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A Tracer Test on Well IDDP-2, Reykjanes, Iceland

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ABSTRACT

By drilling holes to about 5 km depth, the Iceland Deep Drilling Project (IDDP) intends to evaluate whether energy extraction from deep geothermal resources at supercritical conditions is feasible. Well IDDP-1 was drilled in Krafla but hit magma at about 2100 m depth and was not drilled deeper. Well IDDP-2 is planned at Reykjanes and at the end of drilling an injection test will be performed during which a tracer test is planned to establish whether there is a connection between the deep environment and the 1000-2500 m deep geothermal system that is already being produced in the area.

Molecular tracers that have been shown to be stable at the high temperatures (380-600°C) anticipated in the IDDP-2 well are not known and therefore elemental radioactive tracers will probably be used. Informal collaboration has already been established between the IDDP Chemistry Group and research teams in the US, Switzerland and New Zealand that have experience in using radioactive tracers for geothermal investigations. Current plans involve using ^{85}Kr as a vapour phase tracer, ^{3}H in H_2O as a vapour and liquid phase tracer and ^{125}I as a liquid phase tracer.

1. INTRODUCTION

The Iceland Deep Drilling Project (IDDP) plans to drill 5 km into an active mid-ocean ridge hydrothermal system to investigate its temperatures and pressures, its permeability structure and the composition of its fluids and rocks.

In 2007 the three Icelandic power companies announced their commitment to drill at their own cost a 3.5–4.0 km deep well in each of the three geothermal fields operated by them, Krafla, Hengill and Reykjanes. These wells were to be designed so that they would be suitable for deepening to 4.5–5.0 km. The deepening of one of these wells as a joint IDDP project would then be funded by the energy consortium,with additional funds from the International Continental Scientific Drilling Program (ICDP) and the US National Science Foundation (NSF). The first well in the series, IDDP-1, was drilled in 2008–2009 in Krafla, NE-Iceland (Elders et al., 2014a). The drilling had to be terminated at 2.1 km depth when it intersected >900◦C magma (Friðleifsson et al., 2010). HS Orka has decided to continue the IDDP program by seriously considering the drilling of well IDDP-2 at Reykjanes (Fridleifsson et al., 2014). The implementation of that decision, however, will depend to large extent upon the HS Orka plan to expand the Reykjanes Power Plant from the current 100 MWe up to 180 MWe. The IDDP-2 deep drilling is contemplated late in the drillhole sequence of additional production wells for the expansion plan.

2. THE REYKJANES GEOTHERMAL SYSTEM

The Reykjanes geothermal area is situated in the extreme SW of Iceland, about 50 km southwest of Reykjavík (Figure 1). There is history of episodic hot spring activity there from early times (Friðriksson et al., 2010). Exploration of the area started in 1956. An areal extent of 10 km^2 for the Reykjanes geothermal system has been suggested (e.g. Karlsdóttir et al. 1997) whereas surface manifestations only cover about 1 km^2. The geothermal system is not restrained to the SW and it is quite likely that it extends a considerable distance in that direction below the sea-floor on the Reykjanes Ridge which is a projection of the Mid-Atlantic Ridge. Figure 2 shows a simplified geological map of the area, the location of present wells and the proposed IDDP-2. The lavas are mostly Holocene, NSW trending subglacial hyaloclastite ridges less than 20000 years old stick out along the centre of the peninsula. Eruptive fissures are found on both sides of the ridges; the older ones on the east side and the younger ones on the west side where the most recent eruption took place in 1226 AD (Sæmundsson, 2011).

