A Rock Borehole Packer System for Identifying Hydraulically Active Fractures Under Natural Gradient Flow

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

To improve capabilities for understanding and predicting contaminant migration in fractured rock there is need for better field methods to identify the fractures that have active groundwater flow. Current methods have limitations, for example, borehole geophysical imaging, such as acoustic and optical televiewing, identifies fractures appearing on borehole walls but cannot sense groundwater flow. Borehole hydraulic tests determine the transmissivity of fractured zones under conditions altered by the presence of the borehole and its testing and not under natural flow conditions. The natural flow conditions are important because they govern contaminant transport in the whole flow system. Furthermore, conventional tracer tests are used to identify flow in fractures, but these too are typically done under imposed rather than ambient (natural) hydraulic conditions. High resolution fluid temperature logging in lined boreholes can identify some of the hydraulically active fractures, but this method lacks the sensitivity needed to indicate ambient flow in each individual fracture.

This thesis presents a new method aimed at determining whether or not any particular fracture targeted for borehole measurement has substantial ambient flow. This method involves a device lowered into an open hole to a target zone where a packer is inflated. This packer has a water-flow-sensitive dyed cotton fabric wrapped around its exterior so that when the packer is inflated, it not only seals the borehole but presses the cotton fabric against the borehole wall. This set-up causes the exact location of hydraulically active fractures at the borehole wall to show up as imprints marked on the fabric. When viewed under black light, individual fracture markings can be seen, and the distribution of the hydraulically active fractures is identified.

For this new method, a prototype system was developed for use in 10cm diameter wells and was tested first in a conventional slotted well screen in the laboratory and then in a simulated fracture (slotted) PVC pipe installed in a sandy aquifer where groundwater flow rates are well understood. From a large number of fabric/dye combinations tested in the laboratory, it was found that cotton dyed with a particular food grade additive provides the best fracture markings by far. The prototype system uses the double-acting packer system originally developed by Solinst Canada, and this novel packer design provides ease of use and flexibility for configuring multiple packers on a single pipe. This prototype system is now ready for the first field trials in a fractured dolostone borehole in Guelph, ON. While the ability of the device to identify active fractures as effectively as it has in the slotted casing trials may be reduced by the interaction of the dye with the porous rock

matrix, it is anticipated that this new system for identifying hydraulically active fractures under resealed borehole flow conditions (resealing brings flow back to ambient conditions) will be useful in its own right in fractured rock investigations. This device also represents the first step in the creation of a more elaborate device to measure both the groundwater flux and the contaminant flux within plumes in fractured rock.

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1. Introduction

1.1 Problem Statement

To advance the understanding of groundwater flow and contaminant migration in fractured rock, there is a need for methods to identify those fractures in boreholes in which active groundwater flow under natural conditions (i.e. ambient groundwater flow without imposed flow conditions due to pumping, injection or open-hole cross-connection). There are geophysical imaging methods (i.e. optical, acoustic or electrical televiewing) that identify fractures in boreholes; however, these identified fractures do not necessarily have groundwater flow because the fractures may be in-filled with geological cement, or they may not be connected to the active fracture network. Other methods can provide information on hydraulic activity under passive flow conditions, such as high resolution temperature logging inside FLUTe liners (Pehme, Greenhouse, & Parker 2007), but this method lacks sensitivity for low flow fractures and may not identify, closely spaced fractures as separate features. Borehole dilution done in packer isolated intervals provides information on hydraulic activity of the interval under ambient conditions, but it is not specific to any particular fracture in the test interval (Novakowski et al. 2006). Hydrophysical logging is an open full hole dilution test but is compromised due to cross connection flow between fractures (Pehme et al. 2007). There is need for a method of borehole measurement that can focus on particular fractures, such as those identified by televiewing, to determine whether or not each of them is hydraulically active under ambient conditions.

1.2 Thesis Goal

The goal of this thesis is the development of a method to accurately identify the location of individual hydraulically active fractures in boreholes in fractured rock. The impetus for creating this method derives from the need for an in-situ flux measurement method for both groundwater flow and organic contaminant transport in boreholes under passive conditions: such flux measurements can be done in granular media (Hatfield et al. 2004) but not in fractured media because instead of testing interval as done in granular media, specific fractures need to be tested in the fractured rock environment, hence the development of the FIPS device. There are other complications with creating a PFM for fracture rock and is discussed in the Appendix. This thesis is considered to be an initial step in the pursuit of the broader goal aimed at the development of a fractured rock flux meter.

1.3 Premise

This thesis is based on the premise that hydraulically active fractures in rock under natural groundwater flow conditions (i.e. ambient flow) can be identified by a down-hole device that makes use of a material containing a leachable substance or material indicative of the groundwater flow. At present, there exists no such device using a leachable tracer to identify ambient groundwater flow in fractured rock. There are two approaches currently in use for obtaining information concerning fluid flow in fractures in rock boreholes: one concerns groundwater flow (borehole dilution which does not work to identify individual flow specific fractures but covers the interval between the packers), and the other concerns NAPL flow (the NAPL FLUTe system works in boreholes that have mobile NAPL phase flowing through but this is a rare occurrence).

The first approach, the borehole dilution test, a conservative dissolved tracer is instantaneously introduced into an isolated mixing volume located over a section of the borehole. The subsequent decline in the concentration of the tracer in the mixing interval due to the advective flux across the borehole is monitored over time (Drost et al. 1968). In permeable sands and gravels, average linear groundwater velocities are generally between 5-50 cm/day; the decline in concentration of the tracer typically occurs over a few tens of minutes (Freeze & Cherry 1979). In fractured rock, velocities are generally much higher but the darcy flux generally much smaller; this difference in velocities causes tests to last from several days to over one week (Novakowski et al. 1995).

The second approach, the NAPL FLUTe system, is used to locate pure phase NAPLs trapped in the rock formation. Locating these NAPLs is possible by everting a FLUTe liner that has a NAPL-sensitive fabric attached to it. Water is used to evert the liner, and the excess head forces the liner and its fabric against the borehole wall (Figure 1-3a). A noticeable stain is produced when the fabric comes into contact with the NAPL. In order to analyze the results of this process, the fabric must be recovered by pumping down the excess head and inverting the liner from the hole. This peeling process inverts the cover and liner to allow the cover to be removed without touching the borehole wall at any other place than its original location. After the entire liner/cover is peeled from the borehole, the liner is pulled off the covering, exposing the inside surface of the cover. Figure 1-3b shows both the NAPL stains and the location of the NAPL in the borehole. However, this method does not work if the contaminant is dissolved (Keller 2008) because dissolved contaminants do not stain the fabric and discrete features controlling the NAPL flux may not be observable if the NAPL bleeds in the fabric.

The two approaches discussed above have limitations especially when considering the goal of this thesis. The fracture identification device developed in this thesis was inspired by the University of Florida Passive Flux Meter (PFM). The PFM is, like its name suggests, a passive device used in porous media wells to measure both contaminant and groundwater fluxes simultaneously (Annable et al. 2005). To develop a PFM for use in the fractured rock environment, it is imperative to identify individual hydraulically active fractures for proper sampling and accurate flux measurements (more information regarding the PFM can be found in section A.1).

The device developed in this thesis is intended for use in 4” (10cm) diameter holes; however, it can be adopted for holes of other diameters. The 4” (10cm) hole was selected as the focus for this device because it is a common borehole diameter used in studies of contaminated bedrock sites.

1.4 Objectives

In this thesis, the following objectives were pursued:

1. Select a preferred conceptual design from several design options.
2. Select materials and conduct lab bench performance tests for the materials used in the construction of a prototype device for the use in granular permeable media.
3. Construct a full scale prototype device
4. Construct a laboratory apparatus for simulating flow in a normal slotted well screen (sand aquifer material with well understood porous media flow conditions), and use for the initial prototype device testing.
5. Construct a well to simulate fracture flow at the Borden field site and test the prototype device in this well.
6. Design a field test for the device in a hole in fractured rock at the Guelph site.

1.5 Preferred Conceptual Design

1.5.1 Selection of the Preferred Design

The preferred design was selected from the two very different conceptual designs discussed in section 1.3. The first design involves isolating an interval in a borehole and positioning a leachable tracer material in the open interval (Figure 1-1a). This approach, which is a depth averaging or blending approach, is similar to borehole dilution but involves a sorbed tracer on a permeable medium instead of a dissolved tracer in groundwater. This sorbed or leachable tracer is intended to show the effects of groundwater flow. A depth-specific (fracture specific) approach was explored for the second design; this involved pressing a tracer dyed fabric against the borehole wall (Figure 1-1b).

The second approach bears similarities to the FLUTe method, which may or may not identifies individual fractures where NAPLs are present in the borehole, but this preferred design is to detect water flow rather than NAPLs. In this dyed fabric approach, the water from each of the fractures covered by the dyed fabric flows along the fabric to cause leaching of the sorbed tracer. This second design involves sealing a portion of the entire borehole with either packers or a FLUTe liner. For this thesis, a packer with attached flow sensitive fabric was used. This involved using a dyed fabric attached to a packer and positioned in the borehole to identify groundwater flow in specific selected intervals.

The optimal packer for this device must be easy to operate and well suited for use with the attached flow sensitive fabric. The packer needs an annulus that is large enough for the packer to be raised and lowered in the borehole with the flow sensitive fabric attached, but not so large that the fabric can't expand out with the inflated packer to seal the borehole (Figure 1-4). The packer must be long enough to have sections available to seal above and below this fabric, ensuring that only the targeted area has flow around the fabric. By sealing off fractures from each other, the proposed device would test each individual fracture avoiding depth averaging or blending. The attached fabric is pressed tightly against the borehole wall that the fabric is essentially impervious. This device that uses an inflatable packer and flow sensitive fabric attached to the exterior is referred to as the Fracture Identifying Packer System (FIPS).

The major challenge in this thesis was to create a suitable flow sensitive fabric. No such fabric exists in the commercial marketplace, and, therefore, such a fabric had to be invented. For the flow sensitive fabric to be appropriate for FIPS, it must be readily available, be of low cost and have good sensitivity to show fractures with active flow. To render the fabric 'flow sensitive' the fabric is 'dyed' with a substance that shows leaching or disappearance of the dye in the area where fractures with active groundwater flow occur. Therefore, the creation of the flow sensitive fabric requires a successful combination of fabric and dye. The ideal dye/textile combination would have a visual indicator under both visible (normal) and ultraviolet light (black light). The black light is important because the water being tested may be extremely turbid and may stain the textile so that normal light identification may be difficult.

For this thesis, the preferred fracture identification device consists of a particular type of inflatable packer around which the dyed fabric is wrapped. This particular type of packer is the double-acting packer (DAP), originally built by Solinst for CMT multilevels, but never used commercially. Around the DAP, a fabric sensitive to groundwater flow is wrapped so that when the packer is inflated in the borehole, it presses the fabric against one or more fractures. As the water flowing in the fracture goes around the exterior of the sealed hole, the dye is leached from the fabric, thus when the fabric is removed and inspected at the surface, it indicates where the hydraulically active fractures are located (Figure 1-5).

1.5.2 General Approach for Advancing the Preferred Design

Figure 1-6 shows the various steps that were followed to advance the design of the FIPS device. The first step, as noted above, was the conceptual design process. Brainstorming was done on testing methods (open annulus to direct contact with the borehole wall) and types of packers to be used. Throughout each test and planning stage, brainstorming and improvements were performed to create a device that could perform as efficiently as possible. It was decided that attachment of a flow sensitive fabric to a packer causing the fabric to have direct contact with the borehole wall would be the most appropriate. Initial designs were used in a slotted well screen in the laboratory. These slots with an aperture of 254μm simulated fractures with a flow zone and a low/non-permeable zone. In conjunction with developing a favourable flow environment the flow sensitive fabric, an integral part of the FIPS device needed to be created.

To advance this method, a variety of tests needed to be performed to develop and improve the design. Test 1 involved the testing of various fabric/dye combinations. Once a fabric/dye combination was found that was able to determine water flow, the fabric needed to be tested on a packer. The first FIPS device was tested in a box aquifer that had a slotted well screen installed in sand where the slots were used to represent fractures. From the box aquifer, tests were moved to a field environment in Borden. Two wells were installed in the forested section of Borden: one well used a slotted well screen, the other used riser pipes and had three slots cut to allow flow. Testing started in the controlled box aquifer, and then moved to the Borden porous media well (the well uses the same sized well screen as the box aquifer). The results corresponded well with literature values for velocity (9cm/day) (Laukonen 2001) for the Borden aquifer, and thus the process moved to Test 3b, testing in the simulated fracture well. These two well tests helped to determine shortcomings and possible changes for the FIPS device for effective use in a true fractured rock field environment. Each test moved the device closer to an actual field fractured borehole. Test 4 for advancing the design, which has yet to be done, is to test the device in an actual rock borehole in Guelph, ON, that has been extensively examined through a suite of characterization tools, geophysical and hydrophysical logging analysis and depth-discrete packer testing at 30cm intervals.

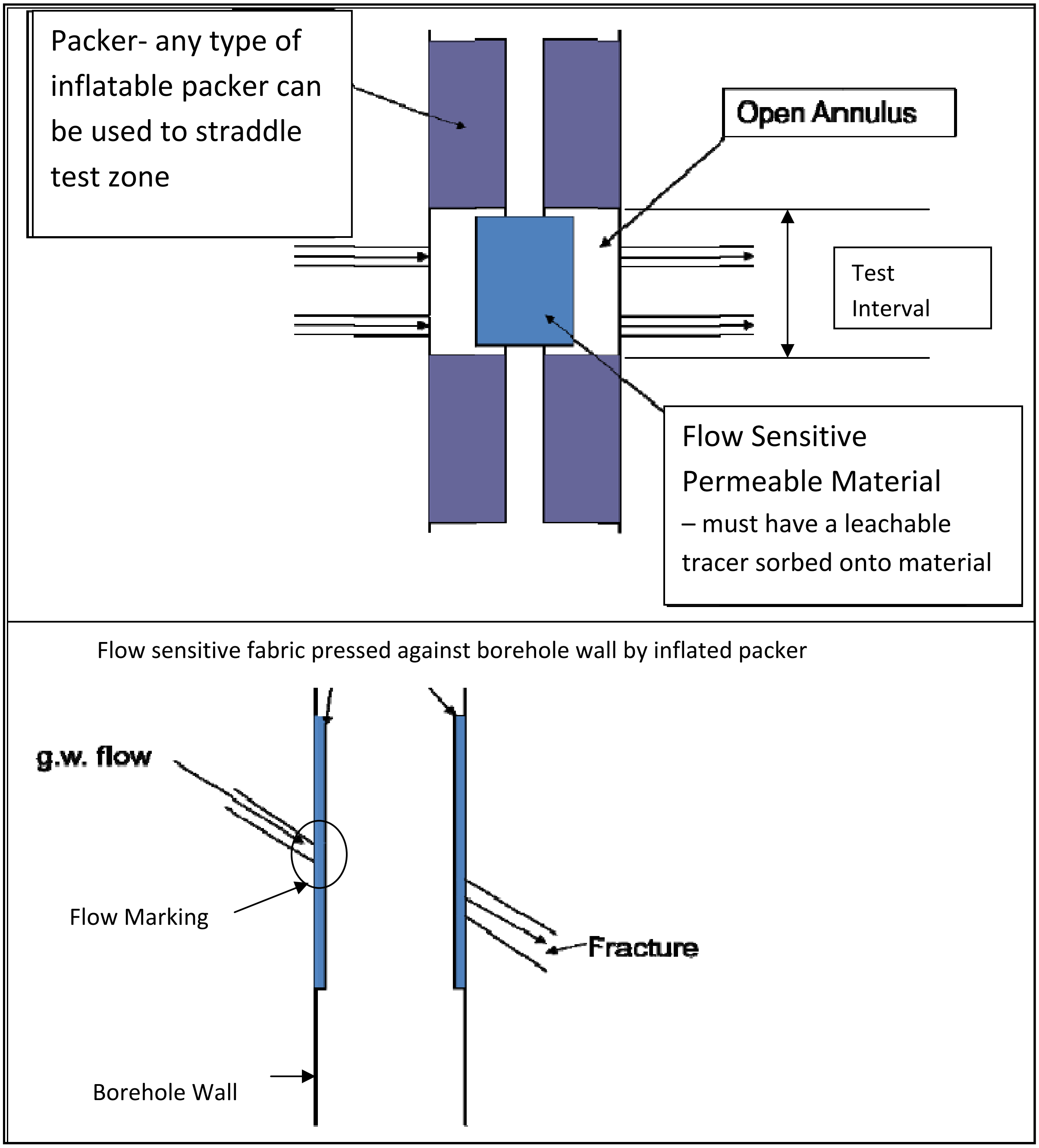


Figure 1-1: Initial design options of Fracture Identification Packer System (FIPS). The top figure shows a design with a packer (standard, double-acting or tapered FLUTe) straddling a sample zone with an open annulus around the flow sensitive fabric. This design has flow that converges into the open hole. The bottom figure is another design where the flow sensitive fabric is pressed directly against the borehole wall; this fabric could be attached to a packer or a FLUTe liner. Here the flow travels around the material, following the curvature of the well.

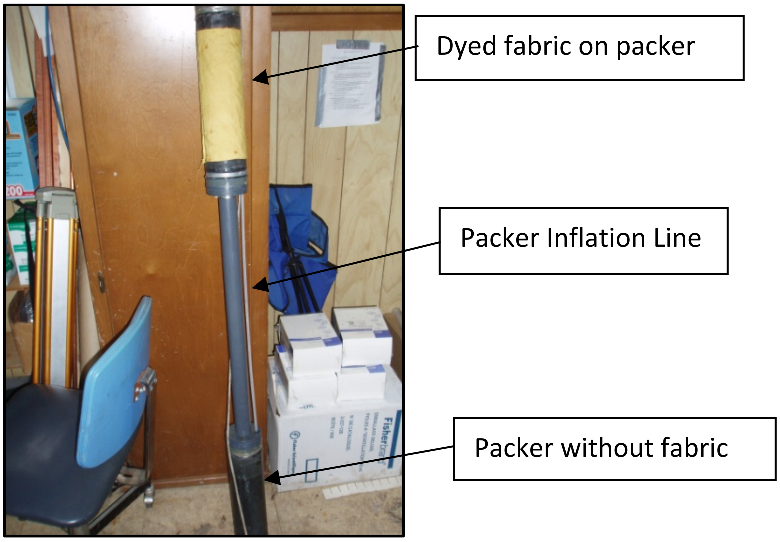


Figure 1-2: Preferred design for FIPS. This design uses a double-acting packer with flow sensitive fabric directly attached to it. The fabric is pressed up against the borehole wall when the packers are inflated. Multiple packers can be put on a pipe to sample several zones

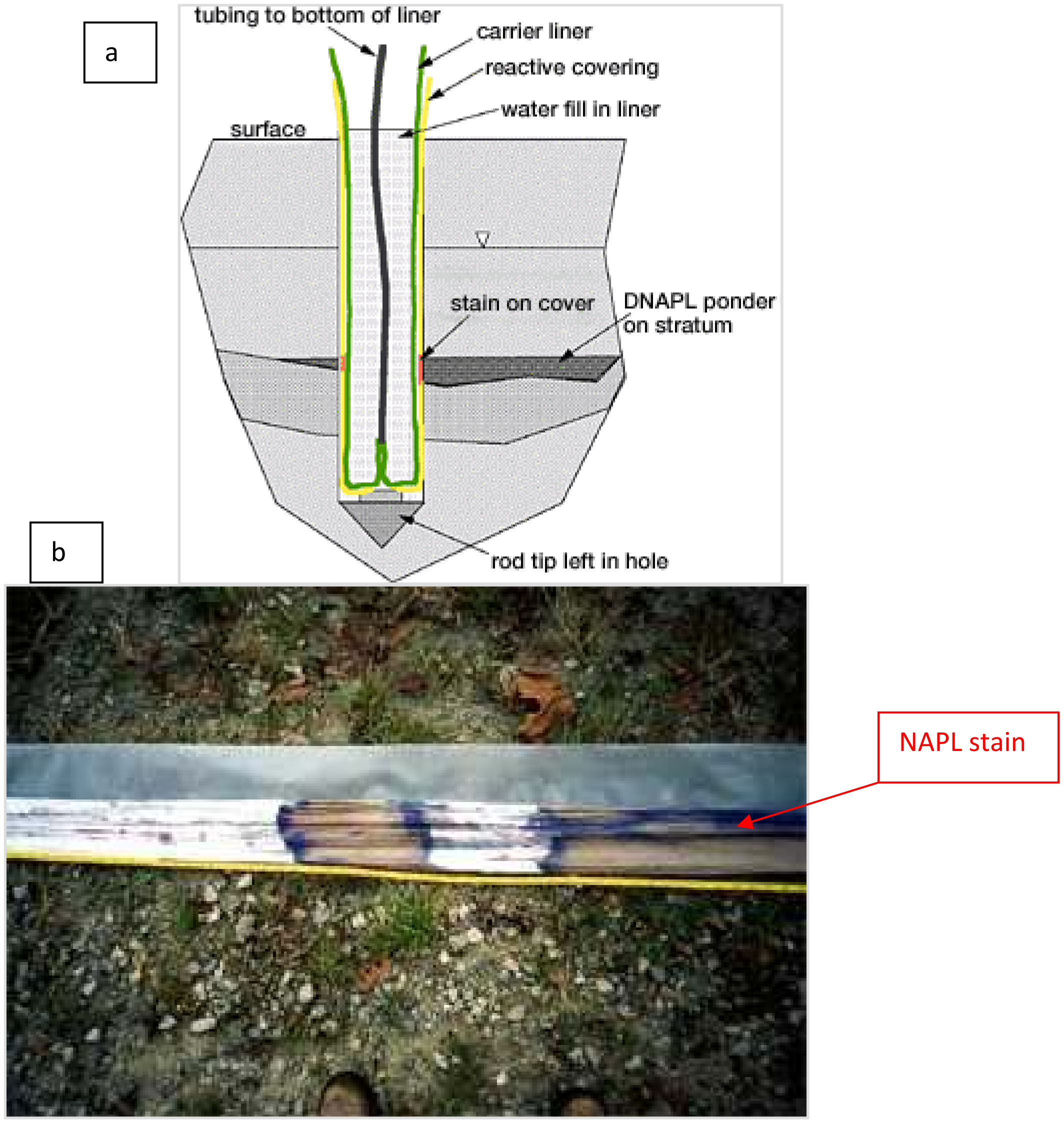


Figure 1-3: (a) Shows the everted NAPL FLUTe liner in a borehole containing free phase NAPL (b) Shows the stain left on the liner cover from a fractured rock borehole. Sudan-4 had been used to detect NAPLs; now a non-toxic chemical is used (Keller 2008).

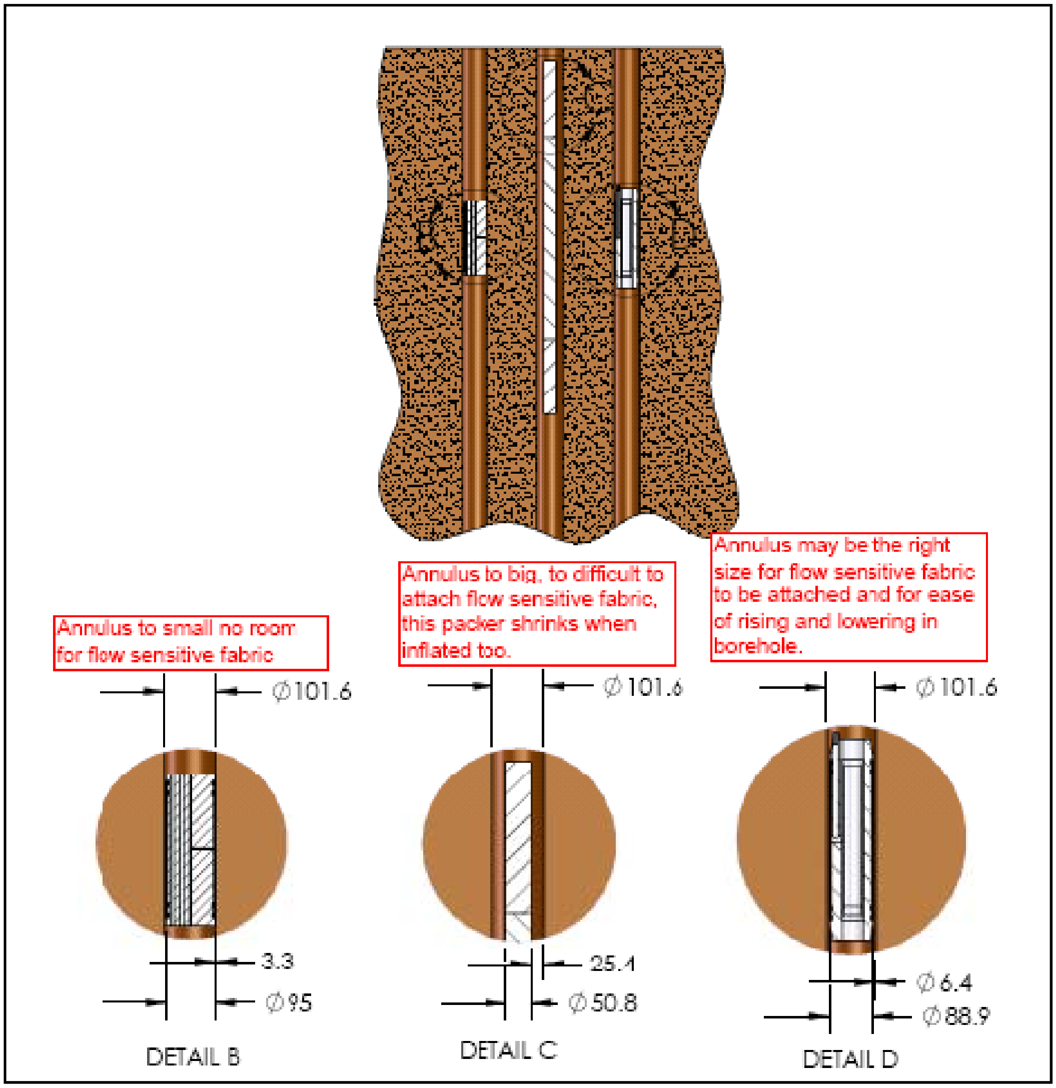


Figure 1-4: Annulus issues with different packer types. Detail B shows the homemade packer with very little annulus; it is so small in fact that the flow sensitive material could not be attached. Detail C shows a standard packer with a large deflated annulus; this would pose a problem for attachment of the flow sensitive fabric because the fabric would have too large a circumference to fit on the packer properly when the packer is raised and lowered. Detail D shows the double-acting packer; this has a 6.4mm annulus which may be enough to fit the flow sensitive fabric on, but also have enough space to raise and lower the packer without affecting the attachment of the fabric. All radius values are in mm, the top number is the borehole diameter, middle number is the annulus spacing and the bottom number is the packer diameter.

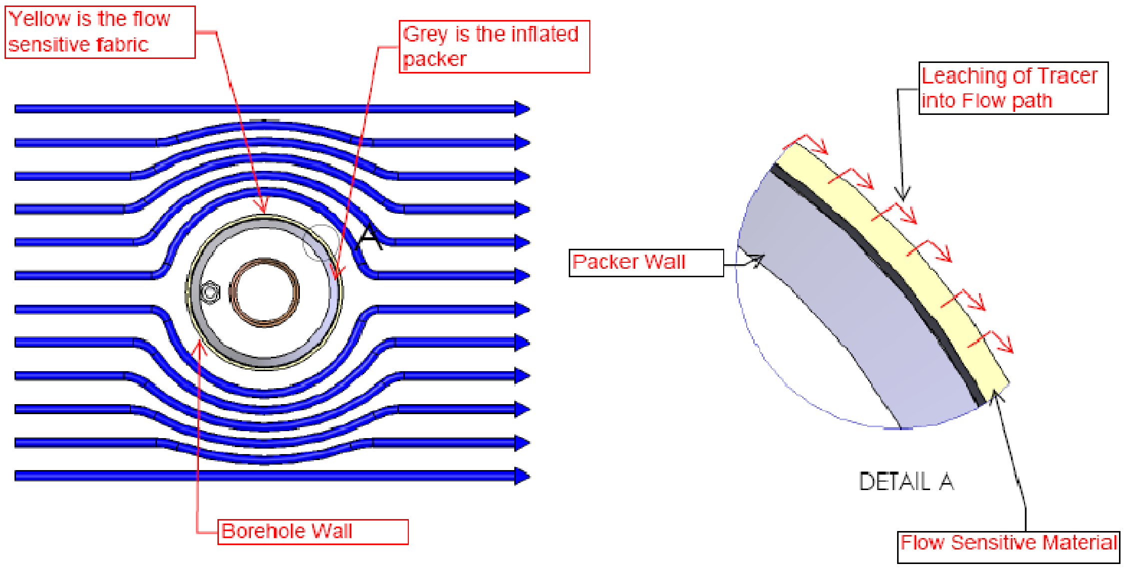


Figure 1-5: Conceptual view of flow around the packed off borehole. As the water passes the dyed fabric, the dye is leached from the material creating a flow indication mark.

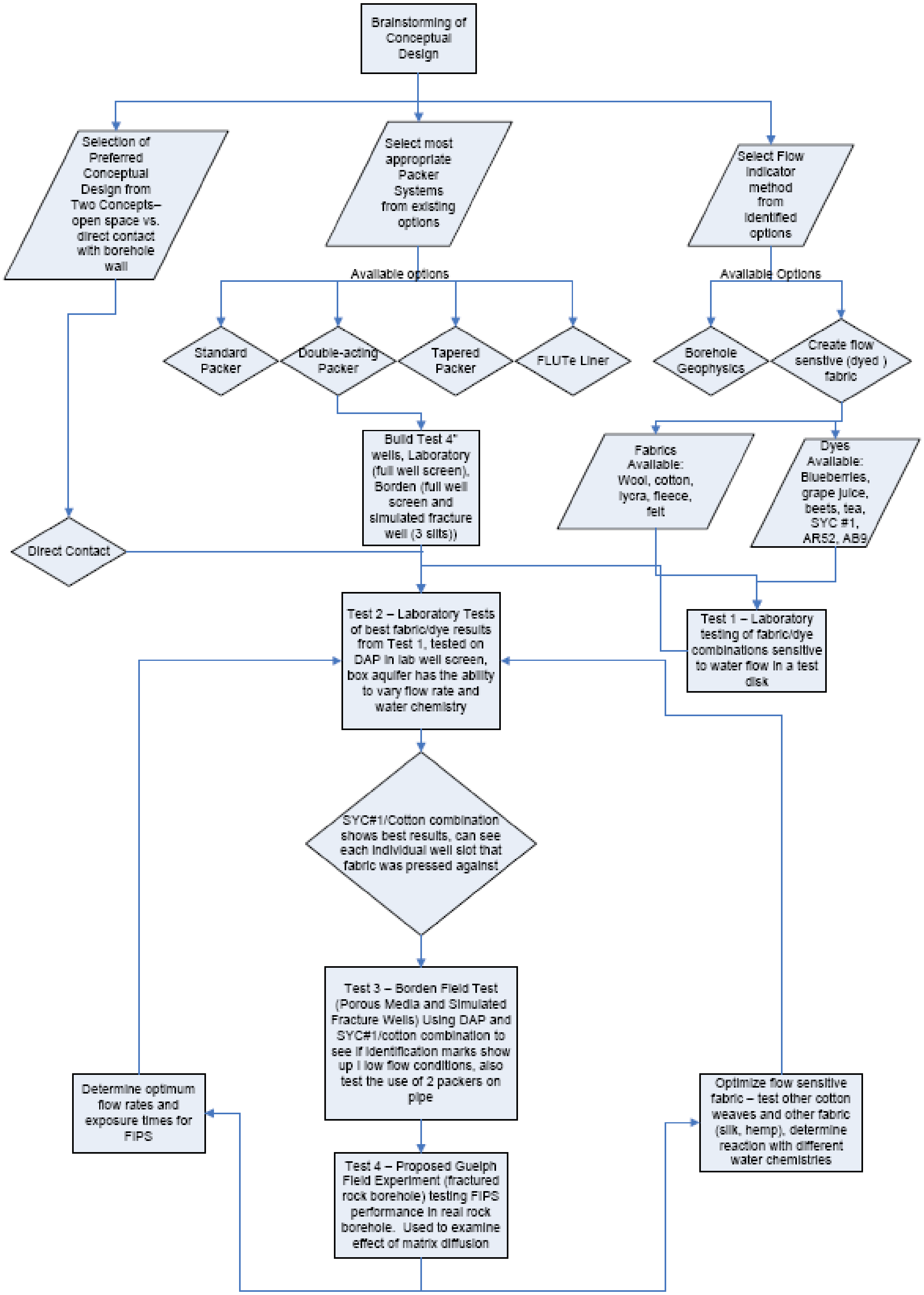


Figure 1-6: Flow chart for the advancement of the prefered FIPS device

2 Methods and Materials

2.1 Two Laboratory Set-ups

The initial phase of testing for the indicator fabric and its use with the double-acting packer (DAP) occurred in the lab. By performing bench scale tests, it was possible to adapt and modify the test environment and to examine the performance of the FIPS device. The first lab set-up was a box aquifer that was created to simulate natural gradient horizontal flow at varying velocities through simulated fractures represented by the slots of the well screen. The second lab set-up was a plexi-glass well that was used to visually inspect the prototype design when inflated and in a saturated environment. Through the lab tests, the FIPS device was optimized to perform as efficiently as possible and to aid in success in more difficult field environments. These improvements involved looking at packer efficiency for ease of insertion and removal, annulus size for material attachment, and indicator fabric performance (i.e. how well the fabric stayed attached to the packer and how well the fabric/dye combinations responded to water flow).

2.1.1 Design of Box Aquifer and Visual Inspection Well

Figure 2-1a shows the components of the lab system. The test system was set up in a sewer pipe approximately 1.4m high and 30cm diameter. A 1.5m long 10cm ID slotted well screen was placed in the centre of the sewer pipe. This slotted well screen represents many closely spaced fractures. Bentonite was placed in the bottom and top 15cm to create plugs; the rest were filled with commercial grade medium grain sand with a hydraulic conductivity of 0.01cm/s (Figure 2-1b). Figure 2-2 shows the schematics of the box assembly and how the flow enters through an injection port, flows through the well screen and exits through the drainage port (Figure 2-3 shows this convergence of flow to the well screen). Two parallel sides of the sewer pipe that were used for flow injection and extraction (Figure 2-1c). Three ports were drilled into each side to help facilitate horizontal flow conditions. Water was injected through either direct attachment to a sink faucet, or through the use of a peristaltic pump. Extraction was done by opening the discharge ports and allowing natural flow out. With this set-up, a simulated sand aquifer was created. This simple set-up helped to simulate potential issues with the FIPS.

