Hydro-geologic Spatial Resolution using Flexible Liners

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Abstract

Spatial resolution of water quality and formation hydraulic conductivity are important to contaminant plume assessment, contaminant transport, drinking water supply well design, and also mining and hydrocarbon extraction. Flexible Liner Underground Technologies, FLUTe, has developed a variety of unique and proven methods for mapping contaminant distribution and flow path characterization in geologic formations. Blank liners are used to quickly and completely seal boreholes. The blank liner installation procedure is also used to obtain a continuous map of the transmissivity distribution of the geologic formation intersected by the borehole (*FLUTe T/K Profiler*). Liners are also used with a reactive cover to map in two dimensions the spatial DNAPL pure product distribution (*NAPL FLUTe*). An activated carbon felt strip is incorporated with the NAPL FLUTe cover to obtain a replica of the contaminant dissolved phase distribution in the pore space of the formation (*FACT*). Multi-level sampling liners (*Water FLUTes*) can obtain depth discrete water quality samples and head distributions in sealed holes. A new technique *FLUTe RHP* (reverse head profile) uses the blank liner stepwise removal to map the formation head distribution after the continuous transmissivity distribution has been measured during the blank liner installation. A new air coupled transducer technique (*ACT*) can dramatically reduce the lifetime cost of continuous multi-level transducer measurements of formation head histories by locating the recording transducers at the surface for reuse, repair or recalibration. These liner methods are used in vertical, angled, and horizontal holes. Advantages of these methods are that they are performed relatively quickly and therefore with reduced labor costs and with a minimum time for the borehole to be open for cross connection. These methods are used in karst terranes and highly fractured rock formations with little concern about leakage past the continuous sealing liners. This paper briefly describes how these several measurements are performed, how the data are reduced to hydro-geologic properties, and some examples of the results are provided.[1]

Purpose of this Paper

This paper treats the following issues as related to liner methods:

1. Where are the contaminants?
    a. In the soil, in fractures or rock matrix?
    b. Where in the soil?
    c. Which fractures?
    d. What form in the soil or fractures, pure product or dissolved phase?
    e. How deep in the formation?
2. How fast are they moving?
    a. The transmissivity?
    b. The gradient?
3. How can they be stopped?
    a. What natural paths are available?
    b. Extraction?
    c. Barriers?
    d. What reactive fluids are useful?
    e. What remediation fluid contact is likely?
4. Are the contaminants being reduced or stopped?
    a. Where are they now?
    b. How fast are they moving now?
    5. Municipal water supply source?
    a. Where are the good aquifers?
    b. How productive?
    c. Where are the poor/bad waters?

The intent is to acquaint the reader with liner methods that are only beginning to be taught in the earth sciences. In that respect, these are relatively new methods. However, they have been in use for 2-20 years depending on which method is considered. Some are less than two years old since the first field application.

These methods all have one thing in common. They all employ flexible borehole liners described hereafter. The liners are used to emplace the measurement systems or the liners are the measurement system. The general advantage is higher spatial and temporal resolution than is available with many standard hydrologic measurements especially compared to water wells. These methods may compliment traditional practice or they may replace it. This paper does not address the optimum circumstances for use of these methods.

Since this paper describes proprietary methods, one would expect some bias of the author. Therefore, any superlatives that appear should be considered his bias. The logical basis of the designs should be clear and the reader is expected to judge whether these are cost effective methods based upon the experience of those who have used these methods. References are available (see *www.flut.com)*. Some of these methods are now in use worldwide which suggests either apparent utility or an aggressive marketing effort. The latter does not exist.

The Flexible Liner Mechanism

Unless one understands the installation and removal procedure for a flexible borehole liner, there cannot be an understanding of the methods described hereafter. The liner is typically made of a urethane coated nylon fabric in tubular form slightly larger in diameter than

1. FLUTe has 18 flexible liner patents, many of which apply to these methods. FLUTe® is a registered trademark.

the borehole. For ease of explanation, the following sequence starts with the liner already in the borehole. Figure 1a shows such a liner already installed in a borehole. The liner is filled with water to a level above the water table in the formation. The result is that the liner is at a higher internal pressure than the fluid in the formation and therefore is pressed firmly against the borehole wall by the excess interior pressure. The hole is sealed wherever it can be sealed. Pulling up on the cord called a tether, which is attached to the bottom interior end of the liner, causes the liner to tend to invert, since inversion is easier than sliding along the borehole wall. Figure 1b shows such an inversion process. As the liner inverts, the inverting end of the liner moves upward like a piston and draws water into the borehole beneath the liner. The water level inside the liner rises and is usually pumped off to a holding tank. The tether, followed by the liner, can be rolled onto a reel at the wellhead for storage. The liner has inverted as it is withdrawn so that it is now inside out on the reel relative to the liner's initial condition in the hole.

