Geothermal Art in the N-German Sedimentary Basin: Grafting EGS with Aquifers

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ABSTRACT

The former gas exploration well 'Horstberg-Z1' was the first in the N-German basin to be used for testing single-well, waterbased, proppant-free techniques of petrothermal heat extraction from deep-seated, tight sedimentary layers (Jung et al. 2005). Besides other options tested ('huff-puff', large-scale circulation), maybe the most innovative, interesting, and promising one (Orzol et al. 2005) was that of a so-called 'frac circulation'. It relied on first creating a large-area fracture, primarily by means of massive water injection into a 4 km deep lowly-permeable sandstone layer. This 'waterfrac' was supposed, and confirmed (Wessling et al. 2009, Tischner et al. 2010) to propagate into adjacent tight claystone-sandstone layers, more or less vertically, and become arrested, upwards, within a significantly more permeable sandstone layer. A special wellbore completion provides for 'two wells within one hole': the inner tubing is screened within the waterfrac initiation layer (lowly-permeable sandstone), whereas the wellbore annulus is screened within the waterfrac-arresting layer (more permeable sandstone). Producing / injecting the hot / cold fluid simultaneously through well annulus / inner tubing requires reliable packer technology and sufficient thermal insulation between upwards / downwards circulating fluids.

The memorable waterfrac + tracer test conducted, almost a decade ago, at Horstberg is still inspiring some new answers to 'old' questions like: why single-well? why fracturing? why tracers? does this only work at Horstberg, or can it work almost anywhere else in the N-European sedimentary basin?

Heat and tracer transport within waterfrac and matrix turn out to fit into a surprisingly simple description, as the plain arithmetic sum of certain 'petrothermal'- and 'aquifer'-type contributions, whose relative weighting can vary from site to site, depending upon stratigraphy and wellbore geometry. At Horstberg, within the particular formations tested ('Solling', 'Detfurth', 'Volpriehausen', comprising mainly claystone and sandstone layers), thermal lifetime results to be petrothermally dominated, while tracer residence times appear to be 'aquifer'dominated. Despite this incongruence, thermal lifetime can reliably be predicted from tracer test results. What cannot be determined from 'waterfrac flow-path tracing', is precisely the waterfrac aperture; aperture uncertainty, however, does not impede upon thermal lifetime predictability. Results of a semianalytical approach are confirmed by numerical simulations using a FE model that includes more details of hydrogeological heterogeneity for the Horstberg site.

Projects and People Involved

'GENESYS' stands for 'Generated Energy Systems', a project initiated and implemented by the GEOZENTRUM HANNOVER (BGR, GGA), with long-term funding from the German Ministry for Environment, Nature Conservation and Nuclear Safety (BMU), at the deep boreholes Horstberg (abandoned gas well) and Groß-Buchholz (new well, drilled 2009) in the N-German Sedimentary Basin (NGSB). An overview of project milestones can be found at www.genesys-hannover.de.

BGR is the 'Federal Institute for Geosciences and Natural Resources' in Hannover, Germany.

GGA was (until Dec. 2008) the 'Leibniz Institute for Applied Geoscience', now the 'Leibniz Institute for Applied Geophysics' (LIAG) in Hannover, Germany.

The tracer test at Horstberg (2004) was conducted within the 'GENESYS' project, by a small invited team from the University of Göttingen (Applied Geology Group): tracer injection was executed by Steffen Fischer and Manuela Lodemann, fluid sampling by Jens-Uwe Brinkmann, H. Behrens, I. Ghergut, with kind assistance from Ralf Junker (GGA), Hermann Evers (BGR), Knut Hofmeister (BGR); multi-tracer slug and aliquot preparation, laboratory investigations on tracer behavior, and tracer analyzes were performed by H. Behrens.

What is So Special About Horstberg?

To begin with, 'geothermal art' is not meant humoristically. It does not refer to the packer blockage that occurred in the first GENESYS well, nor to the salt plug that has developed in the second GENESYS well. It refers to a truly successful experiment, a water-frac + tracer test that has generated new prospects for geothermal heat extraction from tight rock by means of single-well techniques, and has substantiated a new view on hydraulic fracturing in deep sedimentary formations.

