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Comparison of the FLUTe™ Hydraulic Conductivity Profiling results with Straddle Packer measurements

By

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Abstract

The FLUTe technique for location and mapping of the significant flow paths in a borehole using a flexible everting liner has been reported earlier in other papers. The method allows one to map the significant flow paths in a borehole in 1-4 hrs. relatively independent of the borehole depth. The location of each flow path (e.g., fracture, or bedding plane) and the explicit measurement of the flow rate in each path in such a short time with the everting liner (10-15% of the typical time for discrete straddle packer testing of the entire hole) have obvious utility. However, the question is whether the FLUTe measurements are correct, and how do they compare to straddle packer measurements of the same hole. This paper describes the techniques that have been developed to assess the FLUTe method and to make a careful comparison of FLUTe results with the packer tests of the same borehole. The FLUTe measurements usually provide much more spatial detail than discrete packer tests and therefore the FLUTe measurements were integrated over the same vertical interval as each packer test to provide the equivalent average packer value. The differences are obvious. The next step was to use the packer conductivity profile to calculate a synthetic liner vertical velocity in the borehole. The packer data provided a substantially higher synthetic liner velocity than the FLUTe liner measured velocity. A test of the comparison was performed by integrating the FLUTe data to provide an equivalent set of packer results, and then using the integrated FLUTe results to develop a synthetic liner velocity for comparison with the actual liner velocity measured with hole depth. The comparison was nearly perfect, suggesting that there are no errors in the comparison methods used. The conclusion is that the straddle packer testing provided excessively high conductivities in the lower regions of the borehole due to bypass of the packers. There is no bypass in the liner measurement method. The everting liner measurement method seems to provide more accurate results than the packer testing for highly fractured holes. However, the straddle packer tests can measure to lower conductivities in the low flow regions of the borehole than are practical for the everting liner method. The low cost of the everting liner measurement method and the data quality should provide a significant advantage to the characterization of the flow paths in fractured rock sites for design of remediation procedures and for assessment of contaminant transport. Another advantage is that once the FLUTe measurement is finished, cross contamination is prevented by the sealing liner which is left in place.

I. Introduction

FLUTe has developed a technique for locating all significant flowing fractures in a borehole and measuring the flow rate out of each fracture or permeable interval intersected by the borehole. The measurement is performed while installing a flexible liner into the borehole. The liner is often left in place to seal the borehole once the measurement is complete. This paper describes briefly how the FLUTe measurement is performed and how the results compare to a traditional method of flow path measurement, namely the straddle packer technique. It is assumed that the reader is familiar with the performance of straddle packer measurements (Lapcevic, 1999). The

FLUTe technique is called the FLUTe Hydraulic Conductivity Profiling Method (pat. no. 6910374 B2) or more briefly, the FLUTe profiler. The comparison of the two methods is shown for a University of Waterloo investigation site at Guelph, Ontario.

II. The FLUTe Profiler method

The measurement is performed by the eversion of a FLUTe blank liner into a borehole (Fig. 1). The liner is deployed from a reel adjacent to the wellhead. The liner is driven down the hole by the pressure of the water added to the interior of the liner at the wellhead. The liner is inside-out on the reel and everts (the opposite of inverts) as the liner is fed down the hole. The everting liner drives the water from the hole like a perfectly fitting piston. The water is driven from the hole at a rate dependent upon the transmissivity of the borehole below the end of the liner, and in proportion to the driving pressure inside the liner. The driving pressure is simply the excess head inside the liner relative to the water table in the formation. As the liner descends, it sequentially seals the flow paths intersecting the borehole from the top down. It is noteworthy that the driving pressure in the borehole beneath the liner is uniform throughout the hole and there is ample time for the steady state condition to develop as the liner descends. The drawing in Fig. 2 shows the everting liner as it passes a flow path (a fracture as drawn, but it can be a permeable bed as well). The velocity of the liner at any point in the borehole depends upon the flow paths remaining below the descending liner. Therefore the liner starts with a high velocity but drops in velocity each time that a flow path is sealed.

