A New Method for Efficient High-Resolution Mapping of DNAPL <u>and</u> Dissolved Phase Contamination in Fractured Bedrock

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ABSTRACT: Traditional bedrock investigations often rely on rock core analysis, packer testing, passive diffusion bags, and low-flow sampling in open boreholes for assessing the vertical distribution of contaminants in the formation. These methods can be expensive, provide limited spatial resolution and/or are heavily influenced by cross connecting flows in open boreholes with vertical flows. A method is described which minimizes cross connection, provides high spatial resolution and explicitly maps both NAPL and dissolved phase species and degradation products in a sealed borehole. The method described here allows spatial resolution of 0.5 to 3 ft (0.15 to 1.0 m). The objective of the method is to map the distribution of each contaminant species with depth in both fractures and pore space of the rock matrix. This method is called a FACT (FLUTe Activated Carbon Technique). An activated carbon felt strip is attached to a hydrophobic dye striped covering a flexible borehole liner which is everted into place in the borehole. The liner seals the entire hole and the carbon adsorbs the contaminants by diffusion from both the pore space and the fracture flows of the formation. Upon contact with NAPL in the subsurface a depth-dependent prominent stain of the cover is produced. Examples of detailed contaminant distributions are provided from boreholes in several rock types such as shale and limestone. The FACT distributions are compared to multi-level water samples with surprising agreement over two years after the FACT measurement.

THE PURPOSE OF THE METHOD

Site characterization has numerous objectives and many methods. Important objectives are to identify the location of contaminated groundwater and measure the magnitude of contamination. Additional objectives include determining the source of the contamination, the rate of propagation, and the path of propagation. These are relevant to an understanding of the contaminant distribution and the risk of the contamination to drinking water supplies. Another objective is to aid the design of a remediation approach to remove or contain the contamination. The FACT (FLUTe activated carbon technique) is primarily for the purpose of locating the contamination subsurface. The FACT method is a means of providing the relative distribution of contaminants of many kinds including degradation daughter products. The main objective of the combination with the NAPL FLUTe system is to identify the location of pure NAPL product, especially DNAPL, the more elusive NAPL. However, numerous other contaminants can be mapped with the FACT.

One might reasonably ask why a need for another site characterization method? One already has water wells, and many other forms of water sampling, core measurements, passive diffusion bags, and packer testing to mention a few. There are two objectives that are better met with the FACT method. One is higher spatial resolution and the other is **lower cost**. Few of the traditional methods can provide 1 inch resolution or low cost even at the typical resolution of traditional practice. Whereas the FACT does not produce absolute measurements of groundwater

Figure 1. Examples of DNAPL stains on the NAPL cover interior. Left to right: TCE, TCE with oil, and coal tar

contaminant concentrations, it provides a replica of contaminant distribution. As a screening tool, it may be nearer the definitive measurement of contaminant distribution than other methods. The potential limitations of the method and its utility in combination with other methods will be addressed.

THE DESIGN

The NAPL FLUTe cover on a blank everting liner has been in use for over 20 years (since 1997 at the Savannah River Site and at Cape Canaveral). It is a thin hydrophobic cover that wicks NAPL-free product, producing a stain on the cover. Once the cover is removed upon inversion from the well, one can measure the contaminant stains to identify the location of NAPL with depth in a borehole both above and below the water table. The original version was developed at SRS using Sudan IV. The current FLUTe version uses a striped dye pattern without the hazard of Sudan IV. The first installations were in direct push boreholes, though more are now commonly installed in open bedrock boreholes. The NAPL can be nearby and not produce a stain. The FACT was added to overcome that problem of a nearby NAPL. Figure 1 shows the kind of NAPL stains seen on the inside surface of the NAPL FLUTe cover upon removal from the borehole.

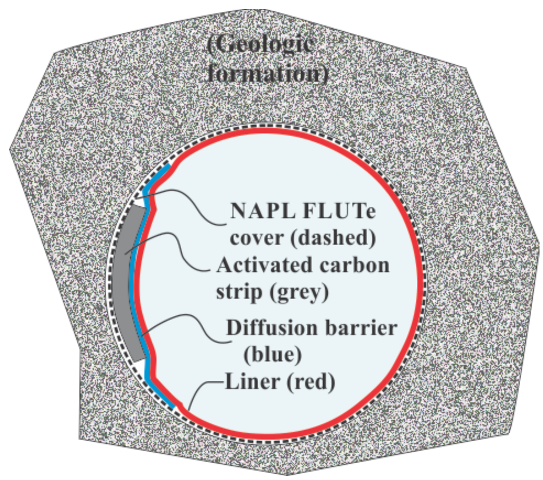

Figure 2. Cross section of the FACT in borehole.