The well screen of the box aquifer simulated many equally spaced and equal aperture fractures. Novakowski et al. (2006) who used hydraulic tests in rock boreholes found calculated hydraulic apertures based on the cubic law ranging from 94μm to 1000μm, with a mean hydraulic aperture of

152μm. Hydraulic aperture refers to the equivalent aperture size assuming that the system is modeled by parallel plates (Schwartz & Zhang H. 2003). The well screen slot size 0.01inch is equivalent to 254μm and falls in the typical range of fracture apertures calculated from packer tests at the Guelph field site, which are 50-500μm (Quinn 2008). With average fracture sized slots and a flow velocity that can be varied from less than 10cm/day to approximately 7000cm/day, as tested when determining the flow parameters of the box aquifer (tests were performed at 5000cm/day), this box system serves as a good representation of variable fractured rock environments.

To help understand the performance of the packers, the FIPS device and other borehole tools, a visual inspection well was also built. Beside the box aquifer, a 4" (10cm) diameter plexi-glass tube was glued onto a plexi-glass base (Figure 2-4). This set-up helped locate packer leakages, determine circulation levels of the Borehole Dilution device, and identify the way the FIPS pressed up against the borehole wall.

2.1.2 Simulation of Flow in the Box Aquifer Flow System

The box aquifer is a unique flow environment because water comes in at an injection port, flows around a circular aquifer and then out a single drainage port. To help understand how the flow system works, the box aquifer was modeled using Hydrogeosphere to show flow lines (Figure 2-3). Hydrogeosphere is a model program developed at the University of Waterloo by Therrien, McLaren and Sudicky to model surface-subsurface flow systems. This modeling helped visualize how the flow converged toward the well screen and then out the drainage port when the well was empty. The model helped to confirm the intended flow system through the creation of a visual indication of how the flow proceeded through the box aquifer. The box used medium grained sand as the porous medium and a standard 10 slot well screen. The exact hydraulic parameters of this box were not of interest as this was built to help modify techniques and designs. Subsequent field tests were then performed on the Borden wells (section 2.2).

2.2 Borden Porous Media and Simulated Fracture Well Set-up

After the laboratory tests, the next tests were conducted at Canadian Forces Base Borden (Borden), located approximately 70 km north-west of Toronto. The BDI forested site in Borden was chosen because the aquifer has been intensively studied, and the hydrogeology and groundwater velocity at this site is well understood (Laukonen 2001;Thomson 2004).

Tests in the Borden aquifer were performed in a standard well screen and a simulated fracture well. The standard well was used to reconfirm the values of groundwater velocity in the sand aquifer at this location. The well with the simulated fractures (i.e. three slots) served to provide a test system that had 'fractures' and that could accommodate field test devices of the same vertical length anticipated for use in rock holes. Due to the depth of the simulated fracture well, it was possible to use multiple packers to test multiple intervals at one time. In this regard, individual fractures could be sealed from one another and the overall performance of the FIPS device when used with multiple packers could be seen.

The BDI section of the Borden forest used previously for several experiments is situated in the unconfined surficial aquifer composed of fine to medium grained sand (Laukonen 2001;Thomson 2004), which is approximately 3m thick overlying a 0.2 to 0.3m transition zone containing fine sand, silt and some pebbles and cobbles. This transition zone is underlain with a regionally extensive clay aquitard approximately 8m thick (Morrison 1998). The sand aquifer is fine- to medium- grained with horizontal lenses on the mm and cm scale which are continuous over lengths of 2.5m (Brewster et al. 1995). Changes in texture and grain size generally correspond to changes in colour, with the thinner strata having a distinct dark-gray colour attributable to a higher percentage of ferromagnesian minerals; these layers have lower permeabilities (Poulsen & Kueper 1992). Laukonen (2001) observed that the average linear groundwater velocity in the sand aquifer varied by a factor of four (6 to 28cm/day), with an overall average of approximately 10cm/day. Figure 2-5 for a detailed map of the Borden BDI location and geology.

2.2.1 Design and Installation

At the Borden site two 4 inch (10cm) wells were installed by water jetting in the sand aquifer, and, at the bottom, a Shelby tube was used to core approximately 60cm into the clay aquitard (Figure 2-6). This core was taken so that there was a 'no-flow' zone in the well, to make sure the flow sensitive fabric only responded to zones of water flow. One well was installed to 3.8m (clay was located at 3.3m); this well had a 1.5m well screen and three 1.5m riser pipes. Table 2-1, Table 2-2, Table 2-3 and Figure 2-7 show the parameters of the 4 inch (10cm), 10/1000 slot well screen; a standard well screen used to monitor porous media flow. The second well was installed at a depth of 4.1m (clay was located at 3.4m). To create the simulated well with fractures, standard 10cm riser pipe (PVC) was used. A 4.76mm horizontal line was machined through the pipe (Figure 2-8) so that 1cm of pipe was left intact on each side of the slit. This remaining pipe, set 180 degrees apart, gave the necessary strength to hold the fracture aperture open. This slot was then covered with Nytex cloth to screen the fines (Figure 2-8). From the top of the casing, the fractures are located at 1.8m, 2.3m and 3.4m bgs.

The goal after the installation process was to inflate the packers to completely seal the inside, causing the water to flow around it. This goal is an attempt to simulate horizontal fracture flow as best as possible in a porous medium environment. Figure 2-9 shows how the flow lines in the porous media converge into the simulated fracture well and out again. Installing the wells involves placing an end cap on the bottom and lowering the pipes to the desired depth. Once installed, the sand aquifer is allowed to collapse around the well. Development of the well, in this case, was done with the use of a Honda transfer pump. The wells were evacuated 10 times to ensure adequate development.

Borehole dilution tests were performed in the porous media well to confirm the literatures reported value of 9cm/day flow velocity and in the simulated fracture well to confirm that the flow was similar to a true fractured rock well. A temperature vector probe was also used in the Borden wells, but it did not provide useful results. Both the borehole dilution and temperature vector probe data are discussed in the Appendix in sections A.2.5, A.2.6 and A.2.7.

2.2.2 Borden Well Performance

The standard porous media well performed as expected, with velocities closely matching those provided by Laukonen (2001) of 9cm/day. The main issue with the characteristics of this simulated fracture well is the fact that flow is moving through porous media into a fracture about 5mm thick. In a sandy aquifer, flow is moving through the whole conductive system, while, conversely in fracture flow, flow only happens in the fracture itself, which typically has a small aperture size, a size very small compared to the flow field of a sand aquifer. Fractures often have higher velocities but smaller advective (darcy) flux than that of porous media flow. With this simulated fracture well in a porous media environment, the flow moving past the simulated fracture is not the same as if it were in a well in a fractured borehole. Figure 2-6 shows how flow has to converge at the simulated fracture to enter the well.

2.3 Indicator Fabric

Building the apparatus and establishing a test site were two key aspects to this project. Another was finding an appropriate indicator fabric. Simplicity was the driving force behind the search for a suitable fabric. With this in mind, it became imperative to find textiles and dyes that were inexpensive and readily available. The use of natural dyes acceptable for human ingestion was also essential, as this device would be put in direct contact with groundwater used for drinking water supply.

The search for fabrics to dye led to tests with five natural and two synthetic fabrics. Wool, cotton, lycra, fleece and felt were all tested to determine their feasibility as indicator materials. Other materials not tested at this time were silk, polyester, nylon and hemp (Table 2-4). Wool and cotton were the preferred natural fabrics because both are readily available and dyed easily. Silk is more expensive, and its fibers are sharp, so there was concern that if sown with thread, it might cut through on the expansion with packer and not stay attached. Lycra was chosen because of its elasticity, which held great promise for attachment to the packer. Fleece and felt were also chosen mainly because they were available and, with their pilly nature, had the potential to hold dyes. While there were many other types of materials available the initial tests involved only the cheapest, purest fabrics (Table 2-4 lists the fabrics used and not used, as well as the desired properties of the fabric to be used with the FIPS device). These fabrics would be cut to size and dyed. Important attributes of these fabrics that were considered were dye fastness, durability, thickness, hydraulic conductivity and accessibility.

2.4 Indicator Dyes

After obtaining fabric samples, selecting dyes became the next step in the process. A practical dye would be one that had a moderate to strong hold to fabric, fluoresced under black light, visually dyed the material, and allowed rapid enough removal (leaching) when brought into contact with flowing groundwater. The natural dyes included blueberries, beets, purple grape juice, tea, and Special Yellow Colour #1 (SYC #1). The blueberries were of the wild blueberry type, flash frozen for storage. The beets were fresh from the market. Welch’s grape juice was purchased and a black tea was used. SYC #1 (Figure 2-10) is likely the least known by this readership, but it is used in food and natural medicines and thus considered safe for human consumption. The local grocery story became the primary dye supplier. By locating natural foods and spices in a grocery store, accessibility and affordability would not be a limitation.

Two synthetic dyes were also tested, diammonium salt (Acid Blue 9) and sulforhodamine B (Acid Red 52) that are fluorescent tracers and are used readily in groundwater studies (Cey 2007). Field et. al. (1995) provides more information on these synthetic dyes and others synthetic dyes used in groundwater studies. These two synthetic dyes were chosen because they are considered safe for use in groundwater, and they were recently used by Cey (2007) in the Walkerton aquifer.

2.4.1 Dye Preparation and Fabric Dyeing

Five 1mx1m fabrics pieces (wool, cotton, lycra, fleece and felt) were purchased from a local fabric store. From the main body of each fabric, a strip of 1mx0.1m was cut then subdivided into seven squares measuring approximately 0.13mx0.1m.

All the dyes (blueberries, beets, tea, grape juice, SYC#1, Acid Red 52 and Acid Blue 9) were prepared individually in a stock pot with a 10L capacity on a hot-plate (Figure 2-11). With the exception of the synthetic dyes, which were just warmed and simmered, the dye solutions were brought to a boil and simmered for an hour to concentrate the dye. The blueberries, beets and tea were placed in 2L of water and left to simmer until there was approximately 1L of liquid left. The 2L container of grape juice was poured straight into the stock pot without diluting and simmered until 1L of liquid was left. SYC #1 was slowly added to 2L of warming water. The water was brought to a boil at which time approximately eight tablespoons of SYC #1 were added. This solution became supersaturated (when the remaining solution was taken off the hot plate, SYC #1 residual condensed out of the solution, but was reabsorbed upon boiling again. Figure 2-12, Figure 2-13, Figure 2-14, Figure 2-15 and Figure 2-16 show the dye uniformity on the fabric. Both Acid Red 52 and Acid Blue 9 used a concentration ratio of 10g/L of water for the dye solution as instructed by Passmore (2008). Figure 2-17 and Figure 2-18 show the dyeing results of the artificial dyes

The five test squares of each fabric were placed in each solution together and soaked for an hour. The mixtures of solutions and fabric were frequently stirred. After the hour soak in warm to boiling water, the fabrics were taken out and dried over night. The dried fabric squares were examined for uniformity and reaction to black light. From this uniformity test, it was concluded that an hour of dyeing was adequate to dye the fabric. AR52 and AB9 dyed the wool and cotton well; however the lycra, fleece and felt did not dye as well. The method to prepare these solutions involved warming the dye solution and placing the fabric in to simmer for approximately an hour.

2.4.2 Dye Fastness Testing

To test the reaction of dried dyed squares to water, a test disk was fabricated from ABS plastic (Figure 2-19). This test helped to understand the fastness of each dye to each fabric, as well as the hydraulic conductivity of the fabrics (qualitatively only). Two equal sized disks were cut with a radius of 6cm; the centre with a radius of 2cm was cut out with a hole-saw. Three bolt holes were drilled close to the outer edge to hold the disks together, and the fabric was sandwiched between. The preparation of the fabric squares for the fastness test involved pulling the test squares through a sink of water; this simulated the fabric being lowered through the water table to its desired depth in a borehole. The now saturated test squares were placed between the two test disks and the bolts tightened. The test disk was then placed under a faucet with the middle hole directly under the water stream (Figure 2-19). The water was run through the fabric anywhere from 10 seconds to 30 minutes depending on the fastness of the dye.

2.5 Packer System

The final essential part of the FIPS is the packer system. The packer serves to press the fabric against the borehole wall. The packer must be easily inserted into and removed from the borehole and also large enough for the fabric to be attached, without over stretching the fabric when the packer is inflated. With a minimal annulus, attachment and expansion of the indicator material would be much easier. However, with too small of an annulus, the FIPS could become lodged in the well. It was important to select a packer system that was sized to be easily inserted and removed from the well, but also sized so that the fabric could be wrapped and expanded easily (Figure 1-4 shows the annulus spacing ranging from 3.3mm to 25.4mm in a 4" (10cm) diameter borehole). In other words, the ideal packer would have an annulus that allowed the packer to be easily inserted and removed from the borehole but did not expand too much so that the fabric could not stretch and rebound when the packer was inflated and deflated.

Three types of packers were considered for this prototype phase, a 'homemade' packer, a standard commercial packer and the double-acting packer (Figure 2-20 compares these three packers). A 'homemade' packer consists of solid stock PVC machined down to fit a 4" borehole, with polygum tubing around the outside that is inflated to seal the borehole. The 'homemade' packers were constructed earlier and used for the borehole dilution tests (see Appendix A.2.5 for details on the borehole dilution tests). Standard commercial packers (manufacturer: RST, model #: BP5074-M55) were also considered, these packers are readily used in boreholes for packer testing (Figure 2-21). A double acting packer (DAP) device, as seen in Figure 2-22, originally developed by Solinst Canada for the CMT multilevel system (Einarson & Cherry 2002), was the chosen packer for the FIPS device. DAPs were created to be able to slide over CMT tubing (under vacuum), and, when in the position on the tubing that was desired to be sealed off the vacuum was released, the inner bladder of these DAPs then squeezed onto the CMT tubing. The DAP had more annulus than the homemade packers, but much less than standard packers as seen in Figure 2-23. As the DAP is fairly rigid, this allowed for easy attachment of indicator fabric and did not over stretch the material. To test the FIPS system's incorporation of the DAP, lab bench tests were done to identify flaws and problems. The different types of packers are explained in greater detail in Appendix A.4.

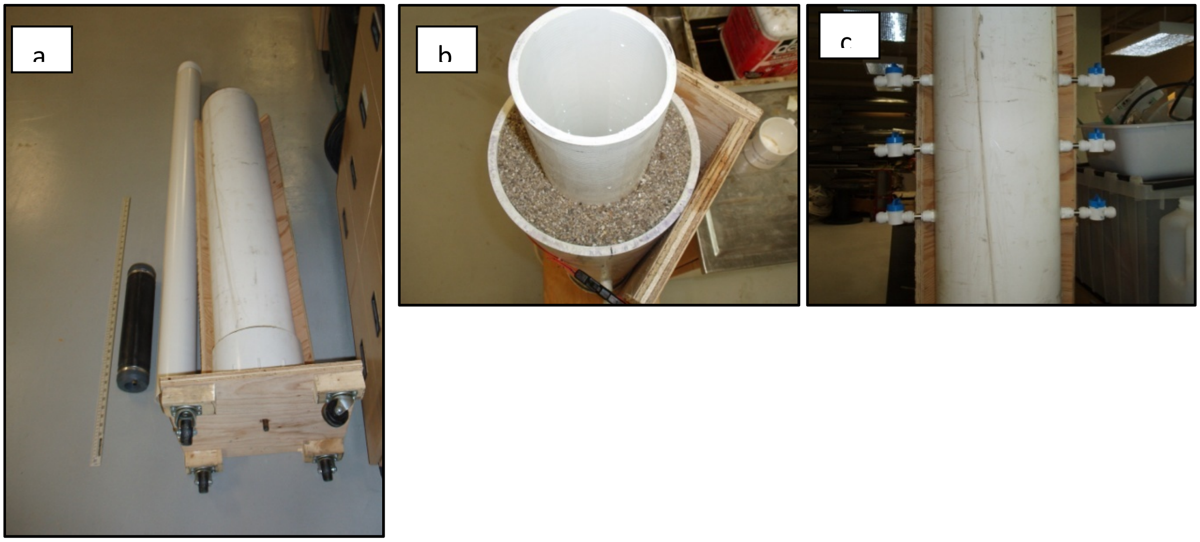


Figure 2-1: (a) Components of the box aquifer: a packer, a 10 slot (0.01inch) well screen that is placed inside the sewer pipe and filled with medium grained sand; (b) is the Sand matrix of Box Aquifer, having a hydraulic conductivity (K) of 0.01cm/s; and (c) shows the injection and drainage ports of box aquifer to ensure horizontal flow and it allowed varied flow rates.

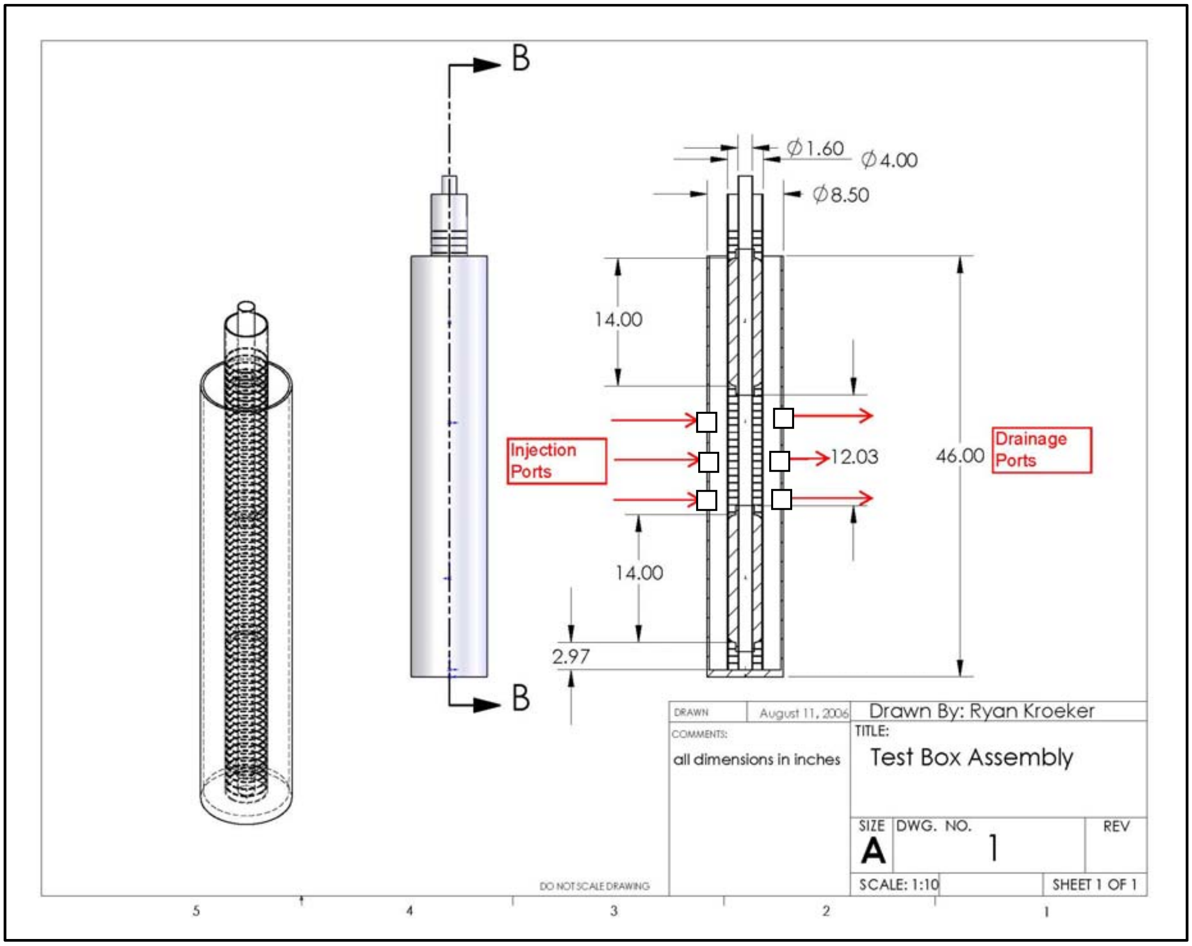
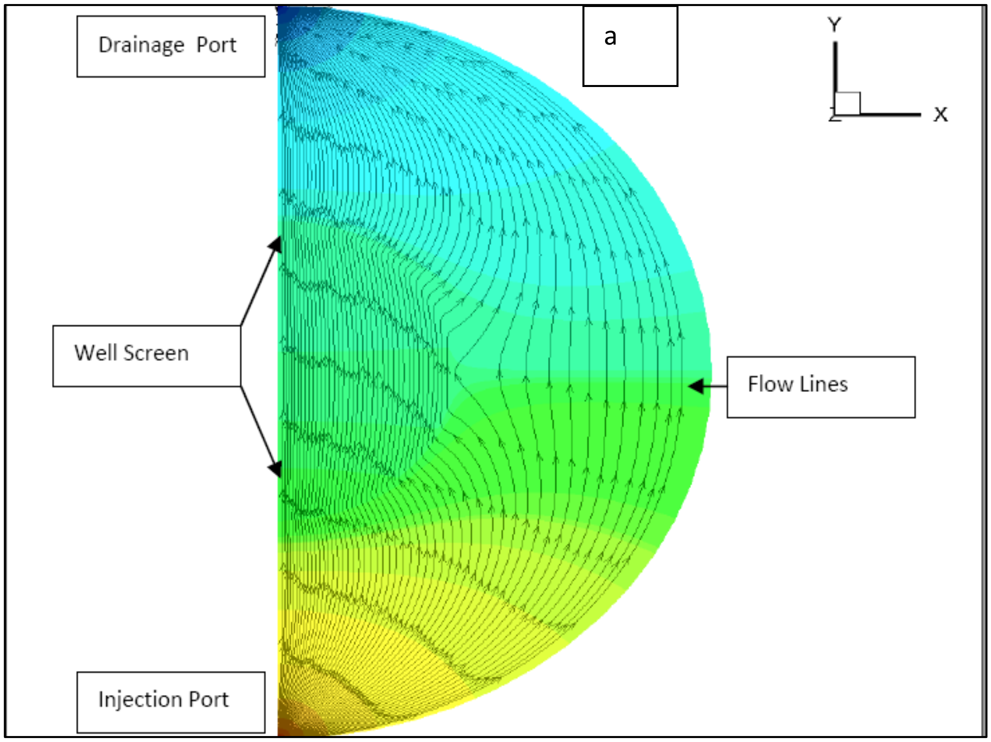


Figure 2-2: Box Aquifer Assembly, notice injection and drainage ports. These ports dictate the direction of flow, and the well screen causing a convergence of flow towards it. The Ø symbol refers to the diameters of the pipes used. 2.97inchs is the size of the bentonite pack used at the bottom of the box aquifer and 14inchs refers to the packer size in the well screen, 46inchs is the full length of the sewer pipe.



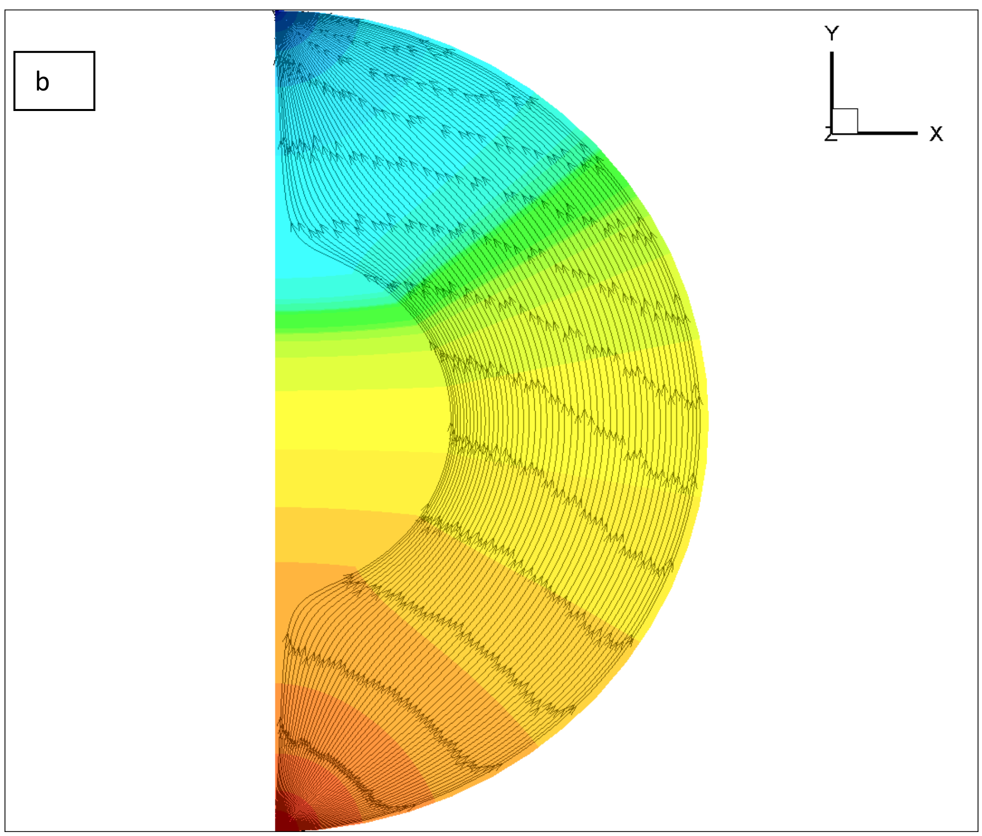


Figure 2-3: Numerical model (Hydrogeosphere) of flow in the box aquifer (a) showing convergence toward the well screen, open hole condition. (b) shows the flow around a packed off well screen. The colour gradient is an indication of the hydraulic head.

Figure 2-4: Plexi-glass well used to examine prototype. This well gave the ability to see leaks in a packer, the mixing disturbance created with different volts sent to the mixing pump (used for borehole dilution tests). This is a no flow system, and used strictly as a visual indicator of what happens in a borehole.

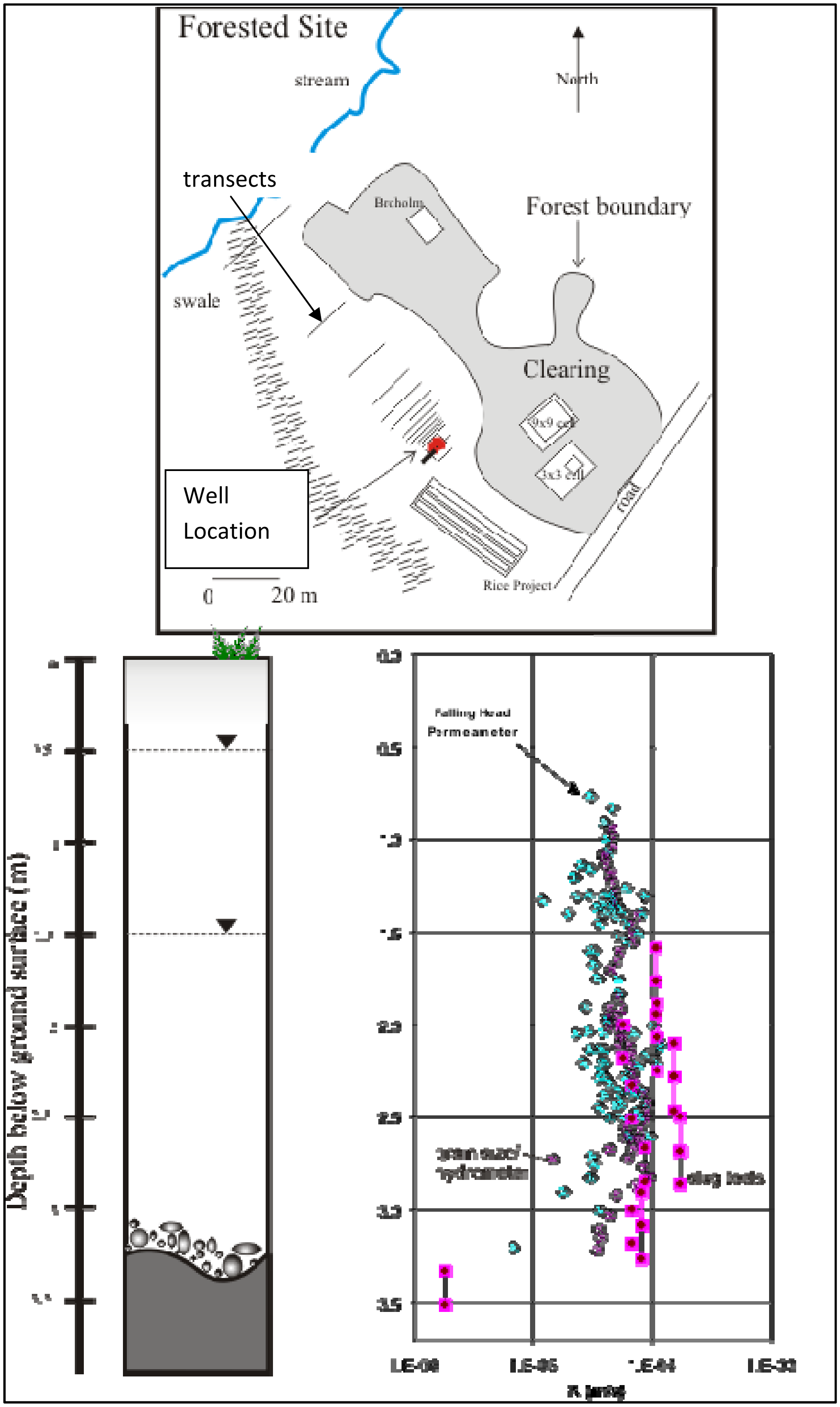


Figure 2-5: Close-up of Borden forested site, schematic of aquifer and hydraulic conductivity (Laukonen 2001)

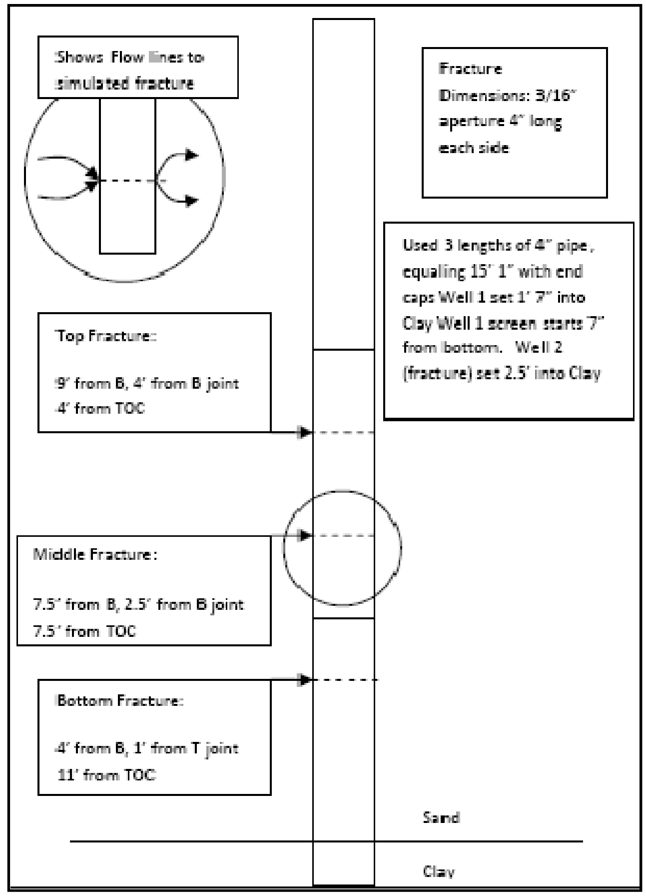


Figure 2-6: Borden Test wells and schematic of simulated fracture well design.

Table 2-1: Parameter of a 4"x5' TLC S40 4thds/inch well screen (Johnson Screens, A Weatherford Company)

Schedule S40 Threaded PVC Slotted Screen

Diameter	Length	Threads/Inch	Slot Width	Slot Spacing
Inches	Feet	TPI	Inches	Inch
4	5	4	0.01	1/8
10cm	1.52m		254µm	3175µm

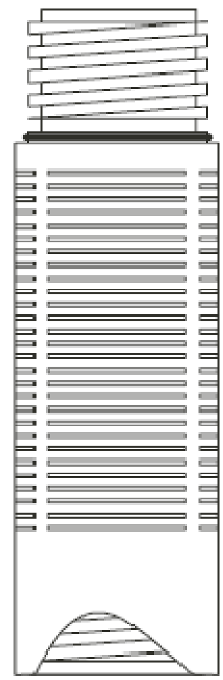
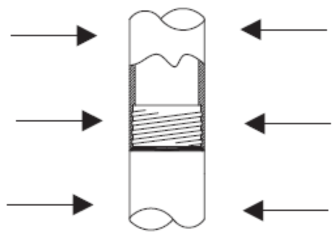
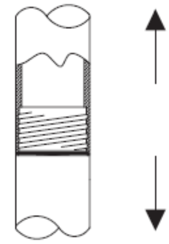


Table 2-2: Well Screen Pressure and Strength Values.

COLLAPSE PRESSURE	BURST PRESSURE	TENSILE STRENGTH
Pounds per square inch of external hydrostatic pressure that can be safely applied.	Pounds per square inch of internal hydrostatic pressure that can be safely applied.	The suspended weight the threaded joint can sustain in a vertical position without causing stretching or failure.
		

PVC Pressure and Strength Table

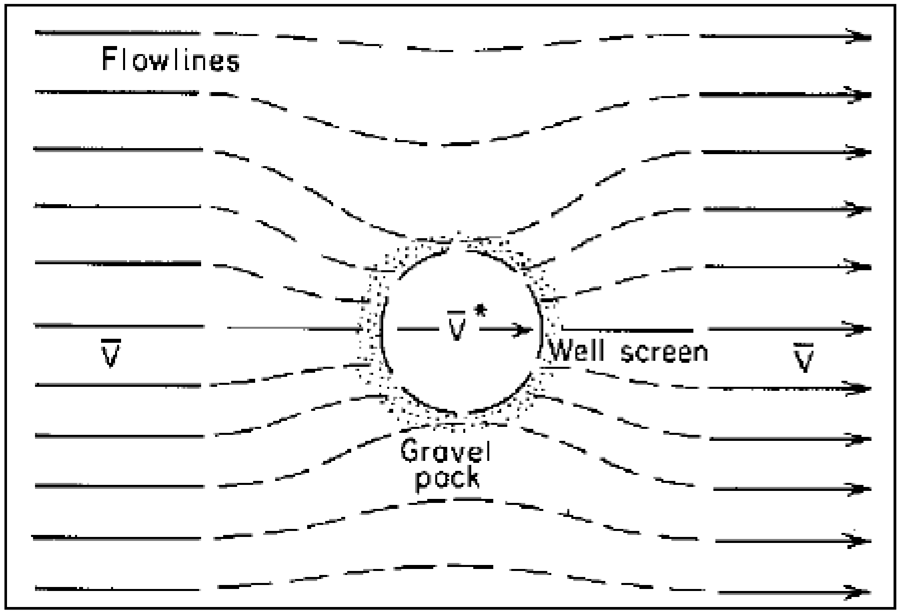
Diameter	Collapse Pressure	Burst Pressure	Tensile Strength
inches	psi	psi	lb
4" 10cm	70 482kPa	110 758kPa	4119 1868kg

Table 2-3: Well Screen Open Area and Transmitting Capacity Values.

