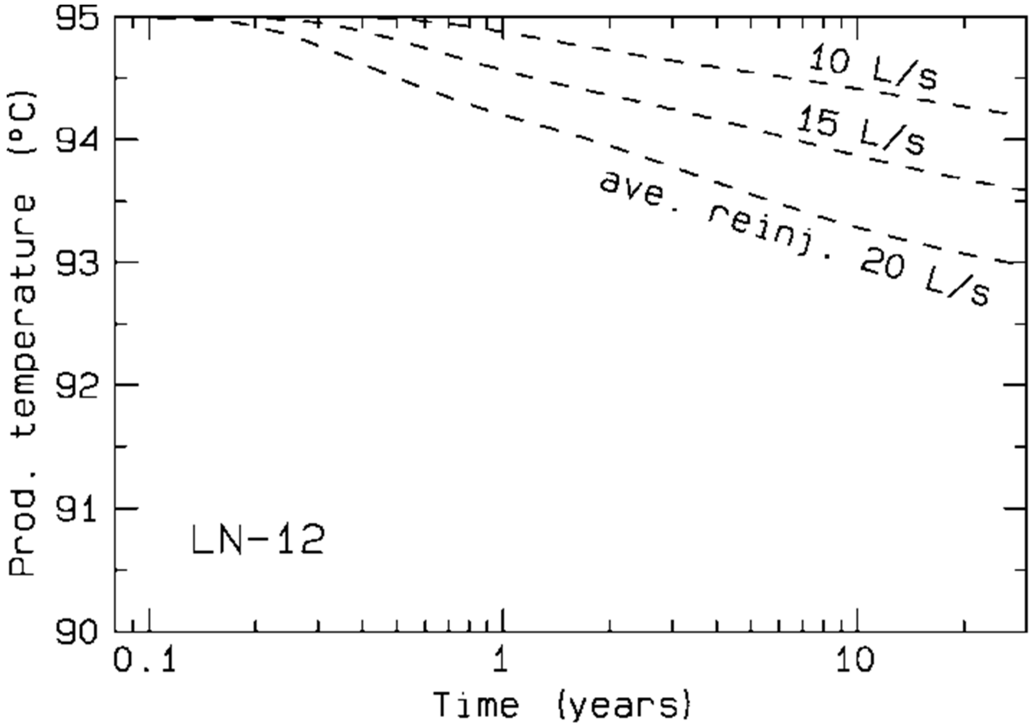

FIGURE 17: Estimated production temperature decline of well LN-12, due to flow through the three channels simulated (Figure 12), for three cases of average long-term reinjection into well LJ-8 and an average long-term production rate of 40 L/s (figure from Axelsson et al., 2001)