Since one of the most interesting experiences made at Horstberg is the ability to unite (so to say 'in one well') the advantages of 'petrothermal'-type to those of 'aquifer'-based EGS, let us first briefly recall what this typology is about (Ghergut et al. 2013). In liquid-phase hydrothermal systems, the formation's permeability, times its thickness over which the geothermal wells are screened, is sufficient for ensuring a thermally viable reservoir (with long enough thermal lifetime, whose correlation with fluid residence time is roughly linear, the relative retardation of the cooling front against the tracer front keeping constant in time). Also, the naturally-given permeability is good enough to prevent excessive pressure buildup/drawdown from developing at injection/ production wells, in spite of the strong hydraulic gradients (sharp velocity divergence/convergence) in narrow vicinity of the wells. The latter is not the case in 'aquifer'-based EGS: here, artificial fractures are needed in order to prevent such hydraulic gradients from occurring, as well as to increase the effective cross section for heat transport; whereas the correlation between thermal and tracer



Figure 1. Geologic and physical conditions encountered at the former gas exploration well Horstberg-Z1, compared to those of broad-realm georeservoir exploration for various purposes. This picture is inspired by Legarth (2003, p. 7), who used a similar kind of diagram to circumscribe the geothermal site of GroßSchönebeck.

fronts remains linear, like for hydrothermal systems. In contrast, in 'petrothermal'-type EGS, the geologic formation's permeability is low enough over a large-enough depth interval, to enable large-scale artificial fracturing; thus created, large-area artificial fractures can be crossed by injection/production well-screens in sufficient distance from each other, to provide for a thermally viable reservoir (the thermal-versus-tracer breakthrough correlation being no longer linear, but dominated by a travel-time-quadratic term), these well-screens belonging to either a well doublet, or to a single borehole with appropriate path design and completion.

Figure 1 shows where the geothermal-target layers at the Horstberg well (a former gas exploration well) range within the broader realm of various-purpose georeservoir exploration: with temperatures about 150 °C in 3-4 km depth, and with permeability values spanning a broad range, that nourishes the expectation of both 'aquifer'-based and 'petrothermal'-type EGS. Whereas layers deeper than 4 km (that had formerly been targeted by gas exploration) were found to be unsuitable for heat extraction, fluid turnover operations at Horstberg can enjoy the special amenity of a permeable layer with excellent injectivity in ~1 km depth ('Calcareous Arenite', free from any hydraulic or fluid transport connection to the geothermal-target layers), into which excess fluid outflow occurring during test operations (with temporarily unavoidable fluid turnover imbalance, e. g., outflow at Ows while Jws is shut-in, cf. infra) can be redirected.

Single-well heat extraction techniques are of interest, in these particular physical-geological settings (as highlighted in fig. 1), for two distinct reasons: (i) while it is true that seismic and geophysi-

cal exploration, with decade-long interpretation work (cf. Legarth 2003, Schulz and Tischner 2008, Hördt et al. 2011, Hahne et al. 2012) was successful in producing a consistent large-scale picture of the NGSB, not much is known about reservoir flow and transport behavior (effective values of permeability, hydraulic / transport / geomechanical aperture, and porosity) at the intermediate-to-small space scales involved, for instance, by a geothermal-well doublet; (ii) in many areas, overall permeability seems too low for an 'aquifer'-based power generation scheme, but maybe not low enough for extensive fracturing; once decided to suspend or postpone power generation, and deal only with direct use of geothermal heat, the scale of a 'single-well heat catchment' becomes adequate for such areas. At the single well in Horstberg, we shall deal with a hybrid setting, involving a small 'piece' of a natural 'aquifer', alongside with a large-area artificial fracture.