The Reykjanes field gives a unique insight into a submarine geothermal system. The geological succession depicts a steady buildup of volcanic strata within a submarine environment (Franzson et al., 2002; Franzson, 2004; Friðleifsson and Richter, 2010). The stratigraphic units from 3 km depth up to some 1400 m are dominantly composed of pillow basalt formations, interpreted to have erupted in relatively deep waters (Franzson, 2004). A few, apparently subaerial lavas of Pleistocene age, occur in the stratigraphic sections in some wells at ca. 1100 m depth. From there up to ca. 400 m depth the eruptive units are characterized by relatively shallow-water lithology composed of phreatic tuffs interbedded with shallow marine fossiliferrous sediments. From there up to ca. 60 m depth, sub-glacial and/or submarine hyaloclastite formations characterize the stratigraphic succession, while the youngest of these form low profile hyaloclastite ridges extending through a Holocene lava flow series (Figure 2). From the lithology, the subsidence rate was estimated to average 0.6 cm/year (Friðleifsson and Richter, 2010), while the extension rate of the slow spreading Reykjanes ridge is about 1.8 cm/year. The intrusive rock intensity within the sheeted dike complex varies but often the dikes occur in relatively dense dikeswarms, 100–200 m thick, with intervening intervals of dike-free pillow basalt (Fridleifsson et al., 2005; Helgadóttir et al., 2009). The volcanic activity acts as a heat source for the geothermal system since considerable portions of the magma cools within the system as intrusions. Frequent, but generally small, earthquakes cause movements on the fractures and maintain good permeability.

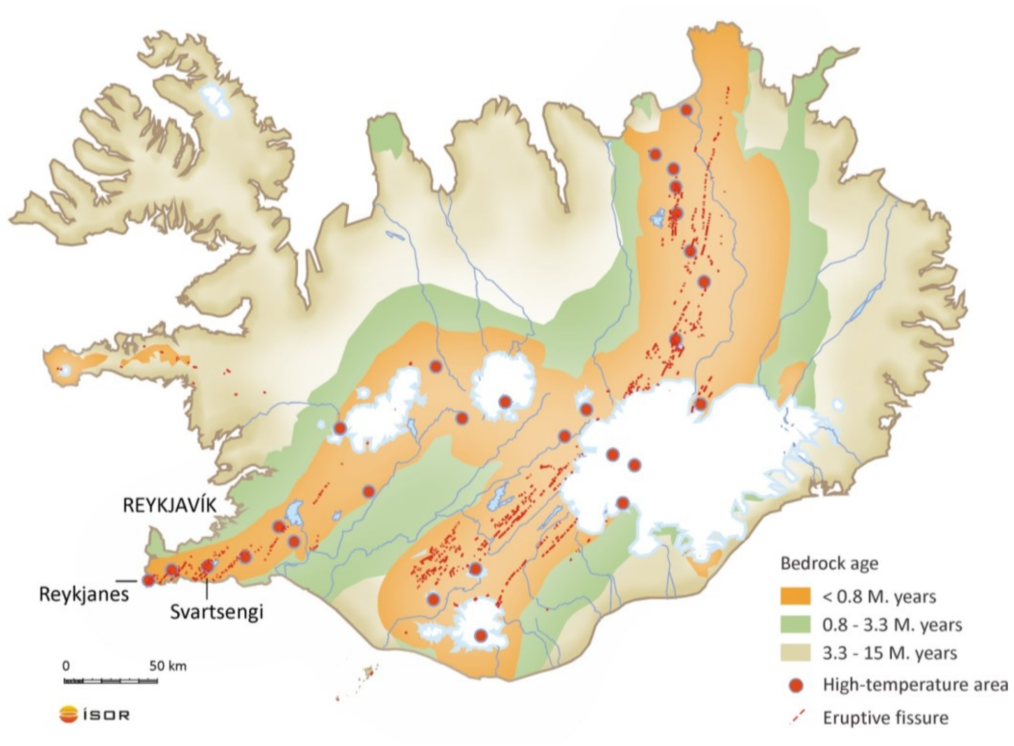

Figure 1. Schematic geological map of Iceland, showing the location of the Reykjanes geothermal area (after Sæmundsson 1986)