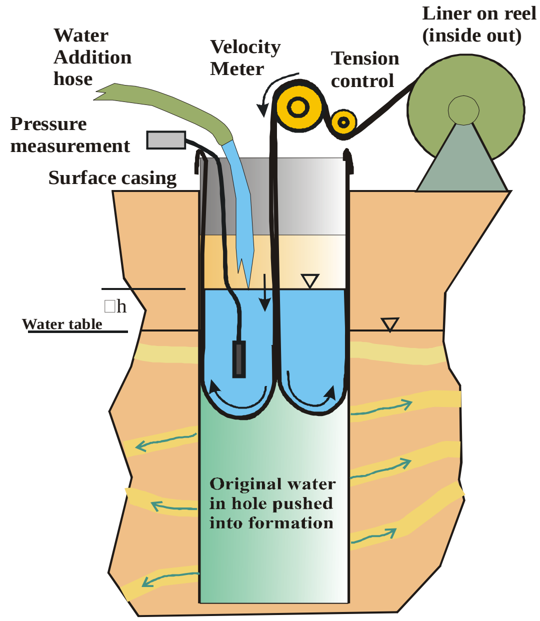
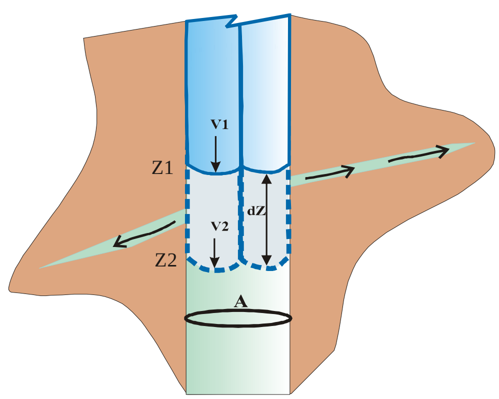


Fig. 1. Blank liner installation with measurements to identify open fractures

The measurement is performed by recording the liner position with time, the tension on the liner, and the excess head driving the liner. The tension on the liner at the wellhead is controlled to be constant and the actual tension on the liner is also monitored and recorded. The excess head is also



Flow rate into the fracture, Q = A(V1-V2) , where V1>V2
Transmissivity over dZ is: C x dZ= fctn(A, dV, dZ, ...)

Fig. 2. The transmissivity over the interval dz is calculated from the liner depths and velocity change between those depths.

controlled to be relatively constant. From the recorded data, the liner velocity is calculated and divided by the driving pressure to obtain the velocity per unit driving pressure. This normalized velocity is simply called the “velocity” throughout this paper.