PVC Screen Open Area and Transmitting Capacity				
Diameter	Slot Spacing	Standard Slot Opening	Percent Open Area	Transmitting Capacity
Inches	inches	inches	%	gallons/minute/foot
4 10cm	1/8 3.2mm	6 15cm	3.98	1.86 23.10L/min/m

Figure 2-7: Images of well screen slits. The left image is a full length 10 slot (0.01inch, 0.245mm) well screen. Each well slot is 254µm in this 10cm diameter well screen. The two images on the right show a close-up of these slots. Notice the inside slots are shorter than the outside, this is due to the curvature of the well screen and how the knife cuts through the well.

Figure 2-8: Simulated Fracture Slit (4.78mm) (Left) Simulated Fracture covered with Nytex (Right)



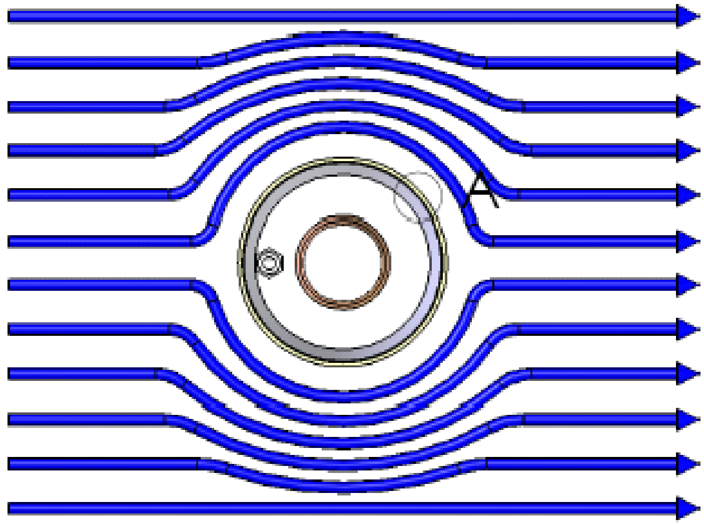


Figure 2-9: Flow into the simulated fracture well with no packer in the well (Freeze & Cherry 1979) (top) (note the convergence of flow into the well). The bottom image shows the flow around the packed off well in porous media (note the divergence of flow around the packer).

Table 2-4: List of the fabrics used and not used, as well as the desired properties in a fabric for the use in the FIPS device.

Desirable Features of Flow Sensitive Fabric Needs to Be

Characteristics

- Inexpensive
- Easy to Dye
- Readily available

Performance

- Easy to attach to borehole packer
- Suitably stretchable
- Visually effective

Fabrics

Fabrics Tested

- cotton
- felt
- fleece
- lycra
- Wool
- *Enough success achieved*

Fabrics NOT Tested

- silk
- polyester
- blends
- nylon
- Hemp
- *More success not needed for thesis*

Figure 2-10: SYC #1 Powder

Figure 2-11: Dyeing Set-up, 9L pot on hot plate used to simmer material for 1hr.

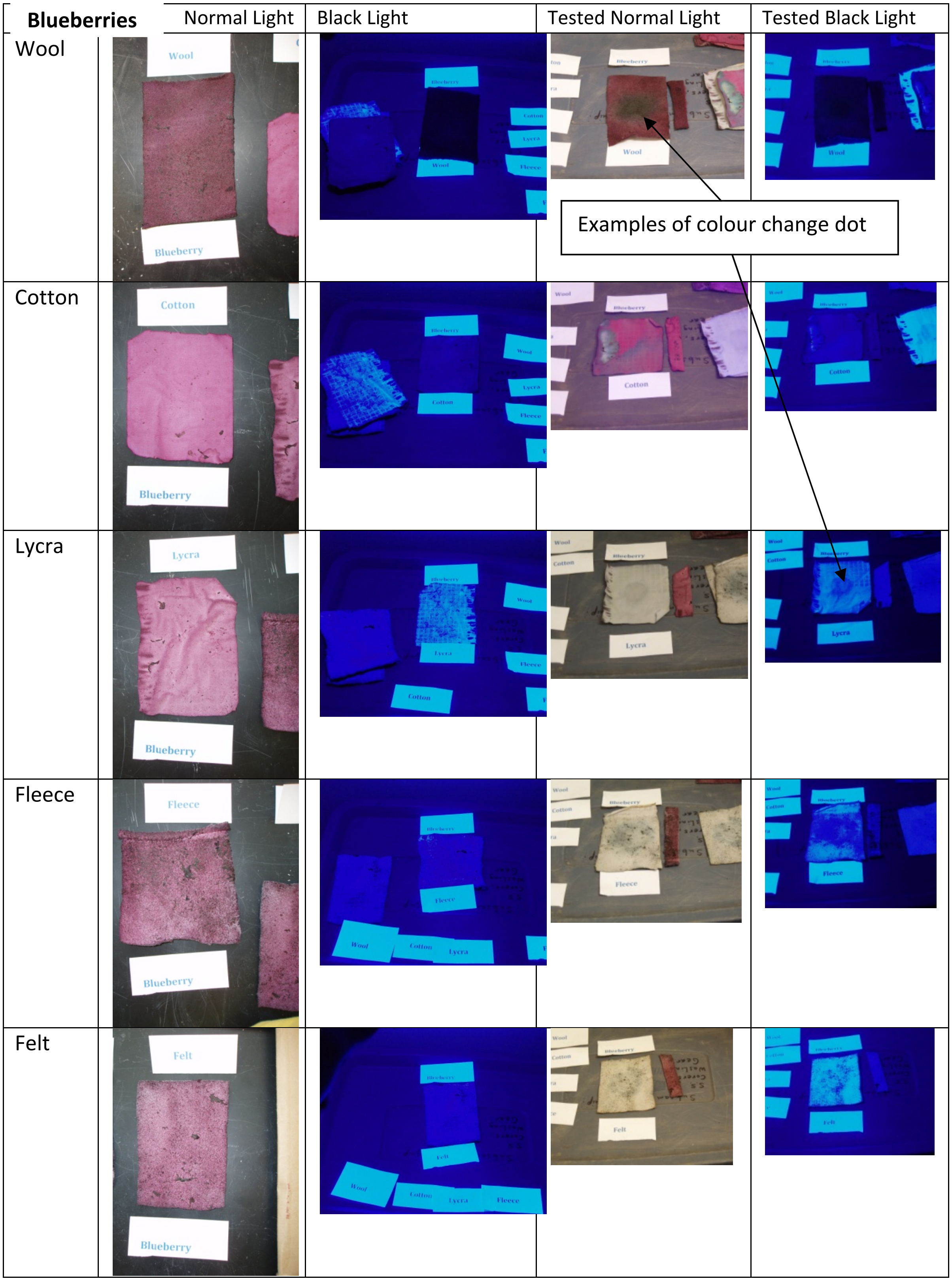


Figure 2-12: Blueberry dye uniformity: blueberry dye under normal and black light, showing the results after water run through material in test disk. Notice the colour changes in the centre of the material; a round dot is the ideal result.

Grape Juice

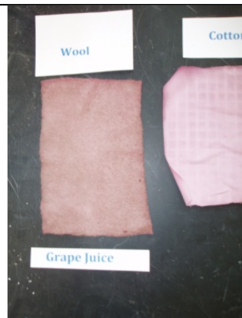
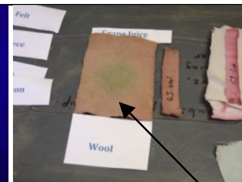
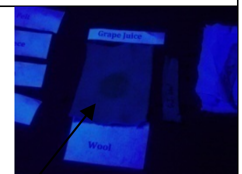
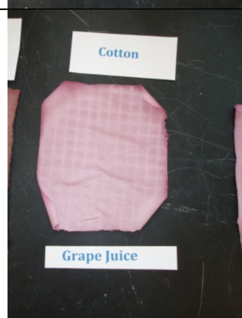
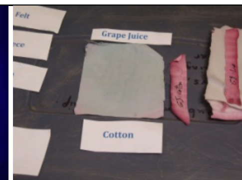
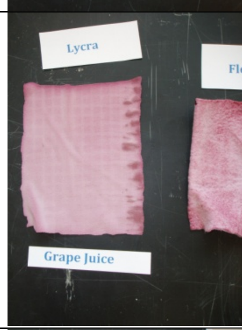
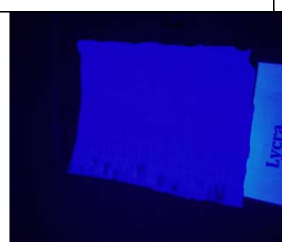
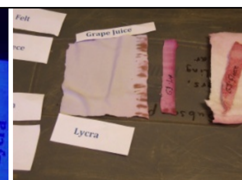
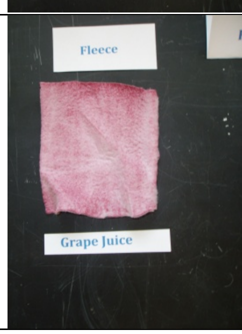
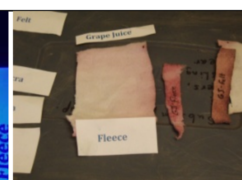
	Normal Light	Black Light	Tested Normal Light	Tested Black Light
Wool			 Examples of colour change dot	
Cotton				
Lycra				
Fleece				
Felt	No picture	No picture		

Figure 2-13: Grape juice dye uniformity: grape Juice dye under normal and black light, showing the results after water run through material in test disk. Notice the colour changes in the centre of the material; a round dot is the ideal result.

Beets

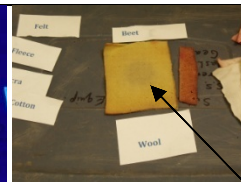
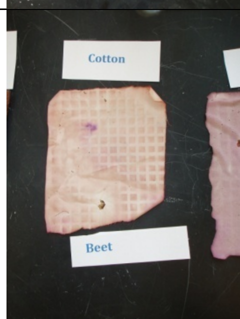
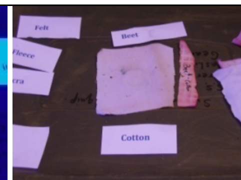
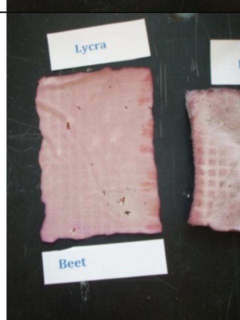
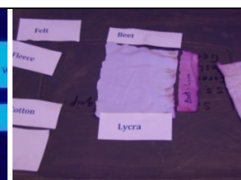
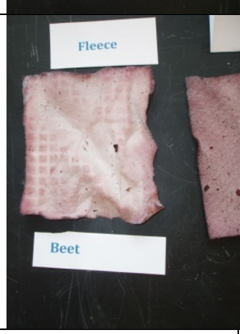
	Normal Light	Black Light	Tested Normal Light	Tested Black Light
Wool			 Examples of colour change dot	
Cotton				
Lycra				
Fleece				
Felt	No picture	No picture		

Figure 2-14:Beet dye Uniformity: beet dye under normal and black light, showing the results after water run through material in test disk. Notice the colour changes in the centre of the material; a round dot is the ideal result.

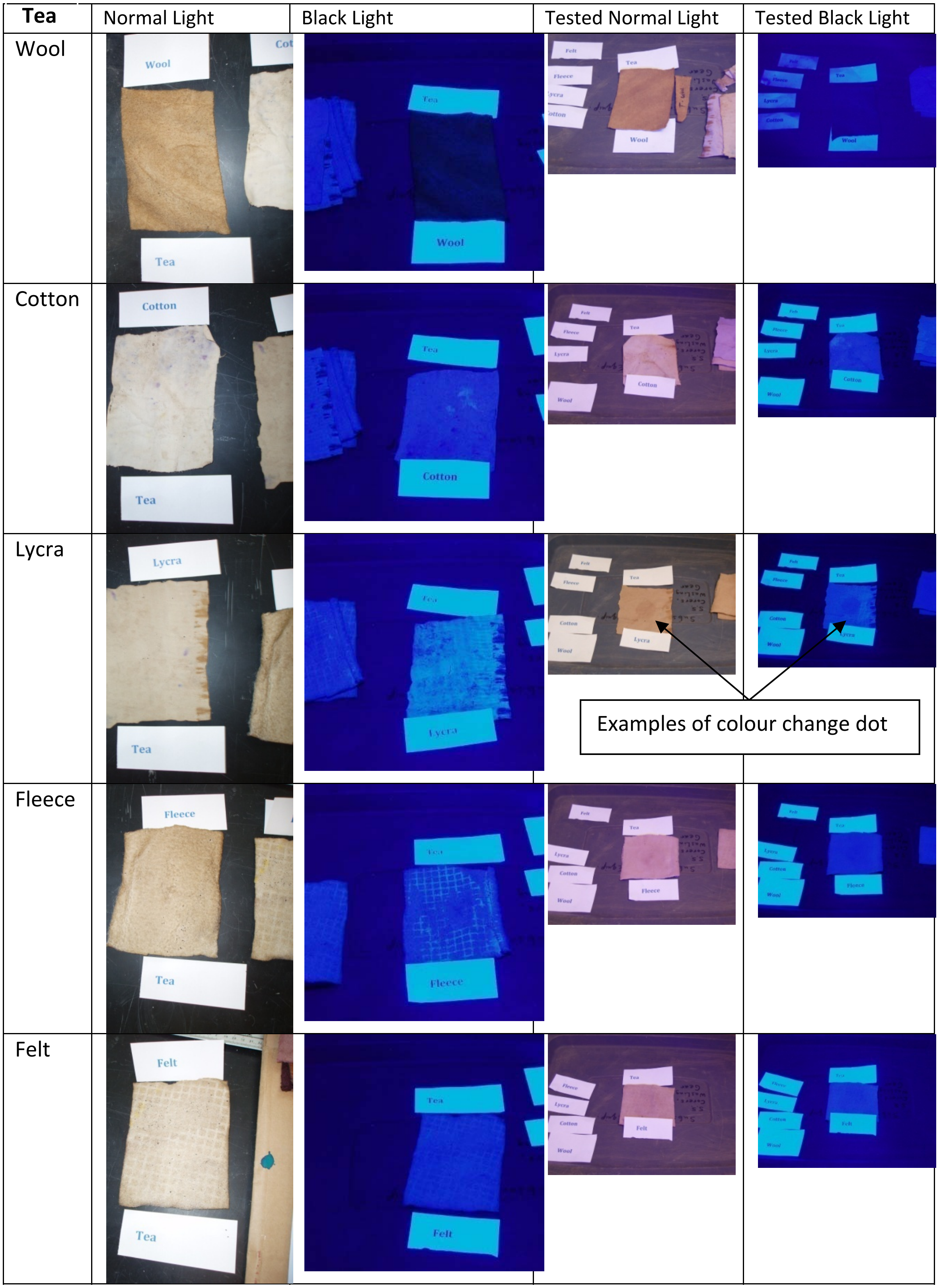


Figure 2-15: Dye Uniformity: tea dye under normal and black light, showing the results after water run through material in test disk. Notice the colour changes in the centre of the material; a round dot is the ideal result.

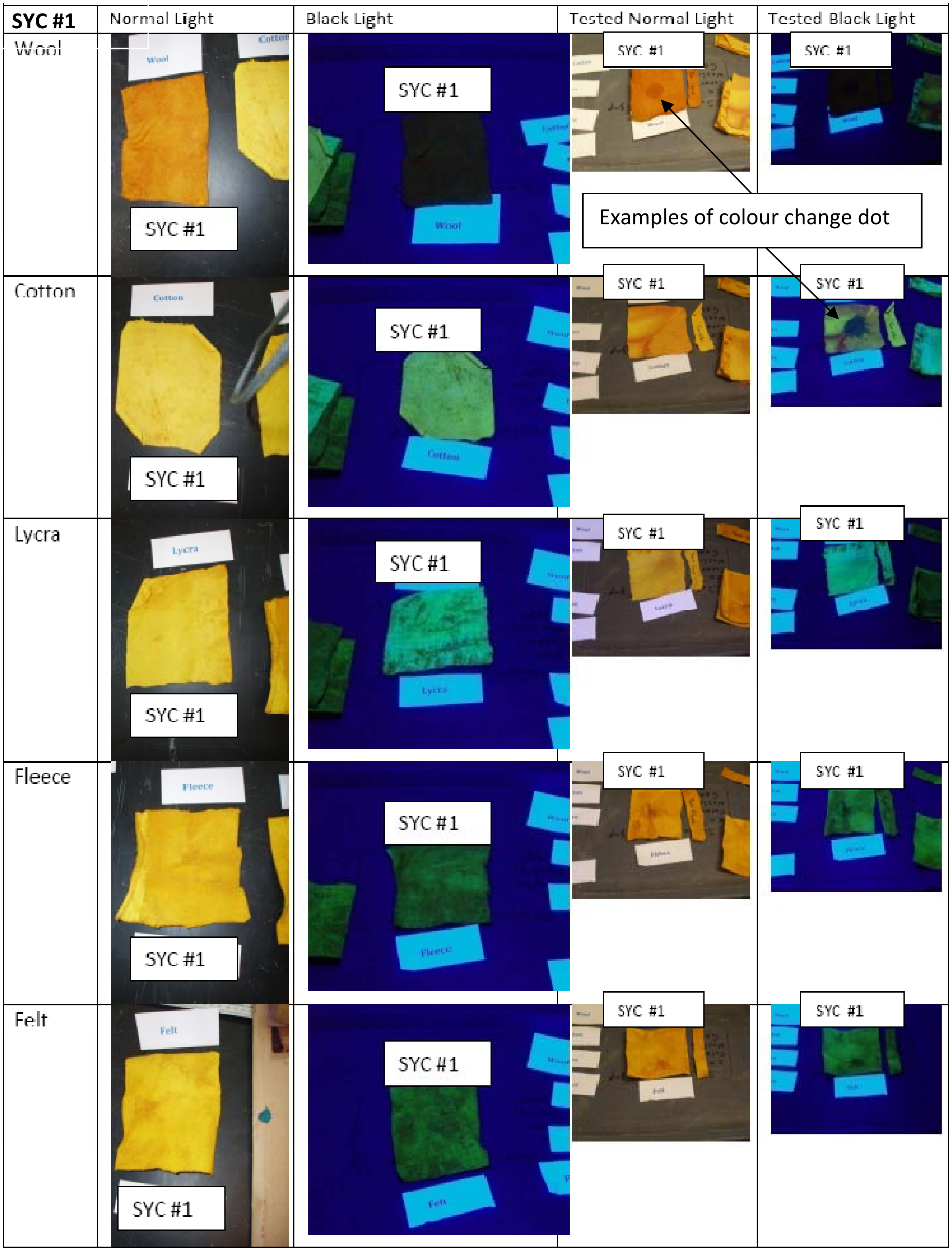


Figure 2-16: Dye Uniformity: SYC #1 dye under normal and black light, showing the results after water run through material in test disk. Notice the colour changes in the centre of the material; a round dot is the ideal result.

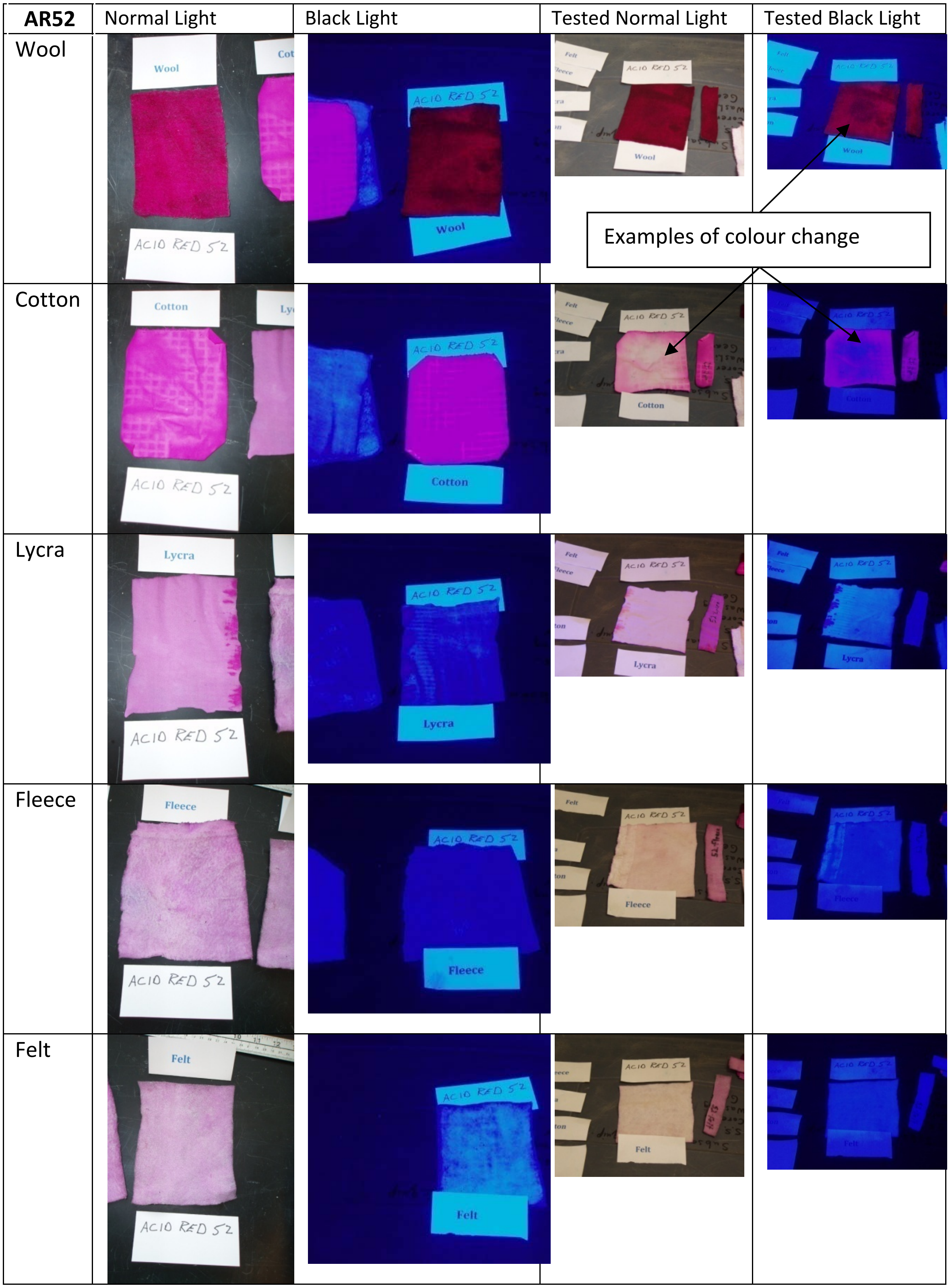


Figure 2-17: Dye Uniformity: Acid Red 52 dye under normal and black light, showing the results after water run through material in test disk. Notice the colour changes in the centre of the material; a round dot is the ideal result. In this example only see running of dye.

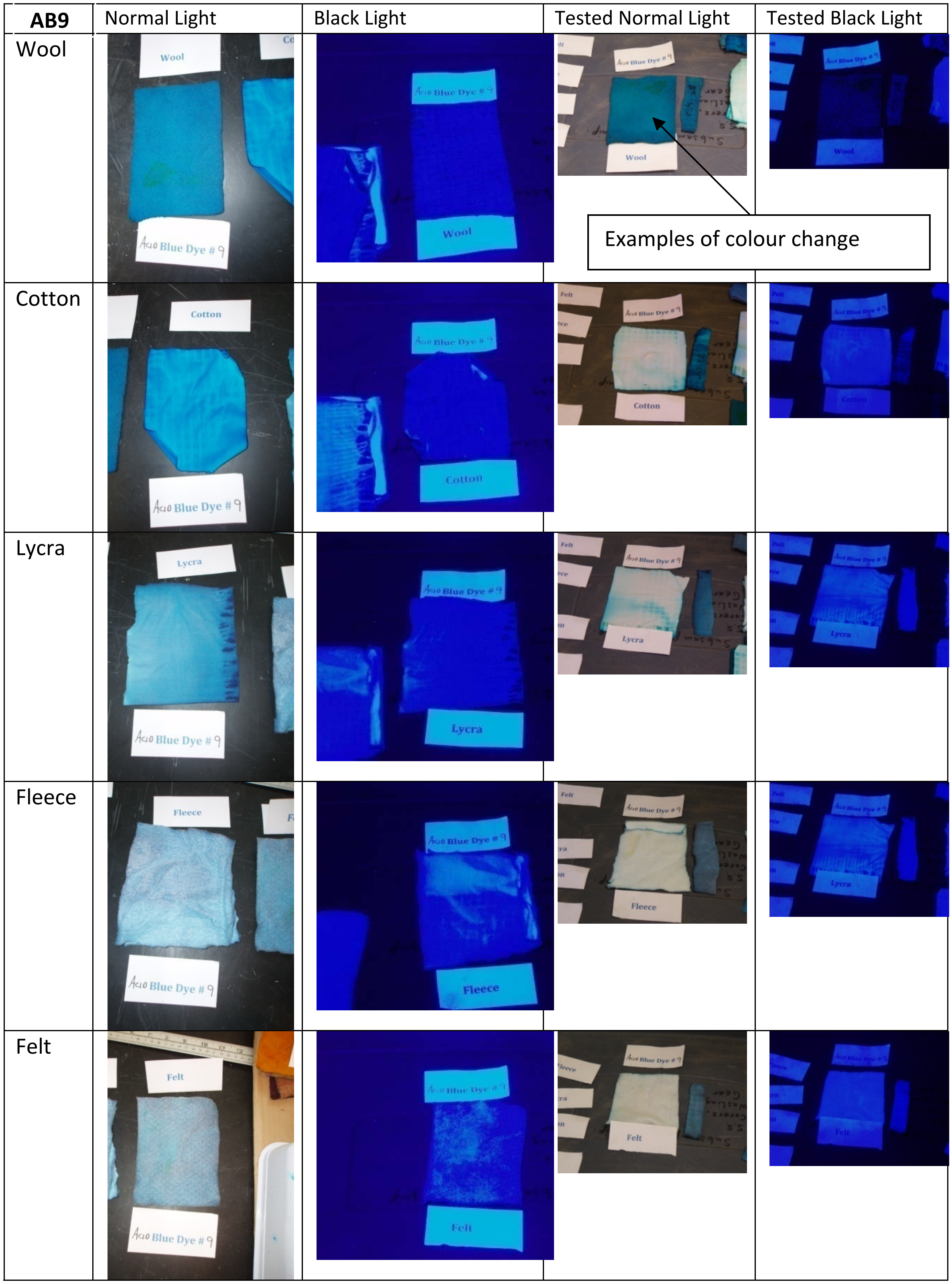


Figure 2-18: Dye Uniformity: Acid Blue 9 dye under normal and black light, showing the results after water run through material in test disk. Notice the colour changes in the centre of the material; a round dot is the ideal result. The colour change in wool was very faint

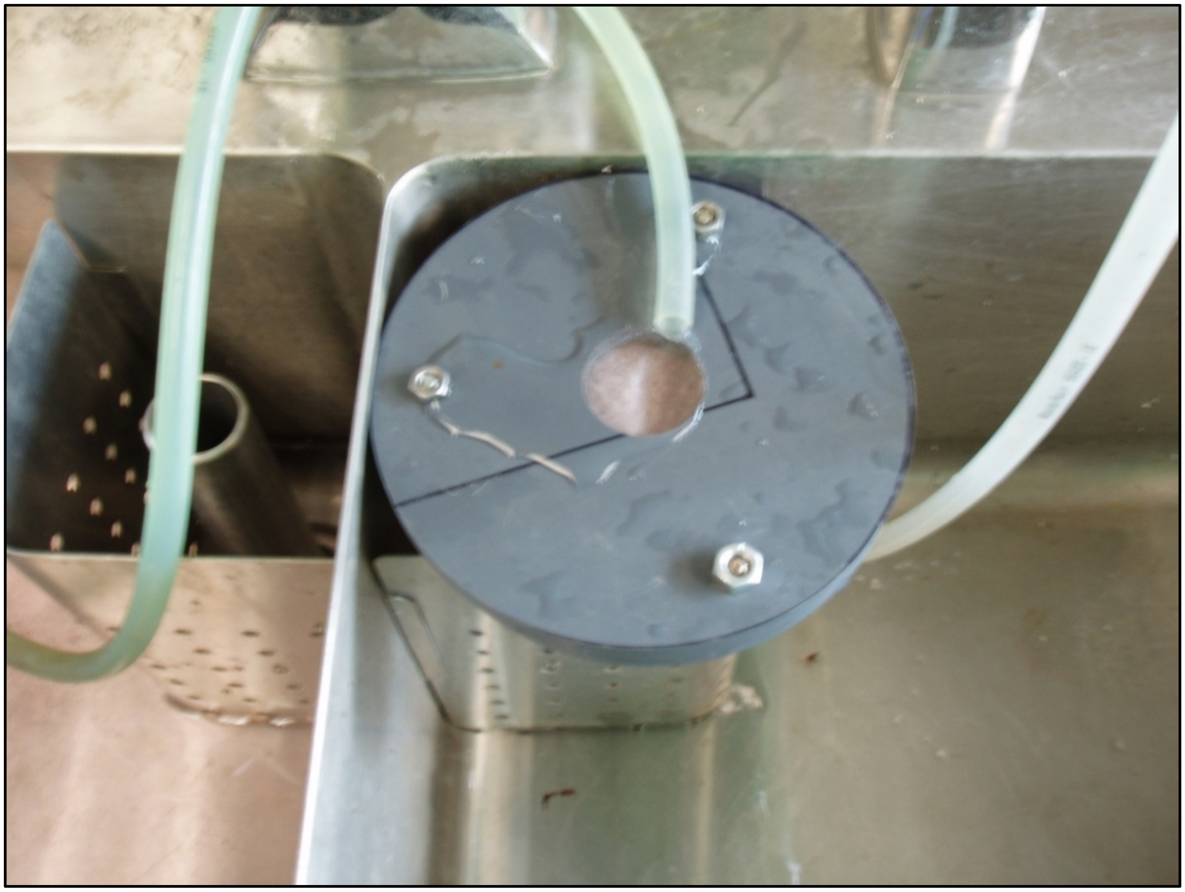


Figure 2-19: Test Disk for dye fastness test. Material is dipped in a sink of water and placed between the two PVC disks, which are then bolted together. Water is run through the bored out section. This tests the fabric's hydraulic conductivity and the dye's fastness and reaction to flowing water.

Homemade Packer	Standard Packer	Double-acting Packer
		

Figure 2-20: Compares the three packers considered to be used for the FIPS device

Figure 2-21: Standard Packer deflated

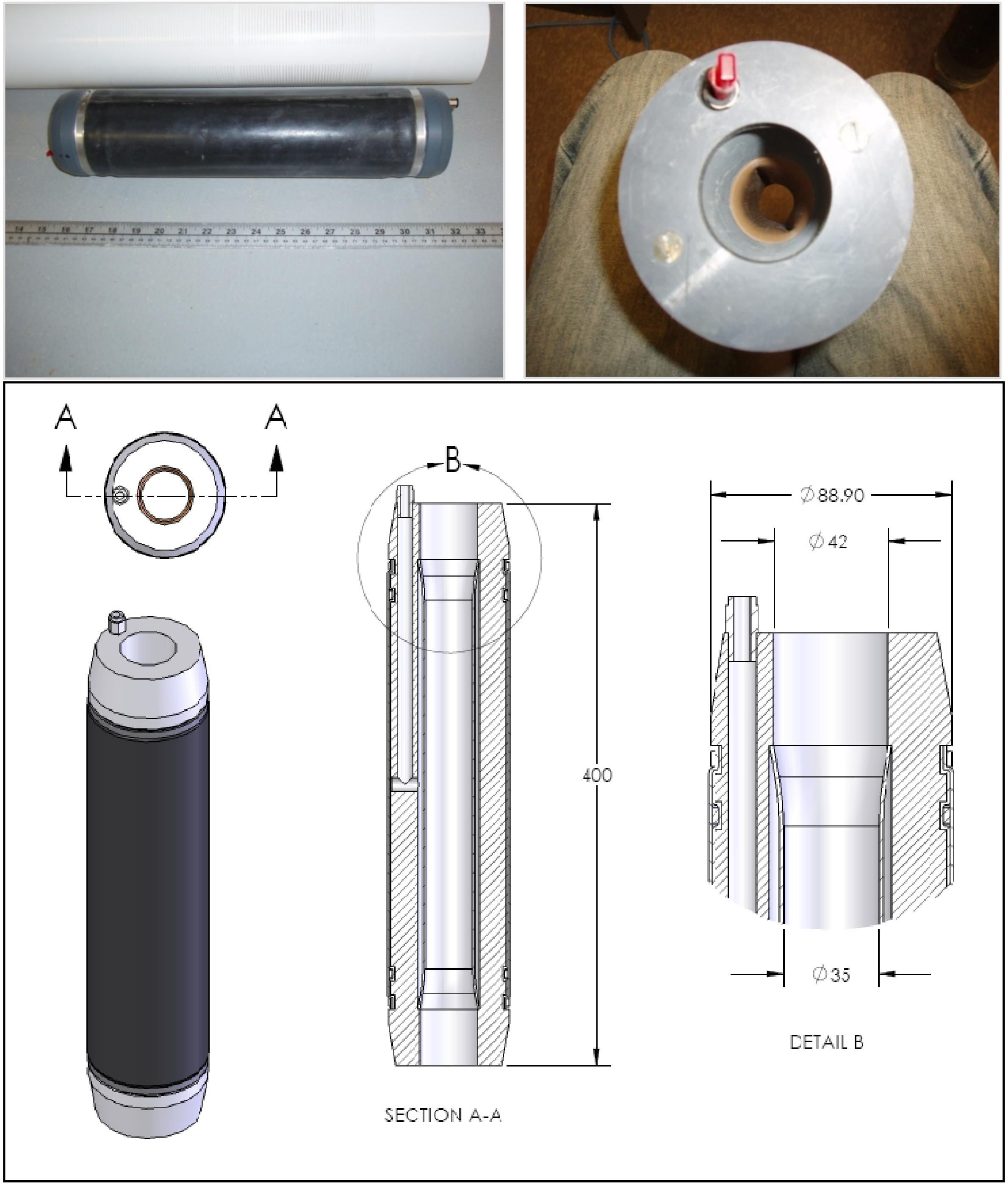


Figure 2-22: Double Acting Packer (top left). Inside view of the Double Acting Packer (top right). This shows the softer flexible inner packer that needs to be deflated to fit over a pipe, it then grips the pipe so it does not move, and the small annulus outer section expands out when inflated to meet the rock wall. Standard packer's ends contract when inflated because of the large expansion needed. The bottom shows the schematics of the DAP where measurements are in mm, 400mm is the length and while the symbol Ø refers to the diameter.