Heat Extraction From Tight Rock: Single-Well Options

Among the various options (fig. 2) for a single-well procedure of geothermal heat extraction that were tested by the GEOZENTRUM HANNOVER (BGR, GGA) at the borehole Horstberg in the N-German Sedimentary Basin (Jung et al. 2004,

2005, 2006, Orzol et al. 2004, 2005, Tischner et al. 2003, 2004, 2010), maybe the most innovative, interesting, and promising one was that of a so-called 'deep circulation' (DC) system (fig. 3). This relied on first creating a large-area fracture or fault, primarily by means of massive water injection into a deep-seated, lowly-permeable sandstone layer ("Detfurth", 'J', with injection well-screen 'Jws'). This 'hydrofrac' was supposed (and confirmed by pressure signals) to propagate from J into adjacent tight claystone/sandstone layers, more or less vertically (downwards \rightarrow "Volpriehausen", upwards \rightarrow "Hardegsen" etc.), and become arrested within a significantly more permeable sandstone layer ("Solling", 'O', with outflow well-screen 'Ows'), in a upwards distance Hf of about 120 m from J. According to Jung et al. (2004, 2005), Orzol et al. (2005), Tischner et al. (2004, 2010), hydrofrac creation during the 2004 fluid injection sequence at Horstberg proved even more successful than had originally been expected, and the hydrofrac remained open during subsequent shut-in



Figure 3. Simplified representation of DC option for single-well heat extraction from deep tight rock, as was tested in Horstberg 2004. Its two possible versions indicated by arrows "1" or "2" involve a trade-off between hydraulic and thermal (dis)advantages.



(2004 – 2006) and outflow / backflow stages (as realized during 2006 at Ows and Jws, successively).

Figure 2 mentions two further options for a single-well heat extraction scheme, which shall not be addressed in this paper. The 'huff-puff' scheme (middle section of fig. 2) was analyzed in detail by Sulzbacher und Jung (2010). The 'large-scale' concept (lower section of fig. 2) could not be implemented at Horstberg: the existence of a large-scale fault zone not far away from the well seems beyond doubt, but a fluid transport connection to it could not be established so far.

To be noted, in the DC scheme, simultaneously injecting / producing of cold / hot fluids through a single well's inner tubing / annulus requires reliable packer technology and sufficient thermal insulation between downwards / upwards circulating fluids (which is quite a demanding material-technical issue, that could not be fully solved at Horstberg). On the other hand, the DC scheme, involving only monotonous operation with smooth pressure changes (once the frac was created) and slow, long-term cooling, is preferable against the 'huff-puff' scheme, in that it avoids a cyclic thermo-mechanical loading on wellbore casing and surrounding rock, whose long-term effects are difficult to predict but are being unanimously regarded as 'undesirable'. A slight disadvantage of the DC scheme, however, is that fluid residence times within the reservoir (between Jws and Ows) cannot be chosen by desire – unlike in the 'huff-puff' scheme, where the fluid residence time is a design parameter.

Tracer Test During DC Experiment

The DC experiment (fig. 3, arrows "1") was accompanied by a tracer test, involving the injection of a multi-tracer slug at Jws, and sampling the fluids produced at Ows. Tracer test design, execution and results were presented and discussed by Behrens

Figure 2. Simplified

representation

of 3 options for

single-well heat

extraction from

deep tight rock,

as were tested in Horstberg during

2003 - 2004:

(i) large-scale

circuulation with

presumed fluid

connection to a nearby fault zone;

(ii) "huff-puff"

into/ from arti-

fracture; (iii)

ficially-induced

so-called "deep circulation" (DC)

through artifi-

cially-induced

piece of more-

permeable layer

at the upper end of the fracture.

fracture and small

et al. (2006), Ghergut et al. (2009). The measured tracer signals provided some information about fluid transport behavior that could not have been derived from pressure signals alone. This is even more to be valued, as microseismic and geophysical monitoring did not yield detectable signals during hydrofrac operations (reasons being explained by Jung et al. 2006), nor was downhole temperature measurement feasible during or after those operations.