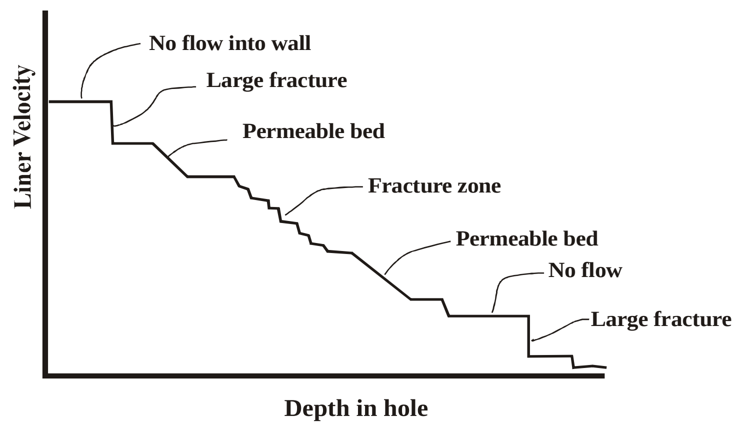


Fig. 3. Velocity profile shows the nature of the flow paths

The typical result is the graph of monotonically decreasing velocity versus depth with the typical features shown in Fig. 3. As each significant flow path is sealed by the descending liner the change in velocity indicates the location of the flow path, and the magnitude of the velocity change is directly proportional to the flow into that path before it was sealed. As shown in Fig. 2, the velocity change, dv, times the borehole cross section, A, is the flow rate into the flow path before it is sealed. The model assumes that the flow into the hole wall occurs uniformly over the interval, dz, which is traversed by the liner in moving from the depth z_i to z_{i+1}. Just as a straddle packer measurement is over an interval dz, the flow rate into that interval is used to calculate a transmissivity of the hole wall over the interval dz. The same steady state assumption is used to calculate the conductivity of that interval of the hole wall as is used for packer measurements. The liner data is recorded every two seconds, typically, so that the liner traverses an interval of the hole wall every two seconds depending upon the liner velocity. The result of the FLUTe measurement is to calculate the transmissivity/conductivity of each interval of the hole wall traversed in every time interval. This produces a very high spatial resolution measurement of the vertical borehole transmissivity. For those sections of the borehole with very little transmissivity, the liner velocity change is essentially zero.

III. The straddle packer measurements at Guelph, Ontario hole no. MW-24

The typical constant-head injection straddle packer system (Lapcevic, et al, 1999) was used to perform ~63 measurements in a 4 inch diameter by 340 ft deep hole over adjacent 5 ft intervals. The technique used a constant driving head supplied by tall tanks of several diameters and measured the flow rate into each straddled interval after achieving a nominal steady state flow rate. The measured flow rate was used to calculate the conductivity of each straddled interval. Figure 4 is a schematic of the packer measurement system used. It was developed for the Canadian Center for Inland Waters and used by the University of Waterloo at Guelph.

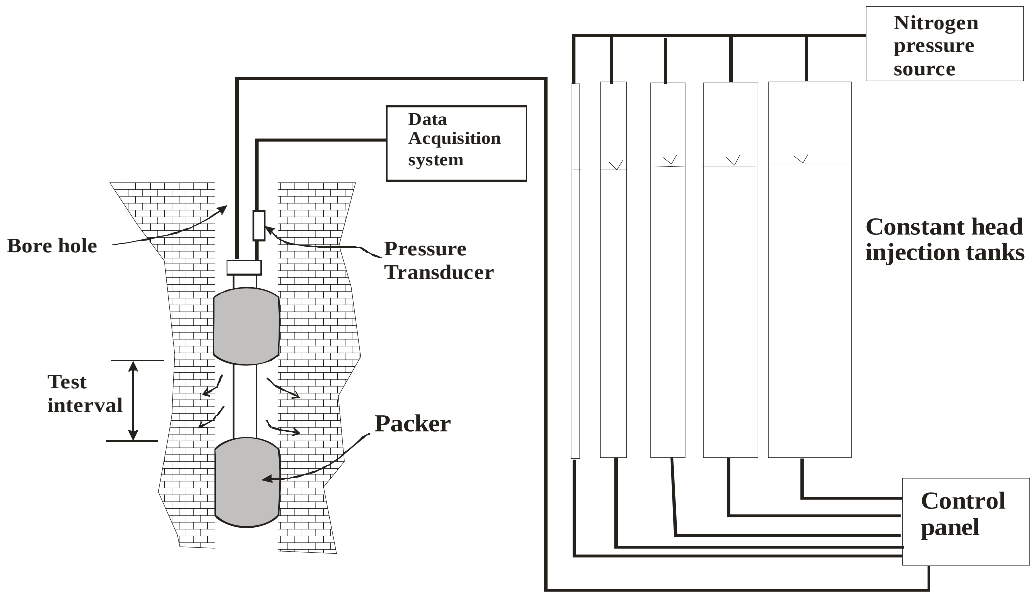
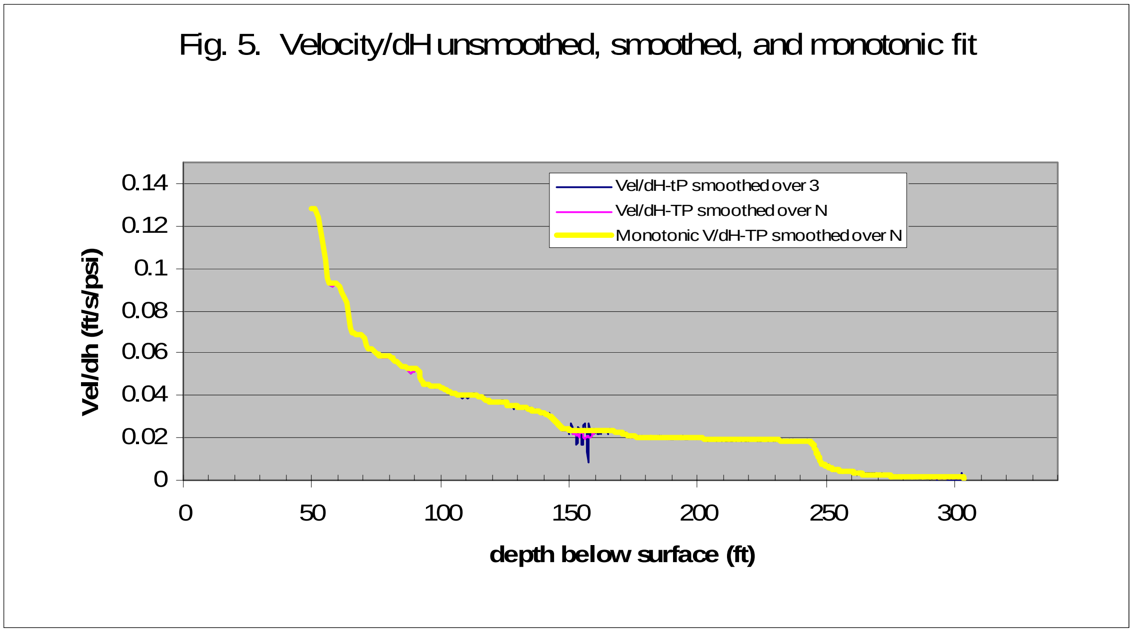


