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Preliminary Collab Fracture Characterization Results from Flow and Tracer Testing Efforts

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ABSTRACT

The EGS Collab project is developing ~10-20 m-scale field sites where fracture stimulation and flow models can be validated against controlled, small-scale, in-situ experiments. The first multi-well experimental site was established at the 4850 level in the Homestake Mine, where hydraulic fractures were created at an injection well drilled sub-horizontal from the drift. Ten tracer tests were conducted to characterize fracture flow pathways during the second hydraulic characterization test for 164' Notch (October 24th to November 14th, 2018) during steady state injection of 400 ml/min at the injection well. Injected tracers include DNA, C-dots (fluorescein nano particles), fluorescein, rhodamine-b, sodium chloride, lithium bromide and cesium iodine. The tracers have been detected in three flowing wells located about 7.5 to 9 meters away from the injection interval. The tracer breakthrough curves from these locations have been adjusted to account for the residence time in the injection and production tubing. At the time of writing this paper, only the fluorescent C-dots, rhodamine-b and chloride have been analyzed for concentration vs time/volume at the production wells. Results from early testing have been re-analyzed as to the amount and location of injected water recovery and the mass of tracer recovered.

1. INTRODUCTION

Enhanced or engineered geothermal systems (EGS) offer tremendous potential as a renewable energy resource supporting the energy security of the United States. The EGS Collab project was initiated by the DOE Geothermal Technologies Office (GTO) to facilitate the success of FORGE (<https://www.energy.gov/eere/forge/forge-home>). This project will utilize readily accessible underground facilities to refine our understanding of rock mass response to stimulation at the intermediate scale (on the order of 10 m) for the validation of thermal-hydrological-mechanical-chemical (THMC) modeling approaches as well as novel monitoring tools. The project is a collaborative multi-lab and university research endeavor bringing together a team of skilled and experienced researchers and engineers in the areas of subsurface process modeling, monitoring, and experimentation to focus on intermediate-scale EGS reservoir creation processes and related model validation at crystalline rock sites (Kneafsey et al., 2018).

The Sanford Underground Research Facility (SURF) in Lead, South Dakota as the EGS Collab project experimental site is located in the former Homestake gold mine and is operated by the South Dakota Science and Technology Authority. The SURF facility offered the EGS Collab project unique opportunities with respect to the accessibility of rock under relatively high in-situ stress conditions with supporting infrastructure, such as electrical power, water, working conditions, and internet. The Collab Experimental 1 testbed was located near the kISMET site on the 4850 level, providing the project with immediately available data on geomechanical stress conditions and thermal profiles around the drift. Two sub-horizontal boreholes were drilled in the direction of the minimum principal stress orientation to be used as an injection (E1-I) and extraction (E1-P) wells 10 meters apart (Figure 1). A notching technique was used in the injection well in an attempt to stimulate the fracture such that it would initiate and continue to propagate perpendicular to the injection well and eventually intersect the production well. The experiment designed called for a double packer to isolate the fracture intersection at both the injection and the production well (see Knox et al. 2017). It was anticipated that a continuous flow loop could be established through the hydraulically stimulated fracture between the injection and the production wells and that the fracture could be characterized using chemical tracers at a variety of flow rates and back pressure conditions (see Ingraham et al. 2018).

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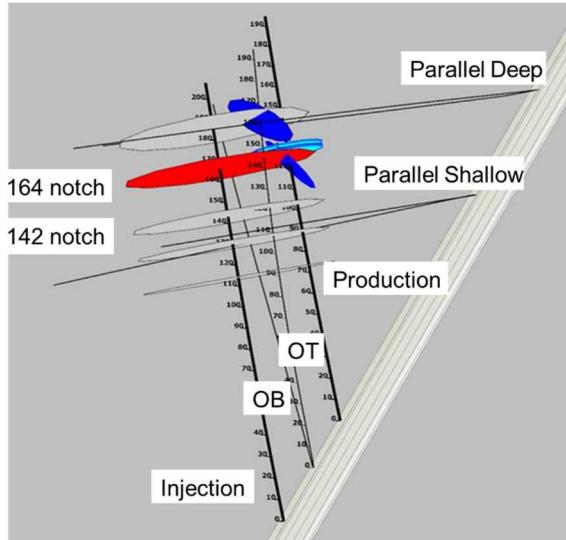


Figure 1: Collab Experiment 1 well layout and notch locations.