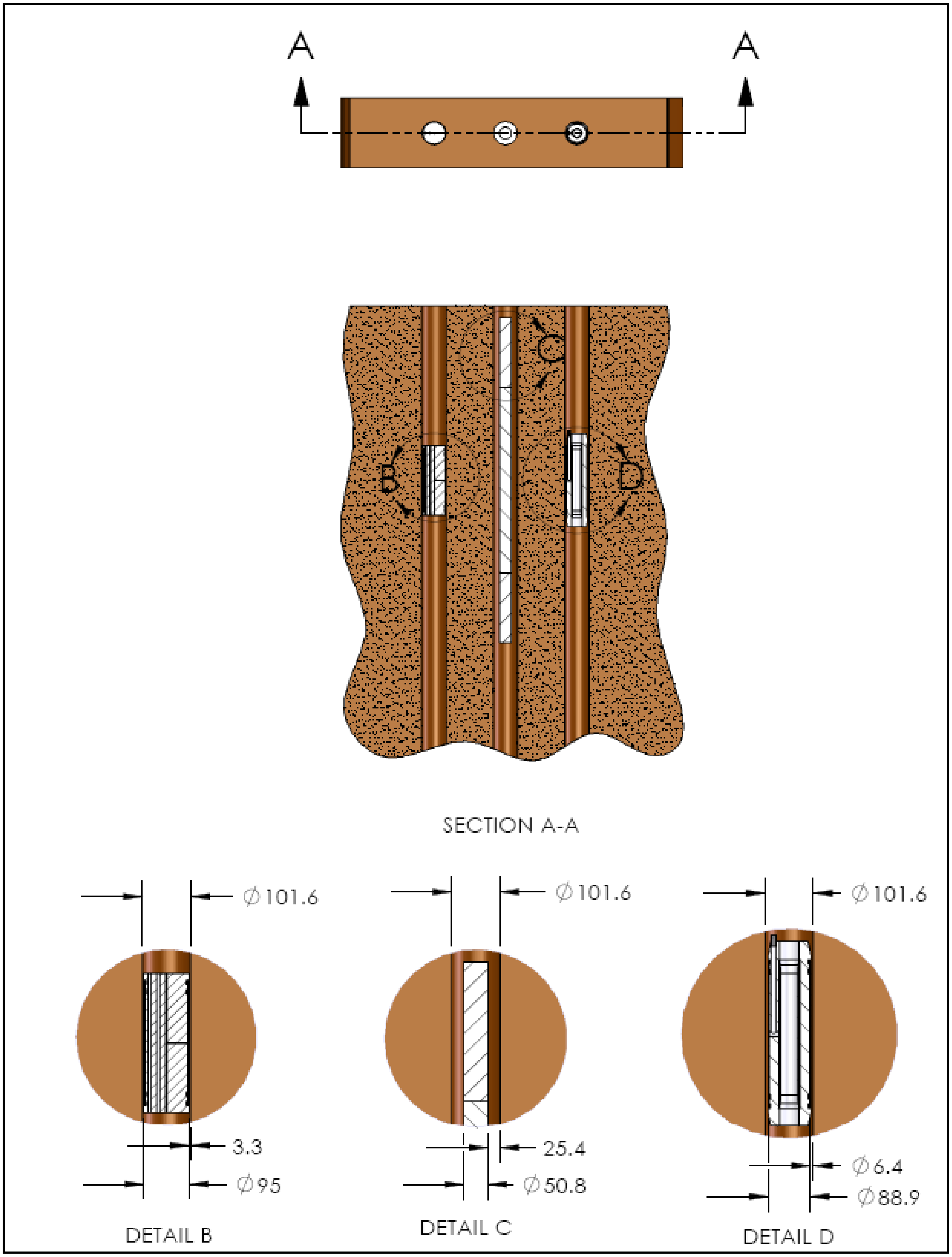


Figure 2-23: This figure shows the annulus space of three different packers: (A) The home-made packer used for borehole dilution test and the first GAC test; (B) a standard packer, used frequently in the hydrogeology field; and (C) Double-Acting Packer, developed by Solinst and used in this study for the FIPS device (all measurements are in mm). Notice it has 6.4mm annulus to the borehole wall.

3 Results & Discussion

3.1 Dye/Fabric Combination Results

As stated in the previous chapter, the first test to examine dye fastness involved placing a square piece of dyed fabric into a test disk and running water from the tap directly through it. All test squares were examined under normal and black light to see if there was a noticeable colour change where the water passed through the fabric. The black light is helpful because it makes another spectrum of light visible by illuminating the phosphors in the fabric. These tests provided varying results as shown in Figure 3-1, Figure 3-2, Table 3-1, and Table 3-2 (refer to Figure 2-12, Figure 2-13, Figure 2-14, Figure 2-15, Figure 2-16, Figure 2-17, Figure 2-18, and Figure 2-19 for detailed, up-close images of Test 1). Table 3-1 and Table 3-2 indicate that all the dyes worked well with the wool and show an indication mark in all but fabrics dyed with tea. Cotton and lycra also hold the dye but not as strongly as the wool, and indication dots showed up well with the cotton/ tea, cotton/SYC#1 and cotton/AR52 combinations. Meanwhile, the lycra showed an indication dot with the blueberries and tea. The fleece and felt did not hold the dye very well, except with tea and SYC#1 , and no indication dots could be seen—in some cases the dye washed out almost completely. The wool/blueberry, lycra/blueberry, wool/grape juice, cotton/tea, lycra/tea, wool/AR52, cotton/AR52, wool/SYC #1, and cotton/SYC #1 combinations of fabric and dye moved on to Test 2, as discussed in section 3.3.

Ultraviolet light, also known as black light, was used to examine the dyed fabric to help see if any flow indication showed up in the shorter wave spectrum. UV light is the portion of the electromagnetic spectrum that lies between x-rays and visible light. In this case, a fluorescent black light bulb was used. Fluorescent black light is similar to a fluorescent lamp but has a different type of phosphor coating, which absorbs harmful shortwave UV-B and UV-C light and emits UV-A light (in the same way that phosphor in a fluorescent lamp absorbs UV light and emits visible light). The "black" glass tube itself blocks most visible light, so that only benign long-wave UV-A light, along with some blue and violet visible light, passes through. UV-A is considered the safest of the three spectrums of UV light. It is the higher energy (shortwave) light in the UV-B and UV-C range that is responsible for the DNA damage that leads to skin cancer (Al-Azzawi 2007).

The performance criteria used in evaluating the dyes included the following:

1. Dye fastness – How well did the dye stain the fabric? When water was passed through it did it smear or run? Was there any residual left? Was the rate of release fast and complete or slow?
2. Degree of colour change – Was there a change in colour after water came into contact with the material? Was the change in colour visible under normal and/or black light? What characteristics did the colour change have?

The material/blueberry combination was tested first. In the dyeing stage, the wool and cotton squares were dyed quite deeply, the lycra was slightly stained, and the fleece and felt did not hold the dye. After testing the squares, the wool and lycra showed a distinct colour change, as seen in Figure 2-12; a darkened circle was noticeable where the water ran through. Based on this result the wool and lycra dyed with blueberries would be further tested.

The beet and grape juice combinations showed the same results. Before the test, the material the wool held the dyes the strongest while the fleece and felt did not hold the dye at all. Wool was the only indicator that showed potential after it came into contact with the water. Figure 2-13 and Figure 2-14 show the contrast between the freshly dyed material and the rinsed and tested material: a faint discolouration can be seen in the wool, indicating that it needed to be tested further.

Tea worked well with cotton and lycra as seen in Figure 2-15. The cotton/tea results showed up well under black light, but minimally under normal light. The lycra/tea combination was the complete opposite, showing up well under normal light but very faintly under black light. Both the cotton/tea and lycra/tea combinations were tested further.

The synthetic dyes used created brilliantly coloured solutions. Their fastness to the varying materials was not as strong, quite often washing away quickly. Both the Acid Red 52 and Acid Blue 9 dyed the wool successfully, but the lycra, fleece and felt washed out immediately. Acid Red 52 dyed the cotton light pink, while the cotton did not hold the Acid Blue 9 at all (Figure 2-17 and Figure 2-18 show these results clearly). These dyes have been used as tracers in porous media aquifers, and they stain dirt and skin quite well. Unfortunately, they did not transfer well to the FIPS device, as seen in Figure 3-1 Figure 3-2. Only AR52 in wool and cotton and AB9 in wool were tested further.

What turned out to be the best fabric/dye combination was tested last. SYC #1 was successful in strongly dyeing all the materials and providing a good fastness in each material. After examination under normal light, a highly noticeable difference could be seen in wool and not as noticeable in the other four materials (refer back to Figure 2-16 for a detailed look). Under black light, however, cotton and wool showed a substantial difference. A slight difference could be seen in lycra, fleece and felt. Of particular interest was the result of the cotton/SYC #1 combination, which, when placed under black light, showed a dark blue colour change where the water came into contact with the material; this colour change was not exhibited by the other fabrics dyed with SYC #1. Table 3-1 shows a chart of the performance criteria for the dye/fabric combinations. The table grades the dye fastness and the colour changes seen in the flow zone. Table 3-2 shows a chart of the combinations that passed the performance criteria and moved onto the next stage of tests. These included wool dyed with all but tea, cotton dyed with tea, SYC #1 and AR52, and lycra dyed with blueberries and tea.

The test described above was designed to begin identifying a fabric/dye combination most suitable to be used as a flow indicator. Results vary from this test to the next tests, which involved having the materials attached to a packer and pressed up against a well wall. This first test used a disk that was open on both ends, meaning that there was no support for the material where the water flowed through. Therefore, the water passing through the material caused a depression in the material as it flowed through. This depression could have resulted in the wicking of the dye to this exposed, unsupported zone. As well, the water in this test came straight from the tap onto the material and at a much higher speed than that of the later tests. Some of the differences seen were also a result of residuals from the dyes being washed into the test section. The dyes were not filtered, so residual particles tended to become attached to the materials. These issues with Test 1, however, were not of much concern as the purpose of this test was simply to see what combinations of fabric and dyes worked best when brought into contact with water.

Though other fabric/dye combinations worked, the cotton/SYC #1 was the by far best and chosen as the combination with which to move forward. Not all fabric/dye combinations showed as significant a colour change or indication as the cotton/SYC#1 combination, but they were still looked at more closely. These secondary combinations were wool with blueberries, beets, grape juice, SYC #1, AR52 and AB9, cotton with tea and AR52, and lycra with blueberries and tea. These dyes had held fast to the fabrics, had minimal smearing and residual left over, and showed some level of colour change in the area where the water passed that was seen under normal and/or black light.

These results provided the incentive to cease seeking other fabric/dye combinations and to move to the next phase of testing.

3.2 Packer System

The other component of the FIPS device is the packer. With a flow sensitive fabric determined, a packer system had to be adapted for use with this fabric. The double acting packer (DAP) (Figure 2-22) was chosen (see discussion about various packers in the Appendix) because of its flexibility and accessibility. Two DAP's were readily available and not in use. Standard commercial packers (Figure 2-21) were available but did not meet the needs of the FIPS device. The design of the DAP is unique in that it is fitted onto a pipe, it can be easily slid along the pipe to specified positions and multiple packers can be positioned on the pipe and be easily repositioned. The DAP has a soft, flexible inside that, when inflated enough under regular conditions, grips a pipe; a vacuum has to be put on the packer for it to slide onto the pipe. The outside of the DAP is sized to have minimal annulus but still have enough space for fabric to be attached. The double acting packer design allows for the packers to slide up and down a pipe so that variable intervals can be sealed. The DAP also makes it possible to use many of these packers on a single pipe, so that multiple intervals can be tested simultaneously.

The double acting packer was developed by Solinst in 1992; however, it did not go into commercial production. The packers were created to be used in conjunction with the CMT multilevel (Einarson 2001). The idea was that the packers could slide up and down the CMT tubing to pack off the desired interval, and then be completely removable after the desired tests had been completed. In a test performed at the University of Waterloo in the early 2000's, the DAP was installed on a CMT multilevel in a borehole on the University campus. Upon removal, the packers failed to completely deflate and were thus destroyed as they were pulled out of the borehole.

For FIPS purposes, these DAPs have many attributes. The DAP radius leaves an annulus that allows for a thin indicator material to be attached (Figure 2-23). The DAP system also allows for a straddle system to minimize the potential for cross contamination. Though the DAP is not as durable as a standard packer, it does offer enough durability for multiple insertions and removals without risk to the FIPS testing. These packers are able to be inflated with water and gas; gas seems to work the best, especially for deflation purposes. To remedy the removal issues previously mentioned, gear clamps are placed below the DAP, and a peristaltic pump is attached to the inflation line. Instead of relying strictly on hydraulic head, a vacuum is created with a peristaltic pump to ensure complete deflation.

3.3 Experiment Results for Laboratory Tests of Complete System

3.3.1 Performance Test of Fabric/Dye combinations

A packer and ten fabric/dye combinations were chosen that meet the performance criteria as indicated in Table 3-1, the best being SYC#1 with cotton, the FIPS system needed to be tested in a well. Test 2 was a laboratory test used to work out the kinks in the FIPS device and give definitive results on the best fabric/dye combination. Test 2 helped to understand insertion and removal techniques, attachment of fabric and the ideal fabric indication results. For this test, fabric strips were attached to the DAP and placed in the box aquifer. After a period of time of being exposed to flow, the material would be reclaimed from the packer with ideal results showing each individual well slit of the well screen on the fabric. Strips of the indicated material from Table 3-2 were cut to a size of 12cmx13.5cm and dyed with their indicated dyes (Figure 3-3). The cotton and wool strips were then sown together at the 12.5cm mark (Figure 3-4), in order to have a circumference similar to that of the DAP. The lycra strips were sown at the 11cm mark, because the fabric is elastic and could stretch over the packer. The strips were sown to fit tightly on the deflated packer, and they had enough stretch to expand when the packer was inflated. Figure 3-5 shows how three strips were placed on the DAP at once. To simulate fractured flow, a “no flow zone” was produced over the fabric by wrapping 1/3 of the fabric with saran wrap. The saran and fabric had elastics placed over them as extra precaution to hold everything in place (Figure 3-5). The DAP was lowered into the box aquifer and inflated. Water flowed through the system at approximately 1L/min, and the test was run for 0.5hrs. The packer was deflated and extracted from the box aquifer. The saran was peeled of and the strips of fabric taken off the packer to be examined under normal and black lighting. The method of attaching the fabric to the packer for the box aquifer test can be seen in Figure 3-6. Figure 3-7, Figure 3-8 and Figure 3-9 show the results of the box aquifer test. Results varied from those seen in the test disk experiment where the water was able to flow through the fabric, as opposed to just around the fabric as was the case in Test 2. Blueberry, grape juice and tea showed no noticeable change at all on the fabrics tested (Figure 3-7). Only cotton/AR52 and cotton/SYC #1 showed any effects from the box aquifer test. AR52 showed a running of the dye, and SYC #1 showed the ideal result: the individual well slits (Figure 3-8).

As seen in Figure 3-10, the cotton/SYC #1 combination is clearly the most effective. Each individual well screen slot is evident under black and normal light (Figure 3-10 and Figure 3-11). Other combinations like the cotton/AR52 showed a difference between the covered and uncovered zone, but the result was more a running of dye than identifications of specific slits. In fact, if a section had not been covered by saran wrap, all the dye would have washed away. Wool seemed to hold the dyes too fast, and individual fractures could not be distinguished (Figure 3-8). The lycra also didn't produce enough colour difference; it did not dye strong enough to show a noticeable change in colour with such a small flow zone (Figure 3-8). A possible reason why the results seen in the test squares were not duplicated in Test 2 is because in Test 1 water was able to flow through the fabric, whereas in Test 2, on the other hand, water simply flowed around the fabric leaching out the dye. Test 2 produced ideal results with the cotton/SYC #1 combination because individual fracture lines could be seen when the fabric was wet, dry and inside out. There was a sharper contrast when the material was wet, even when black light was shone on it under full sun light (Figure 3-10). Under normal light and when dry, the lines were not quite as distinct but could still be easily seen. Figure 2-7 shows a close-up of the 0.01"(254μm) slots that are spaced 1/8" (3.175mm) apart. To be able to see such small slots is impressive considering that all of the other dyes produced smears if anything at all.

3.4 Borden Experiment Results

From the laboratory experiments, the FIPS device was moved to the Borden aquifer. Test 3 involved using the FIPS device with SYC #1 in the Borden simulated fracture well. Two separate zones were tested at one time. The FIPS device was lowered down the well with the two packers spaced to test the 3.35m and 2.29m top of casing (TOC) simulated fractures (Figure 3-12). After a period of five days, the FIPS device was deflated and examined under normal and black light. Results from the Borden experiment came back as anticipated. As seen in Figure 3-13, a distinct line is visible on the indicator material, under both normal and black light. The indicator line is not as sharp or bright as the results obtained by the box aquifer test; this is most likely due to the fact that the flow along the cloth in the slit was orders of magnitude smaller in the Borden test than the box aquifer. It could also be due to the length of time in the ground, the water turbidity, or the fact that less water flowed along the surface of the cloth in the fractures. Whereas, in the box aquifer, average linear velocity was 5000cm/day away from the well screen and approximately 11500cm/day at the well screen, in Borden, the average groundwater velocity in the aquifer was approximately 10cm/day and 16cm/day at the well.

The background groundwater chemistry for Borden in mg/L is found in Table 3-3. These are the values found in Borden, but they would be similar to those found in Waterloo tap water as well.

3.5 Steeping Test

To make sure that the imprints of the well slots on the dyed cotton were caused by water flow and not just water contact, the FIPS was placed in the box aquifer and left to steep for five days. Steeping is the process of letting the material sit in the well with no flow and soak for a period of time; this soaking allows the dye to diffuse out of the fabric. The steeping tests done with both tap and DI water were used to see if flow was the main cause of the colour change, or if it was just the material and dye coming into contact with water. This test is important because, through the first two tests, flow could only happen through a specific zone; this zone was surrounded by an impermeable layer where the material and dye had no contact with the water. As seen in Figure 3-14, under normal light, there is no indication mark on the material. Under black light there is a very slight discolouration. When comparing the five day tests to the six hour tests, the colour change is slightly more after five days, but much less than the difference seen when there is a flow condition.

A steeping test with DI water was also performed. The FIPS device was set to soak in DI water for seven days in the laboratory aquifer. Figure 3-15 shows that the slots are visible from the steeping test in DI water. These slits are darker than the above test done with regular tap water, but not quite as dark as those seen when the water is flowing through the system. Because the lines show up with DI water, this may mean that the colour change is not a result of a reaction with groundwater. Steeping does cause a colour change but not to the degree seen with flowing water conditions as seen in Figure 3-16. Based on the steeping tests, it was concluded that the FIPS performance will likely not be substantially diminished due to steeping affects.

3.6 Design of Proposed Guelph Field Experiment

With the laboratory and Borden tests completed the final step will involve testing in a rock borehole in Guelph. Test 4 will be the use of the FIPS device in a fractured rock borehole in Guelph, ON. The field trial in the Guelph well will try to answer a few critical questions as to the performance of the FIPS in a real fractured rock environment. This test will determine the practicality of using the FIPS prototype in a real borehole. Of particular concern is the annulus space of the DAP. The 6mm annulus is small and, therefore, the device may become stuck in the hole or damaged during insertion and/or withdrawal. As well, the effectiveness of the indicator fabric for showing active fractures will be seen. There is the possibility for the distinctness of the fracture to be blurred by interactions of the dye with the rock matrix, which is a water saturated porous medium.

The Guelph field site has been intensely studied to determine its properties and parameters (Kennel 2008). One type of test performed in Guelph is borehole geophysics; Figure 3-17 and Figure 3-18 show the borehole logging done on the Guelph borehole 367-7. A location in this well was chosen that was close to the ground surface for the initial field tests. Based on the information taken from Figure 3-17, specifically the Acoustic Televiewer, the Gamma, Conductivity, Neutron, Density, and Temperature logs, the depths ranging from 7.5mbgs to 8.4mbgs will be tested (Kennel 2008). Large visible fractures are located at 7.9mbgs and 8.2mbgs; in this zone it is possible to test both fractures on one packer. There are no numerical transmissivity readings as the area around these fractures is too broken up and the packer and FLUTe testing has not been done in this zone (zones that have numerical transmissivity reading through packer and FLUTe testing will be tested after the initial near surface tests are complete). However, based on core images, this location has been determined to be an appropriate zone to test the FIPS device. Low porosity rock surrounds the fractures, and the fractures have a relatively large aperture. Packer testing and FLUTe hydraulic head testing have been performed below this zone. Other areas of this borehole will be tested using the FIPS device after this initial test.

The main reason for choosing a location close to the ground surface is because of packer issues. The DAP that will be used for this preliminary test has a small annulus (6.2mm) to the rock wall. By testing close to ground surface, the chance of having the packer obstructed by the fractured rock borehole wall will be decreased. A potential problem with the FIPS device is the effect diffusion will have on the dye material. The chosen fractures are surrounded by low porosity rock, which should minimize the effect of diffusion.

3.7 Velocity

The flow path and velocity around the FIPS device are an important aspect in the performance of the fracture identification process. The flow around the FIPS device is very different from that of an open borehole; the flow is more representative of the natural flow path of the fracture if the borehole is sealed. With an open interval or completely open borehole flow converges to the open interval, and cross connection is a dominant flow path. With the borehole or fractures sealed off, it is more representative of the natural flow condition. The flow is forced to continue its path, flowing around the sealed portion. Figure 3-19 is a 3D representation of the flow around the packed off section. The flow diverges around the packer but stays on its original horizontal flow plain. Conversely, Figure 3-20 shows how the water converges to the open borehole where it can then move vertically. The flow path and velocities are calculated with the model Hydrogeosphere, which was created by Dr. E. Sudicky of the University of Waterloo. The assumptions the model is based on are that there is steady state flow in both the box and Borden aquifer and for the Borden case there is a uniform flow field away from the well. The importance of this model is that it is able to show the velocity around the FIPS where the water is forced to diverge. This divergence creates greater flow velocities as the water is around the packer. This velocity is the driving force to the leaching of dye from the fabric.

In the natural flow environment, the flow is parallel as it approaches the packed off well. The flow diverges around the well and FIPS device, leaching off the dye and creating an indication mark (Figure 3-21). Flow is similar in the box aquifer, except that the flow is coming from one particular injection port, diverging around the porous media and FIPS device and then converging to the drainage port (Figure 3-22). The flow still comes into complete contact with the FIPS material leaching the dye to create an indication mark.

Based on borehole dilution tests, it was found that individual fracture velocities varied from 100-3300cm/day in a fractured dolostone environment (Novakowski, Bickerton, Lapcevic, Voralek, & Ross 2006). The FIPS device was tested in the lab below and above these average flow rates and showed good results. Velocity calculations were performed to determine the flow rate around the well screen in the Borden wells. The average groundwater velocity is 10cm/day, but around the packer the velocity is approximately 1.6 times faster at a rate of 16cm/day (Figure 3-23). In the box aquifer the average velocity was approximately 5000cm/day. The flow around the packer itself, where the flow lines are forced together, creates a faster velocity approximately 2.6 times faster (11500cm/day) than the velocity along the sewer pipe wall (Figure 3-24). By covering the low and high range of velocities that could be seen in Guelph, favourable results should be found when the FIPS device is tested in the dolostone borehole MW 367.7

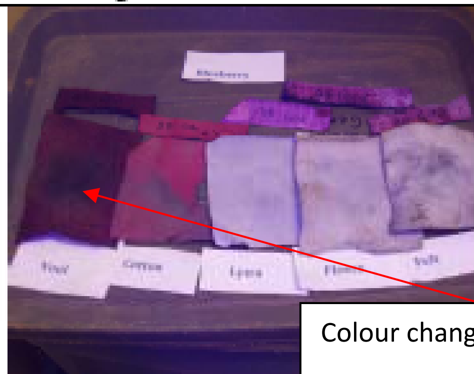
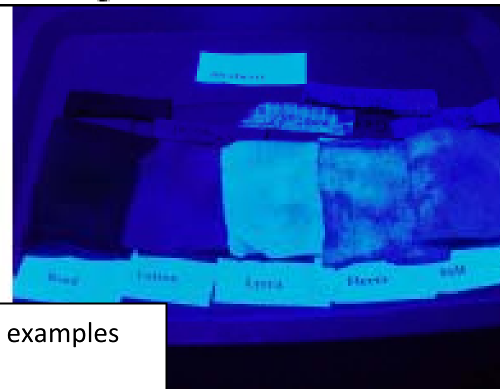
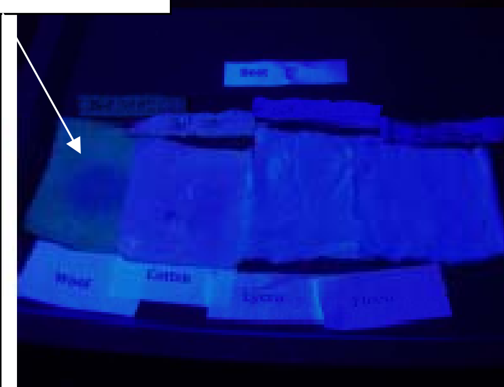
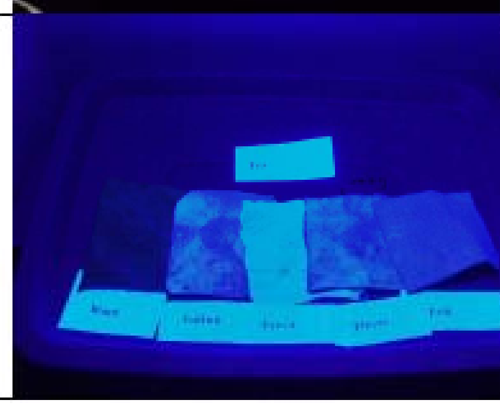
(a)	Normal Light	Black Light
Blueberry Worked: Wool, Lycra		
Beet Worked: Wool		
Grape Worked: Wool		
Tea Worked: Cotton, Lycra		

Figure 3-1: Summary chart of the fabric/dye combinations. Side by side images of the test disk results in normal and black light. For specific close up images refer to Figure 2-12 through 2-18. The pointed out dot is a 'good' result.

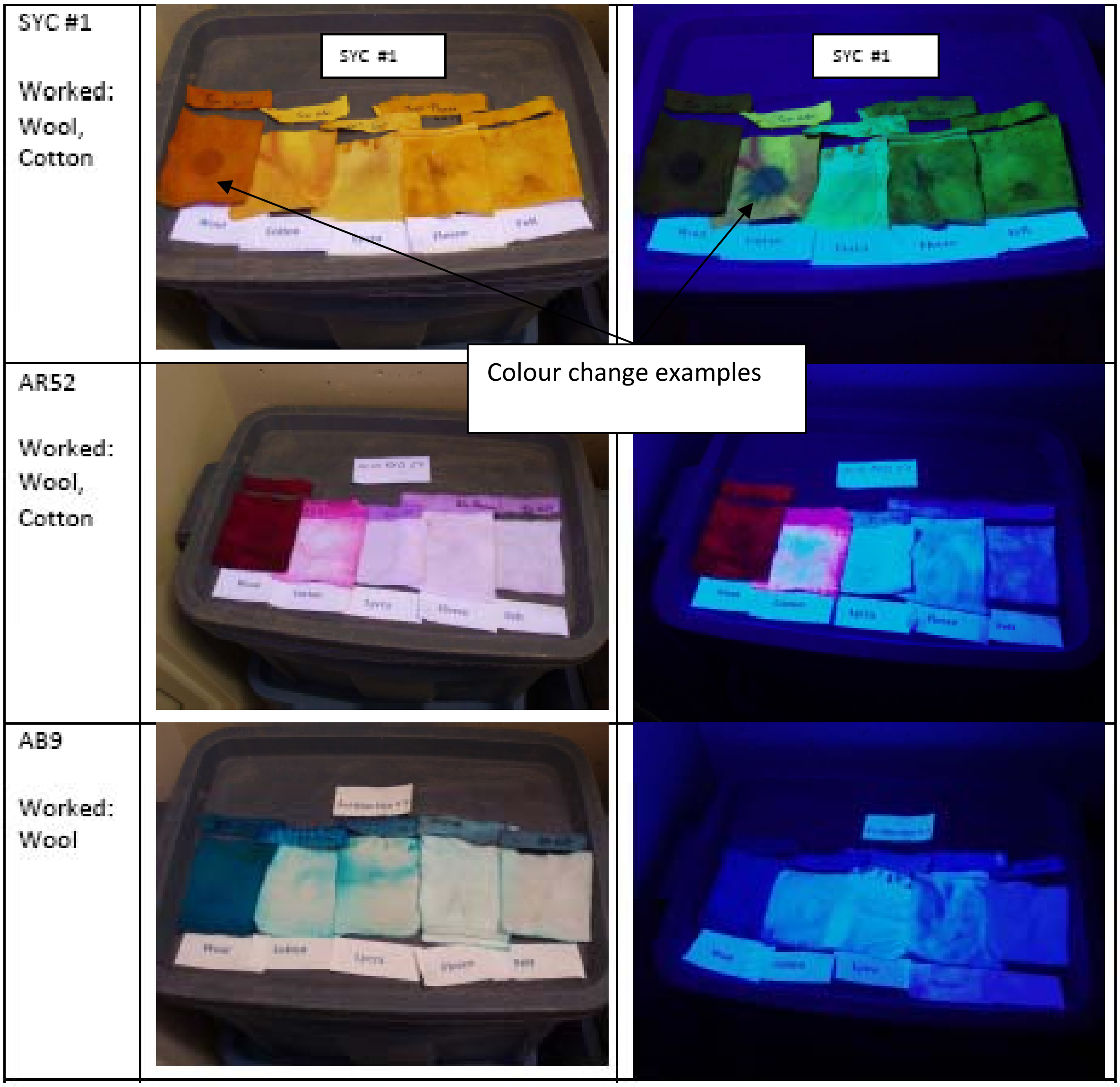


Figure 3-2: Summary chart of the fabric/dye combinations. Side by side images of the test disk results in normal and black light. For specific close up images refer to Figure 2-12 through 2-18. Notice the bleeding or running of the dyes in AR52 and AB9.

Table 3-1: Performance criteria of fabric/dye combinations. The ideal results show a colour change dot in the centre of the material. Those results that showed a defined dot in normal and/or black light were moved to the next stage..

(b)	Wool		Cotton		Lycra		Fleece		Felt	
Dye Performance	Fastness	Colour Change in Flow zone	Fastness	Colour Change in Flow zone	Fastness	Colour Change in Flow zone	Fastness	Colour Change in Flow zone	Fastness	Colour Change in Flow zone
Blueberries	good	yes	good	slight	poor	slight	poor	no	poor	no
Grape Juice	good	yes	good	slight	poor	slight	poor	no	poor	no
Beets	good	yes	ok	slight	poor	no	poor	no	-	-
Tea	good	slight	good	yes	good	yes	good	slight	good	no
SYC #1	good	yes	good	yes	good	slight	good	slight	good	slight
AR52	good	yes	ok (runs)	yes	poor	no	poor	no	poor	no
AB9	good	yes	poor	no	poor	no	poor	no	poor	no

Table 3-2: Evaluation table of fabric/dye combinations. Indicates which fabric/dye combinations moved on to the next test by being placed on a packer and placed in the box aquifer

(c)	Blueberries	Beets	Grape	Tea	SYC #1	AR52	AB9
Wool	good	good	good		good	good	good
Cotton				good	good	good	
Lycra	good			good			
Fleece							
Felt							

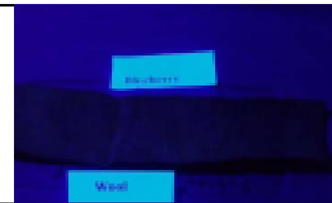
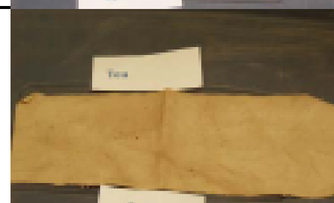
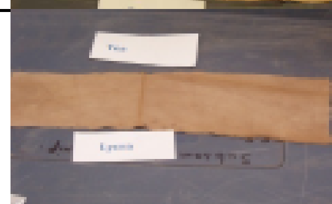
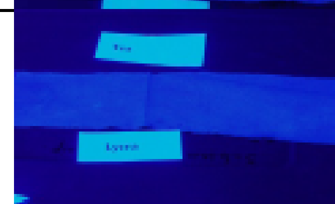
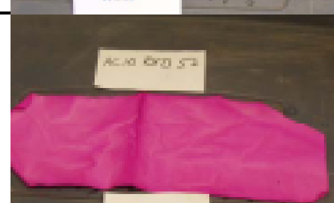
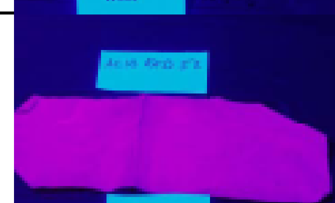
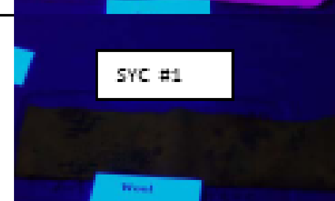
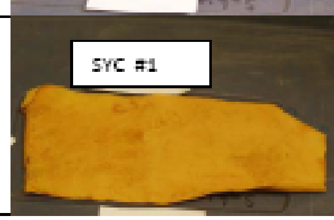
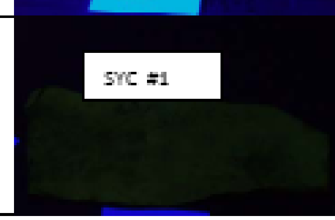
	Normal Light	Black Light
Blueberry – Wool		
Blueberry – Lycra		
Tea – Cotton		
Tea – Lycra		
Acid Red 52 – Wool		
Acid Red 52 – Cotton		
SYC #1 – Wool		
SYC #1 – Cotton		

Figure 3-3: Fabric/dye strips for the bench-test; these were the combinations that showed a flow colour change. Longer strips so they can be sewn and fit onto the packer.