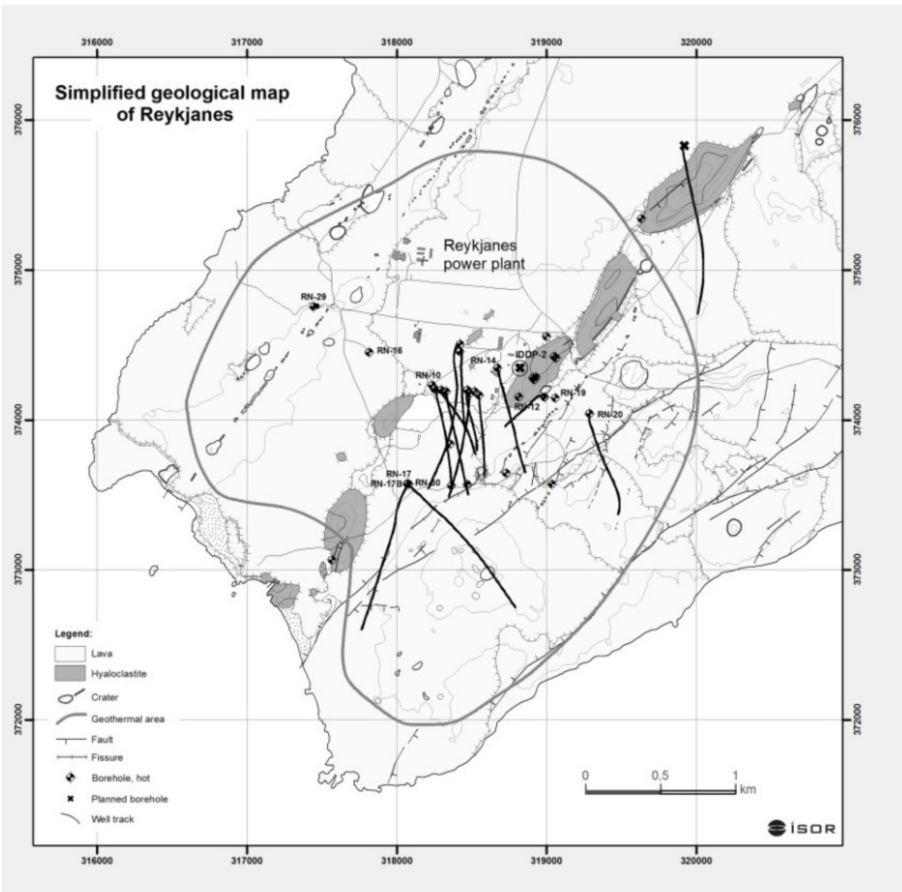

Figure 2. A simplified geological map of the Reykjanes area, showing the locations of boreholes and the proposed site for IDDP-2 (From Sæmundsson 2011)

The alteration pattern is characterized by zeolite and greenschist facies mineralogy. Quartz and epidote occur at an exceptionally shallow depth in places, representing fossil Pleistocene thermal condition within the geothermal system, when an ice-sheet added to the hydrostatic pressure, enabling quartz and epidote to form at shallow depths at temperatures 180◦C and >230°C respectively. The present-day saline hydrothermal system was at that time fed by meteoric fluids, as seen from isotope and fluid inclusion studies (Sveinbjörnsdóttir et al., 1986; Franzson et al., 2002; Pope et al., 2009). Smectite-zeolite facies mineralogy occurs from the surface down to the epidote zone. Epidote and mixed-layered-clays may coexist from there down to 500 m depth or so, where a chlorite-epidote zone takes over down to ca. 1200 m, followed by an epidote-actinolite zone down to 3 km depth.

Within the drill field, from approximately 700 m down to about 1000 m, temperature and pressure follow the boiling point curve. Below 1100–1200 m depth, the Reykjanes system is liquid-dominated with temperature rising along an adiabatic thermal gradient from about 270–290°C to 320 C in a freely convecting hydrothermal system. This extends down to 2.5 km depth, at least, but with increasing depth the temperatures are expected to rise towards magmatic temperatures. The highest temperature recorded so far is ~ 345°C, from the bottom of well RN-17B at about 2800 m true vertical depth (TVD), and from 2250 m (TVD) depth in RN-30.

The results of magneto-telluric (MT) soundings suggest a low resistivity cap underlain by a high resistivity core for the uppermost 2 km as well, as well as a low resistivity column down do 6–8 km depth, with a zone of lower resistivity within the high resistivity core at 2–6 km depth. The zone is under the center of the geothermal field and has an elongated shape in the NE-SW strike direction. This zone of lower resistivity within the high resistivity core is thought to indicate a zone of better permeability and/or higher temperatures (Karlsdóttir et al., 2012). The interpretation of earlier seismology studies (Fridleifsson et al., 2003) suggested that the depth to the brittle/ductile boundary is close to 6 km, semi-brittle depth 4–5 km, and the extrapolated temperature at 5 km depth close to or above 575°C.