The installation of a liner is just the reverse procedure. The liner is shipped to the wellhead with the liner inside-out on a reel. The open end of the liner is slipped over the surface casing and clamped. The liner is pushed down inside the casing forming an annular pocket. That pocket is filled with water whose weight/pressure pulls the liner off the reel and down the hole. Now the liner is "everting" as the reverse of the inverting procedure, Figure 1b. The additional feature not mentioned is the installation of an air vent tube in the casing before the liner installation in order to vent air trapped beneath the liner. The everting liner pushes the borehole water back into the formation in essentially the reverse of the flow into the borehole. It is interesting that the volume of water driven into the various flow paths is approximately that which was drawn into the borehole from each flow path.

Now that the mechanism of an everting liner installation is clear, it is easier to understand how that can be used for a variety of hydrologic measurements to be described.

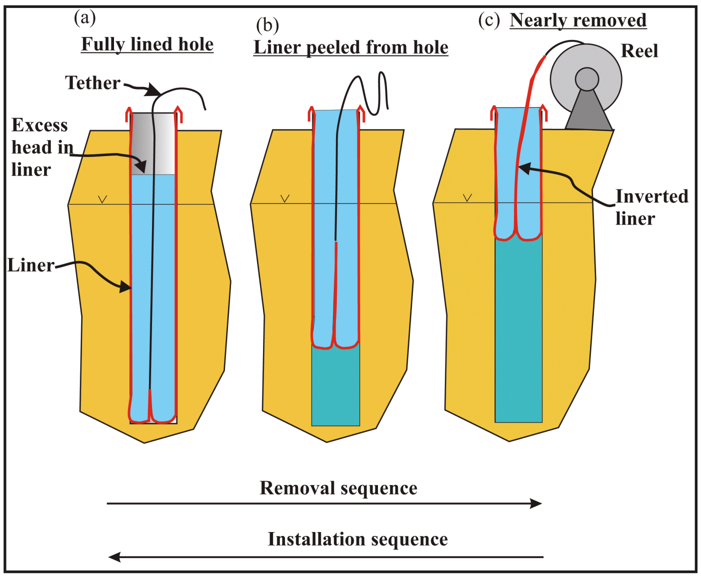

Figure 1. Flexible Liner Installation and Removal Mechanism.

The Hydraulic Conductivity Measurement

This measurement might be better described as a transmissivity measurement. As the everting liner is being installed, it drives the borehole water into all fractures beneath the bottom end of the liner. However, since the everting liner sequentially seals each flow path as it descends, the transmissivity of the borehole below the liner is reduced as each flow path is sealed. Therefore, if the liner is driven with a constant excess head, the liner descent rate will drop each time a flow path is sealed. By measuring very carefully the liner descent rate, one obtains a monotonically (steadily) decreasing liner velocity with liner depth. A step change in the velocity occurs each time a significant flow path is sealed. Hence a plot of the liner velocity looks like Figure 2. It is obvious where the velocity changes are located and it is also easy to understand that since the descending liner acts as a kind of flow meter, the change in velocity, multiplied by the borehole cross section, is the flow rate into each flow path that was sealed by the descending liner. This profile was measured to 524 ft in 4.4 hours in shale, in NJ.