Figure 3-4: Sewing of Cotton/SYC #1 Sleeve. Cut to size, strips are dyed then hand sewn to fit on the packer. The fabric is sown so the material fits tight on the packer, and thus needs to stretch with the packer when inflated.

Figure 3-5: Dyed Test Strips on Packer. They are able to stay on the packer without aid. From bottom to top they are wool/AR52, cotton/AR52 and lycra/grape juice (Left). Elastics are used to ensure the material stays in place (Right), and the saran wrap is used to create a no-flow zone to see how the dyes react to porous media flow through a well screen.

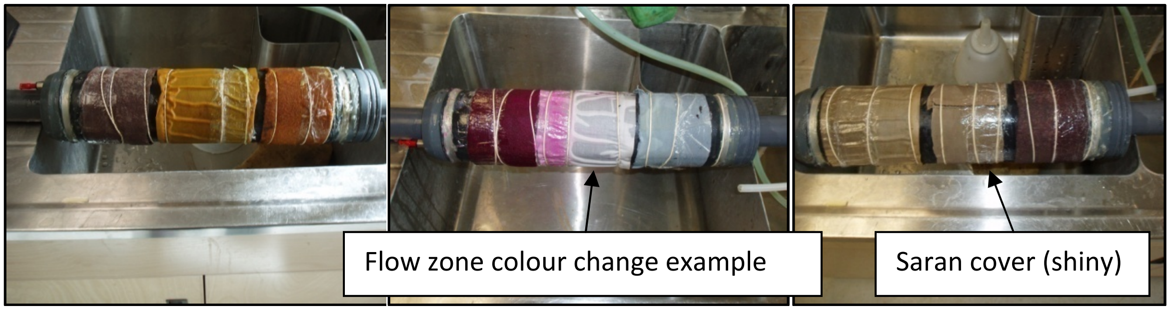


Figure 3-6: Strips on packer after it is removed from the box aquifer. Notice the colour changes between the zones that had flow and those with no flow. The flow zone was created by wrapping part of the material with Saran wrap, this is impermeable so flow could not affect this zone. The elastics moved but the material stayed in place. From left to right: wool/blueberries, cotton/SYC #1, wool/SYC #1, wool/AR52, cotton/AR52, lycra/blueberries, cotton/tea, lycra/tea, wool/grape juice.

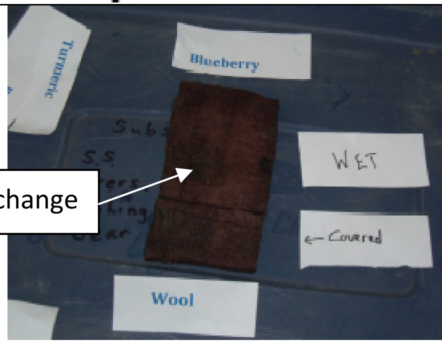
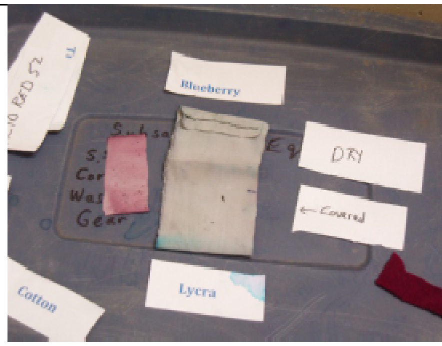
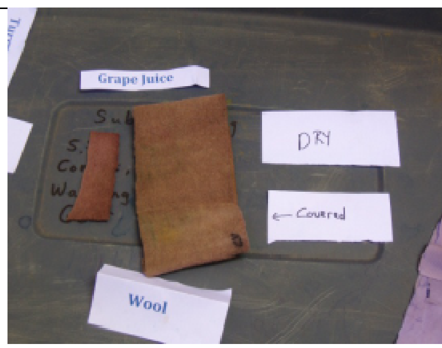
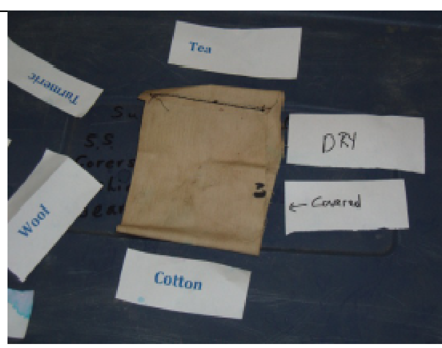
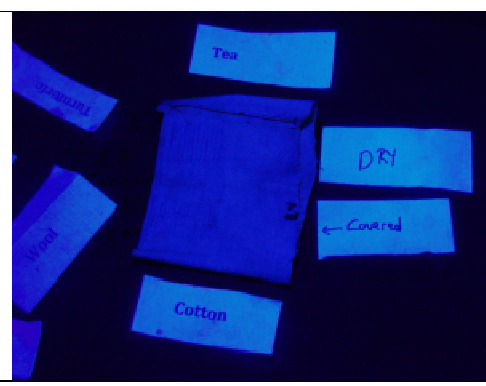
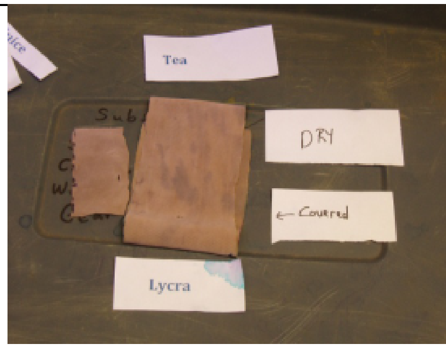
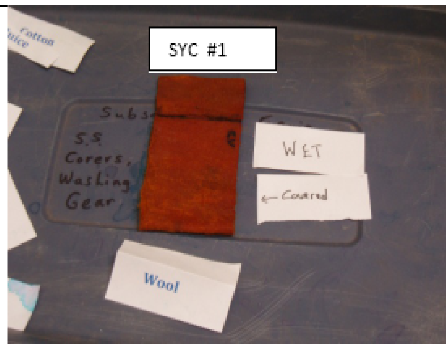
<table>
<tr><th></th><th>Normal Light</th><th>Black Light</th></tr>
<tr><td>Blueberry – Wool</td><td>
</td><td>
</td></tr>
<tr><td>Blueberry-Lycra</td><td>
</td><td></td></tr>
<tr><td>Grape Juice - Wool</td><td>
</td><td>
</td></tr>
<tr><td>Tea - Cotton</td><td>
</td><td>
</td></tr>
</table>

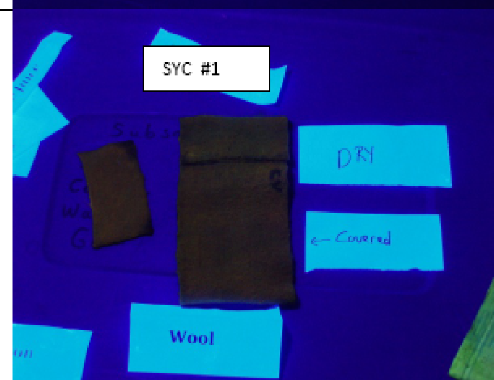
Figure 3-7: Strips from the box aquifer test. These are the material/dye combinations that passed the first round of tests. These strips were placed in the box well and had water pass through the system at 1L/min. Ideal results showed the actual well screen slits, several results showed a colour change, and the rest showed no change at all. Only the blueberry/wool showed any change at all, all the rest showed no change.

Tea – Lycra

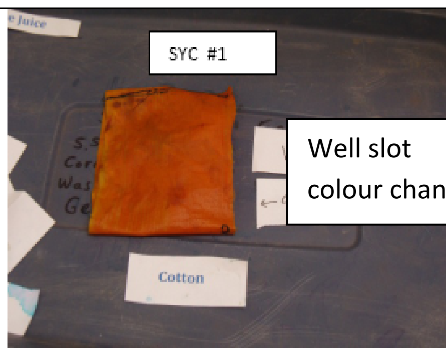


SYC #1 - Wool

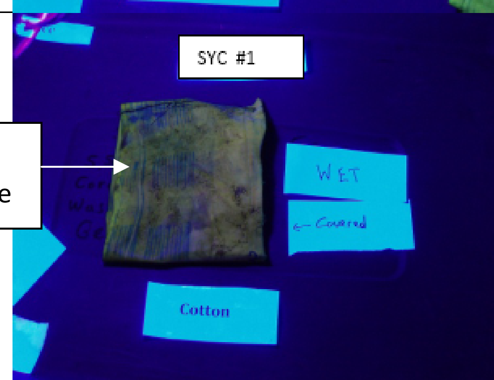




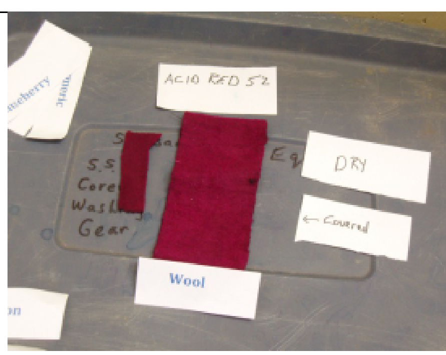
SYC #1 - Cotton



Well slot colour change



Acid Red 52 – Wool



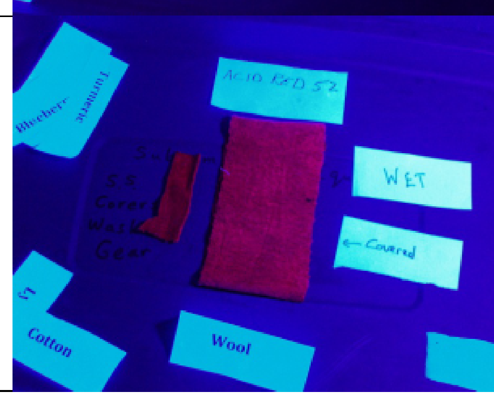


Figure 3-8: continuation of previous figure, but this figure shows the ideal results, actual well slots, as seen in SYC#1/cotton under UV light. The other combinations here showed not colour change at all.

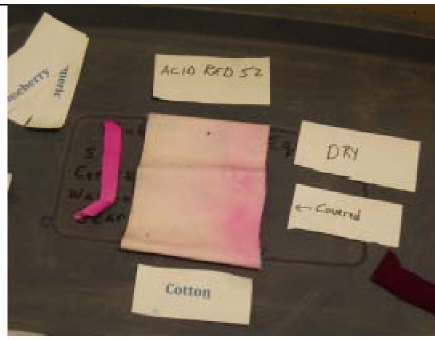
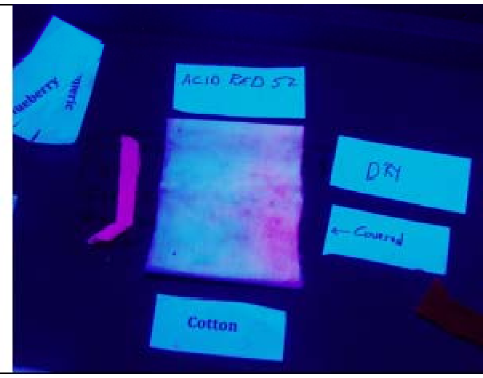
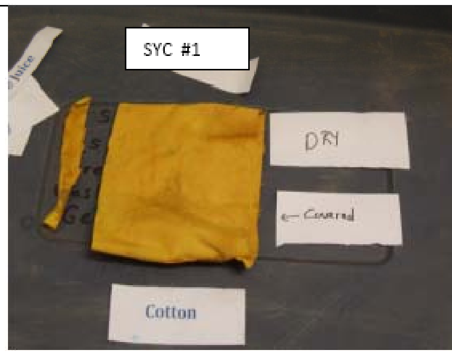
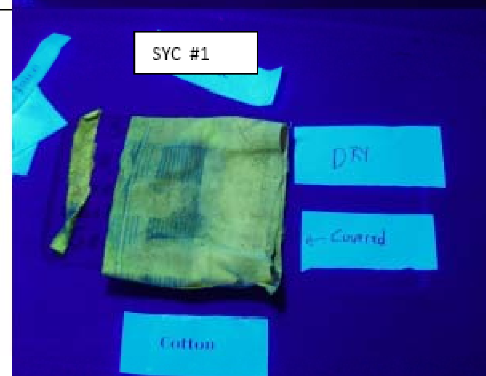
Acid Red 52 - Cotton		

Figure 3-9: A final image from the sequence of the last two pages. Notice the running of the dye, which shows potential but not ideal results.

<table>
<tr><th>SYC #1</th><th>Normal Light</th><th>Black Light</th></tr>
<tr><td>Cotton – Wet</td><td>
</td><td>
</td></tr>
<tr><td>Cotton - Dry</td><td>
</td><td>
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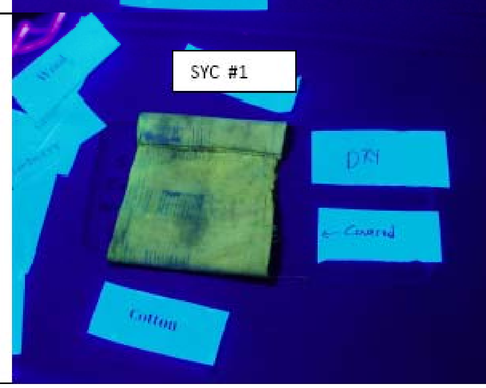
<tr><td>Cotton - Dry</td><td></td><td>
</td></tr>
</table>

Figure 3-10: Cotton/SYC #1 combination. Notice individual well screen slits under black light, these same slits can be seen under normal light but very faint, the view under black light is an ideal result in that it is possible to distinctly see where flow occurred. The botton left image is of the well screen slots to show what showed up on the material.

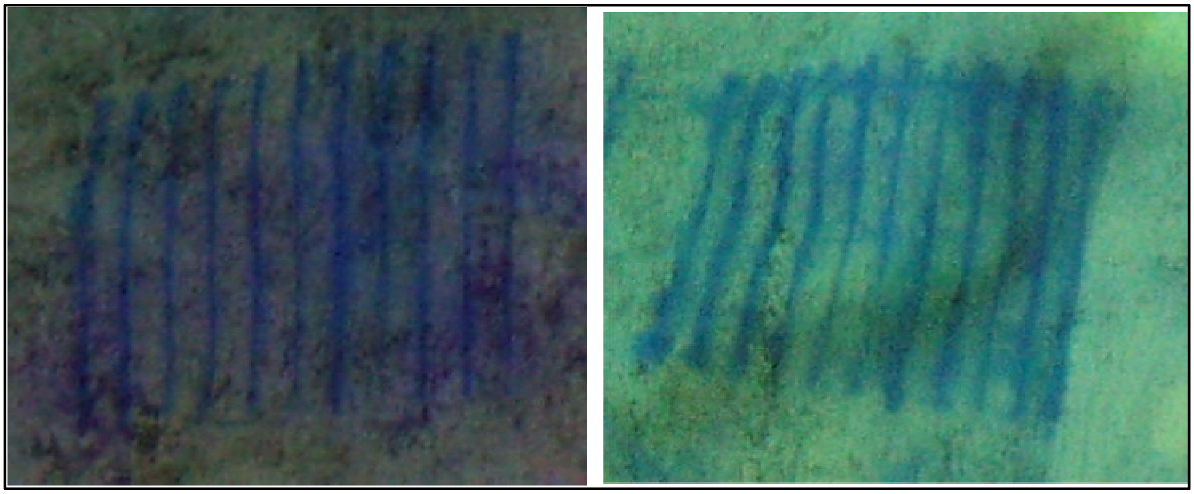


Figure 3-11: Close-up images of the dyed well slots that are 0.25mm aperture and spaced 3.2mm apart, both images are under black light, the left is wet the right is dry.

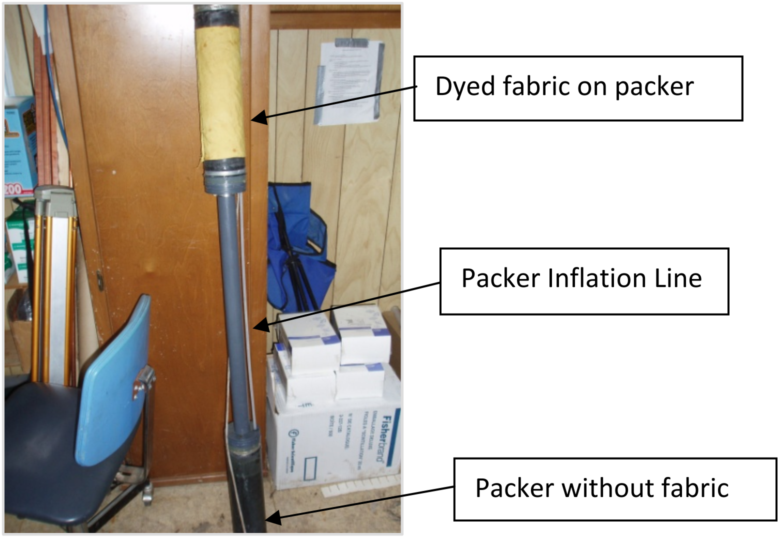


Figure 3-12: Two packers on the pipe set-up for the simulated fracture identification test at the Borden field site. Long strips of dyed fabric are placed on the packer, and two packers are used so two tests can be done simultaneously

.

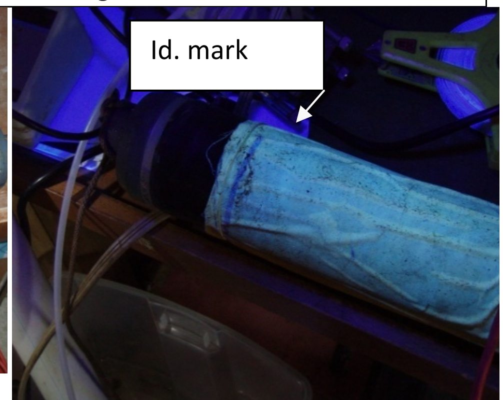
	Normal Light	Black Light
Top Packer (7.5’ TOC)		
Bottom Packer (11’ TOC)		

Figure 3-13: Borden simulated fracture well experiment. The simulated facture can be seen by the discolouration in both normal and black light through the identification mark indicating flow. This was a slow flow rate of 10cm/day and the experiment lasted five days.

Table 3-3: Water chemistry of Borden aquifer in mg/L (King et al. 1999b;King & Barker 1999;Mackay et al. 1986;Nicholson, Cherry, & Reardon 1983).

Ca	50-100
Mg	2.4-6.1
Na	0.9-2.0
K	0.1-1.2
Cl	1-3
SO_4	10-30
Alkalinity as $CaCO_3$	100-250
NO_3	<0.6-6
HN_4	<0.4
Kjed (as N)	<0.1
Fe(II)	0.002-2.8
Mn	0.04-0.03
H_2S	<0.02
CH_4	0.2
Dissolved organic C, DOC	<0.7
Dissolved oxygen, DO	0-8.5
pH	7.1-7.9
Temp, ^oC	6-15

6 Hours **5 Days**

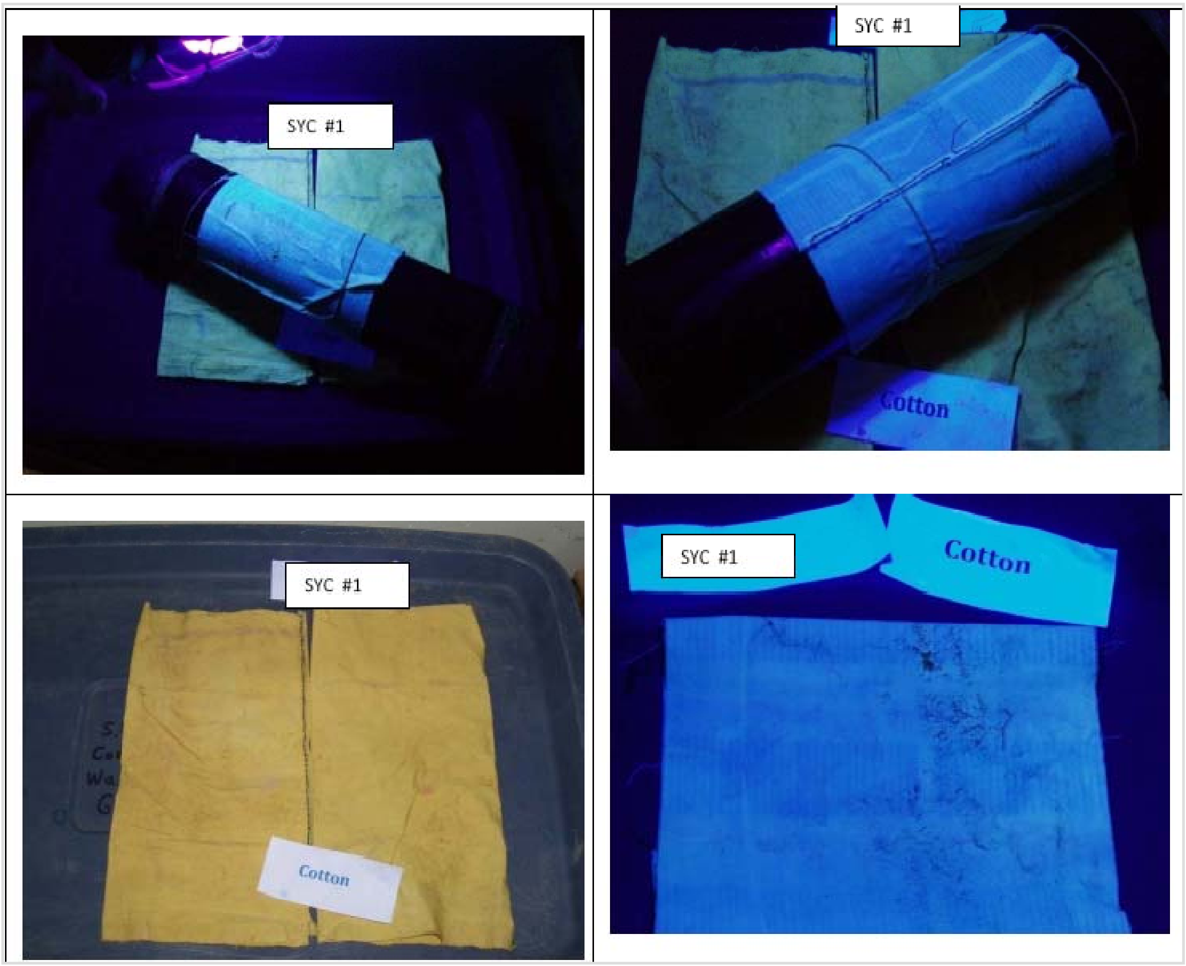


Figure 3-14: Steeping Test - top left shows the result after six hours steeping; top right shows the result five days after steeping; bottom left shows the dry normal results after five days; bottom right shows the dry black light results after five days steeping. The packer and material was placed in the laboratory well and left to soak for five days to see how much influence flow actually had on the colour change that occurs. As shown, the colour change is not a vibrant, these show up very faint, as compared to when there are flow conditions.

6 Days Steeping

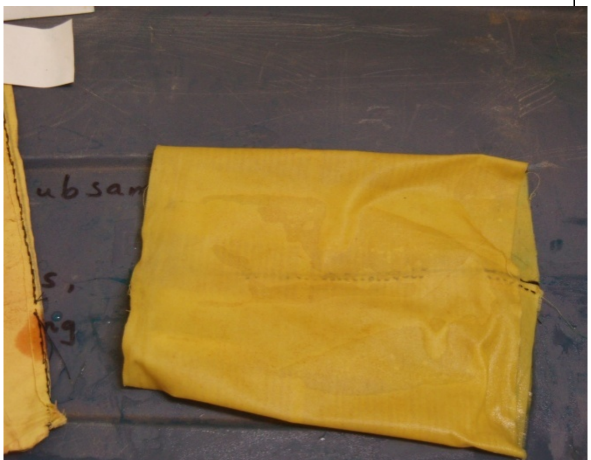
Normal Light	Black Light
	

Figure 3-15: Steeping test done with DI water. This test was used to see if the colour change occurred because of a reaction with something in the water. The colour is darker than that seen with the previous steeping test, but not as vibrant. as that of flowing water.

Flowing Tap Water **No Flow (Tap Water)** **No Flow (DI water)**

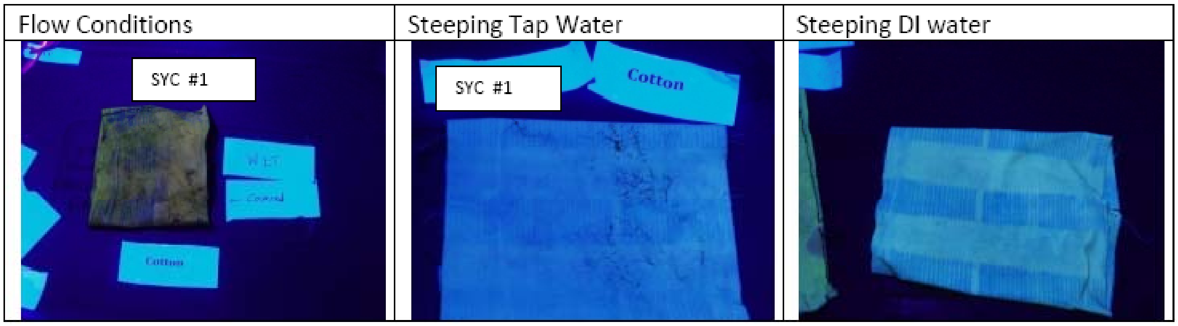


Figure 3-16: Comparison of the flow condition results with the steeping test results The indicator lines (dark blue discolouration on material) are much darker/vibrant in the flow conditions than those in the steeping test.

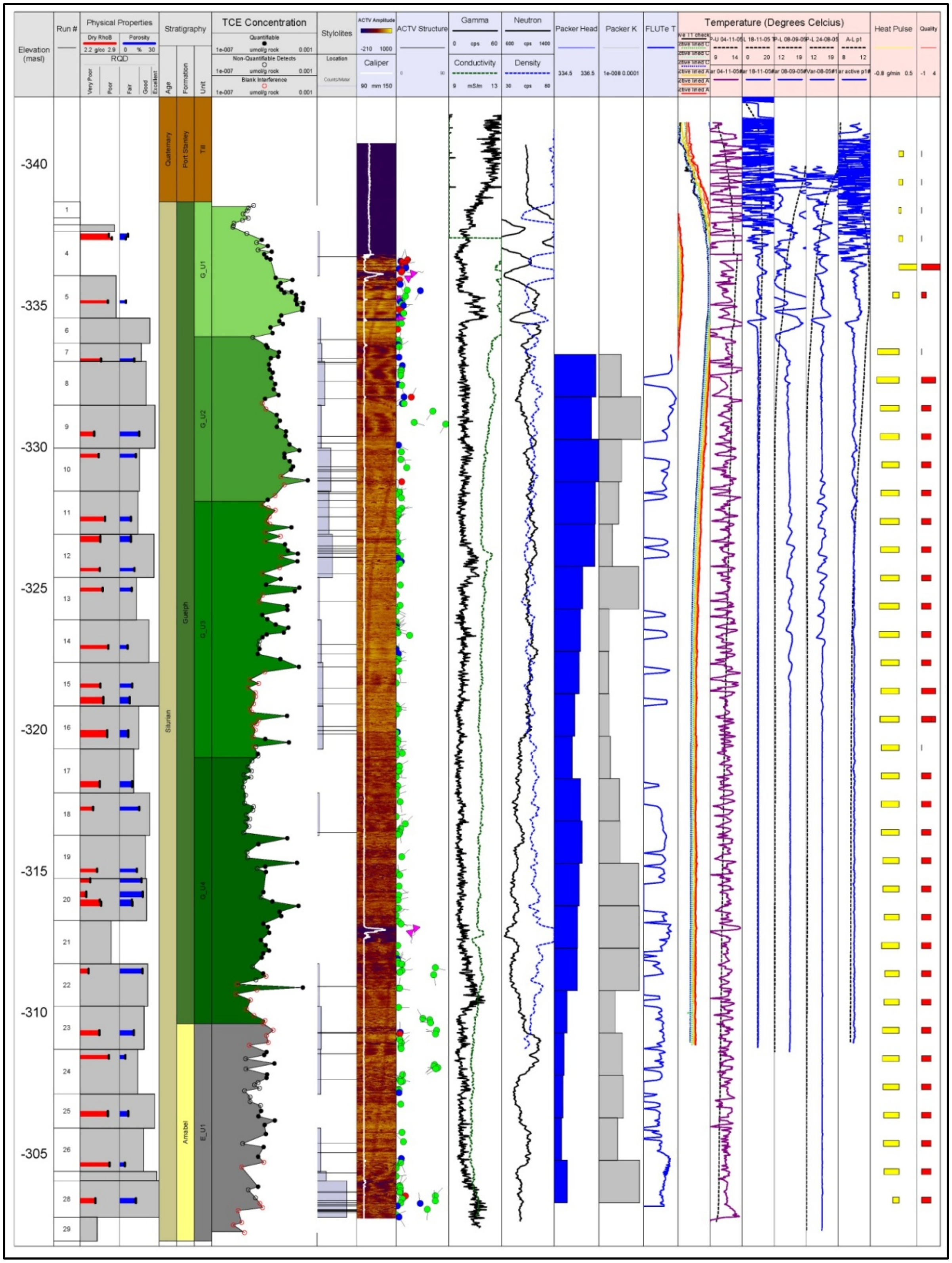


Figure 3-17: Guelph Borehole 367-7, properties and parameters of borehole to be used in Guelph field test (Kennel 2008)

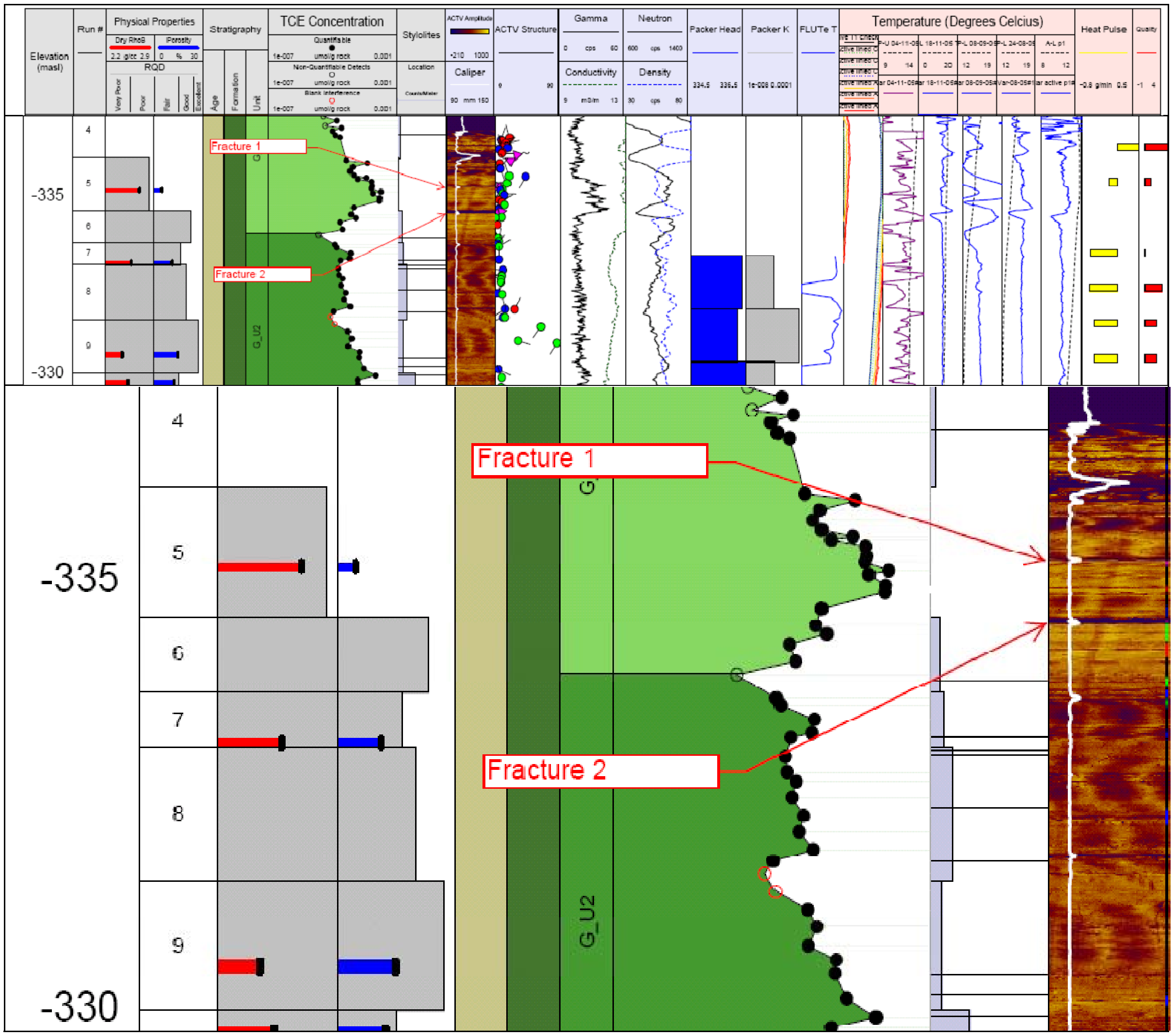


Figure 3-18: Guelph Borehole 367-7, a close up of the suggested test zone. The field test will cover the fracture located 335.1masl and 334.8masl (7.9mbgs and the fracture located 8.2mbgs) (Kennel 2008).