Sveinbjörnsdóttir et al. (1986) and Kristmannsdóttir and Matsubaya (1995) have studied the isotopic (δD, $\delta^{18}O$) composition of the fluids and minerals of the system and related to alteration mineralogy. The former conclude that for a part of the history of the Reykjanes geothermal system, its deeper part has been dominated by meteoric water, rather than seawater, circulation, which probably reflects melt-water input or changing sea-level during glaciation. Thus they warn against attempts to use as a model for sea-floor hydrothermal metamorphism without extreme caution the Reykjanes system. The latter state that their results are compatible with an origin in a mixture of seawater and fresh groundwater with about 80% of the present salinity of Svartsengi-Eldvörp brine followed by evaporation, or alternatively the reaction of brines with sheet-silicates formed at a stage of more dilute water, may have changed their isotope ratios. Lonker et al. (1993) concluded that at an earlier stage the system was hotter and meteoric, possibly glacial melt-water. They suggest that the system is cooling due to heat source decay, cooler water incursions, or both.

The most important deviations from seawater chemistry are magnesium and sulphate depletion and increases in silica, potassium and calcium concentrations all to be expected at high temperatures. The gas concentrations show CO_2 to be the major gas but relatively low H_2S concentrations compared to fluid from many other geothermal areas. There is a significant N_2 concentration suggesting that flow from the surface contributes to the fluid. The H_2 and CH_4 concentrations are relatively low, the H_2 concentration reflecting the temperature of the aquifers and the CH_4 concentration suggesting that little or no gas is derived from organic remains in the area. Downhole scales of iron-magnesium-silicates have been observed while metal sulfides with high contents of precious metals have been precipitated at the wellhead in producing wells (Hardardóttir, 2011).

3. RECENT TRACER TESTS IN KRAFLA AND REYKJANES

In general, three types of tracers are used in geothermal systems, i.e *liquid-phase tracers* mainly halides such as iodide (I) or bromide (Br), radioactive tracers such as iodide-125 (^{125}I) and iodide-131 (^{131}I), fluorescent dyes such as fluorescein and rhodamine, aromatic acids such as benzoic acid and naphthalene sulphonates; *steam-phase tracers* mainly fluorinated hydrocarbons such as R-134a and R-23, the PFC compounds and sulphur hexafluoride (SF_6); and *two-phase tracers* mainly tritium (^3H) and alcohols such as methanol, ethanol and n-propanol

In 2013, a tracer test was performed in Krafla. Tracers were injected into 3 wells, i.e KG-26, the main reinjection well in the area, KJ-39 which had hit magma at about 2400 m depth and IDDP-01. Three liquid-phase (the naphthalene sulphonates 2-NMS, 2.6-NDS, 2.7-NDS), three vapour-phase (the perfluorocarbons PMCP, PMCH, PDMH) and two two-phase (the alcohols ethanol and methanol) tracers were tested. Twenty production wells were monitored. The most important results were that alchohols were observed in most wells but their returns were difficult to interpret due to irregular returns, chemical breakdown, high background values and phase changes in the geothermal system. Naphthalene sulphonates and perflouorocarbons were only found in one or two wells and the paths of those observed seemed to be at a shallow level so they do not seem suitable for tracing deep, hot fluids (Júlíusson, 2014).

In 2013, a two-phase tracer test was carried out by injecting methanol and 2,7 NDS into well REY-20 and, in 2014, a liquid-phase tracer test by injecting 2 NS into well REY-33 (Figure 2). The tracers were recovered from 6 production wells with returns ranging from 0.2 to 5.5% in individual wells and a total return of 8.9%. It seems likely that a substantial part of the problem in Reykjanes is the breakdown of tracers at high temperatures but an indication of the amount of tracer needed for adequate return from the shallow system was obtained (Matthíasdóttir et al., 2015).