Fig. 4. Test system used at Guelph site for packer measurements

IV. The geologic setting
Three holes were profiled with the FLUTe technique, MW-24, 25, and 376-6 at the Guelph site. The total transmissivity of hole no. 24 was 5 cm^2/s with an initial flow rate of 44 gal/min. The transmissivity of hole MW-25 was 9.4 cm^2/s with 64 gal/min and MW-376-6 was 6.3 cm^2/s with flow rate of 43 gal/min. The average conductivities of the three holes were 6e-04, 1.5e-03, and 7.4e-04 cm/s respectively. Both MW-25 and 367-6 had high flow out of the bottom portion of the hole and therefore high liner velocities throughout most of the hole.

The geologic medium is a sequence of dolostone, limestone, and shale.

V. The comparison of the FLUTe results to packer results
The comparison of Profiler and Straddle Packers results for MW-24 is described here in detail. The straddle packer tests for each of the three wells were performed in 7-10 days by 1-2 people. MW-24 was packer tested in a total of 8 days with 3-11 intervals per day (at 10 intervals per day, it would require 6 days). The FLUTe profile of MW-24 was performed in ~2 hrs. by two people. The liner was then removed and reinstalled a second time on the same day, in the same time, with the same people, for a test of the reproducibility of the results. Most of the comparison hereafter is with the second profiling run. The results for both installations will be shown.



The FLUTe liner velocity from MW-24 is shown in Fig. 5. The raw velocity ("smoothed over 3") is calculated over two adjacent intervals centered on the midpoint. It is plotted as the black curve. The velocity data is then smoothed over a variable number of points depending upon the liner velocity (fewer points for a high velocity and more points for a lower velocity). The resolution is better at the lower velocity in the lower portion of the hole, but the resolution based on the smoothing function ranges from 0.35 to 0.1 ft. for this data set. Figure 5 shows the raw data (black curve), the smoothed data (pink curve), and the monotonic fit to the smoothed data (yellow curve). The comparison of the black curve (raw velocity) to the pink curve (smoothed) shows very little effect of the smoothing procedure.