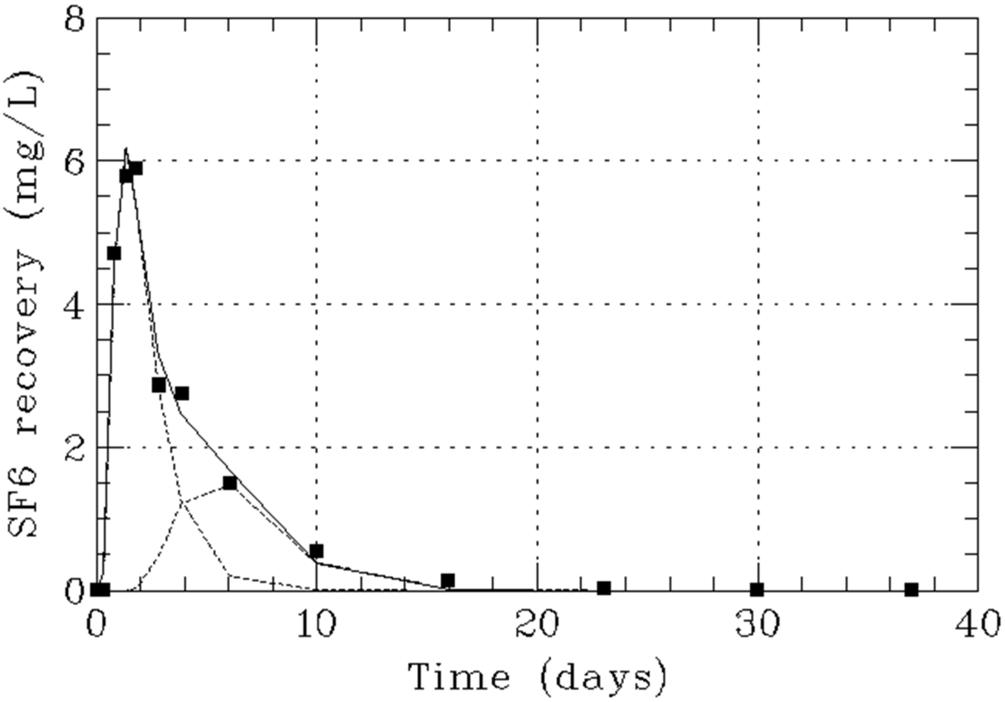

FIGURE 18: Observed and simulated (two flow channels) SF_6 recovery in well AZ-5 in the Los Azufres high-temperature field in Mexico, following injection into well AZ-64 200 m away (Molina-Martínez and Axelsson, 2011). The very rapid recovery is attributed to steam-phase transport. Almost 50% of the tracer was recovered through a combined flow channel volume of 200,000 m^3 (~10% porosity)

5.3 Recent advances

The main uncertainty in reinjection operations and EGS development involves the heat-transfer efficiency of flow-channels between reinjection and production wells. This depends on the surface area of the flow-channels, information which conventional tracer testing using conservative tracers does not yield. Therefore, emphasis has been placed on the introduction of reactive tracers, in particular in EGS-research, as they can provide this information. This includes high-tech tracers such as nano-particles and quantum-dots (see e.g. Rose et al. (2011). By applying two tracers, one conservative and the other reactive, it should be possible to estimate both the flow-channel pore-space volume and its surface area (the transport of the reactive tracer depends on the available surface area as well as the volume).

6. CONCLUSIONS AND RECOMMENDATIONS

This paper reviews the main methods of testing geothermal reservoirs through wells, generally termed well-testing. Both pressure transient testing, which is one of the main tools of geothermal reservoir physics/engineering, and tracer testing are reviewed. Through pressure transient well testing and consequent pressure transient analysis the main reservoir parameters, such as permeability-thickness and storage coefficient, can be estimated along with reservoir boundary conditions (if a test is sufficiently long-lasting). Such estimates consequently provide key information for conceptual model development and revision.

Pressure transient analysis is performed on the basis of appropriate reservoir models and it involves, in fact, model simulation of the pressure transient data collected. Various models are available for this purpose, but most often the well-known Theis model, or variants of that model, are used. Using the Theis model makes it possible to compare results for different wells as well as different geothermal systems, yet the Theis model is based on quite specific assumptions that may not be correct, in particular regarding the reservoir and flow-field geometry (two-dimensional and radial). Therefore, the results of geothermal well-test analyses should be viewed with the model applied in mind. In other words the results are actually model-dependent. Employing different models is therefore recommended during pressure transient analysis, with the conceptual model of the system in question in mind. Using different variants of the Theis model (see above), and selecting the one that best fits the data, is a step in the right direction.

Well tests range from very short step-rate injection or production tests at well completion, via longer production (discharge or pumping), pressure build-up and interference tests to long-term (months – years) reservoir testing, often involving several wells. The longer the test the more valuable the information derived is, because an increasingly larger volume of the reservoir being tested is sensed with increasing test length. Long-term monitoring (mass extraction and pressure in particular) actually constitutes extra long-term pressure transient testing, albeit under uncontrolled conditions (often variable mass extraction). Long-term interference testing provides by far the most important information, as the analysis of single well tests doesn’t yield fully unique parameter estimates.

Tracer testing plays an important role in geothermal research and management, in particular concerning heat-transfer efficiency in reinjection operations and EGS development. Advances have been made in the introduction of new tracers, which both add to the multiplicity of high-sensitivity tracers available as well as being increasingly temperature tolerant. But the geothermal industry needs to follow advances in other disciplines and adopt those which are beneficial. This applies, in particular, to advances in modelling of tracer return data, which has been limited so far, especially modelling of reactive tracer data, which can yield information on flow-channel surface areas in addition to their volumes.

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