Mattson et al. (2018) summarized four modeling studies used to predict the production well tracer breakthrough concentration as a function of time at the EGS Collab Experiment 1 field site. These numerical predictions were based off of limited site characterization data and prior to the Experiment 1 fracture stimulation and fracture flow testing field data. As a result, each of the tracer transport models made different assumptions as to the fracture shape, injection period, injection rate and tracer transport parameters. Depending on the parameters used, peak tracer breakthrough were shown to vary less than an hour to 20 hrs. Based on these predictions, tracer tests were designed to characterize the fracture system at the Collab Experiment 1 site. Data from these tracer experiments will be used to refine the numerical models.

2. METHODS

Ten tracer tests were conducted to characterize fracture flow pathways during the second hydraulic characterization test for 164' notch (October 24th to November 20th, 2018). Table 1 lists the dates of solute tracer injection, the type of tracer injected and location of tracer recovery. Both typical and non-standard tracers were injected in the E1-I injection interval during this characterization campaign. The two non-standard tracers included DNA and C-dots. The first non-standard tracer was DNA and was tested to evaluate its transport potential at the Collab site. DNA can be considered a “smart” tracers as it has ability to be sequenced as uniquely identifiable DNA signatures that can be identified and quantified via qPCR (quantitative polymerase chain reaction). If multiple well tracer test are needed the ability to develop unique DNA segments as tracer could be used to potentially eliminating multiple tracer breakthrough curve ambiguity (Zhang et. al., 2017). The second non-standard tracer is a nanoparticle tracer, referred to as “C-dots”, and was used as a conservative tracer. The C-dot nanoparticle tracer consists of a carbon core decorated with a highly fluorescent polymer. The 3-5 nm diameter particles. C-dots are detectable by their fluorescence to concentrations of ~1 ppb in deionized water and have been previously been used at the Altona field site in New York (Hawkins, 2016).

2.1 Tracer Injection Schedule

The first tracer injection was on October 24th where DNA was injected into E1-I injection interval located 164 feet from the west drift (Figure 2) on the 4850 level of the Homestake mine. These initial DNA injections were followed by injections of fluorescent C-dots, standard Lithium Bromide and Cesium Iodide salts, then injections of Fluorescein, Rhodamine-B and Sodium Chloride (see Table 1). The C-dots, Fluorescein and Rhodamine-B all have the advantage of being able to be analyzed on-site.

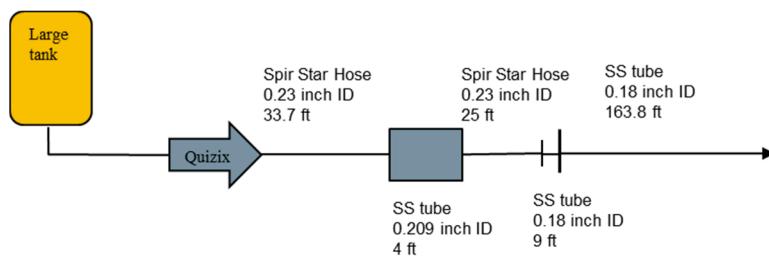
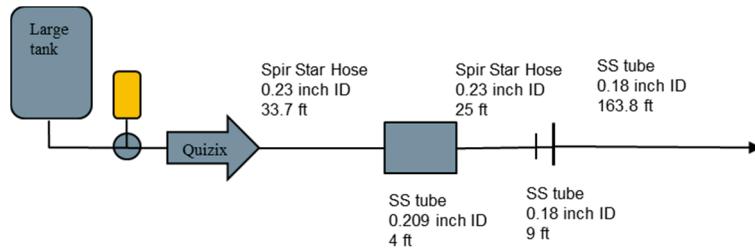
2.2 Tracer Injection and Sampling Locations

2.2.1 Tracer Injection

Due to a learning curve on how to best inject a tracer at the Collab field site and some equipment failure, the ten tracer injections into the E1-I packer interval used several different methods during this hydraulic characterization of the 164 notch fractures. Initial DNA injection (October 24, Figure 2) were mixed in a large (~100 liter) tank to ensure a long tracer pulse. The injection concentration was increased by using a shorter injection period to produce sharper high concentration pulse inputs for the October 25 and 26 tests (Figure 3). Equipment failure (one of the two cylinders of the Quizix flow pump failed) lead to switching of the flow pump to the Triplex system and using the good cylinder of the Quizix pump as a tracer injection pump (October 31 and November 1, Figures 4 and 5). Subsequently, an ISCO pump was installed on November 7th and used to inject ~100 ml of concentrated tracer at a rate of 20 ml/min into the 400 ml/min flow stream for the remainder of the tracer tests (Figure 6). The ISCO tracer injection system resulted in a 5 minute pulse tracer injection. All tracer injections were to an interval located at the 164' notch between a set of straddle packers. The packers are separated by a “dummy” pipe with a calculated liquid volume in the interval of 8.9 liters.