The monotonic fit of the data is done to ignore temporary drops in the liner velocity. Figure 6 shows the liner passing through an enlargement of the borehole. As the liner expands into the enlargement, the velocity drops due to the larger cross section of the liner driving the water from the hole. However, as the liner passes into the normal borehole, the liner cross section decreases to its area before entering the enlargement. That decrease in liner cross section as it exits the enlarged portion of hole causes a liner velocity increase. The monotonic fit therefore ignores any temporary drops in liner velocity for any reason (e.g., brief increase in liner tension coming off the reel). The yellow monotonic fit is very close to the smoothed data except at ~150 ft where the end

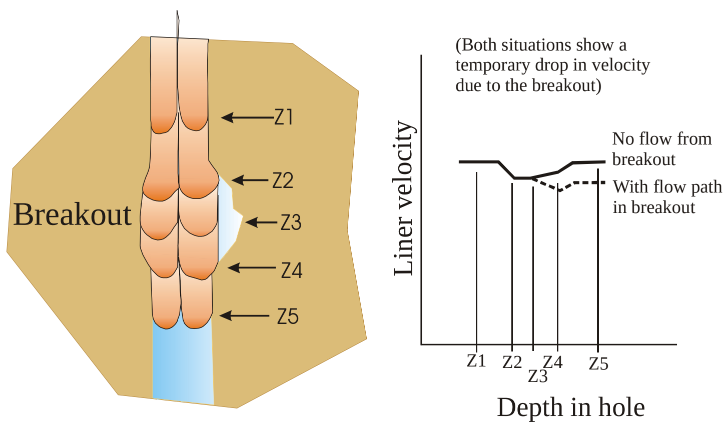


Fig. 6. Effect of liner moving thru breakout in borehole

of the liner and associated fittings passed through the rollers of the machine and caused some brief fluctuations.

From the velocity data of Fig. 5, the transmissivity of the borehole is calculated and is shown in Fig. 7. This very detailed transmissivity result is difficult to compare to packer data measured in 5 ft intervals. The FLUTe data was therefore integrated over the same 5 ft intervals as the packer tests to obtain the conductivity for the larger averaging intervals.

Figure 8 shows the packer conductivity results and the FLUTe results for the 5 ft intervals. The agreement is excellent except for the three very large packer results below 245 ft. Which is the correct result?

Fig. 7. FLUTe Transmissivity with depth MW-24 sec. run

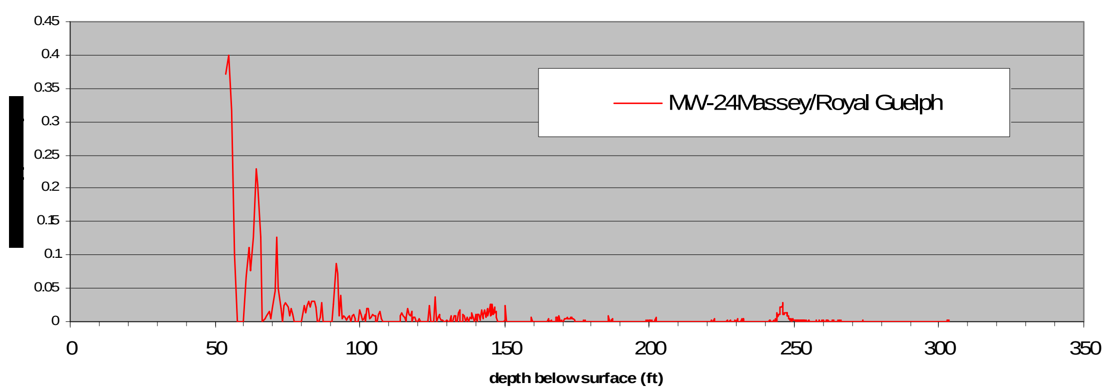
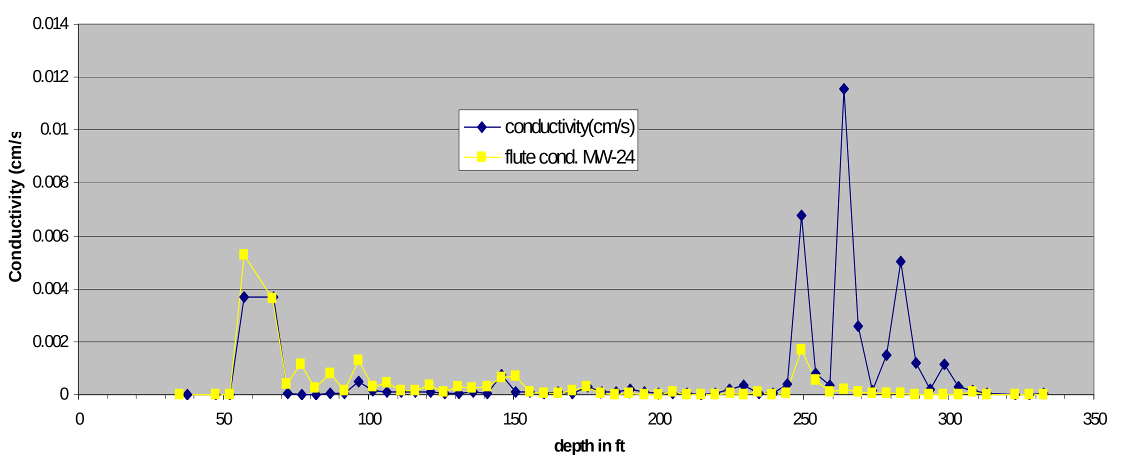