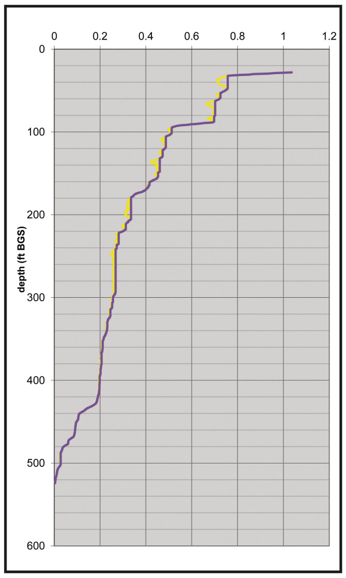

Figure 2. Velocity profile in borehole.

Figure 3 shows the machine that collects the velocity data, controls the liner tension, measures the tension on the liner, and monitors the water level inside the liner. The data is recorded every 0.5 or 1.0 second depending upon the liner expected descent rate. The driving pressure beneath the liner is measured directly with a recording transducer placed in the borehole or is calculated from the driving pressure/head inside the liner.

Dividing the liner descent rate by the driving pressure beneath the liner, either deduced or measured, and multiplying by the borehole cross section, the resulting flow rate per unit driving pressure is directly proportional to the integrated transmissivity from the bottom of the hole to the bottom of the everting liner. For the better transmissivity profile, we use a recording transducer in the bottom of the hole to measure the driving pressure in the hole above the original blended head in the hole. Figure 4 shows an integrated transmissivity profile obtained with this technique from the velocity of Figure 3. Given the

Figure 3. Profiling Machine.

integrated transmissivity distribution in the borehole from the bottom to the top, the difference in the integral between any two elevations is the transmissivity of that interval of the borehole.

It is clear that Figure 4 shows a remarkable definition of the transmissivity in the bore hole on a scale much smaller than most straddle packer measurements or normal flow meter measurements. Due to the effect of noise in the data sets, not every miniscule drop in velocity can be interpreted as a small fracture, but the substantial flow paths are well defined and almost always obvious on a video log. However, every feature on a video log does not have sufficient flow capacity to be measured by this technique. In fact, many visible features have no significant flow. The liner descent displaces one borehole volume of water and maps where that flow leaves the borehole. This means that the entire data set is consistent and sums to the initial total transmissivity. This is not the case necessarily for the sum of transmissivity measurements with a straddle packer.

It is also noteworthy that the measurement of the transmissivity of the entire borehole is normally done in 1-4 hours, depending upon the transmissivity. What this means is that the descending liner can map the significant flow paths in a 300 ft borehole in a small fraction of the time of continuous straddle packer testing (60 packer tests, using a five foot packer spacing) and with better spatial resolution. Other advantages are that there is little chance of any leakage bypassing the liner regardless of the fractured state of the hole. The liner is usually left in place to prevent cross connection between flow zones in the open borehole.

Many comparisons of liner measurements have been made with straddle packer measurements. In general there is good agreement when one calculates the transmissivity from Figure 4 over the same interval as the straddle packer. The transmissivity over any interval in the borehole is the difference in the values of the integral curve of Figure 4 between the depths of that interval. That is the subject of another paper in publication. However some differences have been noted due to packer leakage, non-linear flow rates of liner measurements or packer measurements, and slight depth discrepancies which may include a different fracture set for the comparison. However, the liner transmissivity plot is often used for selection of sampling intervals for the flexible liner multi-level system installed later for water quality and head measurements. The multi-level system is described hereafter.

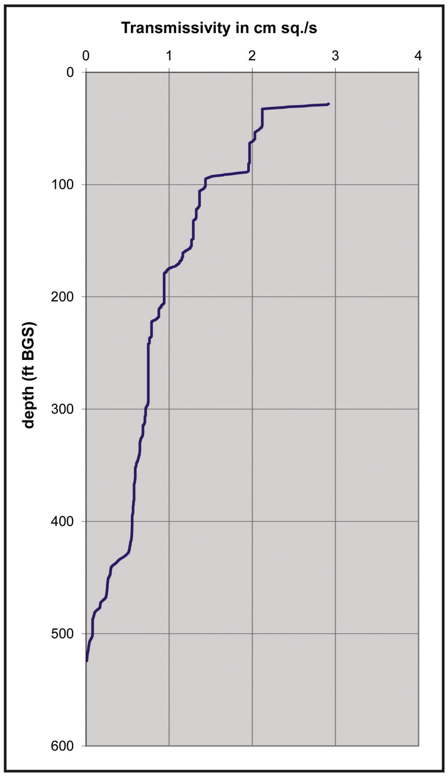

Figure 4. Borehole transmissivity below the depth.