The FACT design adds an absorber to the NAPL FLUTe to adsorb the dissolved phase of the contaminant (see Figure 2). The use of an absorber on a flexible everting liner dates back to the first use in 1991 of an absorber on a flexible liner used to wick tritiated water samples from the vadose zone at Lawrence Livermore National Lab in California. The absorber of the FACT system is a more aggressive absorber material of an activated carbon felt. The felt is more flexible and continuous than the common granular activated carbon. The FACT carbon felt is a strip of typically an inch and a half (38 mm) in width and an eighth inch (3 mm) thick and the length of the borehole liner.

An additional feature of the patented FACT system is a diffusion barrier that separates the carbon from contact with the flexible liner. Figure 2 shows the other construction details of the FACT. The drawing is a cross section of a borehole containing an inflated liner (the red curve), the diffusion barrier (the blue line), the activated carbon (the gray rectangle), and the outer hydrophobic cover (the dashed curve). The pressurized liner presses the flexible assembly of the cover against the borehole wall.

The dissolved contaminants in the pore space or fractures are able to diffuse through the cover material to be strongly adsorbed in the activated carbon felt. It is a slow process and may take a day or two in the vadose zone as first tested in Denmark, but in water it takes longer. Two weeks is the recommended residence in place against the borehole wall. The diffusion barrier is to assure that only compounds in the formation reach the carbon and not any that may migrate from the liner or the water in the liner.

THE PROCEDURE

The flexible liner with the outer NAPL FLUTe / FACT cover is everted into a borehole (or sometimes installed through a direct push rod) in the usual manner of a FLUTe liner. The water beneath the everting liner is often pumped to the surface to avoid forcing the borehole water into the formation, but open holes are often a path of cross connecting flow before the liner is installed. The effect of cross connection will be addressed hereafter.

Once the liner is in place and filled with water, the contaminants of both the pore water and the fracture water are free to diffuse from the formation into the carbon. The carbon is compressed to only a few millimeters of thickness.

After 2 weeks in the saturated interval (or 2 days in the vadose zone) the liner is inverted from the borehole. The liner is now inside out with the cover inside the liner. The liner is slipped off the cover. The cover is inside out with the white inner surface visible. A tape measure is laid next to the white cover material and the DNAPL stains are photographed. Figure 1 shows examples of typical DNAPL stains on the inner surface of the cover. The stains and tape measure define the depth of the stains, often due to DNAPL in fractures.

The diffusion barrier is now visible on the inside surface of the cover. The diffusion barrier is slit, and the carbon felt is cut into appropriate lengths each associated with the depth in the borehole. The cut sections are installed into DI water in jars and shipped to the lab for analysis using EPA Method 8265. The entire carbon strip should be analyzed to avoid missing contaminated fractures or pore space.

RESULTS

Figure 3 is a graph of the FACT results from a borehole in mudstone and shale near Trenton, New Jersey (1 ft carbon sections). The borehole was 150 ft deep by 100 mm (4 inches) in diameter with the water table at ~10 ft BGS. The contaminant was mainly TCE. It is noteworthy that the ratio of cisDCE to TCE changes from the top to the bottom of the hole.

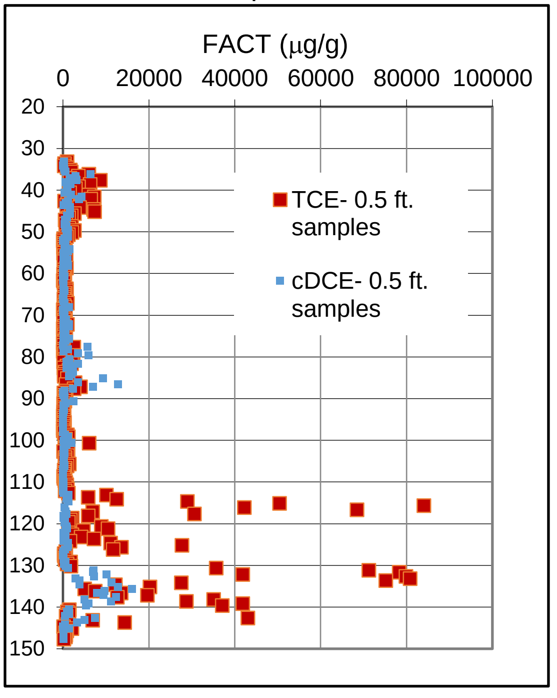

FIGURE 3. FACT measurement using 6 inch carbon sections in a New Jersey borehole.