Table 1. Tracer injection dates, tracer injected, and tracer injection methods.

Date	Injected Tracer	Injection method	Tracer Detected at wells	Notes
October 24	DNA (S4, S11)	See Figure 4	DNA still under analysis	DNA still under analysis
October 25	DNA (S13)	See Figure 5	DNA still under analysis	DNA still under analysis
October 26	C-dot	See Figure 5	E1- PI, PB, OT	
October 31	C-dot, CsI, LiBr, DNA (S3, S12)	See Figure 6	PI, PB, OT	CsI, LiBr, DNA still under analysis
November 1	C-dot, CsI, LiBr, DNA (S2, S3, S4, S11, S12, S13)	See Figure 7	PI, PB, OT	CsI, LiBr, DNA still under analysis
November 7	C-dot, CsI, LiBr	See Figure 8	PI, PB, OT	CsI, LiBr, still under analysis
November 7	Fluorescein	See Figure 8	PI, PB, OT	Fluorescein still under analysis
November 8	C-dot, CsI, LiBr	See Figure 8	PI, PB, OT	CsI, LiBr, still under analysis
November 9	Rhodamine-B, NaCl	See Figure 8	PI, OT	Fraction collector on PB failed to collect samples
November 14	C-dot, CsI, LiBr	See Figure 8	PI, PB, OT	CsI and LiBr still under analysis

**Figure 2: October 24th tracer injection schematic.****Figure 3: October 25th and 26st tracer injection schematic.**

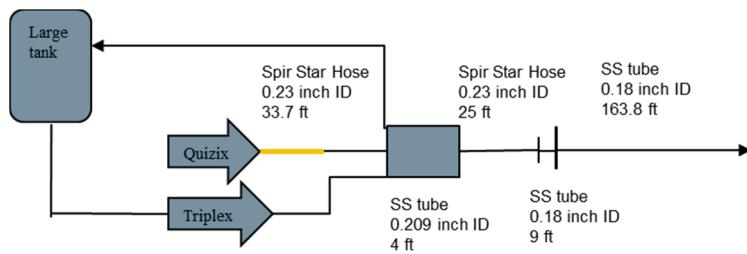


Figure 4: October 31th tracer injection schematic.

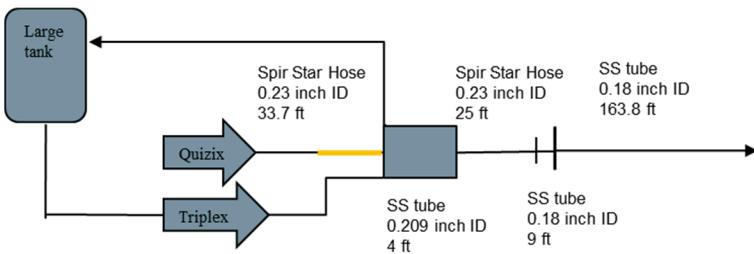


Figure 5: November 1st tracer injection schematic.

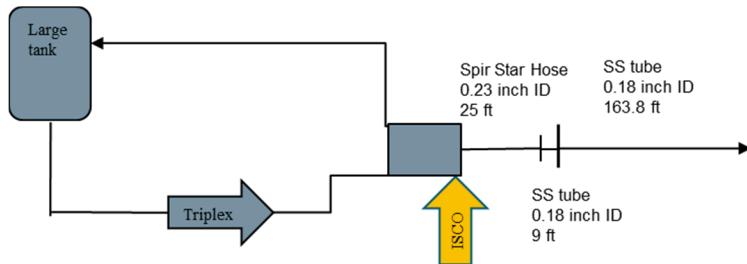


Figure 6: November 7th to the 14th tracer injection schematic.