The DNAPL and Dissolved Phase Mapping Techniques

Where is the DNAPL (dense non-aqueous phase liquid, for example trichloroethylene) and is it in the pure phase or dissolved phase, in the fractures, or in the matrix? These questions are addressed by several liner methods both old and very new. The blank liner is often covered with a color reactive covering which is then everted into a borehole and pressed against the borehole wall by the liner. The hydrophobic covering is dye stripped on the outside surface. If a DNAPL pure product such as TCE contacts the cover, it is wicked into the cover and carries the dye to the inside surface of the cover which is normally white. The resulting stain shows clearly the presence of the pure product in fractures, bedding planes or sand lenses. However, the absence of a stain does not prove that a DNAPL is not present, but only that it did not contact the cover material. The covered liner is inverted from the hole and the carrier liner is slipped off the inverted cover to examine it for stains. A tape measure beside the cover gives an excellent indication of the depth of the stain.

Figure 5 shows the stains on a reactive cover installed in a cored hole where no DNAPL was observed in fractures in the core. This technique in various forms is called a NAPL FLUTe and has been in use for over 10 years. Less than an hour exposure is required to obtain a stain. Many DNAPLs have been detected with this technique including TCE, PCE, gasoline, coal tar and creosote. A long list of reactive compounds is available.

Figure 5. DNAPL Stain on Reactive Cover.

The above NAPL mapping technique only responds to the pure product. In an effort to obtain a similar map of the dissolved phase, a very different mechanism is used. A strip of activated carbon felt (0.125 inches thick x 1.5 inches wide) was added to the interior surface of the hydrophobic cover material with a diffusion barrier separating the carbon felt from the liner contact. This device has been named a FACT (FLUTe Activated Carbon

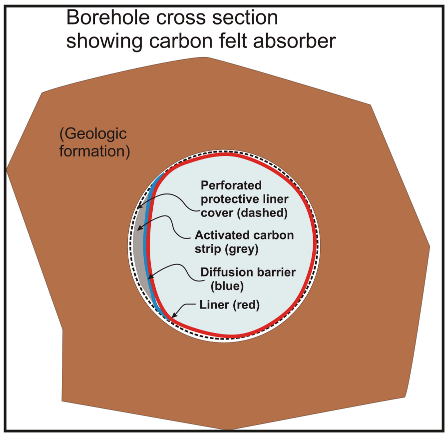

Figure 6. FACT Components.

Technique). Figure 6 is a drawing of the cover, absorber, diffusion barrier, and liner geometry. When this assembly is pressed against the borehole wall for a day or two, the activated carbon felt adsorbs the dissolved phase of chlorinated solvents and other compounds from the pore space of the borehole wall. When the cover system and carrier liner are inverted from the borehole, the carbon felt is cut into sections, submerged in methanol in a bottle to extract the contaminant, and then assessed in a GC MS for concentration of contaminant per gram of carbon. This is not a direct measure of the concentration per unit weight of pore fluid, but it is a replica of the available contaminant in the pore space of the borehole wall.

This technique has been compared with the Geoprobe MIP and soil core measurements in the vadose zone in a glacial till at a site in Denmark in April, 2010 with very good agreement (Figure 7). The comparison plot on the left is of a Geoprobe MIP measurement within about 2 ft of the carbon felt measurement hole. A comparison with concentrations in the pore water has not been made in the saturated zone, but in the single test done in the saturated zone, there was a good correlation with the transmissivity distribution measured with the liner profiling technique described above. The crystalline rock was gneiss, and the TCE was probably residing mainly in the fractures. However, the largest flow paths did not show the highest concentrations. Rather the smaller fractures beneath the large flow paths showed higher concentrations.