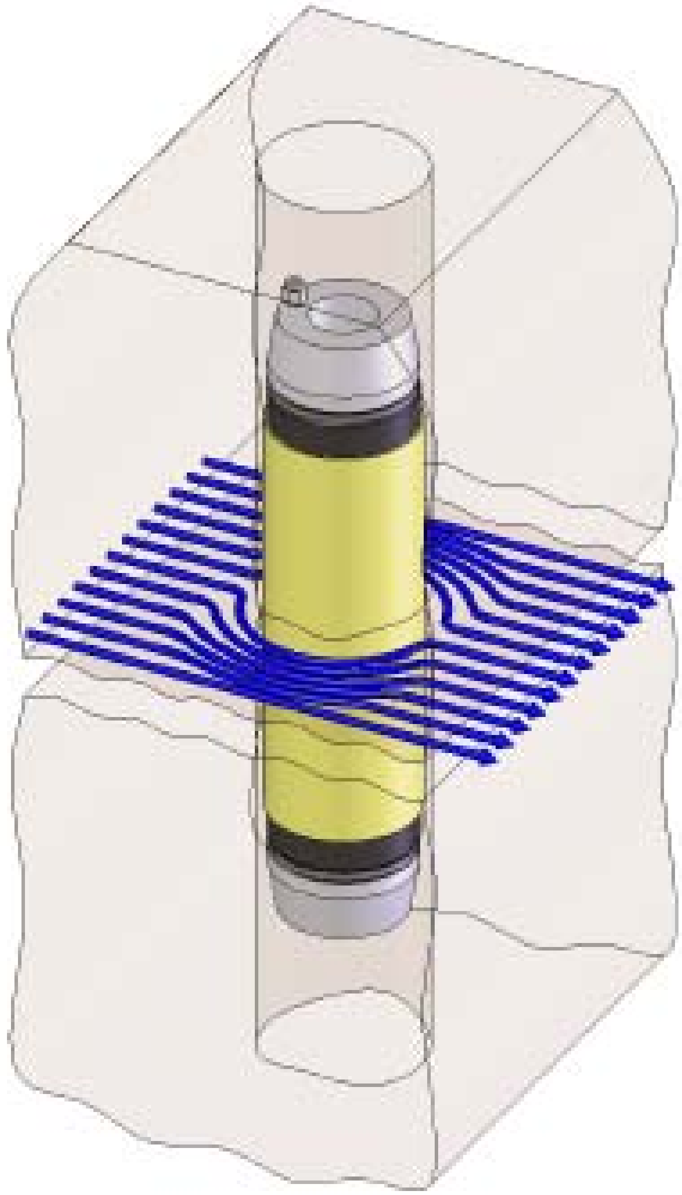


Figure 3-19: Shows a 3-D conceptual image of flow around the FIPS device as water flows through a fracture

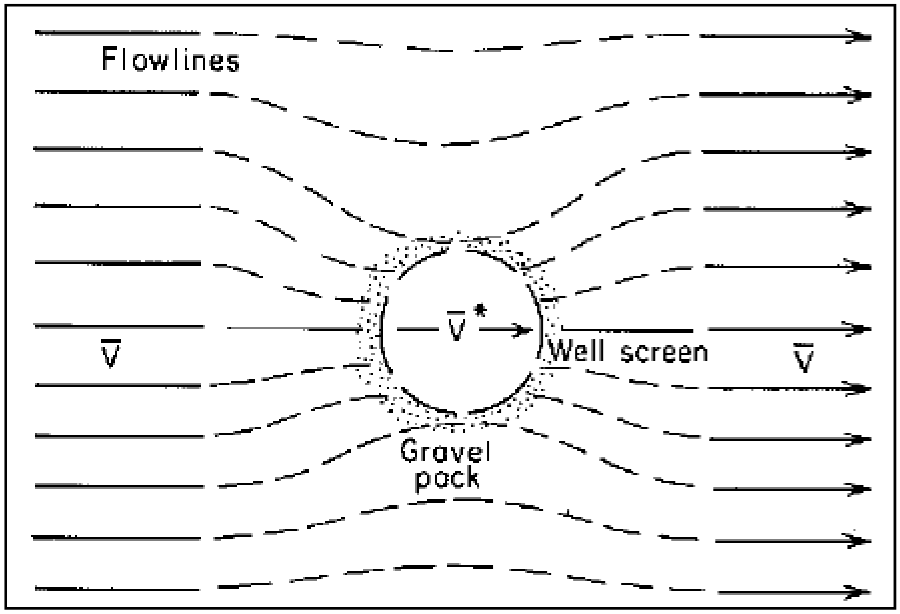


Figure 3-20: Porous media flow with an open well screen or borehole, notice how the flow converges toward the well (Freeze & Cherry 1979).

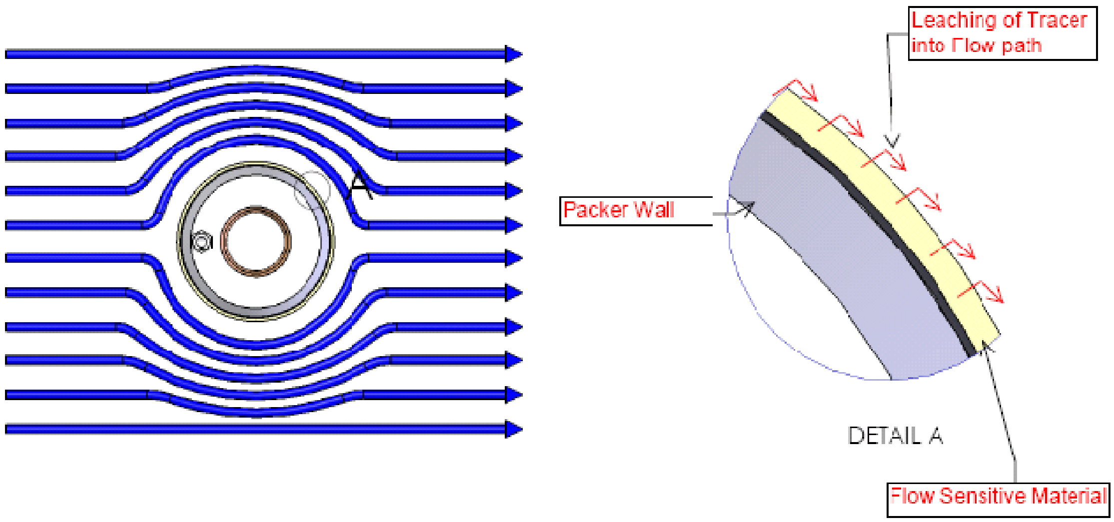


Figure 3-21: This figure shows the flow path with a packed well screen or borehole. Notice how the water diverges around the packer. On the right is an image of the dye being leached out into the flow path, creating an flow identification mark.

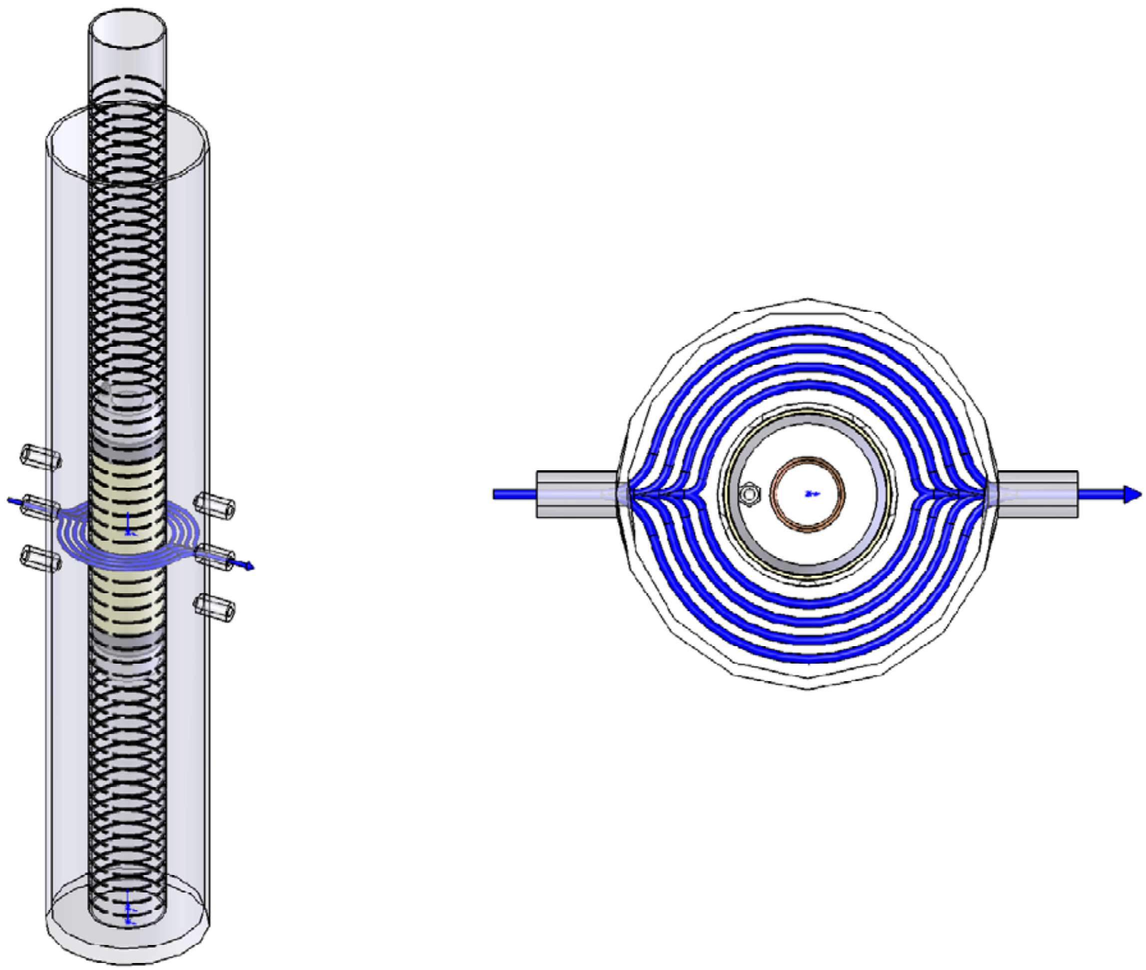
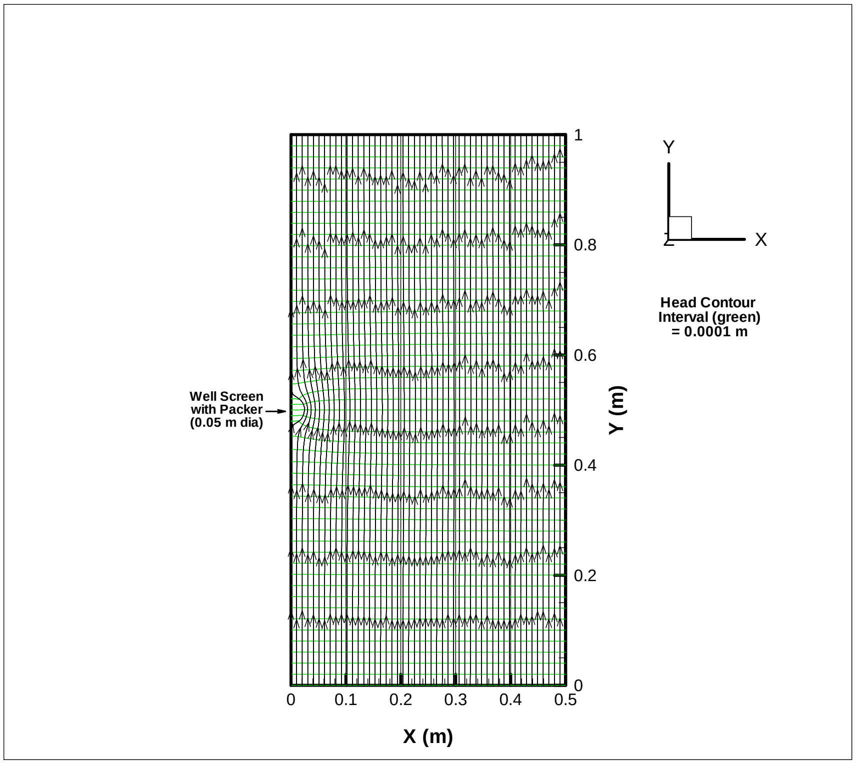


Figure 3-22: Shows the flow path in the box aquifer when the well screen has the FIPS device deployed. Flow comes in the injection port and diverges around the porous media and well screen. It then converges to the drainage port. Again dye is leached off the FIPS device into the flow path creating a flow indication mark



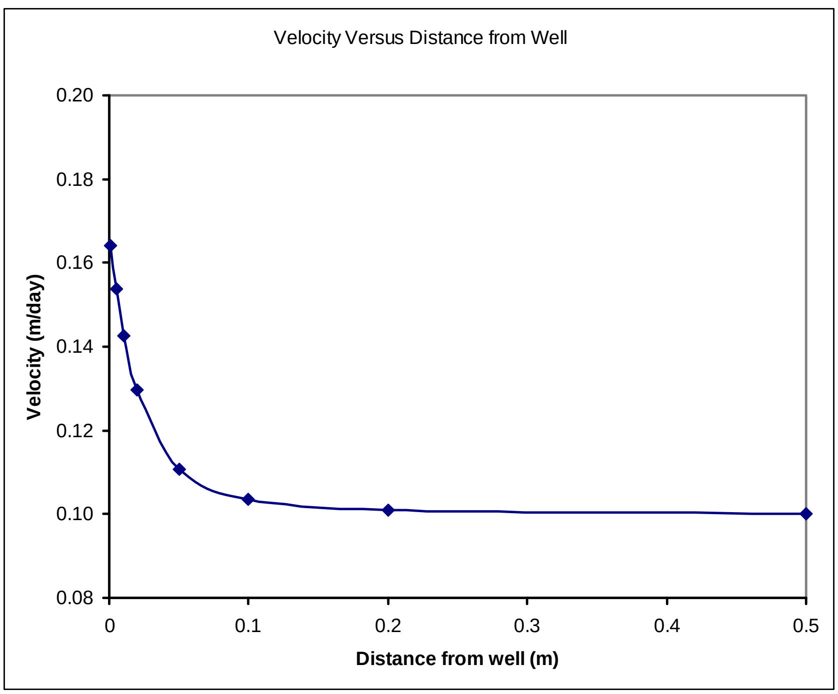


Figure 3-23: Numerical simulation of groundwater flow around the simulated fracture well with packer inflated, in the Borden aquifer. The flow is approximately 1.6x higher at the well than the average groundwater velocity in the bulk aquifer. Flow lines are the arrows, heads are the green lines.

Dist from well (m)	0.005	0.01	0.02	0.05	0.1
Vx (m/s)	-2.13E-06	-8.70E-07	-8.98E-07	-9.40E-08	-8.98E-08
Vy (m/s)	6.00E-05	5.51E-05	4.75E-05	3.46E-05	2.66E-05
V (m/s)	6.00E-05	5.51E-05	4.75E-05	3.46E-05	2.66E-05
V (m/d)	5.2	4.8	4.1	3.0	2.3
Ratio	2.3	2.1	1.8	1.3	1.0

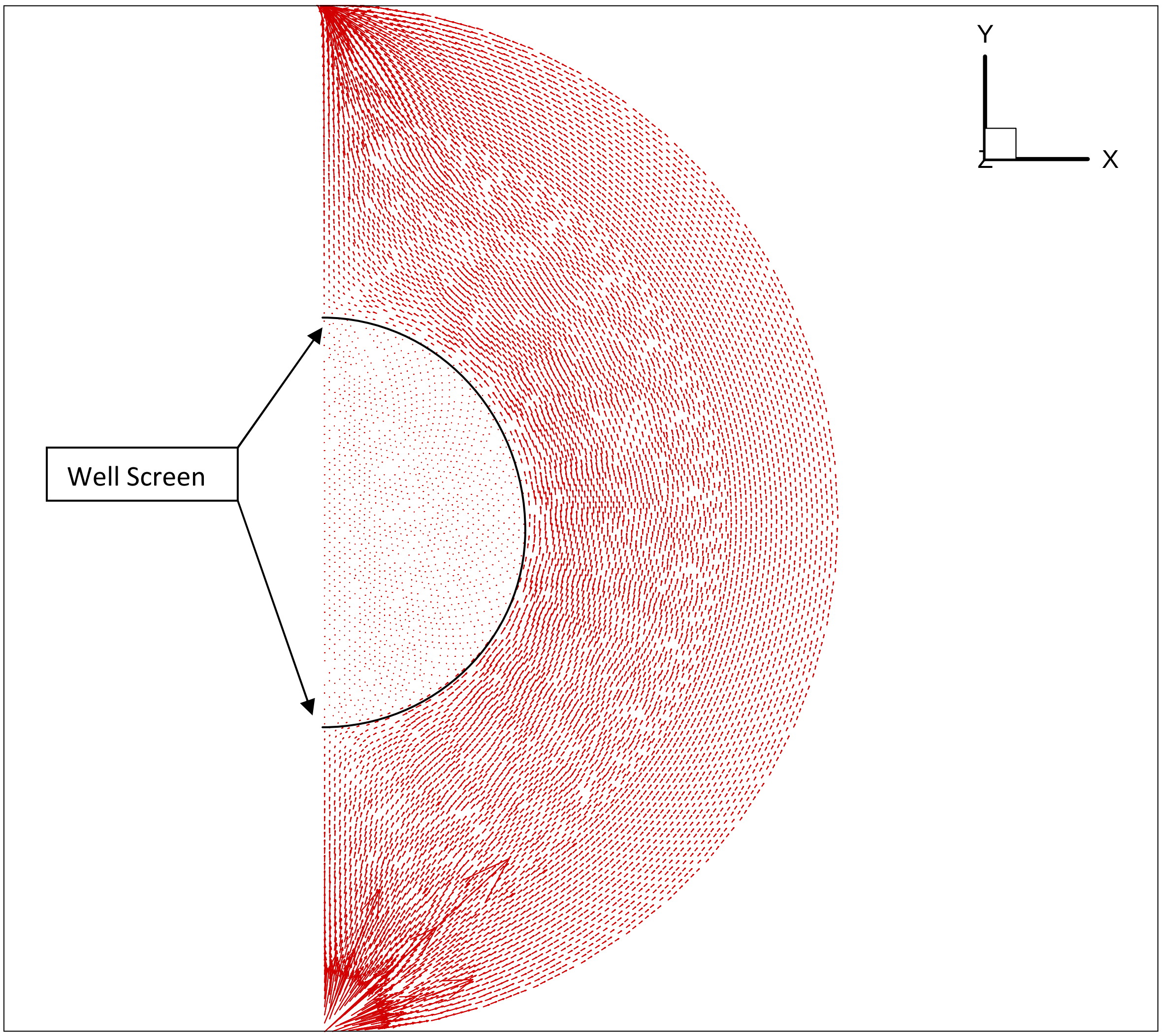


Figure 3-24: Shows the velocity of the flow around the packer in the box aquifer. Flow is 2.5x higher around the well screen than at the edge of the box.

4 Summary and Conclusions

The following five steps highlight the main goals and tasks of this project:

1. The goal of this thesis was to develop a borehole device for identifying fractures with active groundwater flow under natural flow conditions. The thesis' work focused entirely on the development and testing of a prototype device in this preferred design. This design had two main components: an inflatable packer and a fabric (cloth) wrapped around the exterior of the packer. When the packer was inflated, the dyed cloth which is sensitive to flow, was pressed tightly against the borehole wall. Water then flowed around the device, leaching the dye to leave a visual identification mark on the cloth. When the packer was deflated and retrieved to the surface, the cloth showed the location of the hydraulically active fractures on the borehole wall.
2. Step 2 in this process was to convert this conceptual design to an actual functioning prototype device. It was necessary to develop the water sensitive cloth through a process of trial-and-error, involving many combinations of dyes and fabrics. This selection process resulted in the identification of various, possibly useful, combinations of dyes and fabrics
3. Step 3 involved subjecting the potentially useful combinations of fabrics and dyes to laboratory tests to determine the best combination for identifying hydraulically active fractures. A laboratory apparatus (the 'sand box test well') was constructed in which a standard 10cm diameter slotted well screen is situated in medium-grained sand subjected to steady-state water flow. The slot sizes (i.e. aperture) are 254µm, within the range of apertures common in fractured rock aquifers. The various fabrics were tightly pressed against the well screen using the double-acting packer system (DAP) developed by Solinst in 2001. These tests showed that there is a particular dye/fabric combination (cotton with a food additive – SYC #1) that performed better than all others. This is referred to as the preferred dye/fabric combination. Using this combination, the many slots on the well screen were clearly visible, with the best visibility apparent when exposed to black light (ultraviolet light). The tests were conducted with the use of tap water, at one water flow rate (5000cm/day) and for one exposure time (five days).
4. Step 4, the testing of the prototype device (the SYC #1 on cotton attached to the double-acting packer system) involved tests in 10cm wells installed in a well-characterized flow system such as the surficial sand aquifer at Canadian Forces Base Borden where the average

linear groundwater velocity is approximately 10cm/day (Laukonen 2001). The significant test at the Borden site involved a PVC casing in which three slots were cut to represent fractures located 2.3m, 2.8m and 3.4m below the ground surface. These fractures have an aperture of 3175µm.The Borden test was done to demonstrate the versatility of the double-acting packer system, to test multiple intervals simultaneously and determine whether the dyed fabric would be capable of showing the two tested fractures after five days of exposure at extremely low velocities relative to what is common in fractured rock. This test was very positive in terms of these two test purposes; the DAP proved to be versatile and efficient, and the two tested fractures showed up with good clarity.

5. The fact that the preferred dye/fabric combination was proven to be fully capable of identifying the well screen 'slots' does not on its own indicate that this identification is due to flowing water. Therefore, tests referred to as 'steep tests' were done in the lab apparatus to determine whether flow is required to cause the fracture imprints. These tests, using no flow conditions, showed only faint slot markings on the fabric, and, therefore, it is concluded that flow is required overall to produce definitive indication of active flow.

The results obtained from the five steps outlined above indicate that the prototype device developed in this thesis has strong potential to be a useful device for identifying hydraulically active fractures in fractured rock boreholes. This device is unique, however, in order for this device to be deemed fully effective, it must be demonstrated in boreholes in rock. Therefore, a particular borehole at a particular site (hole MW 367-7 at the Guelph Tool site in Guelph, ON) has been selected for the first field trial. Two fractures identified in this hole have been selected as the initial targets for testing using the FIPS prototype. It will be compared to various indirect and direct lines for fracture presence, distribution and hydraulic activity identified/available in the discrete fracture network toolbox. This test will take place after the completion of this thesis.

5 Recommendations for Further Work

5.1 Improvements to FIPS Device

The FIPS device is in its infancy. It performed well when showing hydraulically active fractures in the lab facilities and Borden site. However, work needs to be done to better understand this device and its properties, especially its effectiveness in fractured rock environments.

5.1.1 Sensitivity to Flow Rates and Exposure Time

In order to continue to improve the device, several aspects of the device need to be further tested. In the box aquifer with the slotted well screen, tests will be run at different flow rates (velocities) to assess its sensitivity at slower velocities and at different time intervals. Determining the sensitivity at low velocities is important. It may be possible to determine an optimum exposure time to best see the fracture identification mark. By minimizing time in the borehole, this would likely decrease the effect of matrix diffusion blurring the results. Changing the exposure times in the Borden wells could also provide insight concerning the performance of the FIPS device. It may be possible to leave the device in the ground for a shorter time at the slow flow rate and see if the indication mark still appears because a slow velocity is likely the limiting factor.

5.1.2 Fabric Improvement

There are further tests to be done and improvements to be done to the fabric/dye combinations tested. The fabric/dye combination of cotton/SYC #1 was only tested on one type of cotton, t-shirt type material. There are many different types of cotton ranging from shear to heavy canvas. Therefore, some of these different grades of cotton should be tested to determine if there is an optimum weave. As well, other fabrics, particularly hemp and silk should also be tested to see if they will perform better than the cotton/SYC #1 combination. These other fabrics may prove more sensitive to groundwater flow when dyed.

5.1.3 Assess Potential Interferences

Different chemistries of water have to be tested on the device as well. Ph, salinity and various other geochemistry components may affect the performance of the FIPS device. The different geochemistry of water can be tested in the box aquifer by injecting these different waters. The different water compositions and even rock materials may affect the performance of the FIPS device, and, therefore, many variables need to be tested. The effects of varying porosity, permeability and composition of the rock matrix could also affect the results the FIPS device gives and need to be explored as well. The variability of the rock borehole is more difficult to test in the lab; these parameters will have to be tested in actual fractured rock boreholes.

It may also be found that there is a more efficient or practical packer system to use. For example, a tapered packer has potential. If the DAP used right now has too small of an annulus to be totally efficient for use in a fractured rock borehole (Figure 2-23). There is risk of the device getting stuck or hung-up with only a 6mm annulus, so a slightly smaller diameter DAP could be made.

Through the initial tests this device performed adequately in southern Ontario conditions; it is just a matter of optimizing the FIPS device to its fullest potential and improving the understanding of its performance before it can be tested elsewhere.

5.2 Future Use of FIPS Device

The impetus for creating the FIPS device derives from the pursuit of a broader research goal, which is the development of a flux measurement method for both groundwater flow and organic contaminant transport in boreholes under passive conditions.

In order to understand the future goals and capabilities of the FIPS device, background to the flux meter is necessary. The University of Florida flux meter was designed to measure cumulative dissolved solute fluxes and groundwater flux simultaneously when placed within a flow field in a porous media environment (Annable, Hatfield, Cho, Klammler, Parker, Cherry, & Rao 2005;Hatfield, Annable, Cho, Rao, & Klammler 2004;Hatfield et al. 2007;Hatfield, Annable, & Rao 2005). The device consists of a self-contained permeable unit that intercepts the groundwater flow without retaining it. A matrix of hydrophobic and hydrophilic sorbents in the device sorbs dissolved organic and inorganic solutes present in the water intercepting the unit, thus indicating the amount of contaminant carried by the groundwater. The sorbent matrix is also impregnated with known amounts of fluid soluble “resident tracers” that leach from the sorbent at a rate proportional to the fluid flux (2004) and provide an estimate for the fluid flow. The flux meter has been validated and used for estimating fluid flow and contaminant flux for various organic contaminants.

Working in fractured rock poses a variety of problems not faced in granular media aquifers. Granular media aquifers typically have well casing or screen covering the complete depth of the hole. In fractured rock wells, casing is typically only installed in the granular media. The abrasive nature of the rock matrix makes the use of a nylon sock impossible; the nylon would rip and all the GAC would fall to the bottom of the borehole.   Matrix diffusion is a challenge upon pressing a flux meter directly against the rock matrix wall. In granular media, water flow through the hydraulic producing zones, in fractured rock, locating active fractures is difficult. Because the hydraulically active zone in the fractured rock environment could be so much smaller than in the porous media environment, it becomes imperative to locate active flow zones to know where to sample so the flux measurements are not diluted. For example, if a fracture has a 5mm aperture, but the sample material covers 30cm, the affected zone is quite small compared to the whole sample. Cross contamination and vertical flow are also challenges that need to be addressed. Other challenges include the advective flow, though GAC is different than flow in a fracture. As well, traces are stripped from a small section of the PFM; knowing where to sample over an interval is of importance for accurate results.

In conjunction with the FIPS device a layer of granular activated carbon or activated carbon cloth, impregnated with alcohol tracers would be placed on the packer and used to measure the groundwater and contaminant flux. The use of FIPS will help identify areas to test and sample in a fractured rock borehole.   Because this flux measurement device will also use a carbon cloth instead of granular activated carbon (GAC), the carbon cloth will allow for attachment to a packer, with the FIPS material placed behind. Spacer material employed by FLUTe will be put on the outside to address the issue of matrix diffusion. The flux device would be a layered system on a packer with a spacer, carbon cloth and the FIPS material attached.

Further work needs to be done in regarding finding a packer system that will work with a multi-layered system attached to it. The annulus with the DAP is too small for more layers to be attached. The exploration of a FLUTe packer, one that is tapered and flexible has potential. The DAP may also have to be redesigned. As well, properties of carbon cloth need to be further explored. GAC is a material commonly used, and its properties are well known, it is important to have carbon cloth as well understood. By placing a carbon material over the flow sensitive material that is attached to an ideally sized packer, the flux device should work well.

A. Appendix

A.1 Flux Measuring Device and Design

As stated in chapter 5, future research is to be done in creating a contaminant and groundwater flux measuring device. The following section outlines in more detail the flux measuring device.

A.1.1 Definition of Flux

Contaminant/groundwater flux is the rate at which a chemical/fluid passes through a defined cross-sectional area.

$$Jc = qw * C$$

J_c=contaminant mass flux, q_w=water flux, C=cross-sectional area

Contaminant Mass Flux combines two important quantities: the concentration of the chemical and the rate at which the chemical is migrating within the plume (Nichols 2004).

Flux measurements are used to optimize groundwater remedial systems and assess performance. They help to estimate the contaminant source strength and assess the natural attenuation and environmental risks (Annable, Hatfield, Cho, Klammler, Parker, Cherry, & Rao 2005).

A.1.2 Methods of Measuring Flux

There are several methods of measuring flux. By collecting groundwater samples from closely-spaced monitoring wells installed in a transect across a plume, one can estimate the contaminant mass discharge (Figure A-1).

Figure A-2 shows how estimates of contaminant mass discharge have also been made by drawing the contaminant plume into one or more pumping wells installed across the plume's path and sampling the effluent from the well(s) (Einarson & Mackay 2001).

Other methods of measuring flux include multilevel samplers (King et al. 1999a), and transects and integral pump tests (Bockelmann et al. 2003;Bockelmann, Ptak, & Teutsch 2001;Kubert & Finkel 2006). Flux can also be derived from borehole dilution tests.

A new method of measuring flux is through the passive flux meter (PFM) developed by the University of Florida group. The PFM was successfully developed for simultaneously measuring contaminant and groundwater fluxes in granular media. The technology has been used to measure flux in several holes across a plume in order to measure plume discharge (Figure A-3) and in a remedial extraction well capturing the plume (Figure A-4 and Figure A-5). The Florida PFM consists of two components, granular activated carbon (GAC) and sub-dividers (Figure A-6).

A.1.3 Principles of the Florida Passive Flux Meter

"Contaminants in the groundwater that flows through the flux meter are intercepted and retained in the GAC (Figure A-7 and Figure A-8). The mass of the contaminant retained, Mc, is used to quantify cumulative contaminant mass flux, Jc (Hatfield, Annable, Cho, Rao, & Klammler 2004).

$$Jc = \frac{qMc}{\alpha \pi r^2 LArc\theta Rdc}$$

(Mc mass of contaminant sorbed, L is length of the sorbent matrix or the vertical thickness of aquifer interval sampled, Rdc is the retardation of contaminant on the sorbent, Arc quantifies the fraction of sorptive matrix containing contaminant, α is flow convergence)

The groundwater flux is calculated from the mass of resident tracer retained on the sorbent after a known period of exposure (Figure A-8)(Hatfield, Annable, & Rao 2005).

$$q = \frac{1.67(1 - Mr)r\theta Rda}{\alpha t}$$

(Mr=the relative mass of a resident tracer retained after time period t where that tracer has the same retardation as Rdc).

Figure A-9 illustrates converging groundwater flow on the up-gradient side of a meter, parallel streamlines or uniform flow inside the device, and diverging flow as water exits the meter; this depiction is consistent with the hydraulic conductivity of the sorptive matrix, kD, being greater than that of the surrounding aquifer, ko, and with a PFM installed in an open borehole (i.e., in the absence of a well screen). Assuming qD is measured with a PFM, the value of a must be known to assess the ambient groundwater flux or qo. For a circular meter installed in an open borehole, (Strack & Haitjema 1981) provide the following estimation of α

$$\alpha = \frac{2}{1 + 1/KD}$$

where KD=kD/ko, the dimensionless ratio of kD, the uniform hydraulic conductivity of the PFM sorptive matrix (L/T), to ko, the uniform local hydraulic conductivity of the surrounding aquifer (L/T). For the problem addressed herein, the following equation derived by (Klammler et al. 2007) is required, as it characterizes a given a PFM installed in a fully screened well without a filter pack.

$$\alpha = \frac{4}{\left(1+\frac{1}{K_s}\right)\left(1+\frac{K_s}{K_D}\right)+\left(1-\frac{1}{K_s}\right)\left(1-\frac{K_s}{K_D}\right)\left(\frac{1}{R_s}\right)^2}$$

where Ks=ks/ko the dimensionless ratio of ks, the well screen hydraulic conductivity (L/ T) and ko; and Rs=ro/r the dimensionless ratio of ro, the outside radius of the well screen (L); and r the PFM radius (L). The value of a must be known to assess the ambient groundwater flux or qo; this, in turn, means that prior estimates of hydraulic conductivity parameters ko, kD and ks are needed. The former two can be measured directly using a permeameter, while ks can be estimated indirectly through a borehole dilution test.

Figure A-9 displays a single resident tracer distribution over two circular cross-sections of a PFM configured as a column unit for installation into a well. The initial condition is such that after resident tracer is uniformly distributed over the sorptive matrix. After installation and following a period of exposure to local groundwater flow, the tracer is displaced from the PFM. The pertinent assumptions supporting this conceptualization are the following: (1) transport is primarily advective; (2) tracer desorption is linear, reversible and instantaneous; and (3) specific discharge within the bounds of the sorbent is uniform, horizontal and in direction parallel to local groundwater flow. Strack & Haitjema (1981) previously demonstrated the uniform flow assumption for a homogeneous permeable element of circular geometry situated in a locally homogeneous aquifer of contrasting permeability.

It may be surmised that the mass of resident tracer remaining in the PFM is both a function of the initial mass equilibrated with the sorptive matrix and that displaced as a result of groundwater flowing through the matrix; thus,

$$mR = ml - mL$$

where mR is the residual resident tracer mass on the sorptive matrix after exposing the meter to a groundwater flow (M), mI is the initial mass equilibrated to the sorptive matrix (M) and mL is the cumulative mass displaced (M). Because the mass of tracer remaining on the sorbent is inversely proportional to the cumulative groundwater flow intercepted, it may be surmised that cumulative or time-averaged water fluxes can been estimated from measurements of mR.

Because the mass of tracer remaining on the sorbent is inversely proportional to the cumulative groundwater flow intercepted, it may be surmised that cumulative or time-averaged water fluxes can be estimated from measurements of mr.

Analytical tools to characterize the relationship between mr and groundwater flux can be derived by approximating tracer transport over the PFM cross-section as transport through a bundle of parallel stream tubes."(Hatfield, Annable, Cho, Rao, & Klammler 2004)

A.2 The Fractured Rock Approach (Timeline)

Currently there is no passive device used to measure flux in the fractured rock environment. The benefits of a passive device are that it is cheap and creates very little waste water. Most flux measurement devices are labour intensive and create large amounts of waste water. By creating a passive flux meter for fractured rock, it is possible to measure both contaminant and groundwater flux by simply placing the device in a borehole and leaving it for a period of time.

A.2.1 Timeline

In order to design the fractured rock passive flux meter (FRPFM), the following timeline was followed:

1. Visual, design, draw fractured rock flux meter
2. Design and Draw Test Facilities (explored in earlier chapters)
3. Test and determine parameters of test facilities (explored in earlier chapters)
4. Test in laboratory, then Borden (standard well, simulated fracture well), then Field
5. Compare results
6. Develop Solutions to Issues (indicator dye)

Several of these steps have already been achieve; the following is a description of what has been done and still needs to be completed: The first step in designing FRPFM involved conceptual thought and design. The procedure followed was to modify the sandy aquifer PFM for the unique fractured rock environment, to develop conceptual designs from this previous version, and to build prototypes and test.

The reason for a FRPFM was because rock drilling is expensive and the FRPFM must function effectively in open holes in rock ~4-7" (10-18cm) in diameter. As well, active fractures occur, but their positions in the borehole are unknown. The design goals are to locate active fractures, measure fluxes for individual fractures and/or fracture groups and avoid borehole cross connection (i.e. vertical flow).