2.2.2 Tracer Recovery

Although we initially planned for a single point of production at the production well, three locations produced water with detectable tracer concentrations. Figure 2 illustrates the location of tracer recovery from the fracture network (see Figure 7).

What we believe the shortest connection from the E1-I interval to the drift is the E1-OT monitoring well. E1-OT was not designed as a liquid sampling port but exhibited significant leakage through the grout filled instrumented borehole. Water recovered from this well generally exhibits a high pH (~12) with a modest electrical conductivity (~1200 microsiemens per cm). The high pH is speculated to be due to water contact with the grout as it travels from the fracture intersection with the well to the drift. Neither, the diameter of the flow pathway nor the pressure gradient along the OT borehole is known.

E1-P interval (designated as PI on the figures) represents the sampling interval between the straddle packers in the production well. For this set of tests, the LBNL's Simfip tool was placed between a set of straddle packers. This tool resulted in a shorter packer interval as well as more of the borehole volume was occupied by the tool. The calculated liquid volume of this sampling interval was less than the injection well and contained 3.5 liters of fluid. Similar to the injection interval, a ¼ inch stainless steel tube is used to remove liquid from this zone where it passes through a production well control panel before being collected as a sample.

The third sampling location was also in the production well (E1-P) but below the lower packer (designated as PB in Figure 3). At the location of this packer there is 158 liters of fluid. Fluid from this interval is sampled through a ¼ inch stainless steel tube with an opening just below the lower packer. Unlike the PI sampling port, fluid sampled from below the packers do not pass through a production panel and simply discharge to a collection system.

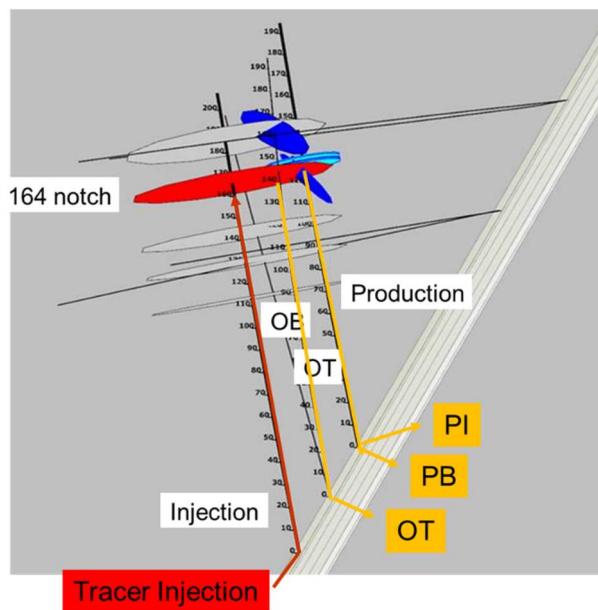


Figure 7: Collab Experiment 1 Tracer Injection and Sampling Locations.

2.2.3 Sample collection

Two methods were used to collect liquid samples for analyses. The first method was manually collecting ‘grab’ samples in 10 ml amber sampling tubes. Typically these samples were collected in less than a minute each, capped, labeled with the collection location and sampling time.

Fraction collectors were also used to collect samples from the three locations. The fraction collectors were set to advance at a set time interval and a peristaltic pump was used to control the rate of sampling such that the 10 ml sampling tube would be filled during the sampling interval. Unlike the grab samples, which represent a sample concentration at the moment of sampling, the fraction collector samples represent an integrated sample concentration over the sampling interval.

2.2.4 Adjustment of the Sampling Time

Most field tracer reservoir characterization tests are of such duration and flow rates that accounting for the time it takes for a tracer to reach the injection interval and be retrieved from the sampling interval are inconsequential. For the Collab project, this is not the case. The injection rate used during these tracer tests was generally 400 ml/min. This resulted in a time delay from the point of injection (Figs 4-8) to the injection well interval at the 164' notch of approximately 3 minutes. Although the distance of the sampling location to the drift at the production well is less than the injection well, the produced water flow rates were much less than the injection well resulting in a significant time difference from when the tracer reached the production well sampling location to where it was actually sampled in the drift. Unfortunately the exact liquid volume in the production well sampling tubing/panels are not known at time this paper was submitted and will be acquired during the next field campaign in early February. Estimates of the sampling port volumes (and liquid residence time) have been made for this paper and will be updated before submitting the data to the data repository. For the OT well, we do not have sufficient information on the flow pathway through the grout in OT and therefore assumed a delay time of zero for this sampling location. The distance from the drift to the bottom of the lower pack is known and we have assumed an additional 20 feet of $\frac{1}{4}$ stainless steel tubing to calculate the sampling delay time. PB delay times vary from 0.14 to 0.33 hours. Figure 8 illustrates the effect of the tracer BTC for PB for the October 31 test. For this example, the tracer BTC is shifted by $\frac{1}{2}$ hr changing the time to the peak concentration from 1.35 hrs to 1.02 hrs. PI is more complicated than PB since the production control panel contains an assortment of filters, flowmeters, pressure regulators, etc. For this paper we have assumed the volume of this panel and accessories is the same as the injection interval (although it will likely much greater). Using this assumption, time delays for PI vary from 0.22 to 0.78 hours.