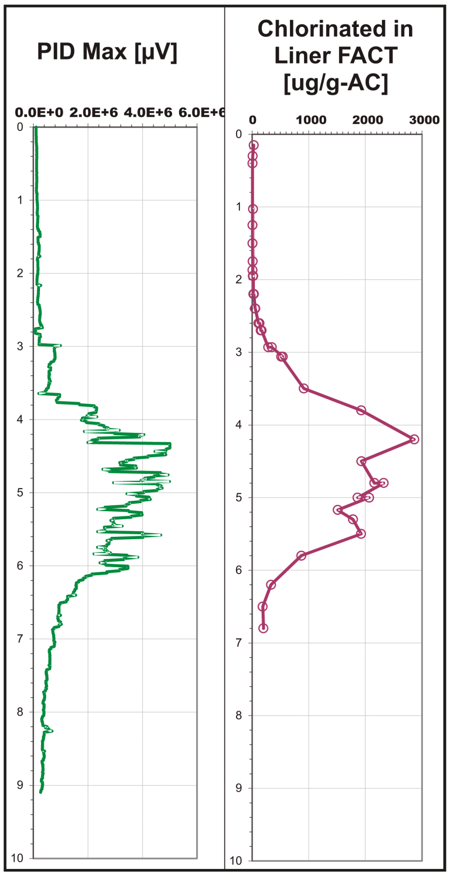

Figure 7. Comparison of MIP with FACT.

For this activated carbon absorber technique to be considered reliable in the saturated zone in porous rock, several precautions are obvious. The hole must be sealed as quickly as possible after drilling with a continuous seal, such as a flexible liner, to prevent significant absorption into the pore space from potentially contaminated borehole water. The liner with the cover must be everted relatively quickly into the borehole using a pump tube placed in the hole to remove the borehole water beneath the liner to prevent contamination of the carbon by the borehole water. The hydrophobic cover material does provide protection against borehole water contact during the eversion process. If there is a borehole water effect, it might be seen as a background level throughout the hole with the contaminated zones superimposed on that background. Time will tell if this is a useful method for obtaining a good replica of the contamination distribution in both fractures and the pore space of the formation in the saturated zone of porous rock beneath the water table. Above the water table, there is no concern about the effect of borehole water. A variation of both the NAPL FLUTe and this method, called a FACT, can probably be used to detect contaminants in core recovered in a variety of methods. The NAPL FLUTe cover has been used to map DNAPL in sediment cores from direct push or sonic drilling. The NAPL FLUTe covered liners are often installed through the interior of direct push rods in the softer sediments. The FACT emplacements in Denmark described above were done through direct push rods using air as the liner pressurizing fluid.

The Multi-level Sampling Liner

Once the information is in hand from the above measurements plus any other information such as the several geophysical measurements, the intervals that are to be sampled, and for which head measurements are to be made, can be specified. A liner is then constructed with those sampling intervals defined by external spacers on the liner defining unsealed intervals on the outside of the liner. Those spacers are thin flexible surrounds covering the prescribed interval of the liner. A port is located behind the spacer which collects the water flowing from fractures into the spacer interstitial space. This instrumented liner is everted into the borehole much like the blank liner. However, a bundle of pump tubes (one pump for each port) follows the liner into the borehole. The pump tubes are supported on the tether. See Figure 8 for a drawing of the spacer, port, tubing and pump geometry for each port. The pumping and tubing system can be of relatively large volume because the liner occupies very little space in the hole. The pumping system is filled with water from the port to the formation head level in the pump tube. Figure 9 shows how the system is pumped. A gas pressure is applied to the top of the pump tube driving the water up the sample tube to the surface since the first check valve closes. The first pressure applied is the "purge pressure" and sufficiently high to drive all the water from the pump tube. The three-way valve is opened to drop the gas pressure allowing the pump tube to refill from the port-to-pump tube and the spacer. A second application of the purge pressure empties the water from the port-to-pump tube and the spacer and some formation water. Now the system is refilled with formation water. A lower pressure is applied ("sample pressure") which cannot drive all of the water from the pump tube. These pumps are of essentially the same length (>100 ft) regardless of the port elevation so they can be completely purged and sampled simultaneously with a manifold with a single purge pressure and a single sample pressure. Since the sampling pressure is less than the purge pressure and unable to drive the air/water interface to the bottom of the pump, there is no risk of aeration of the sample water (Figure 9). The purge volume per stroke is about 1 gallon. The liner seals the entire hole except for the spacer intervals. The TAG tube allows the water level in the liner to be measured with an electric water level meter.