Figure 4 is a plot of FACT concentrations from a site in Texas (1 ft sections). The FACT carbon has been subdivided into sections ranging from 6 inches to 3 ft. The main difference is the cost of analyzing the additional samples if finely divided. The rest of this paper will address the situation in the New Jersey borehole.

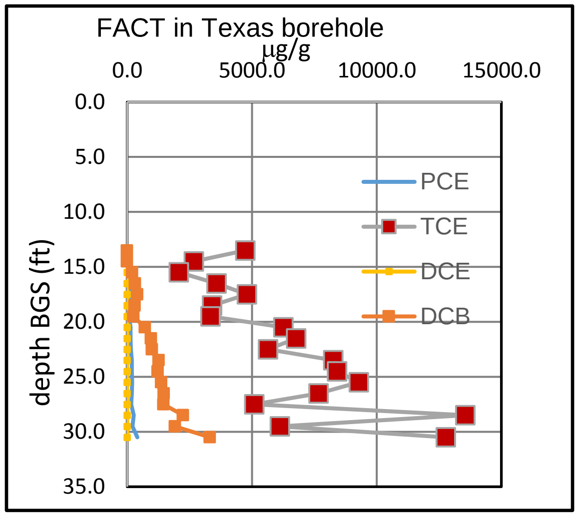

FIGURE 4. The red squares are 1 ft. segments of carbon results at a site in Texas. Also shown are the other species adsorbed in the carbon felt.

COMPARING FACT WITH WATER SAMPLES AND OTHER MEASUREMENTS

Figure 5 shows the FACT TCE results in New Jersey with the water samples obtain from a 10-port multi-level sampling system called a Shallow Water FLUTe (SWF). The water sample data sets shown were obtained ~1 year (blue) and 2 years (black) after the FACT measurement. They show essentially the same distribution as the FACT

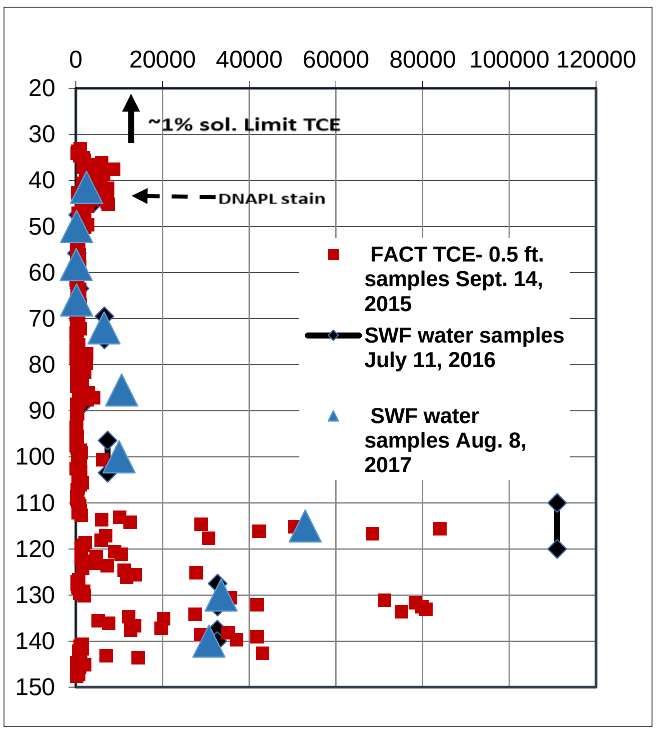

FIGURE 5. Comparison of FACT distribution in µg/g to water samples in µg/l collected over a two year period. The water samples from 110 ft. to 140 ft. are ~10% of the solution limit of TCE. Yet there were no NAPL stains so low in the hole.