A second time adjustment is required depending on if the sample collected was a grab sample or a fraction collector sample. Sampling time for both samples is when the sample is collected. For the grab samples no adjustment is needed. For the fraction collector samples, an additional time correction is needed to account for the residence time of the liquid in the peristaltic pump tubing at the peristaltic pumping rate. A secondary correction is also needed for the fraction collector samples by adding $\frac{1}{2}$ the sample interval time such that the time represents the middle of the interval.

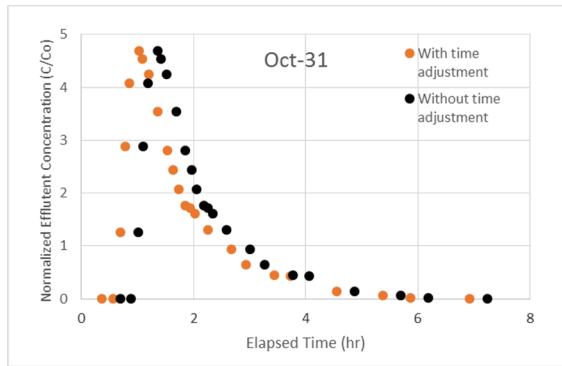


Figure 8: Example of tracer BTC shift due to tubing residence time.

2.3 Tracer Analysis

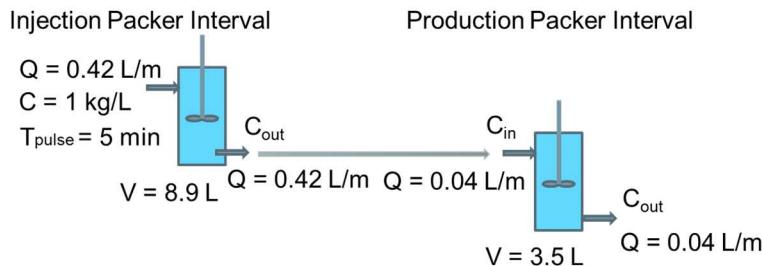
The DNA, CsI, and LiBr tracers are currently being analyzed by Sanford University and will not be discussed in this paper. NaCl was analyzed by INL using a Dionex ICS-2100 ion chromatograph at the Center for Advanced Energy Studies in Idaho Falls. The C-dots, fluorescein, and rhodamine-B were analyzed using an Ocean Optic spectrophotometer system (Ocean optic FIA-SMA-FL-UTL cell, PX-2 pulsed xenon lamp, QEPRO spectrophotometer). Table 2 lists the excitation and emission wavelengths. The advantage of the fluorescent tracers is that it allows near real time analysis of the fraction system behavior allowing for actionable information for subsequent tests.

Table 2. Excitation and Emission wavelengths

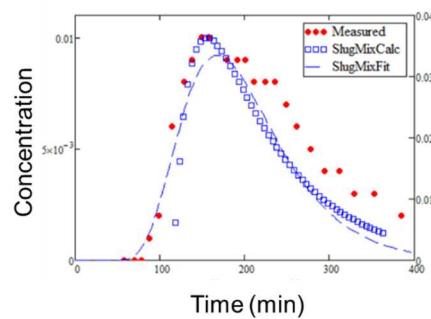
Tracer	Excitation nm	Emission nm
C-dots	358	440
Fluorescein	492	513
Rhodamine B	510	560