Essentially all of the water in the borehole is inside the liner and does not need to be purged. The sampling system tubing is all PVDF (poly vinyldene fluoride) to minimize any effect on the sample water. A diffusion barrier is built into the spacer to prevent contact of the sample water in the spacer with the

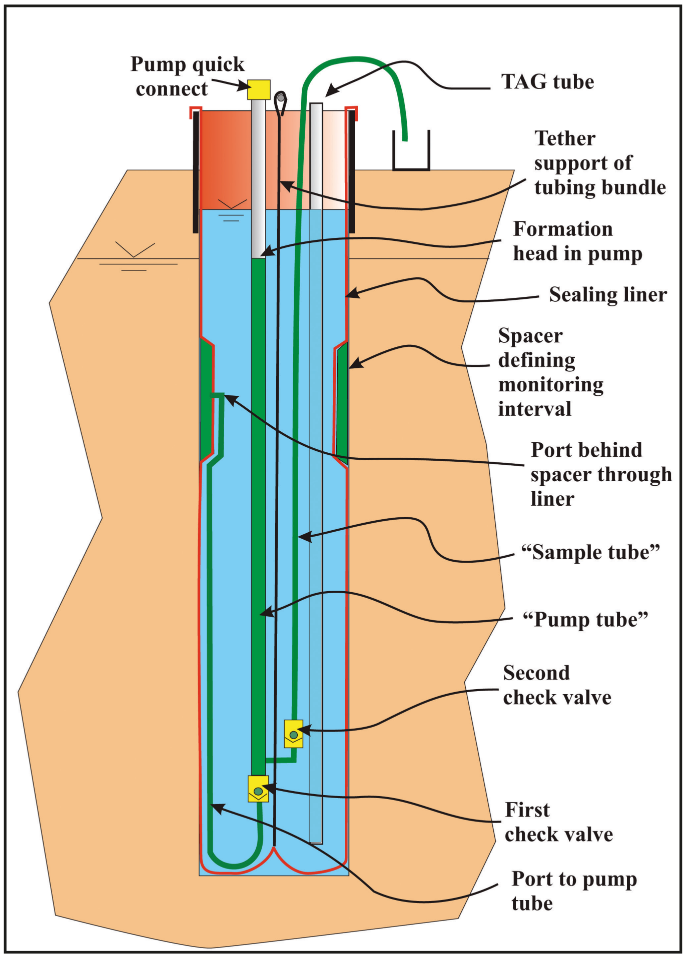

Figure 8. Water FLUTe System. (Single port system shown for clarity, with pump system filled.)

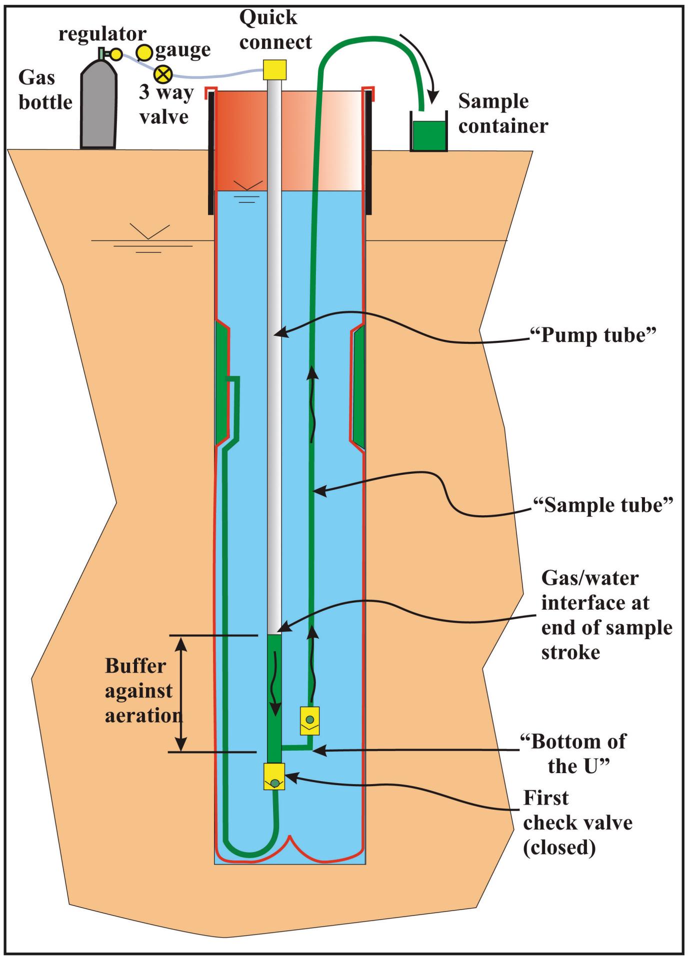

Figure 9. Pumping Procedure.