4. PROPOSED TRACER TESTS WITH INJECTION INTO IDDP-2

From Rose's work (Figure 3) and the results of the above tests, it was concluded that chemical compounds such as naphthalene sulphonates and perfluorocarbons are unsuitable for tracer work at the high temperatures encountered in the IDDP wells. Thus, it was decided that radioactive tracers preferably elemental ones should be sought. A literature search was conducted and in IAEA (2004) there is a summary of radioactive water and gas tracers that have been used in oil reservoir examination. These were studied with reference to possible use in the present application and those selected as possibilities are listed in Table 1.

Further search showed that the same tracers had been tested in geothermal work and experienced people within the industry were contacted. After deliberations, it was decided that a two-phase tracer test with tritium and a vapour-phase tracer test with ^{85}Kr

would be optimal. Checks of the licenses for the use of radioactive tracers revealed that the regulations regarding the use of radioactive substances in Iceland are not particularly strict and decisions are based on individual cases. There is a government body, The Radiation Protection Agency, that receives data in each case and issues utilization licenses and import licenses or declines issuing such licenses based on the application. This agency has recently issued both a utilization license and an import license to another project, the Carbfix project, in which the sequestration of carbon dioxide by basalt is being studied, for using ^{14}C as a tracer. These licenses are for the insertion of 740 MBq.

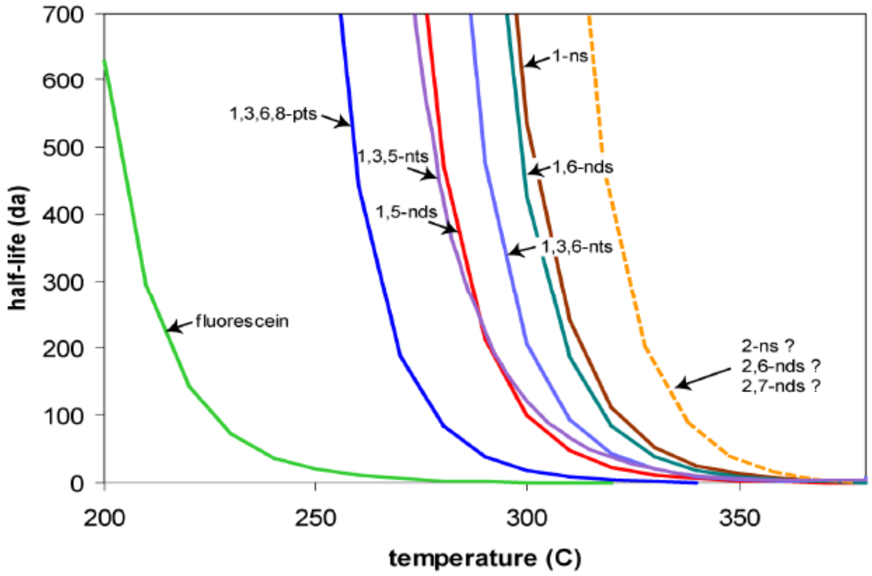

Figure 3. Breakdown of fluorescein and various naphthalene sulphonates as half-lives at different temperatures (P. Rose, pers. comm.)

Table 1. Some common radioactive tracers used in oil reservoir examinations (After IAEA 2004)

Tracer	Phase	Half-life	Radiation characteristics	Comments
^{3}H	Liquid + vapour	12.32 a	β^- (18 keV)	Generally applicable
$^{36}Cl^-$	Liquid	3×10^5 a	β^- (709 keV)	EMS analysis. High background concentration
^{125}I	Liquid	60 d	γ (35.5 keV), e^-	Reducing conditions. Relatively short half-life
^{131}I	Liquid	8 d	β^- (606 keV), γ (364.5 keV)	Reducing conditions. Short half-life
$^{22}Na^+$	Liquid	2.6 a	β^- (545 keV), γ (1274.5 keV)	Slight sorption. High background concentration
$^{134}Cs^+$	Liquid	2.065 a	β^- (658 keV), γ (604.7 keV, 795.8 keV)	Sorption on clays
$^{137}Cs^+$	Liquid	30.2 a	β^- (512 keV), γ (661.6 keV)	Sorption on clays
^{85}Kr	Vapour	10.76 a	β^- (687 keV)	Long successful history
^{133}Xe	Vapour	5.25 d	β^- (346 keV), γ (81 keV)	Short half-life
^{127}Xe	Vapour	36.4 d	β^- (202.9 keV), γ (172.1 keV ,375.0 keV)	Relatively short half-life