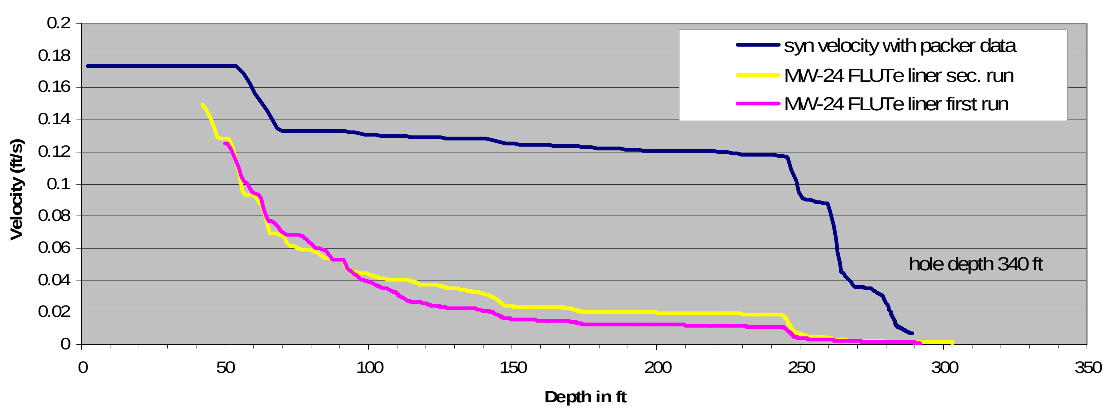
Fig. 8. Packer conductivity (cm/s) and FLUTe values from the liner velocity



VI. The synthetic velocity comparison

As a test of the packer result, a spreadsheet was developed which calculates the flow rate out of each packer interval for a constant driving pressure in the borehole, similar to the constant driving pressure for water flow out of the hole driven by the liner. For a discrete time interval, the flow rate out of the hole was summed for that time interval. The distance traversed by a hypothetical flexible liner is calculated by dividing the total flow in that time interval by the borehole cross section. In the next time step, that portion of the borehole flow that would be covered by the descending hypothetical liner is set to zero. The resulting flow is summed, and so on. This calculation produces the depth versus time that a hypothetical liner would descend in a hole with the conductivity profile determined by the packer measurements. This synthetic liner velocity is compared to the FLUTe liner velocity in Fig. 9. The first liner velocity of the two liner measurements is also shown. The two liner velocity curves are very near each other (the second run was slightly faster probably because of the development of the well as the first liner was withdrawn.) However the synthetic velocity developed from the packer conductivities is much higher until below 290 ft. Thereafter, the synthetic velocity and FLUTe liner velocity converge in the relatively tight lower portion of the hole.