Some challenges in this design stage included:

- Can't press up against rock wall because of matrix diffusion and abrasion
- Fracture flow, locating active fractures
- Cross contamination, vertical flow
- Advective flow through GAC, different then flow in fracture
- Tracers stripped from small section of PFM, how to sample this

A.2.2 Design Thought Process

There are three main components to the FRPFM:

1. Packers (double acting packer, tapered FLUTe packers, standard packers, FLUTe sock)
2. Annulus (space between rock wall and sample material, pressed up vs. space, optimal spacing)
3. Sample material (GAC, carbon cloth)

Figure A-10 and Figure A-11 show the design thoughts in this process.

Three prototype avenues were developed from this though process:

1. Discrete Interval Open Borehole Conditions
    a. double acting packer
    b. tapered packer
2. Discrete Interval FLUTe Spacer Flow Zone
    a. Triple Tapered Packer
    b. Single Continuous Long Tapered Packer
3. Everted FLUTe Liner
    a. Segmented FLUTe liner
    b. Continuous FLUTe liner

Two available sorptive materials were considered for the device: GAC, tried and tested, and impregnated felt like material, new and in need of testing properties (Figure A-12).

A.2.3 Implementation of Thoughts

The design closest to the original PFM would involve the use of straddle packers, with a sock of GAC in-between, this was the first avenue explored. This first step was done in Borden; the PFM had been tested there, so that acted as a control against which to compare all future results (Figure A-13).

Many issues arose with the first prototype test. There were installation problems with putting on the sock, proper packing and sloughing of GAC. Leaking packers, trapped air, durability, and if moving to a fractured well, the small test zone is compared to the sample area, were also problem areas. Figure A-13 shows the initial prototype.

Possible solutions to the problems listed above were explored. For sloughing, the use of baffles could help with the potential of vertical flow, using DAP's so the sock is packed then the top packer is slid into place. Installation issues would see the use of DAP's, so the sock doesn't have to be pulled over everything, and possibly putting a metal rod onto the packer for ease of installation and removal, as there was an issue of plastic lines stretching and breaking with too much weight.

The only possible solution for leaking packers is better manufacturing, all packers were modified to stop leakage. The durability issue is tough, a shield could be put on for insertion and removal, a nytex sock is too sensitive so the move to carbon cloth may help. The test zone issue could be resolved with an indicator dye or material to know the sample zone.

From these initial issues and failures it was decided to move onto a different design, specifically the use of carbon cloth instead of GAC.

A.2.4 Borden Parameter Tests

This was explored earlier; a set-up was designed and built. Tests were done to compare known Borden parameters. This was also compared with a temperature vector log.

A.2.5 Borehole Dilution Test

To conduct a borehole dilution test, a conservative tracer was instantaneously introduced into an isolated mixing volume located over the desired section of formation in which measurements was to be taken. The subsequent decay in the concentration of tracer in the mixing interval due to the advective flux across the borehole was monitored over time (Drost, Klotz, Koch, Moser, Neumaier, & Rauert 1968). In permeable sands and gravels having groundwater velocities up to a few m/day, the decline in concentration may occur in a few tens of minutes (Figure A-14) (Freeze and Cherry 1979). Experiments conducted in fractured rock, where velocities are often higher and the advective flux much smaller, may last several days to over a week (Novakowski, Lapcevic, Voralek, & Bickerton 1995).

In this study, the borehole dilution experiments were conducted using an apparatus designed and built for use specifically in fractured rock systems. In fracture flow, the advective flux is small; therefore, the volume of the test interval was minimized and only individual fracture features were investigated.

The design used for the Borden field experiment consisted of two packers isolating a zone of 33 cm in length, and 2.6 L in volume. The packer elements were approximately 0.30 m in length. A CTD diver, conductivity and pressure probe was mounted in the top of the mixing zone. A 12V Whale pump was mounted in the bottom of the mixing zone. The Whale pump was connected to a power supply where the voltage could be adjusted to vary the mixing rate in the test zone (Figure A-15 and Figure A-16). This set-up and the tests were similar to those done by (Novakowski, Bickerton, Lapcevic, Voralek, & Ross 2006).

The packers were inflated over a specific simulated fracture feature and tied off. The dilution experiment was initiated by the instantaneous injection of a 10cc volume of a conservative tracer (NaCl) into the test zone. The CTD diver was used to record the electrical conductivity every 1.5 min. Advective mixing in the test zone was conducted during the entire period of the experiment.

A.2.6 Interpretation of a Borehole Dilution Experiment

The decay in tracer concentration in the test zone over time is interpreted using (Drost, Klotz, Koch, Moser, Neumaier, & Rauert 1968):

$$\frac{dc}{dt} = -Ava\frac{c}{V}$$

In this equation, c is the concentration of the tracer compound, A the cross-sectional area of the dilution volume perpendicular to flow, va the apparent velocity of groundwater flowing through the well bore, and V the volume of the isolated zone in the borehole. Solving this equation for the case of an instantaneous, fully mixed injection of tracer, and relating the apparent velocity in the test section to the true groundwater velocity, vf, yields the following result (Drost, Klotz, Koch, Moser, Neumaier, & Rauert 1968):

$$vf = -\frac{V}{nAt}\ln\frac{c}{co}$$

For this calculation, co is the initial concentration at t =0, c the concentration at time, t, following tracer injection, and n a dimensionless correction factor accounting for the additional flow captured by the open well due to the convergence of flow lines in the neighbourhood of the well bore. Groundwater velocity (vf) in a single fracture intersecting the test zone is determined from the measurements of dilution by plotting the results in the form of 'ln c versus t' and fitting a linear regression line to the data. In the case of a zone containing a single fracture in an open borehole, A is equal to the diameter of the borehole times the hydraulic aperture and n=2 (Drost, Klotz, Koch, Moser, Neumaier, & Rauert 1968).

The borehole dilution tests produced the results that confirmed the literature (Laukonen 2001), with velocities in the normal well screen at 9cm/day. In the simulated fracture well, the velocity was approximately 1.35m/day when corrected for mixing, these results for the simulated fracture well came back as expected, once corrected for mixing in the packed off interval (refer to Figure A-17 for detailed results). Figure A-18 and Figure A-19 show the graphs for each well borehole dilution test and the varying circulation rates. The results compare well to the literature velocities of approximately 10cm/day for porous media flow in Borden (Laukonen 2001).

A.2.7 Temperature Vector Probe

Another test to determine the flow characteristics of the simulated fracture well employed the use of the Temperature Vector Probe developed by Peeter Pehme. This is a new device not yet fully tested and proven.

Detailed temperature profiling was performed in boreholes to detect temperature variations of a few 10,00ths of a degree Celsius (0.0001 C), which according to Greenhouse and Pehme (2002), can be used to identify hydraulically active fractures (Greenhouse & Pehme 2002;Pehme, Parker, Cherry, & Greenhouse 2007).

The Temperature Vector Probe is slowly lowered down the borehole after precise vector measurements have been taken. By taking the vector measurements, the rotation of the probe is corrected by the readings of the gyroscope. Temperature measurements are taken as the probe is lowered. There is a temperature variation in the hydraulically active zone compared to that of the stagnant zones. Through this method, it is possible to determine the depth of the active zones. It should also be noted that this is the first test of the TVP probe in a porous media well. Figure A-20 shows the TVP plot, it is not a clear cut result but arrows were placed on the graph to indicate the location of the fractures. There are small blips at the marked location.

A.2.8 Indicator Material/Dye

These were the final tests done before this thesis came out.

A.3 Fractured Rock Passive Flux Meter Prototype Designs

Further work with the FIPS device would include creating a passive fractured rock flux meter as described above. Through brainstorming, three prototype avenues were explored. The first avenue looked at a discrete interval open borehole conditions, with double-acting packers and/or tapered packer straddling an interval with GAC or Activated Carbon (AC) cloth. Second there was a discrete interval FLUTe spacer flow zone, triple tapered packers and/or a single continuous long tapered packer, with AC cloth attached to the packers. The third was the everted FLUTe liner that would be segmented with AC cloth at desired sample locations with the non-sample zones packing off the rest of the borehole.

GAC is a material that seems likely to be used only in a straddle packer type design. GAC is a tried and tested material, as per the Passive Flux meter(PFM) which was designed at the University of Florida (Annable, Hatfield, Cho, Klammler, Parker, Cherry, & Rao 2005;Hatfield, Annable, Cho, Rao, & Klammler 2004). The difficulty with this material though is its attachment to said device. There are also issues with durability, sloughing, and sampling a distinct flow zone area. The AC cloth, on the other hand, holds much promise for many of the challenges faced with GAC are not an issue with AC cloth (Figure A-12). Being a cloth, attachment to a packer system is much easier, and it completely erases the issues of sloughing. As well, the FIPS device can be incorporated with the AC cloth to indicate the exact sample zone, so there is no averaging over a sample interval. Properties of the AC cloth needs to be examined, how it sorbs contaminants and releases tracers, and how it interacts with a flow zone, but there is promise in this technology.

With the discrete interval open borehole condition, a sample zone would be straddled with packers, sealing off this zone from the rest of the borehole. Sample material, be it GAC or AC cloth would be attached between the straddle packers. An issue with this design, with both sample material, is that there would be an annulus between the material and the borehole wall. This annulus would affect the flow in the sample interval causing inaccurate reading of contaminant and groundwater flux.

The discrete interval FLUTe spacer flow zone design option would be to press the material directly up against the wall. This design would place AC cloth directly onto a packer or a FLUTe sock. When installed, or when the packer is placed at the desired depth, the material is pressed up against the rock matrix. This design poses the potential problem of matrix diffusion skewing the results. Though matrix diffusion is an important variable, it does not yield the fracture results desired (Figure A-11). The device could be modified to read matrix diffusion, but initially the flux of the fracture is what the design is meant to measure.

To address the issue of matrix diffusion, the idea of using a permeable spacer was proposed. The spacer stops the effect of matrix diffusion, causing the only contamination on the sportive material to come for the fracture flow zone. Again the borehole can be sealed by the FLUTe sock or with a packer (Figure A-21).

The issue of determining active fractures is addressed by the use of dyed material. By dying cotton with SYC #1, one is able to see flow zones clearly under black light. This allows one to sample the affected zone for proper results.

A.4 Packer Systems

Multiple packer systems were explored to determine their feasibility to be used in the fractured rock passive flux meter.

A.4.1 Straddle Packer

The design thought process went from minimal adaptation of the PFM (Figure A-22) to a completely different design with new materials. The simplest design involved placing a standard GAC filled PFM between two straddle packers (Figure A-10). The packer options for this design included double acting (Figure 2-22), tapered FLUTe (Figure A-23), and standard packers (Figure 2-21). The GAC in a permeable sock would hang between the chosen packers with an open annulus between the sock and the wall. This annulus poses a problem, as there will be mixing in the zone, and the fracture effect will be diffused through the entire GAC sock. The result would be a decreased flux reading.

The double-acting straddle packer allows for a variable sample area size, based on easy adjustment on packer spacing. The packers are very durable and can act as centralizers to help protect the sample material upon insertion and removal. An added benefit of the double acting packer is that if there are more than two packers they can be used in series to have multiple sample zones on one pipe. This method allows for easy adaptation between GAC and AC cloth.

There are disadvantages to the double acting packer as well. Because the sample is not pressed up against the wall, the sample is only an average over the whole sample area, not a reading from the discrete fracture itself. The double acting packers have problems with deflating, especially if filled with water. As well, the inner material that clamps onto a pipe is not very durable, and it is prone to leaks. The packers act as centralizers, but because of this, and due to their design, there is minimal space between the packer and the borehole wall; this could cause potential insertion and removal problems.

A.4.2 Design of Straddle Packer

The prototype straddle packers were homemade and set up to also be used for borehole dilution tests. They started out as two 8”x4” (10cmx20cm) solid PVC columns. These columns where machined down to a diameter of 3.45” with a 1” step on the top and bottom 3.75” diameter. An inflation line was bored through the PVC vertically, with a connecting horizontal boring. Two circulation lines were also bored into the packers. One line was connected to the bottom packer, which had an opening at the top for the injection. The other circulation line was drilled through the top packer and left open as the other side of the circulation loop. Fittings were installed at the top and bottom of the upper packer and in the top of the lower packer. The fitting in the test interval section of the packers were set into a hollowed out section. A 2” pipe was put in this section for stability, protection of inflation lines and for attachment of material for the flux tests. This center pipe was attached with set screws. Pear-gum tubing was fitted over the machined PVC. This material was stretched over the lip to fit snug over the 3.45” radius section, approximately 6” in length. Silicone was used to help seal the packer, and Oetiker clamps ensured a tight seal. The top packer was also fitted with eye bolts with a rope attached for retrieval (Figure A-24).

The prototype straddle packer used for the vertical slit flux meter followed a similar design. No circulation lines were installed. An extruded base was set on the top and bottom packer and a 3" pipe was fitted over this section. The pipe had two vertical slits cut at an angle of 75 degrees apart, 1/8" wide and 12" long. The concept behind this design is similar to that of an airplane wing. The off-set slit creates a natural gradient for flow through the pipe (Figure A-25).

A.4.3 Tapered Packer

There are two main tapered packer ideas, the first idea is to have three tapered packers together (Figure A-26), with the middle packer acting as the test zone. The second idea is to have one long tapered packer (Figure A-23), with the sample area in the middle of the packer and with enough space above and below to seal the borehole. The setup on both designs would have a spacer material pressed up against the rock matrix. This spacer would stop matrix diffusion from occurring in the AC cloth. Next to the spacer material would be AC cloth (this is the sample material). This sample material would be followed by another layer of spacer because this helps facilitate flow through the sample material. The final layer would be a diffusion barrier, which is particularly important in the FLUTe sock setup to stop cross contamination. The indicator material would likely be setup between the diffusion barrier and the spacer so as not to interfere with the flow coming into the sample.

A distinct advantage of the tapered packer is its seal against the borehole. The packer surface area stays the same whether inflated or deflated, and this makes for easier attachment of material. A normal packer will shrink in length to accommodate the expansion in width; it also bulges up and down the borehole when inflated. Being pressed directly up against the borehole wall, it is possible to get a fracture network map, and individual fracture data by using the indicator material. The flexibility of this material makes it possible to compress to avoid abrasion with the borehole wall.

However, flexiblity sacrifices durability, and a sharp edge could be the end of the packer. By placing the sample material on only one packer, only one sample zone will be tested. As well, only one sample material may be used: AC cloth. To go along with the durability issue, to keep the material away from the borehole wall when rising and lowering, some sort of centralizer will need to be installed. Removal can also be a problem when it is not possible to compress the packer upon deflation

A.4.4 Everted FLUTe Liner

Attached to a FLUTe sock in the sample zone there would be a segmented five layer system: spacer, AC cloth, spacer, diffusion barrier, FLUTe (Figure A-21). These sample layers can be spaced along the length of the sock. The separation between each sample zone stops cross connection. Material could be attached to the FLUTe sock via Velcro, this would allow for easy installation and removal of sample material. The layers would need to sewn together, and, after the test is complete and the material removed from the liner, the affected zone would be cut out of the sample material. Eversion would follow standard FLUTe technique as would removal (Figure A-27).

Implementing this idea completely seals the borehole, and the material only touches the desired location, being protected inside the sock on installation and removal. The FLUTe technology is a proven method (Cherry, Parker, & Keller 2007), and would allow for geophysical tests (i.e. high resolution temperature logging) to be run in the liner while flux measurements are being taken (Figure A-28). FLUTe uses a technique of placing a fabric on the FLUTe liner to indicate NAPL presence, this would be a similar technique and technology used for fracture flow indication (Keller 2008).

Removal of the sample material after the liner is pulled could prove to be difficult. As well, more equipment is needed in this set-up than some of the other designs for entry and removal. The time required to insert and retrieve the device, especially in tight formations needs to be considered, as it can take a day to move a few meters in a tight formation. Another area of concern is that contaminated water is forced into the matrix on insertion. This issue would take considerable though as to how this affects the results?

A.5 The Vertical Slit Straddle Packer Flux Meter

The vertical slit straddle packer flux meter is a unique design thought up by Kirk Hatfield, a professor at the University of Florida. The principle is similar to that of an airplane wing. The wing of an airplane is shaped so that as air passes over it, creating lift also known as a pressure gradient. This concept is adapted for water flow. Two vertical slits are cut into a pipe (sized to minimize the annulus with the borehole wall) and spaced in such a way that there is an angle around 75 degrees. This angle creates a natural gradient to encourage water flow based on Darcy's law (Figure A-25), flow from high pressure to low pressure. The same principle as an airplane wing, where wind flows over the wing and based on the angle there is higher pressure below then above creating lift.

Based on calculations completed by Hatfield, for this design to work as a flux meter device, the groundwater velocity would need to be in the range of 400m/day. This could be possible in karstic environments or in stream systems.

A.6 Continued Work

Design and development work is on-going. The FIPS device was an important breakthrough in the fractured rock passive flux meter (FRPFM) work. With the ability to locate individual fractures it is now possible to create a device without having averaged fluxes over a test interval. The next step is to finish parameter and property tests on the AC cloth and start inserting the FIPS plus AC cloth on different packer systems to see how they react in varying flow environments. Through the test process of the FIPS device, the systems that will be tested for the FRPFM will be used on packer systems (DAP and tapered FLUTe packers) as well as the everted FLUTe sock design.

Conventional flux tests will need to be performed to reference the results from this new FRPFM. Initially, tests will be performed in the box aquifer before moving to the Borden environment. In Borden, a variety of flux test could be performed. In a gated system an imposed flux could be initiated with a pumping well. This type of test would be a controlled environment in which to compare the FRPFM results too. As well, the parameter in the BDI aquifer are well know, and previous PFM tests have been performed here, so results can be compared to those previous test.

After the "bugs" are worked out in the laboratory and Borden the device will be tested in a fractured rock environment, likely in the same well used for the FIPS device in Guelph. With the FIPS device and AC cloth tests, a successful FRPFM is not far off.

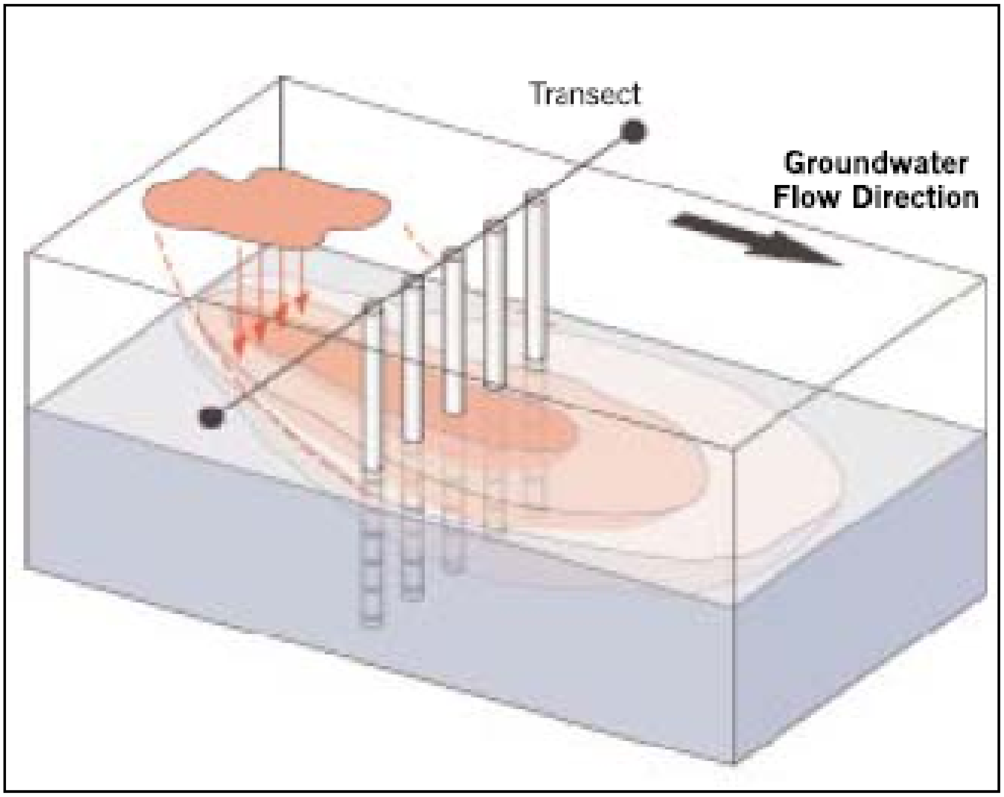


Figure A-1: Measuring Flux with a Transect (Nichols 2004)

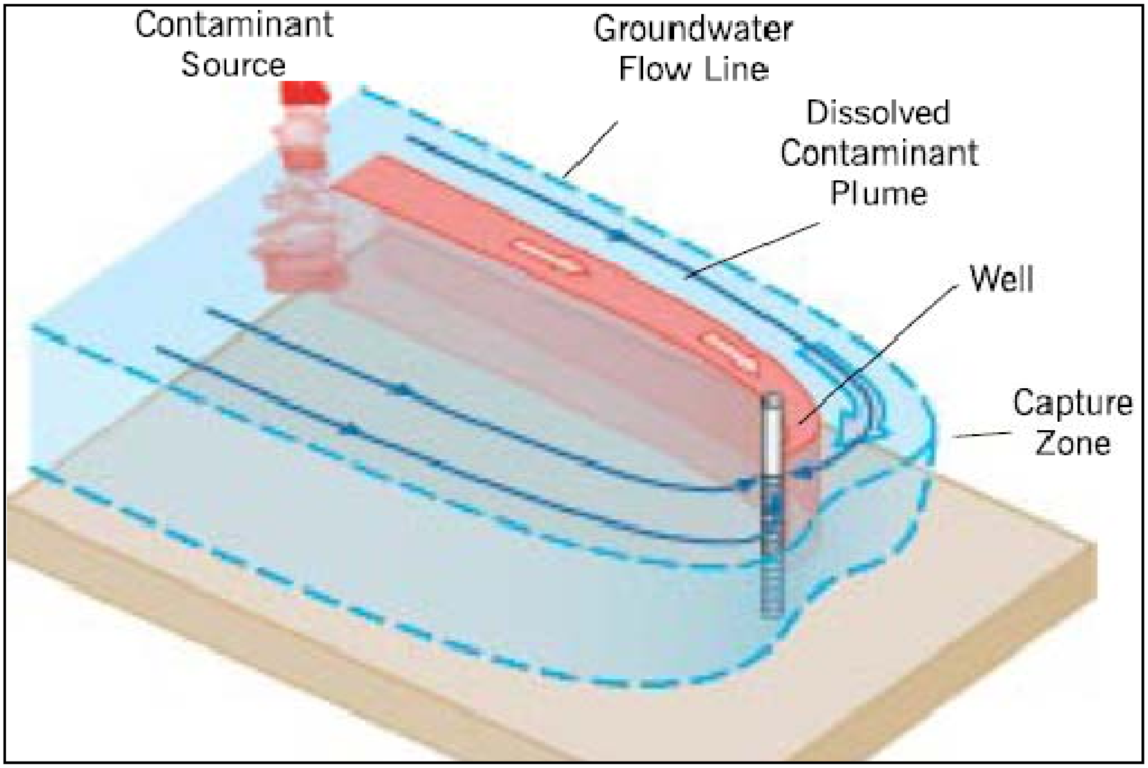


Figure A-2: Measuring Flux with a Pumping Well (Nichols 2004)

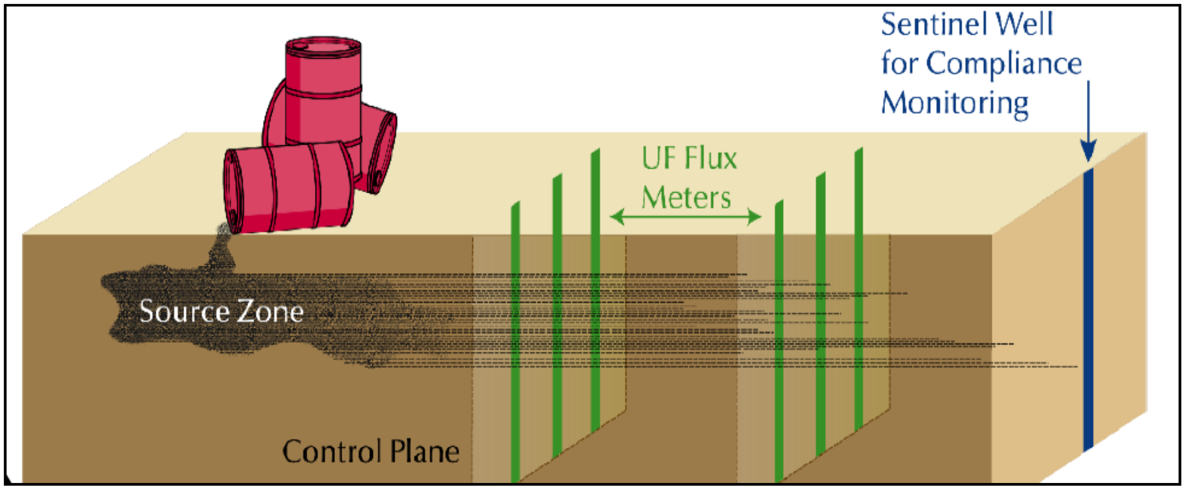


Figure A-3: Use of PFM to measure flux in plume (Hatfield, Annable, & Rao 2005)

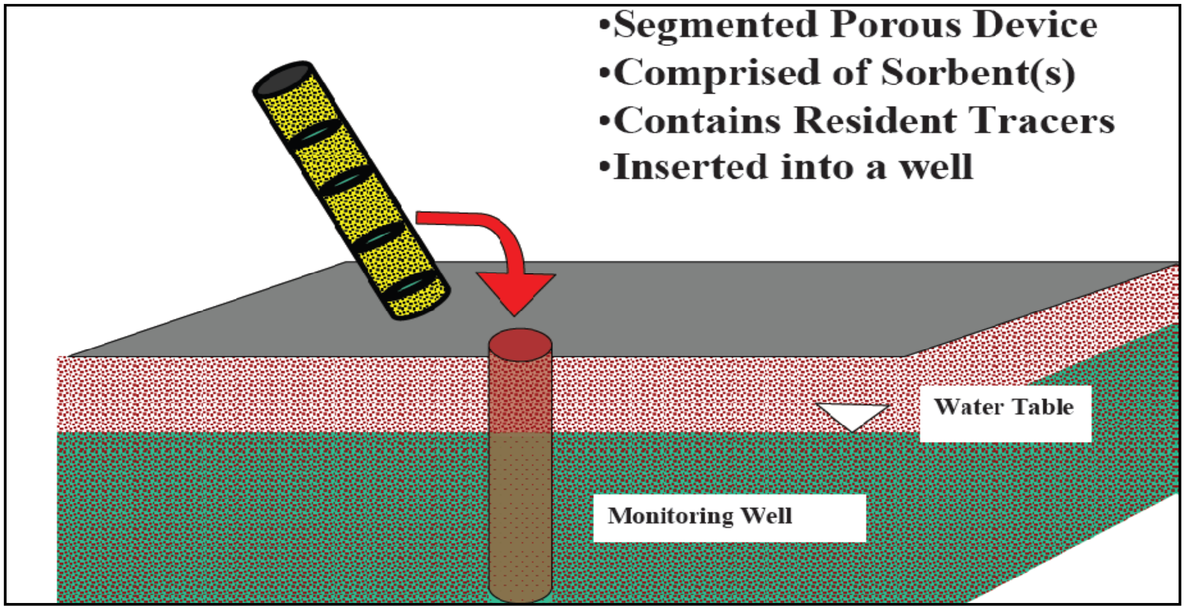


Figure A-4: PFM in Granular Aquifer (Hatfield, Annable, & Rao 2005), explaining the process and make-up of the PFM

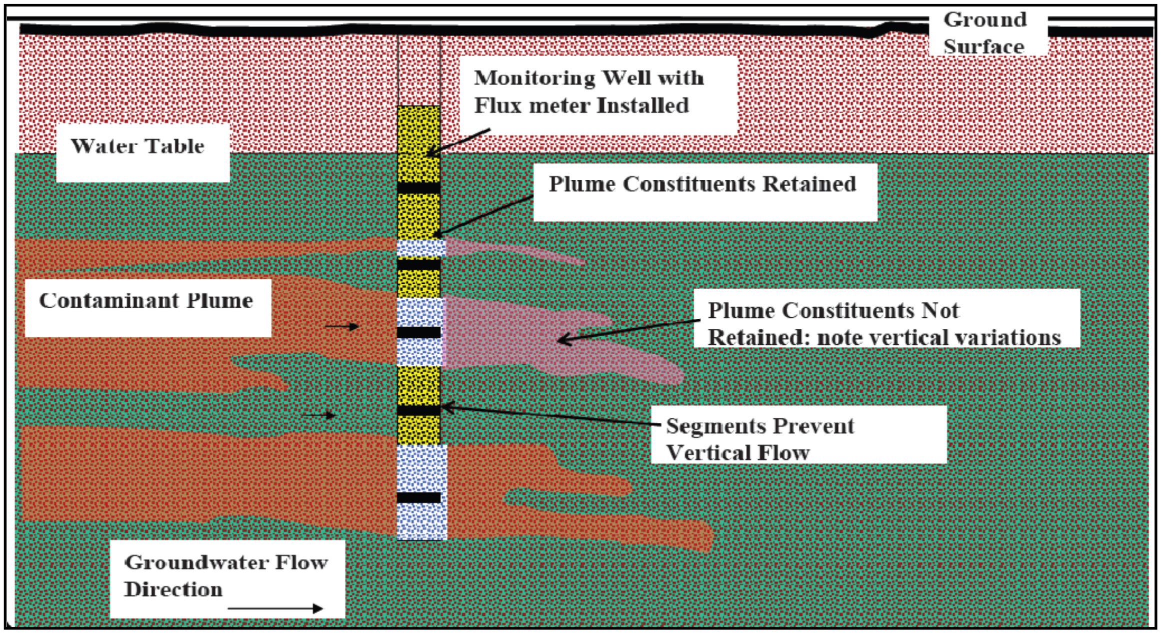


Figure A-5: Flux measurement in Granular Aquifer (Hatfield, Annable, & Rao 2005), a cross section on how the PFM works.