From the results of the chemical tracer tests at Reykjanes described above, the conclusion was reached that to obtain a response for the flow from the system at 4-5 km depth to the shallower system at 1-3 km depth, the use of at least 5 Ci of radioactive tracer such as tritium should be implemented. Joe Beall, who has a long experience in the use of tritium in the Geysers area, California commented that a large unknown in all this is what the storage capacity is of the formation between the depth of IDDP-2 and the currently productive reservoir and since tritium is a very safe tracer due to its exceptionally low decay energy, a large tritium activity in a large volume of water should be injected. Individual injection well tritium tracer tests at The Geysers have generally used a 10 Ci slug injected with 400-500 gpm (about 30 l/sec) over a period of about 4 hours. This would allow for a relatively large volume of porosity between the injection zone and the producing reservoir. His conclusion is: "I have to think that these IDDP wells are "once in a lifetime" opportunities to explore deep into a high temperature thermal zone. Consequently, I would hate to be left wondering if the tracer test utilized enough volume and activity to find its way to the producing reservoir." This large slug will certainly give a good chance of observing the tracer in produced fluids. Daily samples should be collected over the first month or so. They need not all be analyzed. Initially for example, samples from Day 15 and Day 30 could be analyzed. Depending on when the tracer shows up, additional samples can be run to narrow the breakthrough timing.

Joe Beall has furthermore recommended the firm ProTechnics, a Division of Core Laboratories Ltd. to supply and implement the injection of the tracer and they have confirmed that they can supply such a quantity of tritium. Furthermore, he has recommended Tracer Technologies International for the analysis of tritium and they have made an offer.

For the use of ^{85}Kr, Roland Purtchert of the Physics Institute, University of Bern, Switzerland, where there is extensive experience of ^{85}Kr use in connection with work on radioactive waste, has acted as an adviser. He has prepared a plan involving background determinations of Kr, the insertion of 25-40 MBq in the form of ^{85}Kr, spiking of samples with ^{85}Kr-free Kr gas followed by Kr separation by GC, and finally determination of the ^{85}Kr AC by low level counting. Statistical analysis completes the process.

At a meeting of the preparation group, it was suggested that complete information about the flow from the deep system to the presently drilled area would not be obtained unless a liquid-phase tracer were injected too. After further study and a reference to Table 1, the most convenient tracer was deemed to be ^{125}I. Neither of our advisors had experience with this tracer but Bernard Barry has, in co-operation with GNS Science (New Zealand), made an offer. He has recommended a dose of 0.5 Ci of ^{125}I to be injected with the 50 Ci slug of tritium. Experts would be provided for the injection and the analysis would be carried out by GNS Science. None of the three advisers expects any conflicts in the determination of the three tracers.

5. CONCLUSIONS

When and if well IDDP-2 is drilled, there is interest in an attempt at using tracer tests to establish a connection between the deep system of low resistivity (Karlsdóttir et al. 2012), and the present production field. In view of the extreme conditions, the use of chemical compound tracers is not advisable and elemental radioactive tracers are the recommended tracers. Three tracers have been selected, the two-phase tracer tritium to be injected in a slug of 50 Cl, the vapour-phase tracer ^{85}Kr to be injected at 0.7 to 1.1 Ci, and the liquid-phase tracer ^{125}I to be injected at 0.5 Ci. Experienced collaborators and advisers have been found for all tests, and at the time of writing only minor information is missing before a financial plan can be completed. When ready, this will be presented to the project management and if the plan or a modification of it is agreed on, it will be presented to the Radiation Protection Agency and Import and Utilization licenses applied for. If and when these are granted, the tracer tests can go ahead as soon as well IDDP-2 has been drilled.

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