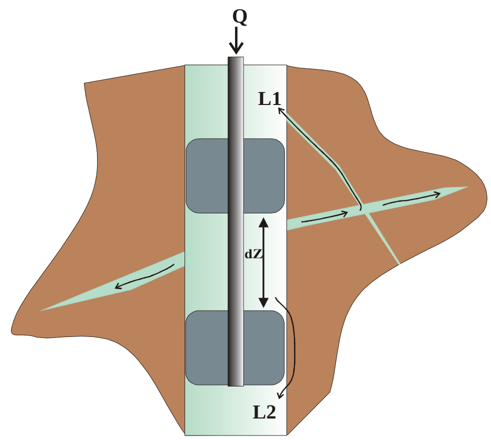
Fig. 9. Comparison of measured liner velocity and the synthetic velocity calculated using packer test results



It seems very unlikely that the two liner conductivities distributions would reproduce the packer distribution in most of the hole, but not the lower portion where the packer measurements are very high, and the liner has its best resolution. The liner velocity is a very simple displacement of the water from the hole. We believe that the packer data is probably in error due to the effect of bypass of the packer. Figure 10 is a drawing of the two possible flow paths that could add to the measured flow, Q, during a packer test. The first path, L1, is via a fracture that connects with a straddled fracture to the hole above or below the packers. The second path, L2, is via a permeable matrix that allows the packer interval to connect to the open hole above or below the packers.

These two kinds of bypass paths do not exist with the liner method. The top part of the hole is sealed by the liner and the rest is completely open. There are no bypass terms in the measured flow into the hole wall.

Only one hole volume of water is displaced by the liner. The liner measurement is continuous in time and space. There is therefore no concern about overlapping intervals or missed sections of the hole. Only flow paths that connect to distant regions are measured by the liner since the entire hole beneath the liner is at the same pressure. These generalizations are not the case for packer tests.



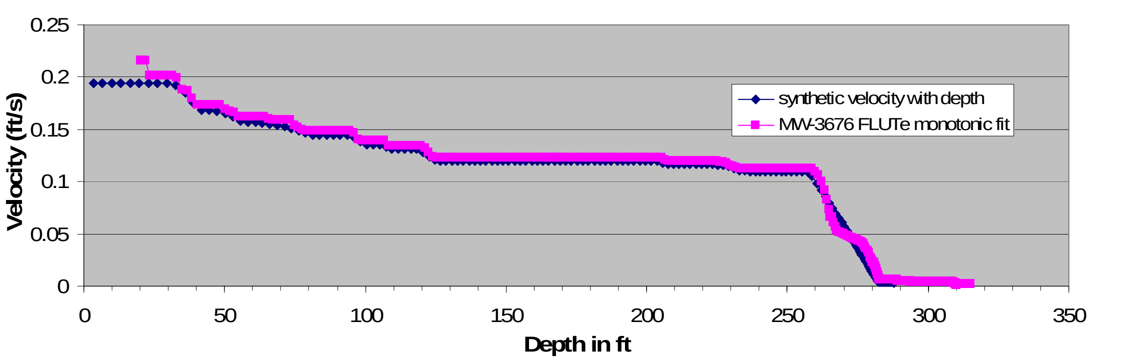
Flow rate into the fracture is Q-L1-L2, where L1 and L2 are flow paths past the packer.

Fig. 10. Potential flow past packer

VII. A test of the synthetic velocity and integration methods

Given the real possibility that there is an arithmetic error in either the integration of the FLUTe transmissivity profile over the packer intervals, or in the synthetic velocity calculation, the two calculations were tested by using the FLUTe packer interval conductivity values in the synthetic calculation spreadsheet to see if the synthetic calculation would reproduce the FLUTe liner velocity. Figure 11 shows the result for hole no. 367-6. The velocity curves are essentially identical with the obvious effect of loss of detail when the FLUTe data is integrated over the large packer intervals. This seems to support the general conclusion upon examination of Figs. 9 and 11 that the packer results can not produce the spatial resolution available in the FLUTe liner measurement.