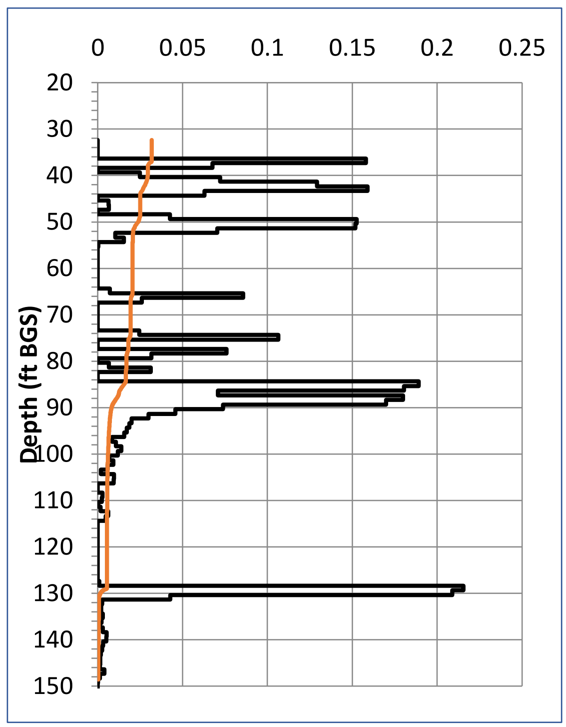

FIGURE 6. Transmissivity distribution in cm^2/s measured as part of the FACT assessment. Note the highest FACT and water sample results were in a relatively low transmissive interval (115 ft.).

measurement. The first water samples obtained only a day after the SWF was installed showed much lower levels in the bottom half of the borehole because the downward flow of ~10 borehole volumes per day from above 70 ft to below 70 ft (see Figure 5 for measured concentrations). The downward flow overwhelmed the normal contaminant levels as seen in the SWF samples much later. This is a suggestion that packer tests in the open hole would not provide representative values since the removal of the 900 gals of the cross connecting flow each day of the several days the hole is open is not a common packer purge volume. One may not know vertical flow rates and sources of flow with concentrations before packer testing.

The transmissivity distribution measured in the same borehole is shown in Figure 6. The measurement was made using the FLUTe transmissivity profiling technique. The entire measurement of the borehole was done in less than one hour. The highest FACT results at 115 ft (Figure 5) are in an interval of relatively low transmissivity as seen in Figure 6.

The assessment of the flow in the open borehole was based upon the head distribution measured and the continuous transmissivity profile data. The 1 ft interval values of Figure 6 are from the continuous data.

The comparison of the distribution of the water sample TCE levels two years later and the distribution of the FACT measurements made a couple of days after the borehole was cored is surprising. Whereas other such comparisons have shown similar distributions for the water samples and the FACT samples, it is unusual that these results can be plotted on the same linear graph with the FACT results in μg/g of carbon and the water samples in μg/L (see Figure 5). That is not always the case for other sites.

A comparison with core from the same borehole with the FACT data showed similarities in the distribution with depth with some exceptions. The high core values are seen in the FACT data, but not the reverse. Some high FACT results were not seen in the core. The simple reason is probably that they are two different kinds of measurements. The core analysis does not include the fracture water or analysis of core that was not recovered. The similarity of the FACT to the water sample distribution suggests that the FACT is heavily influenced by the fracture water contamination as well as the pore space contamination.

POTENTIAL PERTURBATIONS OF THE FACT

One early critic expressed the opinion that the method would not provide useful results. Those concerns have been addressed in a paper for publication that is in preparation. The concerns addressed in the paper are only listed here. The concerns reasonably expressed were:

1. Effect of drilling fluids on contaminants in the pore space. The New Jersey hole was cored with recirculation of the drilling fluids.
2. Subsequent migration of open borehole water contaminants into the pore space and fractures of the borehole wall.
3. Exposure of the carbon to borehole water during eversion into place.
4. Effect of borehole water trapped between the liner and the rough borehole wall.
5. Does the contaminant migrate along the carbon felt?
6. Loss of contaminants during handling of the carbon at the surface (Beyer et al.).

Those concerns were addressed with diffusion calculations and other quantitative assessments using the measured water sample contaminant levels and a previous author's work (Schaefer et al., 2012) on effective diffusion coefficients for this particular formation.

The first comparison of FACT to Geoprobe MIP measurements and soil samples was done in Denmark in 2010 in the vadose zone. See the FLUTe web site for the comparison. The agreement was excellent and a pleasant surprise. The sufficient residence time for the FACT in the vadose zone was only 2 days due to the higher diffusion rate in air.