Basically, tracer test results have (i) proven the existence of a fluid transport connection between Jws and Ows, which can be attributed unambiguously to a large reservoir (and not to some wellbore shortcut, or alike); (ii) allowed to estimate some of the reservoir's sizing-relevant parameters (determining its thermal lifetime); (iii) revealed the dual nature of (flow and) transport processes within the reservoir, providing some evidence for either (or both) highly-dispersive large-scale flow within the waterfrac, and significant exchange between im-/mobile fluid regions at and within the rock matrix, with pronounced kinetic (non-equilibrium retardation) character. In the sequel, tracer test results shall be re-examined with regard to their relevance for thermal lifetime prediction.

Principle Model, and Main Parameters

The principle model used in this paper (for the purposes of correlating thermal lifetime to tracer signals) relies on a drastic simplification: all hydrogeological details that preexisted or were 'created' after fracturing in 3 - 4 km depth at the Horstberg well can be condensed into three main units (fig. 4), namely: (i) a more or less vertical, large-area fracture, within (ii) a rock matrix unit (mainly claystone) treated as impermeable, adjacent to (iii) piece of an 'aquifer' layer, of limited thickness and length (within the "Solling" sandstone, <20 m thickness, <10 m length).

Unlike in the 'huff-puff' configurations (whose design was analyzed numerically by Sulzbacher and Jung 2010), flow and transport in the DC configuration are essentially 3-D (not reducible to a 2-D flow and transport problem). The DC problem only allows for halving the size of the model domain (once or twice)



Figure 4. Principle model of DC in the hybrid (petrothermal + 'aquifer') system at Horstberg, and its main transport parameters.

by virtue of assumed symmetries (w. r. to one or two planes).

The transport behavior (fig. 5) of this system is determined by 5 geometric parameters (waterfrac height Hf taken between Jws and Ows, waterfrac half-length Lf and aperture wf, 'aquifer' layer thickness Ha, distance Xa between Ows and the waterfrac intersection with the 'aquifer' layer), one dynamic flow parameter $Rf \rightarrow a$ ('focus' or 'capture angle', as defined by fig. 4), and only one out of all hydrogeological parameters, namely the 'aquifer'layer porosity Φa . Parameters Hf and Ha are predetermined by stratigraphy and by well-screen length within the 'aquifer' layer. Parameter wf is pressure-dependent, under constant pressure it is hydrogeomechanics-determined, and under steady flow conditions it can be assumed as approximately constant (as long as aperture changes induced by water-rock interactions or by THMC processes remain negligible). Parameter Xa results from hydrofrac orientation (local stress field) and the deviated well path. Parameter $Rf \rightarrow a$ is essentially unknown; under steady flow conditions, it corresponds to the outflow/inflow rates ratio. To be noted, steady flow conditions could neither be reached, nor had they been expected at the Horstberg well, given the massive fluid injection that took place prior to the tracer test. Therefore, using injection and outflow rate values as monitored during the tracer test cannot provide a reliable measure for $Rf \rightarrow a$.

Tracer-Based Prediction of Thermal Lifetime

The thermal lifetime of the three-compartment system defined by fig. 4 can be estimated as the sum of four distinct contribu-



Figure 5. Main transport processes (determining thermal drawdown and tracer signals) in the hybrid (petrothermal + 'aquifer' system (fig. 4) during DC.



Figure 6. Numerically simulated thermal drawdown (outflow temperature evolutions), using the FE model depicted by figure 7.



Figure 7. Assumed hydrogeological parameters of FE model used for simulations of fig. 6.



Figure 8. Measured breakthrough signals at Ows for two conservative tracer species with slightly different diffusion behavior; and provisional interpretation.

tions, namely the longitudinal (advective) and the lateral (diffusive) heat-exchange contributions from waterfrac and 'aquifer', respectively. Strictly speaking, this linear addition of advective and lateral-diffusive contributions is only applicable for systems with constant heat exchange area density (area-per-volume ratio), according to Pruess and Bodvarsson (1984). Though at the Horstberg well this restriction was clearly violated, approximating thermal lifetime as the sum of longitudinal and lateral contributions was found to still be adequate, in surprisingly good agreement with numerical simulations (fig. 6) of thermal drawdown performed on a more detailed hydrogeological model (fig. 7). From further analytical considerations, this plain summation appears to remain valid as long as the 'aquifer' thickness is much smaller than waterfrac height.