Fig. 11. Comparison of measured liner velocity and synthetic velocity using FLUTe conductivities integrated over packer intervals, MW-376-6



It is not obvious from the geophysical data and borehole video why the packers may not have been well placed for the two high peaks at 265 and 285 ft except that region (260-320 ft) is much more coarse-grained than the rest of the hole (matrix or fracture bypass?).

The other two holes had higher transmissivity rates and showed similar zones of probable packer bypass.

VII. Discussion and conclusions

The first concern is whether the new FLUTe method gives the correct results. We believe that the results are not only correct, but provide better spatial detail than the packer measurements in these boreholes. It seems important that the packer measurement is susceptible to bypass and therefore may produce erroneous results in regions of porous matrix or highly fractured media.

Because of the concern about bypass of the packers, pressure measurements are essential above and below the packers to possibly detect such leakage. However, the pressure measurement does not allow determination of the amount of leakage. The use of guard packers above and below the straddle packers makes pressure monitoring for leakage much more sensitive. However, such bypass is not a concern with the liner method.

The second major comparison is the time and labor required to produce the FLUTe results versus the packer results. The FLUTe liner installation took about 2 hrs. The packer tests took 7-11 days with much more equipment in the field. However, there was no need to perform the packer measurements quickly. Other similar holes have been measured in 4 days with two people. Even then, the FLUTe measurement was done in less than 10% of the time.

An advantage of the straddle packer method is that regions of very low conductivity can be measured with the straddle packer. The FLUTe liner can not resolve the difference between very low conductivity and zero flow zones. FLUTe does have a multi level sampling system called a *Water FLUTe*™ which does allow the verification of very low flow zones or aquitards. Using the Profiler data, the multi level sampling intervals are easily selected.

A potential disadvantage of the liner method is that the topmost portion of the hole below the water table may not be well measured if the transition to steady state velocity has not been completed before the liner exits the casing. Abrupt changes are obvious even if imposed on the transient velocity, but a permeable zone may not be obvious until the transient has decayed away. The transient zone may be 5-50 ft long depending upon the liner initial velocity.

Finally, when the FLUTe profiling measurement is complete, the blank liner is usually left in place to seal the entire hole against cross contamination. That is not an option with straddle packers.

The synthetic velocity calculation does not introduce any new information beyond a direct comparison of packer versus liner conductivity measurements, but it does make the judgment of the data easier. In this case, the liner measurement, performed twice, is not likely to be in error by 600% in the flow rate out of the hole. A simple pumping test would be useful to confirm the liner velocity.

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Biographical Sketches –
Carl Keller has Bachelors and Masters degrees in math, physics, and engineering science from Valparaiso University and the Rensselaer Polytechnic Institute. He was employed with the U.S. Department of Energy and Department of Defense from 1966 to 1984 as an underground nuclear test containment scientist, developing a variety of models for multi-phase flow in the earth. In 1989 he developed the first everting flexible liner system for collection of pore water samples. He holds 12 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 chief scientist / engineer. Carl Keller is principal scientist at Flexible Liner Underground Technologies, LLC, 6 Easy St., Santa Fe, NM, 87506 (www.flut.com).

John A. Cherry has geological engineering degrees from the Universities of Saskatchewan and California, Berkeley and a Ph.D. in hydrogeology from the University of Illinois and has been a faculty member in the Department of Earth Sciences at the University of Waterloo since 1971. Since 1996, he has held the NSERC-GE Research Chair in contaminant hydrogeology. His research is focused on field studies of contaminant behavior in groundwater.

Beth L. Parker has a Bachelors degree in environmental science/ economics from Allegheny College, a Masters degree in environmental engineering from Duke University and a Ph.D. in hydrogeology from the University of Waterloo. She joined the faculty of the Earth Sciences Department at the University of Waterloo in 1996 where she is currently a Research Associate Professor. Her research involves field studies of transport, fate and remediation of chlorinated solvents in diverse hydrogeologic environments including fractured rock, clayey aquitards and sandy aquifers.