In summary, those effects of concerns 1. Through 6. only explain the background levels and the lack of non-detects in the FACT data. They do not affect the overall distribution of contaminants or peak values. The forthcoming paper describes the actual analysis. A remaining mystery is the exceptionally high FACT results below 120 ft compared to the core measurements. Further assessment is being funded by the SERDP program.

DISCUSSION

The agreement between the FACT measurements shortly after the hole was drilled with the water samples a year and two years later is encouraging. The partial agreement with the core concentrations may be that the core pore water measurements are a subset of the pore and fracture water measurements of the FACT. The only water sample that was not a good match with the FACT was at 43 ft (Figure 5) where the FACT, core and DNAPL stain would have led one to expect a higher water sample. The suspicion is that the water sample was diluted by flow from a high flow fracture measured by the transmissivity profile at the same location (Figure 6). Because the elevation is so near the surface, that fracture may have been flushed of the contaminants that caused the other high measurements at the same elevation.

The fact that there were no non-detects in the carbon suggests that the cross connection in the open hole and the recirculation of drilling fluids, as is common for core drilling, do provide a background level if the drilling fluids and borehole flow are contaminated. This borehole shows a relatively high contamination level well above the 1% criteria for suspicion of nearby TCE NAPL. This site has been heavily investigated by the USGS and the high levels are common in the area and in deep boreholes. See the Goode et al. (2016) paper for the stratigraphy and other investigation results. Other reported use of the method is included in a peer reviewed journal by Broholm et al. (2016). The Danish Technical University has done extensive analysis of the FACT carbon and its use as described. Riis et al. (2010) reports on the first test comparison of the FACT in Denmark.

A description of the methods used for the transmissivity profile, head profile, and water sampling is available at www.flut.com and in the peer reviewed papers in the three references with Keller as author. The Sterling et al. (2005) paper is particularly useful in the assessment of cross connection as was possible for the FACT. Since cross connection effects are expected to diminish in time, the agreement with water samples even after two years is reassuring that the cross connection is not overwhelming the FACT results.

It would seem especially prudent to sample and analyze the open borehole water flow and the drilling fluids during drilling to aid in the assessment of potential cross connection effects on subsequent measurements.

CONCLUSIONS

The FACT method has the ability to map the contaminant distribution in pores **and** fractures. The high spatial resolution (0.5 to 3 FT) generated by the FACT is unmatched by most other methods such as low flow water sampling, rock core analysis, packer tests, or passive diffusion bags. The method works equally well in the vadose zone. The carbon is best left in place for 2

weeks in the saturated zone. Leaving the FACT for a longer time in the borehole is not a concern for FACT utility but may result in blurred NAPL stains. The NAPL stains are useful additions to the FACT results for understanding the dissolved phase distribution.
The FACT results compare surprisingly well with the water sample distribution at much later times.

The assessment of the FACT has led to the understanding of several processes that make straddle packer contaminant measurements potentially unreliable when performed in open flowing boreholes. A conclusion is that the core measurements are a different measurement of pore fluids only, whereas the FACT is also influenced by the fracture flows and therefore agrees with both the water sample distribution and the core peak values.

The collection of data of many kinds like water samples, transmissivity, head distribution and core data greatly aided the assessment of the FACT uncertainties as a new hydrologic measurement. Another important conclusion is that the FACT measures contaminant distribution continuously, in a sealed borehole, from all zones regardless of transmissivity. As such, the FACT results have shown that often the highest contaminant concentrations are located in intervals with low transmissivity. These data are useful for the development of conceptual site models (CSMs) and remedial designs. The water sample at 43 ft was probably diluted by a high flow fracture at the port.

The liner used for the NAPL/FACT measurement is the same flexible liner used for the transmissivity profile and other FLUTe measurements, providing a cost-effective means for measuring contaminant distribution, transmissivity, and head distribution, in comparison to other methods.

ACKNOWLEDGEMENTS

The first test and validation of the FACT method was done in Denmark by Anders Christensen and associates of NIRAS. The DTU (Danish Technical University) has provided especially useful measurements of the carbon felt response to adsorption and desorption rates. The borehole in New Jersey was at the NAWC site near Trenton. The drilling of the borehole was provided as part of a SERDP project. More detailed testing of the FACT is currently underway as part of another ESTCP-funded project (ER-201630).

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