liner. An outer layer of filter fabric on the spacer prevents the ingestion of sand and silt into the pumping system. Any concern about the liner integrity is addressed by monitoring the interior excess head in the liner which will drop if there is any leakage. Liners have been filled with weighted mud for artesian conditions or a bentonite-grout slurry for other situations such as the extreme drawdown of wells in close proximity to the lined hole.

The number of sampling intervals available depends upon the borehole diameter with 6 ports per 4-inch hole, 10 per 5-inch hole and 15 ports per 6-inch hole. The system is entirely removable unless grout filled.

The water table at each port can be tagged manually via the ½-inch I.D. "pump tube" of Figure 8. However, a recording pressure transducer can be built into the system attached to each port tube just beneath the "first check valve", or a brand new technique using an air filled tube allows the transducers to be located at the surface for easy repair, replacement or reuse. This air couple transducer technique (called an ACT) has been able to monitor the water table in a pumped well with ¼-inch resolution on the one second time scale for a water table depth of 48 ft from the surface. The typical installed system with smaller tubing can resolve about a one inch water level change. This brand new technique is being field tested under a wide range of conditions including Canadian winters and Alabama summers. It looks very promising. The main advantage is that the transducers are readily accessible. The disadvantage is the reduced depth resolution. However, in fractured rock, water level changes tend to be much larger than one inch. In highly porous and permeable sediments, one inch is not sufficient resolution. Either kind of transducer installation still allows the manual tag of the water level at each port.

This liner multi-level monitoring system has been in use since about 1999 in its early form. There have been many refinements in the subsequent 12 years. It is called a Water FLUTe system.

Liners and Geophysical Measurements

Many geophysical measurements can "see through" the liner, and have been made inside the blank liner while the borehole is sealed. Those measurements include the natural and induced gamma or neutron radioactivity, temperature mapping for flowing fractures, sonic televiewer hole wall mapping, and radar measurements with special fluids inside or outside the liner. The main precaution is that the sondes must be faired, reducing any sharp edges, and well-padded so as to not damage the liner when impacting a ledge or edge of a fracture while going downward or upward in the hole. Running the geophysical measurements with the hole sealed has numerous advantages including prevention of cross connection and other open borehole effects.

Head Profiles Using a Liner

A very new method, just being field tested, uses the continuous profile of the transmissivity obtained as described above and the stepwise removal of a liner after that profile is completed to obtain the formation head distribution. This technique is also best performed with a recording transducer in the bottom of the borehole. The method involves the inversion of the blank liner uncovering discrete borehole intervals with the measurement of the steady state borehole equilibrium pressure, Bh_i, after each interval is uncovered. By using each new "blended head" beneath the liner, writing the flow equations for each increment that has been uncovered, defining the net flow into and out of the hole to be zero, and using the transmissivity, T_i, measured for each increment in the hole, one has only the formation head as an unknown for each newly exposed interval of the hole. For the first open hole interval beneath the liner:

$$T_1(Bh_1\text{-}FH_1) = 0,$$

Hence the formation head, FH_1, equals the blended head, Bh_1, in the borehole. The transmissivity for each interval, T_i, is obtained from the continuous transmissivity integral, for example, Fig. 4. Upon inverting the liner to uncover a second increment of the borehole:

$$T_1(Bh_2\text{-}FH_1) + T_2(Bh_2\text{-}FH_2) = 0,$$

Solving for FH_2,

$$FH_2= [\ T_1(Bh_2\text{-}FH_1)+ T_2\ Bh_2\ ]/T_2$$

Note that for each new position, a new blended head, Bh_i, is measured.