Similarly, fluid residence time between Jws and Ows can be estimated as the plain sum of advective travel times within waterfrac and 'aquifer'. While the thermal lifetime needs to be predicted before waiting for thermal drawdown to occur, the fluid residence time is supposed to be directly measurable by a tracer test (as was conducted in Horstberg in December 2004 and described by Behrens et al. 2006), namely in terms of tracer 'arrival time'. Notably, in spite of the relatively short duration of the tracer test at Horstberg (~10 d), the measured tracer 'arrival times' are strongly affected by retardation, caused by non-advective processes like matrix diffusion (at waterfrac-claystone) and 'intra-particle' diffusion (within the "Solling" sandstone laver): in more general terms. they are affected by (kinetic or equilibrium) exchange between im-/ mobile fluid regions. Thereby resulting retardation cannot be neglected, thus the measured tracer 'arrival times' (fig. 8) need to be corrected, in order to provide an estimation of the purely advective travel time (assumptions and methods for performing this correction were discussed in Ghergut et al. 2009). In the sequel, Ttracer denotes the corrected value of mean residence time (MRT), assumed to be identical to that of the fluid itself, i. e. determined solely by advective processes.

In order to use tracer test results for thermal lifetime prediction, it is useful to express the correlation between fluid MRT and thermal lifetime in terms of quantities derivable from tracer test signals. Alongside with the corrected residence time T^{tracer} , the focus angle $Rf \rightarrow a$ is a further parameter that can only be measured by tracer tests. Since the outflow/inflow rates ratio cannot be used as a measure for $Rf \rightarrow a$ (for the reason explained in the preceding section), we suggest to use the tracer's asymptotic recovery instead. Here again, we face a nontrivial issue: extrapolating the measured values of relative recovery of tracer mass from finite to infinite times. Extrapolation is always model-dependent, i. e, some assumptions need to be made regarding matrix diffusion, 'intra-particle diffusion', etc. (cf. discussion in Ghergut et al. 2009). The values of parameters composing the coefficients that multiply tracer-test output quantities T^{tracer} and $Rf \rightarrow a$ in the thermal-tracer correlation cannot be known exactly; rock thermal capacities, thermal diffusivities etc. are difficult to measure in-situ. However, these coefficients can be roughly estimated with sufficient certainty. Further, taking into account that the Horstberg well is only slightly deviated, with "Solling" layer thickness being considerably smaller than waterfrac upward height, thermal lifetime is found to be determined by mainly two contributions (out of all four contributions mentioned above). Thus, the cooling front advances transverse-diffusivelydominated within the waterfrac, and advectively-dominated within the 'aquifer' layer. Remarkably, waterfrac aperture *w*f no longer appears explicitly in the thermal-tracer correlation, though being the major parameter of diffusive heat exchange between waterfrac and rock matrix.

Using the values of Ttracer and Rf \rightarrow a derived from measured tracer signals (fig. 8), we get a thermal lifetime in the order of 110 days, which is in good agreement with the results of numerical simulations of thermal drawdown (fig. 6), the latter using a FE model that also accommodates more details of hydrogeological heterogeneity in the depth interval between "Detfurth" and "Solling" (fig. 7). A thermal lifetime in the order of 3 months seems sufficient for the intermittent use of heat generally endeavored by the GENESYS project.

How Much 'Petrothermal', How Much 'Aquifer'?

A closer look at the distinct lifetime contributions in the thermal-tracer correlation reveals the following relative weightings, for the Horstberg case: fluid and tracer spend 60× more time in the 'aquifer', than in the waterfrac. Advectively, the cooling front advances even 420× slower within the 'aquifer', than within the waterfrac. In contrast, its retardation by transverse-diffusive exchange is 150× stronger within waterfrac, than within 'aquifer'. This transverse-diffusive retardation is the reason why thermal lifetime finally results to be waterfrac, than from the 'aquifer'. On the other hand, the waterfrac and 'aquifer' contributions to thermal lifetime are closely interrelated, via the parameter $Rf \rightarrow a$ (focus angle, or flow capture angle, cf. fig. 4).