3. POTENTIAL MIXING DUE TO WELL BORE VOLUME

Besides the residence time of the tracer in the access tubing and panels, the well borehole volumes also may present a complication in interpreting the tracer breakthrough data for the Collab fracture characterization. As mentioned in Section 2, the liquid volume contained in between the straddle packers is 8.9 L at the injection well and 3.5 at the production well. Mixing of the tracer in these volumes could result in an apparent increased dispersion of the tracer at the sampling ports. One method to evaluate the potential magnitude that these volumes have on the calculated dispersion parameter is to evaluate the tracer breakthrough shape due to complete mixing in the two borehole intervals. For this case, we used a simple analytical mixing calculation between a sequence of two tanks with representative flow rates and volumes of the Collab test bed (see Figure 9a). In addition, we added a velocity term that is fairly typical of the tracer breakthrough curves observed at the Collab Experiment 1 test site. Figure 9b illustrates the calculated mixing (blue circles) and a fitted one dimensional advection dispersion equation (blue dotted line) to this data. These results from these calculations suggest that the dispersion for the two well intervals with complete mixing is on the same order of magnitude as what we are seeing with our field measure tracer breakthrough curves. It should be noted that complete mixing of the well interval is a worse-case scenario and is likely not completely true for our system and will need additional analyses.



a)



b)

Figure 9: Calculation of complete mixing on a tracer BTC, a) conceptual model, and b) dispersion due to borehole mixing.

4. WATER AND TRACER RECOVERY FACTORS

The total mass of injected tracer and recovered tracer mass was calculated for each tracer test. In addition, the percent of the water recovered from the production wells was also calculated. Table 3 lists the three main production zones and the percent tracer mass and water volume recovered from the three production zones. The total recovery is the sum of all the wells at the test site.

In all cases (except for the chloride November 9th values for PI) significantly less tracer was recovered as compared to the water. In a completely closed ideal system, these ratios should be the same. Potential reasons for this discrepancy could be; an inflow of water that does not contain tracer from the stimulation/natural system, filtering/sorption/degradation of the C-dots, and analytical measurement errors. At this time, the reason is not known and will be further investigated in future tracer characterization campaigns.

Table 3. Tracer and Water Recovery Percentages

Date	Tracer/water	PI	PB	OT	Total
October 26, 2018	C-Dots	6.2	5.1	0.6	11.8
	Water	30.0	30.7	6.5	85.1
	C-Dots	3.1	4.6	0.3	7.9
October 31, 2018	Water	18.8	20.5	2.2	73.0
	C-Dots	5.8	10.0	0.2	16.0
	Water	17.5	21.3	2.5	81.4
November 1, 2018	C-Dots	0.7	4.2	10.0	14.9
	Water	8.8	10.0	29.5	55.3
	C-Dots	0.2	2.3	19.3	21.7
November 7, 2018	Water	7.5	10.0	28.3	49.9
	Rhodamine-B	0.04	NA	6.2	6.2
	Chloride	12.4	NA	8.4	20.7
November 8, 2018	Water	7.3	10.3	32.5	52.9
	C-Dots	0.5	3.1	14.4	17.9
	Water	6.5	13.5	47.5	71.9
November 14, 2018					

5. SORBING TRACER RESULT

Cesium, lithium, and rhodamine-b have all been injected into the E1-I injection interval as sorbing tracers. To date, only the rhodamine-B has been analyzed, Stanford is currently analyzing the collected samples for cesium and lithium. Rhodamine-B and chloride breakthrough concentrations as a function of time for OT are presented in Figures 10a and b. As seen in Figure 10a, samples were analyzed for approximately 40 hours after injection where the concentration of both tracers approached zero. As seen in Table 3, only 1/3 of the rhodamine-B was recovered as compare to the chloride for the OT sampling location. Although the two tracer exhibited the same travel time for first arrival, the peak arrival of the rhodamine-B takes approximately twice as long as the chloride tracer (Figure 10b). A retardation coefficient will be calculated after final adjustments to the arrival times is complete.