Solving for the formation head each time the liner is inverted allows theoretical determination of the head distribution in the formation while removing the same liner that was used to measure the transmissivity and to seal the borehole. The equation for solution of the formation head of the current interval, i, is:

$$FH_i = [\ T_1(Bh_i\text{-}FH_1) + T_2(Bh_i\text{-}FH_2) + \ldots\ldots + T_i\ Bh_i\ ]/T_i$$

Where T_i is the transmissivity of the i^{th} interval in the hole determined from the liner continuous transmissivity profile, FH_i is the calculated formation head of the i^{th} interval, and Bh_i is the blended head measured in the borehole after each new i^{th} interval is uncovered. Watching the transducer measurement beneath the liner allows one to judge when a steady-state head has been achieved beneath the liner.

Cost

The most common questions of someone not familiar with the liner technology are the cost of the systems and who can install them. The FLUTe liner system prices are available on the FLUTe web site. Current prices for blank flexible liners are about $14/ft up to 8-inch diameter. The reactive covers range from $4-8/ft depending upon liner diameter. The other methods add to that price per foot. The transmissivity profile and the Water FLUTe installations are only performed by FLUTe staff. The blank liners are often installed by the customer. A complete quote is available upon request which includes labor, liner systems, ancillary equipment rental, shipping, and travel costs. Custom liner systems for special applications are available.

Summary

Many of these methods are relatively continuous measurements. Therefore, one can expect relatively high spatial resolution. Most of the temporal resolution is related to the ability to collect ground water samples and to measure head at subsequent times. All of these methods use the ability to seal the borehole with a continuous liner and to transport a variety of measurements into boreholes and against borehole walls with good isolation. Some measurements such as the transmissivity profile have been done at different times over several years showing a dependence of the transmissivity on the time the hole is open.

The initial list of hydrologic issues is reproduced here with the utility of the several methods indicated by a simple x to show where each method is potentially useful.

Note, the blank liner is indicated as useful far beyond expectations until one realizes that locating contamination is frustrated by cross connection between contaminated and uncontaminated regions when the borehole is open. Therefore sealing the borehole immediately is important to a reliable mapping of the contaminant distribution with other techniques and at later times. It is not yet determined as to what are the limits of the activated carbon absorption of dissolved compounds so there may be other useful adsorbed contaminants beyond the VOCs tested so far. The Water FLUTe system is useful for locating contamination and for tracking its propagation over time.

If high spatial and temporal resolution is the objective, the flexible liner methods offer some attractive features. Many papers on these methods are available upon request or at the FLUTe web site *www.flut.com*.

Carl Keller received his Bachelors and Masters degrees in math, physics, and engineering science from Valparaiso University and the Rensselaer Polytechnic Institute. As an underground nuclear test containment scientist with the U.S. Department of Energy from 1966 to 1974, he developed a variety of numerical models for multi-phase flow in the earth. From 1974 to 1985, he was responsible for the research and containment design of all Department of Defense underground nuclear tests. In 1989 he developed the first everting flexible liner system for collection of pore water samples from the vadose zone, and in 1995 he produced the first flexible liner system for monitoring in the groundwater zone. He holds 18 patents concerning vadose zone and groundwater monitoring and other flexible liner methods. He established Flexible Liner Underground Technologies in 1996 where he is owner and Principal Scientist.

Where are the contaminants?	**Blank**	**T profile**	**NAPL+FACT**	**Water FLUTe**
In the soil, in fractures or rock matrix	x	x	x	x
Where in the soil?	x		x	
Which fractures?	x		x	x
What form in the soil or fractures, pure product or dissolved phase?			x	x
How deep?	x		x	x
How fast are they moving?				
The conductivity?		x	x	x
The gradient?		x		x
How can they be stopped?				
What natural paths are available?		x		x
Extraction?	x	x	x	x
Barriers?		x	x	x
Reactive fluids?				
What remediation fluid contact is likely?		x	x	x
Are they being reduced or stopped				
Where are they now?	x		x	x
How fast are they moving?	x	x	x	x
Where is the good drinking water?				
Where are the good aquifers?	x		?	x
How productive are they?	x	x		x
Where are the poor/bad waters?	x		?	x