The Horstberg Message

The Horstberg experience has demonstrated how the 'pure waterfrac' technique can be successful also in sedimentary layers where one would expect to need the more expensive hydraulic+proppant and chemical fracturing techniques.

A major advantage of the DC scheme is to avoid those cyclic thermo-mechanical loads on wellbore casing and surrounding rock, that were inherent to the 'huff-puff' scheme. Technically challenging, with the DC scheme, is the need for good thermal insulation downhole (between well annulus and inner tubing), as well as proper hydraulic uncoupling between two well-screens within one hole (Jws and Ows).

The thermal lifetime of the DC 'reservoir' created at Horstberg turns out to be frac-dominated, while tracer signals are 'aquifer'dominated. Nonetheless, thermal lifetime is predictable from tracer signals. Not determinable from tracer signals is precisely the transport-effective frac aperture, but thermal lifetime is largely independent of it (or, rather, it can be expressed in terms of tracerderived quantities such that frac aperture no longer occurs as an independent parameter). The waterfrac being still 'open' (without proppants), further experiments, including tracer tests, look feasible, and would be very welcome at the Horstberg site (cf. fig. 3, arrows 1/2/3/4).

Horstberg is Special, But Not Unique – it Can Be Repeated Elsewhere in the NGSB

The DC operation scheme that was successfully tested at Horstberg can be regarded as the small-scale (single-well) version of a 'deep aquifer' system, in the sense of the '**gebo** benchmark-model' typology defined and investigated by Hördt et al. (2011), Hahne and Thomas (2012). Parameter sensitivity analyzes with regard to Hf, Ha, Xa, and $Rf \rightarrow a$ enable to evaluate the applicability of the DC concept (as tested at Horstberg) to other geological settings of the NGSB, in which a deviated well crosses at least one fairly-permeable rock layer ('deep aquifer'), bounded by tight layers of sufficient thickness Hf.

Whereas parameter *X*_a can be 'chosen' (before/during drilling) and parameters Ha, $Rf \rightarrow a$ can be influenced (via fluid injection rates Qin) to a certain extent, parameter Hf is prescribed by stratigraphy and in-situ stress conditions. Once the well was drilled and the suitable layers and well-screens (Jws and Ows) identified, Xa can no longer be modified, either. Influencing $Rf \rightarrow a$ via Qin enjoys very little freedom, as Qin is bounded from below by economical requirements (the minimum-desired outflow rate), and it is bounded from above by technical and material constraints (the maximum sustainable wellhead pressure). Also in terms of X_a , since pressure buildup at Jws will ~linearly increase with Xa, there will exist an upper bound Xmax dictated by the maximum sustainable injection pressure (which in turn is associated with energy costs). Thus, a fundamental problem with any single-well DC scheme is that (i) parameter $Rf \rightarrow a$ cannot really be controlled by desire; (ii) parameter Xa cannot be known with certainty before drilling, being a matter of 'lucky guess', or of highly-performant MWD, and it can no longer be changed once the borehole has been drilled.

If, after drilling and fracturing and DC testing, thermal lifetime, as predicted by tracers, turns out to be lower than was originally expected, a reasonable workaround is to use DC only intermittently (with periodic interruptions, say, during summer, weekend, and/ or night hours). In order to identify optimal periodic operation schemes (analogously to Sulzbacher and Jung 2010 for 'huff-puff' schemes), tracer tests can provide valuable information on the transport-effective values of wf, Ha, and Xa (which may depend upon the operation regime; further, wf may also change with time, during reservoir operation and shut-in stages, by virtue of midterm induced THMC processes). Tracer tests can be conducted during DC from Jws to Ows or the other way round (flow-path tracings "1", "2" in fig. 3), as well as in single-screen push-pull configurations at Jws and at Ows, resembling the 'huff-puff' operation (arrows "3", "4" in fig. 3), but for the purpose of DC characterization and (prospective) estimation of thermal lifetime.

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