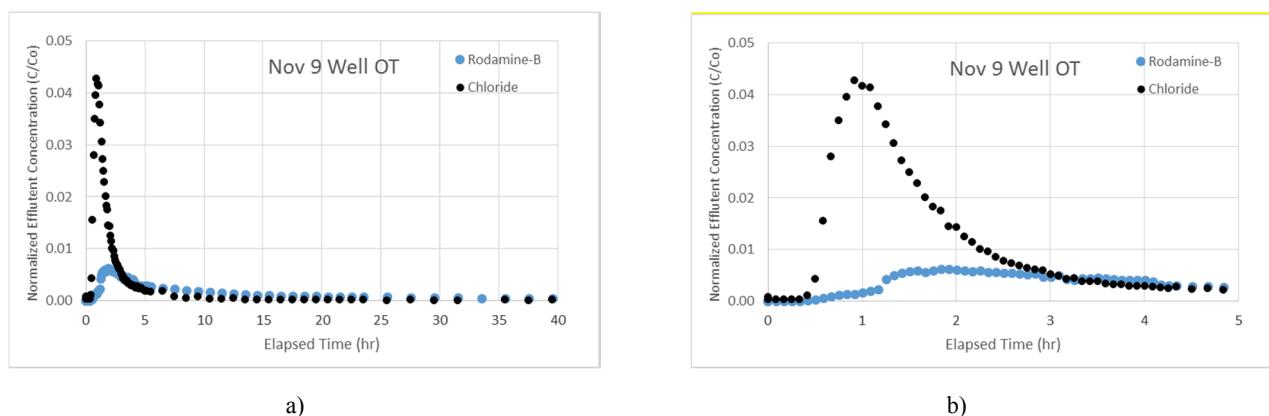


Figure 10: Breakthrough curves as function of time for rhodamine-B and chloride in the OT well, a) full breakthrough curve, b) first 5 hours of the breakthrough curve.

6. SUMMARY

This paper presents an overview of the tracer tests conducted in October/November 2018 at the Collab Experiment 1 at the 164 foot notch in the E1-I production well. During this fracture characterization campaign, ten tracer were injected using a variety of conservative and sorbing tracers. The tracers include a set of tracer typically used for subsurface flow analyses as well as DNA and C-dots. Although the injection well system has been well characterized as to the tracer residence time from the injection point to the packer interval, the production locations residence time calculations need more work. Due to incompletely analysis of the production location sampling systems, corrected times for the tracer travel time between the production well interval between the packers (PI) and the zone below the packers (PB) are not presented in this paper but should be available at the time of the conference. A field campaign is in progress to remedy this uncertainty. Despite the lack of corrected sampling times a number of observations can be made.

The Collab Experiment 1 testbed system design was not designed to test a single hypothesis in a homogenous system, but to test multiple hypotheses in a real heterogeneous system. As a result it is impossible to optimize the stimulation and flow system for all hypotheses. For the tracer tests, the system stress state allowed a low injection rate (0.4 L/min) without raising the injection pressure beyond the fracture propagation pressure. As a result, the potential residence time for the tracer in the injection borehole interval can be significant. The even lower fluid production rates at the production zones create a second large fluid residence time. Calculation, assuming complete mixing, in these two borehole intervals, suggest that the mixing of the tracer in these volumes could produce a dispersion term that is on the same order of magnitude as that seen in our tracer breakthrough curves. Future experiments could be redesigned to minimize these effects.

In a non-reactive closed system, one would expect the same water and tracer mass recovery ratios for each of the production zones during the tracer tests. For the tracer tests conducted at the 164 notch, preliminary analyses of the C-dot breakthrough concentrations suggest that ratio of tracer recovery to water recovery was less than one for all tests and all production locations. Possible explanations could include; filtering/degradation/sorption of the C-dots, inflow of non-tracer laden water, or analytical measurement error. More analysis is need to understand this phenomena.

Typically a sorbing tracer breakthrough arrival at the sampling location will be delayed as compared to a conservative tracer. Although the arrival of the peak concentration for the rhodamine-B was about twice as slow as the chloride peak arrival, the initial arrival time for the rhodamine-B was the same as the chloride tracer. This result may suggest that for the tracers transport times at the Collab Experiment 1 testbed, the assumption of sorption equilibrium may not be correct. For these tests, the kinetic sorption parameter of rhodamine-B may have to be incorporated into the sorption tracer analyses. A laboratory evaluation of the sorption kinetics of rhodamine-B (as well as cesium and lithium) tracer will need to be conducted to obtain these parameters to assess the potential role of sorption kinetics on tracer breakthrough.

The fluorescein tracer breakthrough concentrations have recently been completed and results will be ready in time for the workshop presentation. CsI, LiBr and DNA analysis is on-going at Stanford and should be available shortly. The analysis of these additional tracers breakthrough should help resolve some of the uncertainties discussed above.

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