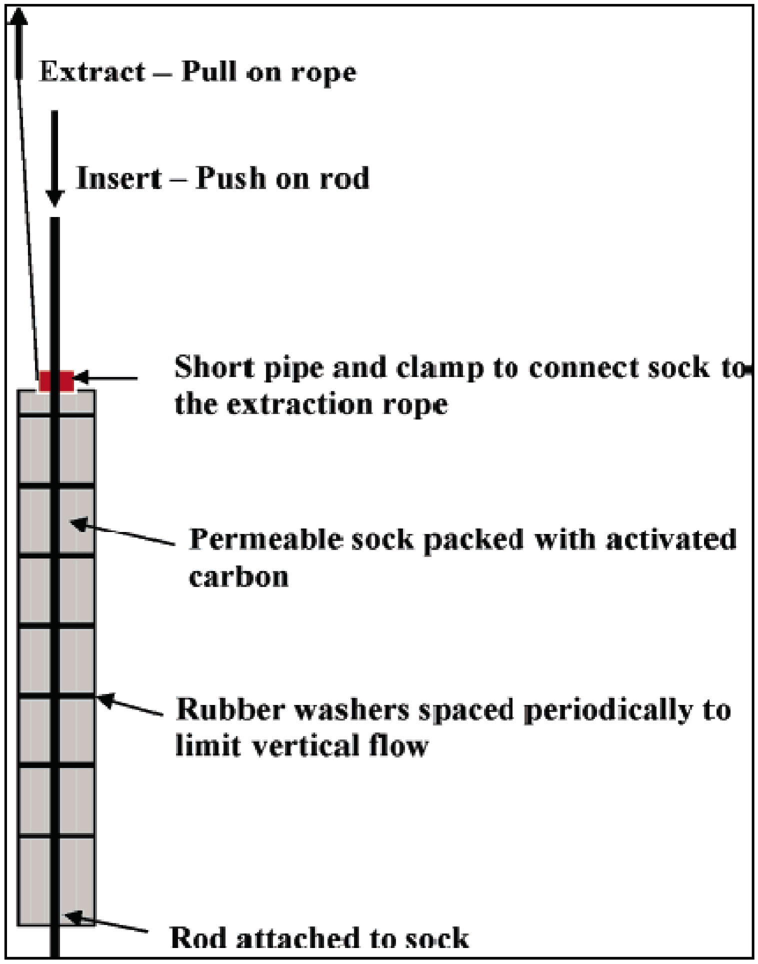


Figure A-6: Components of the PFM (Annable, Hatfield, Cho, Klammler, Parker, Cherry, & Rao 2005)

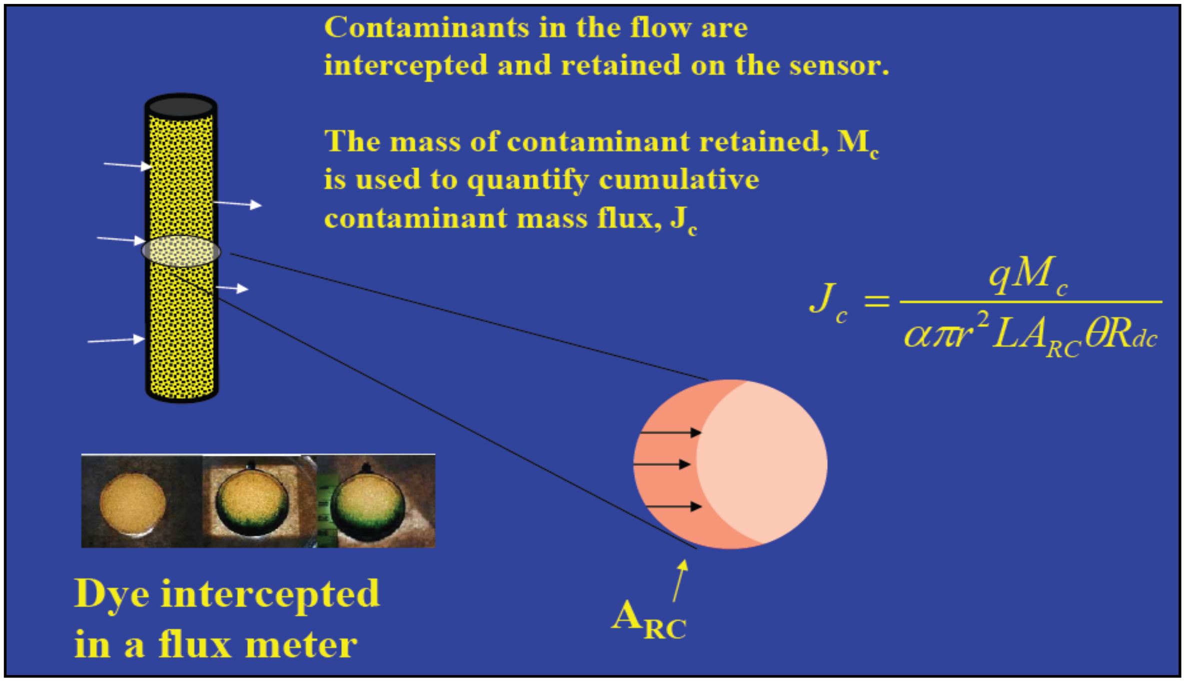


Figure A-7: Contaminant Flux Measurement calculations (Hatfield, Annable, & Rao 2005)

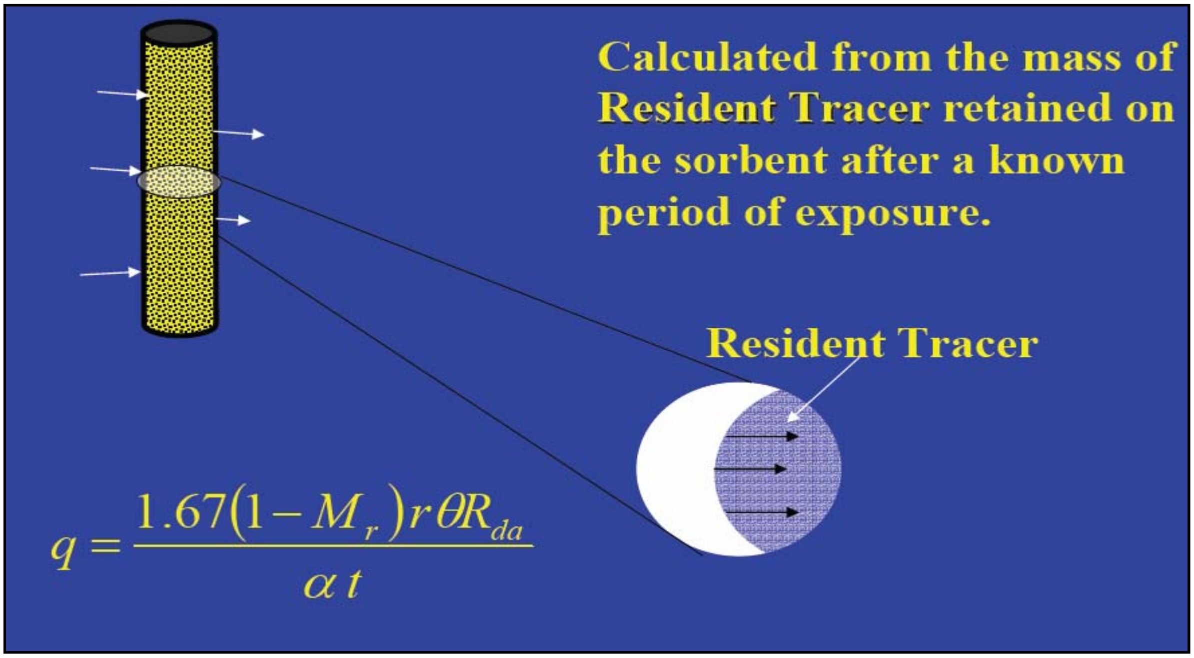


Figure A-8: Water Flux Measurement calculations (Hatfield, Annable, & Rao 2005)

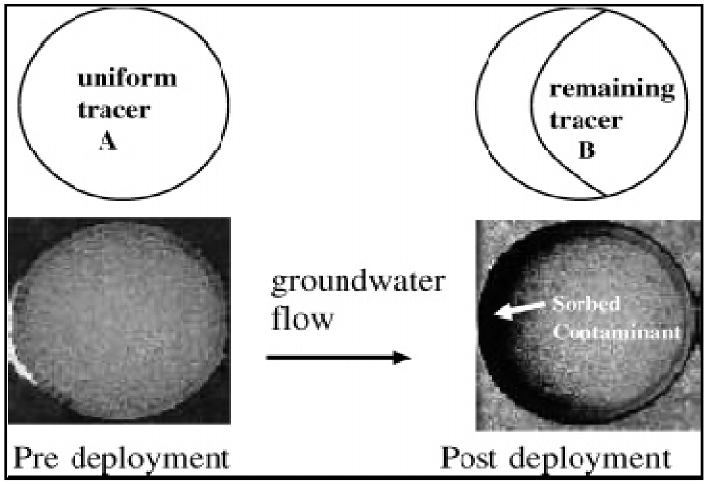


Figure A-9: Pre- vs. Post- deployment images of the PFM (Annable, Hatfield, Cho, Klammler, Parker, Cherry, & Rao 2005)

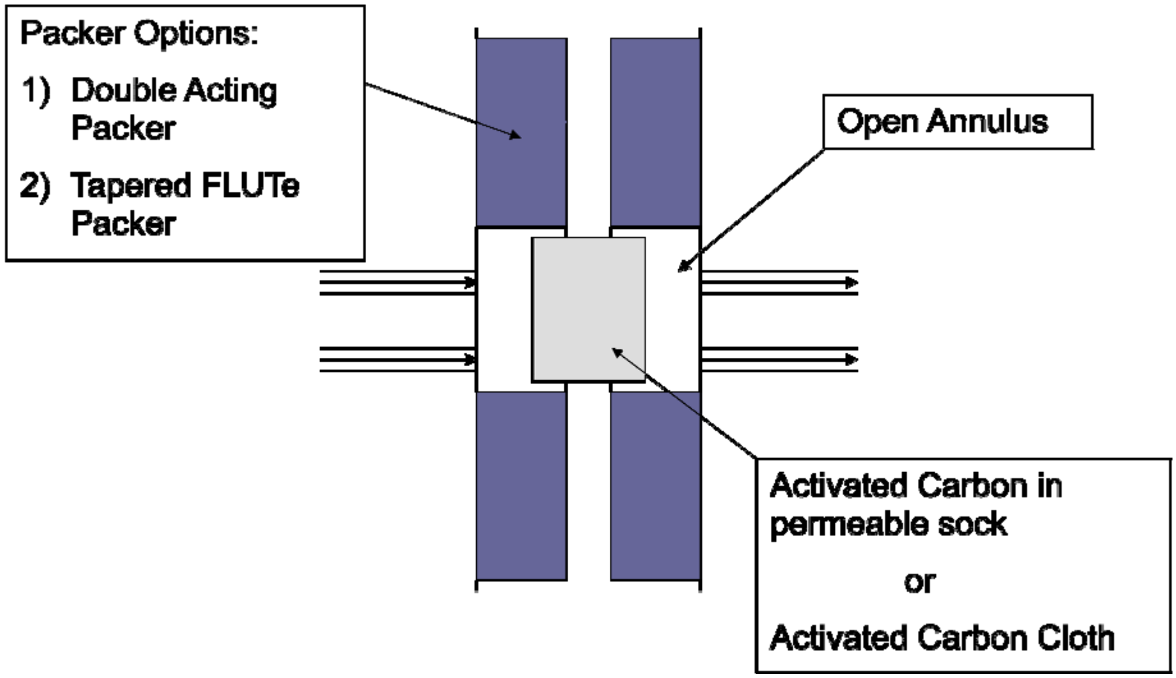


Figure A-10: Straddle Packer thought process and design

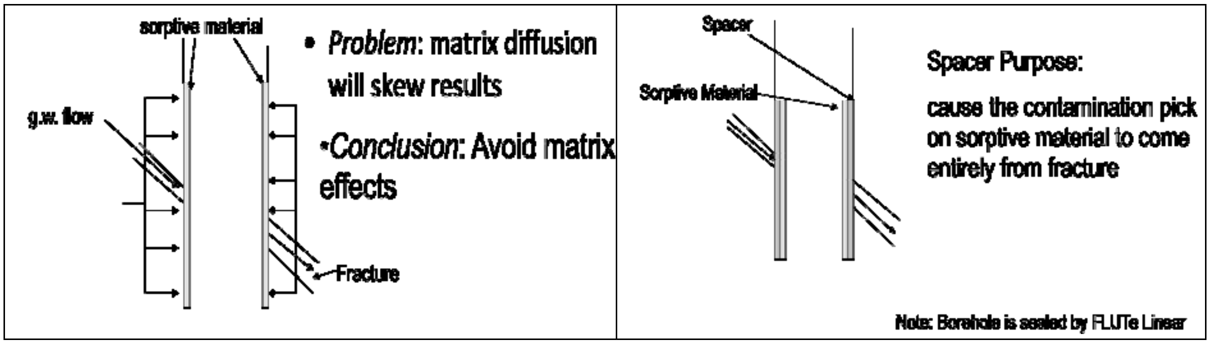


Figure A-11: Sorptive Material thought process and design

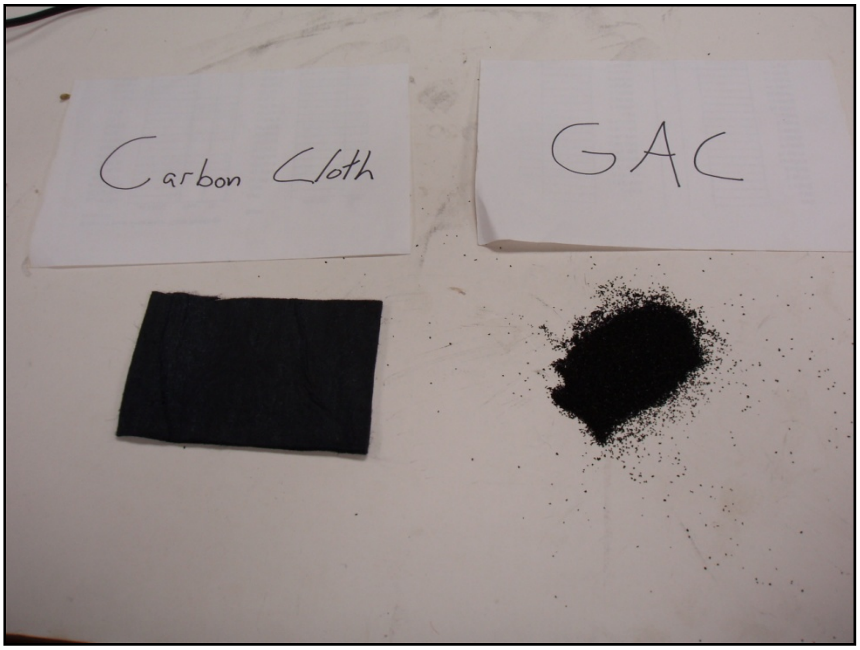


Figure A-12: Sorptive Material Options - Carbon Cloth and Granular Activated Carbon

Figure A-13: Assembly issues with Straddle Packer GAC design, issues with putting sock on, and sloughing of GAC

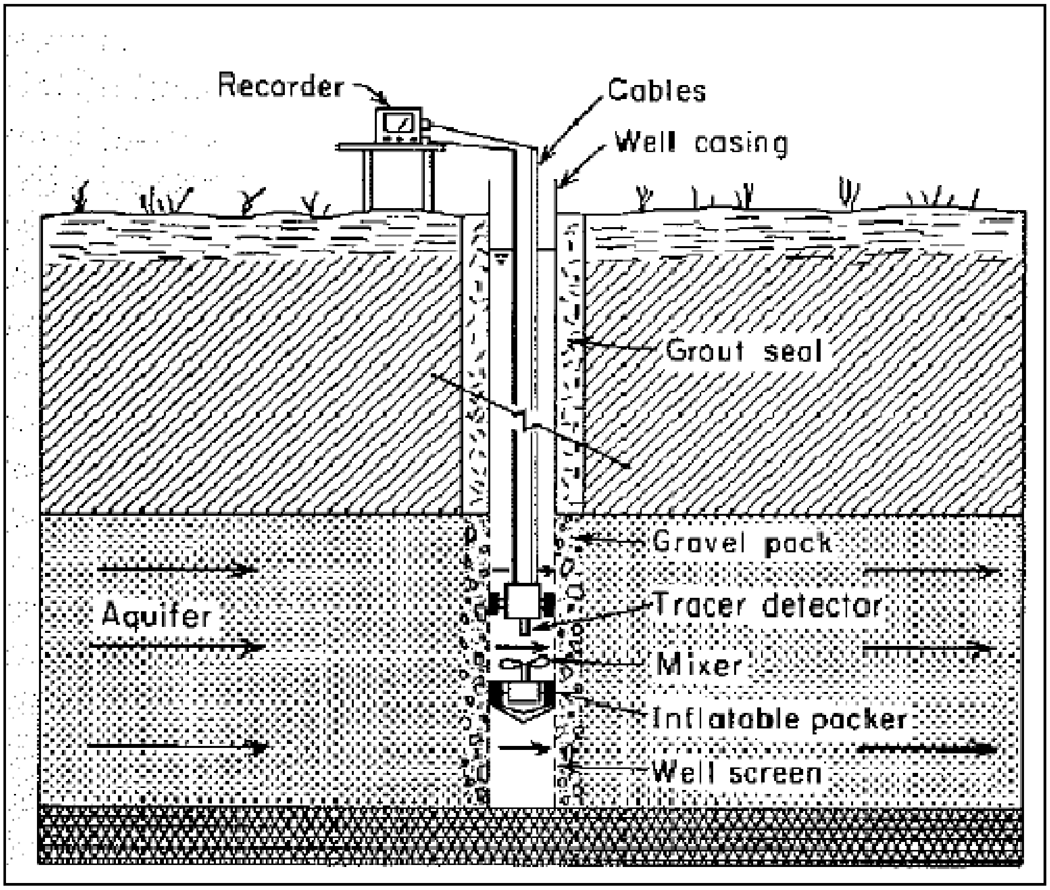


Figure A-14: Schematic of Porous Media Borehole Dilutions set-up from Freeze & Cherry (1979)

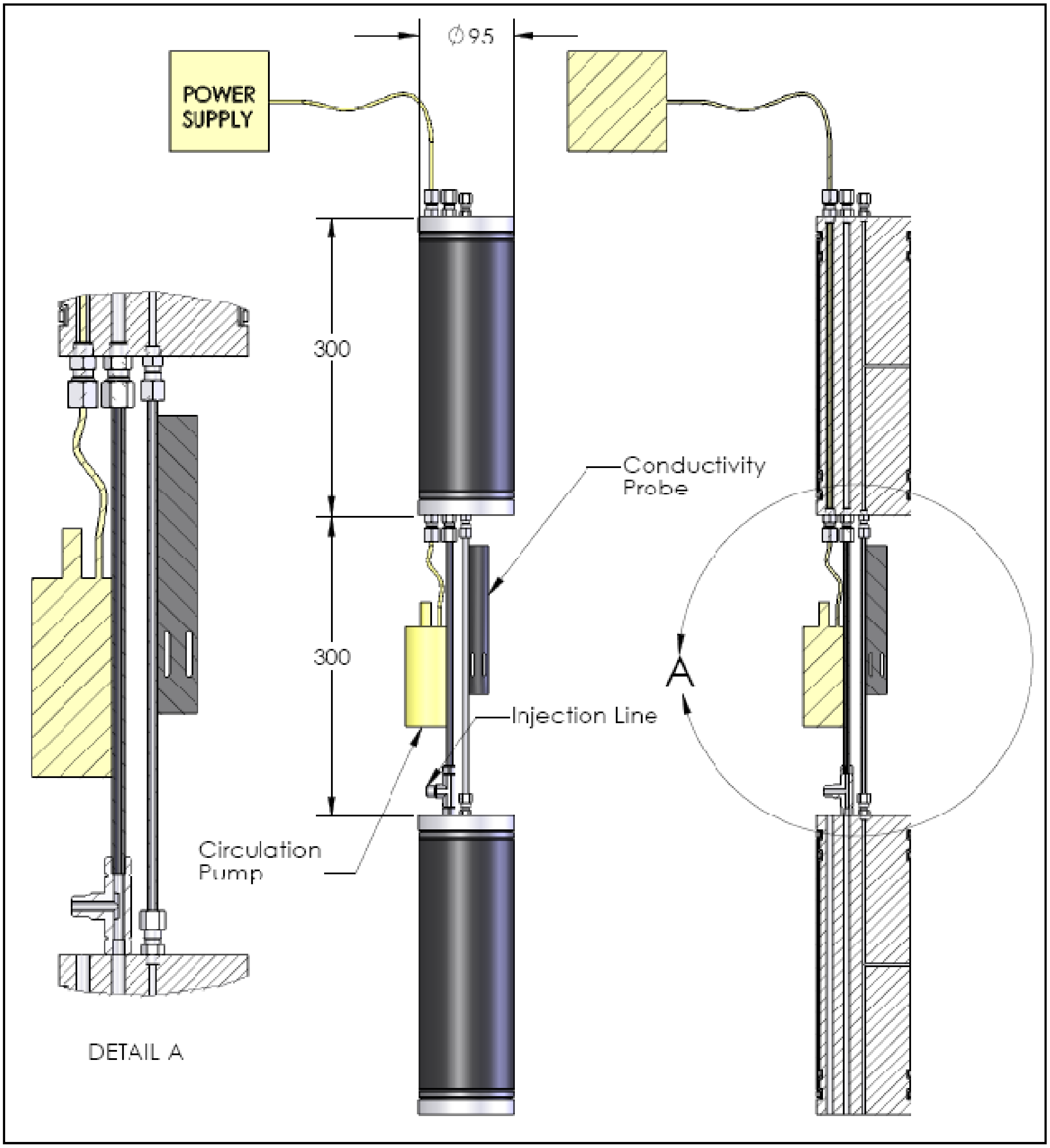


Figure A-15: Borehole Dilution Set-up. The packers straddle a fracture or set of fractures, creating a secluded flow zone for a borehole dilution test to be performed. A tracer is injected from surface entering the seclusion zone through the injection line. A pump that is controlled by a power supply at surface circulates the water in the packed off zone and a CTD diver takes conductivity and pressure readings. All measurements are in mm.

Figure A-16: Borehole Dilution Set-up - Inflation Line, Whale Pump, CTD Diver and Power supply

q=-V/(aAt) * ln(c/co)		v=q/ue
V=	measuring volume	
A-	x section of flow area	
t=	time	
co=	c start (-background)	
c=	c (-background)	
n=	porosity	
a=	slope factor	

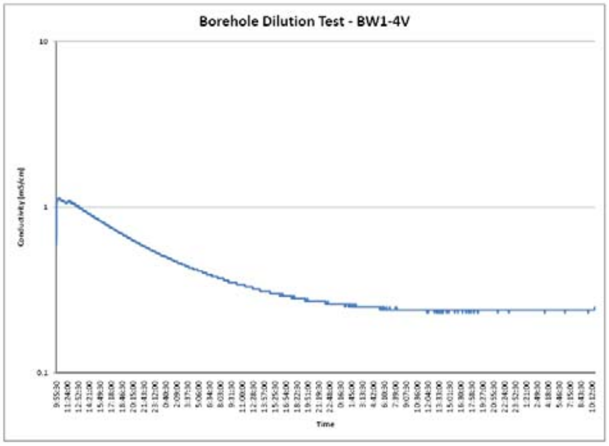
V=pir^2h	2675.415	cm^3		
A=2pir^2+2pirh	1215.46	cm^2	apeture*dia	4.8768

r=	5.08	cm
h=	33	cm
n=	0.33	

	BW1-4V	BW1-6V	BFW7.5-6V	BFW7.5-4V	BFW7.5-2.1V
co	1.12	1.2	1.22	0.95	1.07
c	0.56	0.6	0.92	0.62	0.69

Time (hr)	12	12	42	67	56	
	BW1-4V	BW1-6V	BFW7.5-6V	BFW7.5-4V	BFW7.5-2.1V	
q=	**0.002119**	**0.002119**	**0.000246523**	**0.000233663**	**0.00028741**	**cm/min**
v=	0.006421	0.006421	0.000747039	0.000708071	0.000870938	cm/min
	9.246816	9.246816	1.075735996	1.019621817	1.254150718	cm/day
	0.092468	**0.092468**	**0.01075736**	**0.010196218**	**0.012541507**	**m/day**
(corrected for just horizontal flow)				**apeture * diameter**		
q			0.061441629	0.058236618	0.071631947	cm/min
v			0.186186756	0.176474599	0.217066505	cm/min
			268.108928	254.1234219	312.5757674	cm/day
			2.68108928	2.541234219	3.125757674	m/day
a=2			**1.34054464**	**1.27061711**	**1.562878837**	**m/day**

Figure A-17: Calculations of Borehole Dilution test in Borden wells



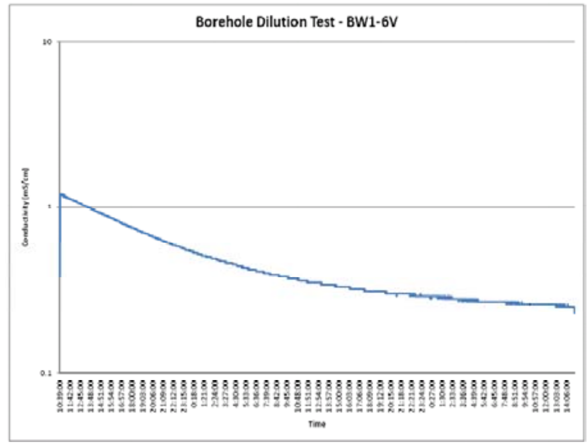


Figure A-18: Borehole dilution test graphs for porous media well. Same results of 9.25cm/day

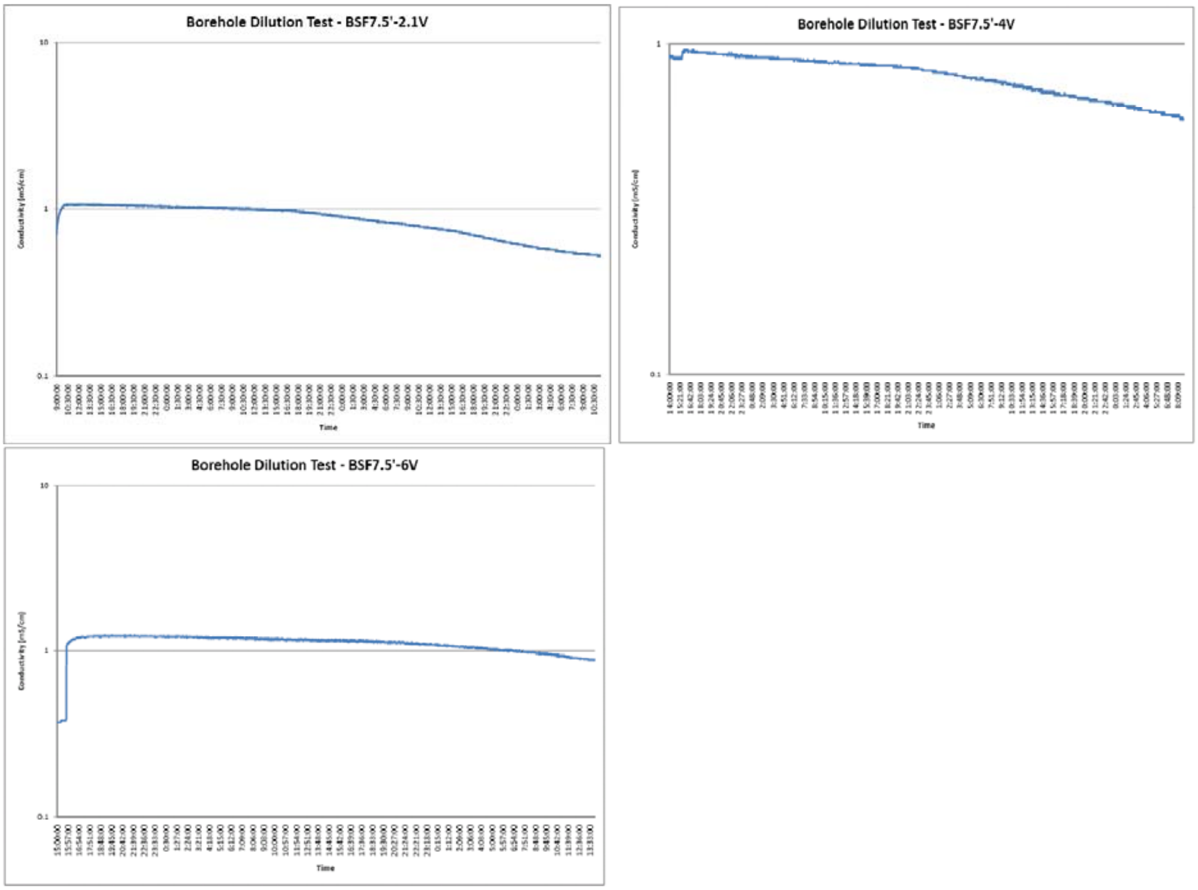


Figure A-19: Borehole Dilution Results for simulated fracture well with a horizontal groundwater velocity of approximately 1.35m/day

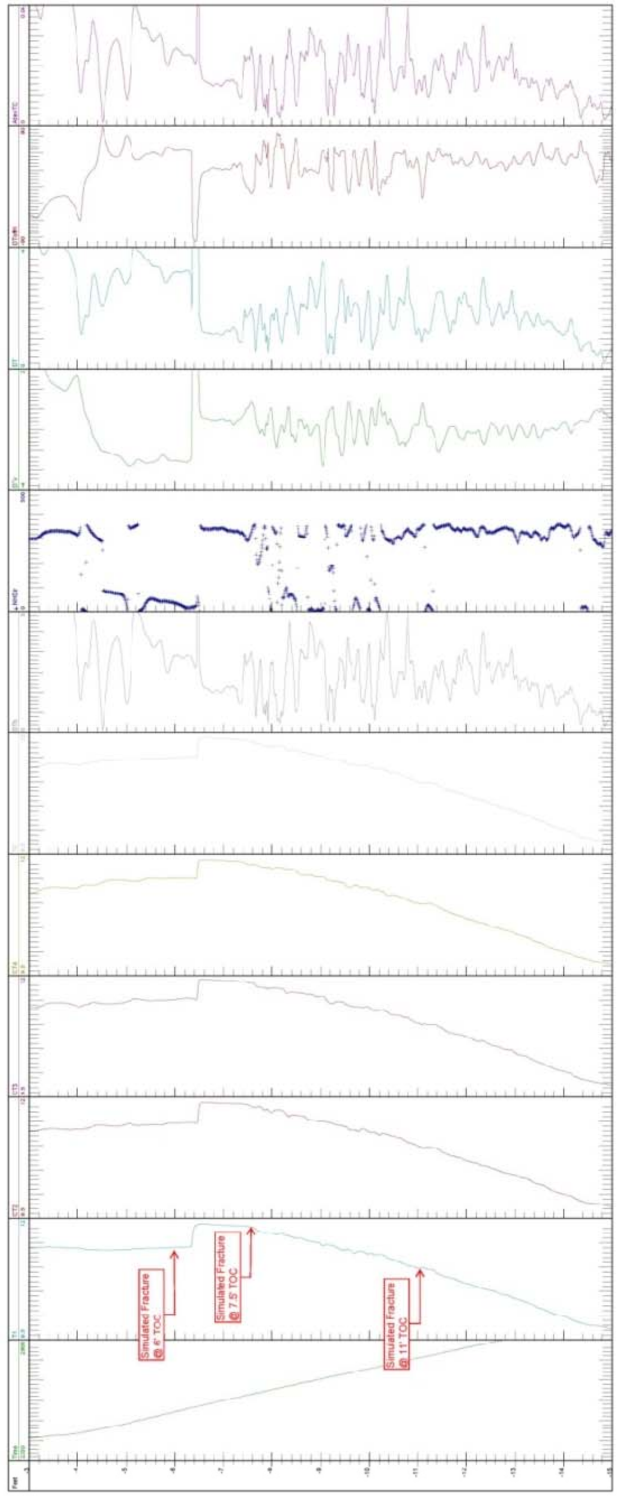


Figure A-20: Plot from the Temperature Vector Probe, balloons indicates where simulated fractures are located.

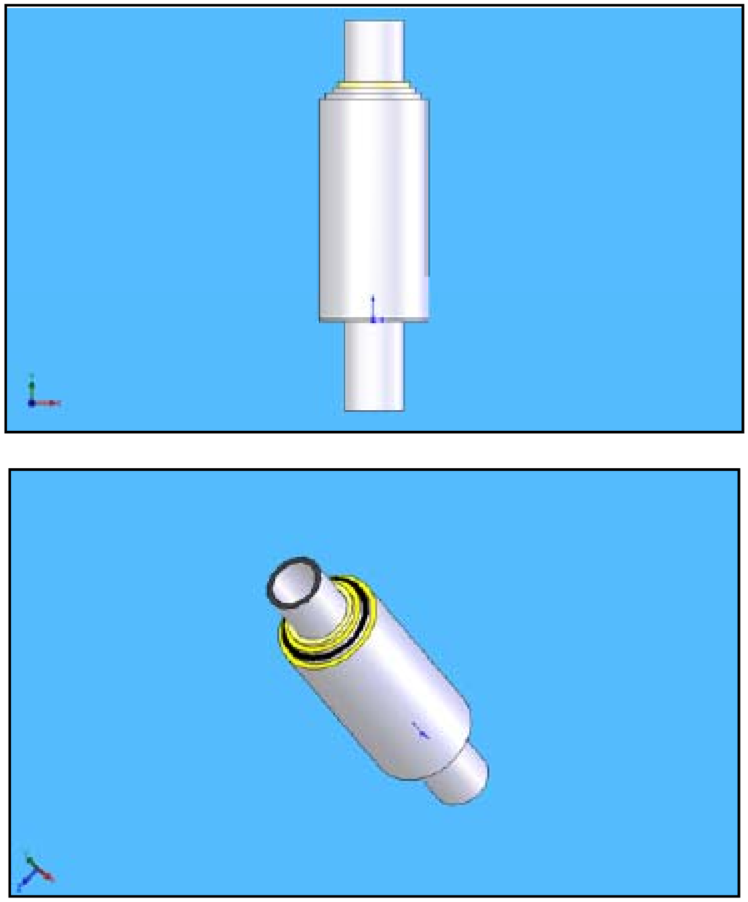


Figure A-21: 5 Layer system - Spacer, Carbon Cloth, Spacer, Diffusion Barrier, FLUTe liner

Figure A-22: Passive Flux Meter for Porous Media (Annable, Hatfield, Cho, Klammler, Parker, Cherry, & Rao 2005). A picture of the actual PFM used by the University of Florida, GAC in a sock and baffled to stop vertical flow.

Figure A-23: Tapered FLUTe Packer- Deflated (left), Inflated (right)

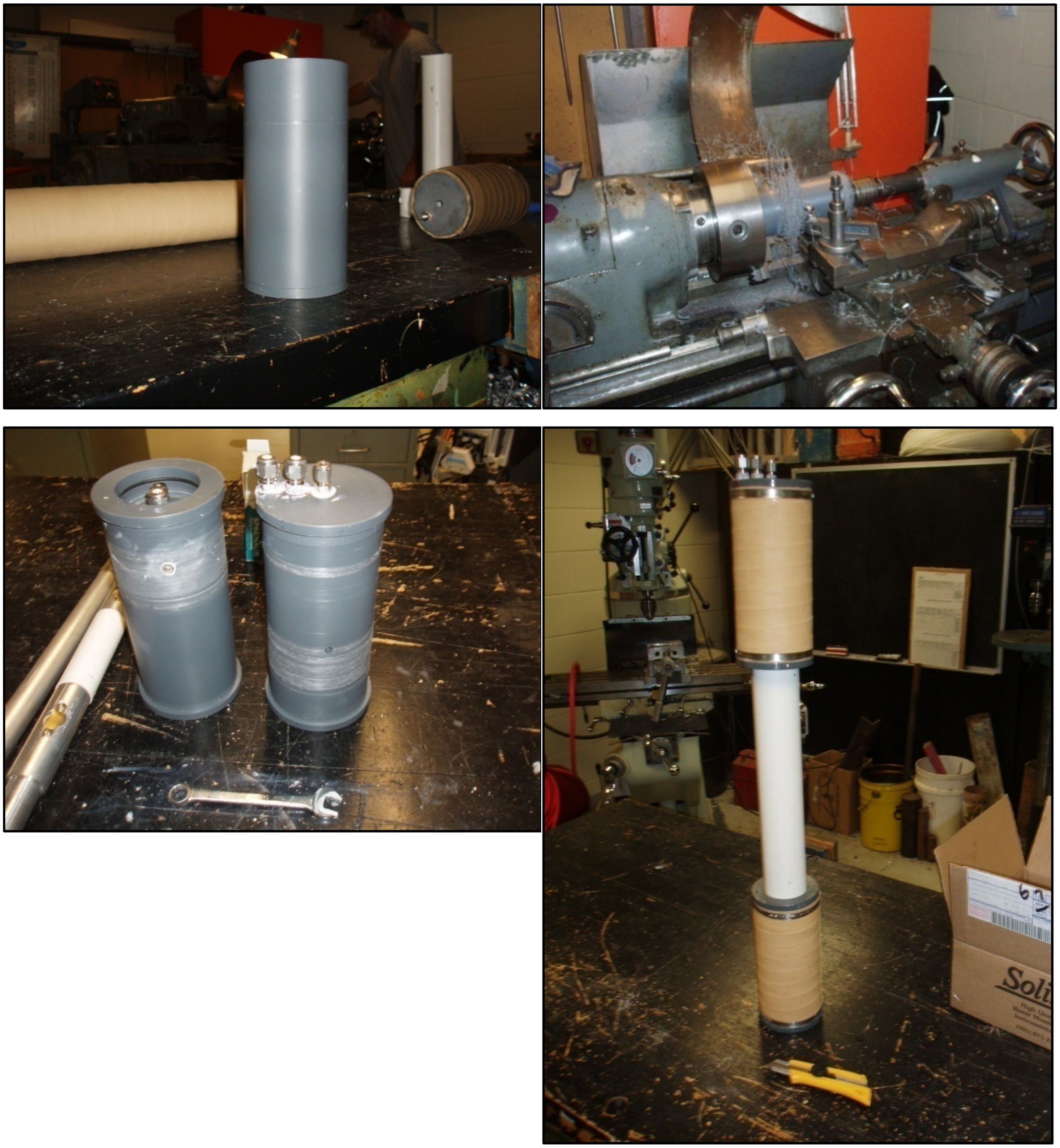


Figure A-24: Assembly of Straddle Packer- used for Borehole dilution tests and initial PFM test. This design allows for mixing and insertion of NaCl.

Figure A-25: Vertical Slit Straddle Packer Design and assembly process. Vertical slit is spaced 75 degrees apart, and is 12" long set between two packers.

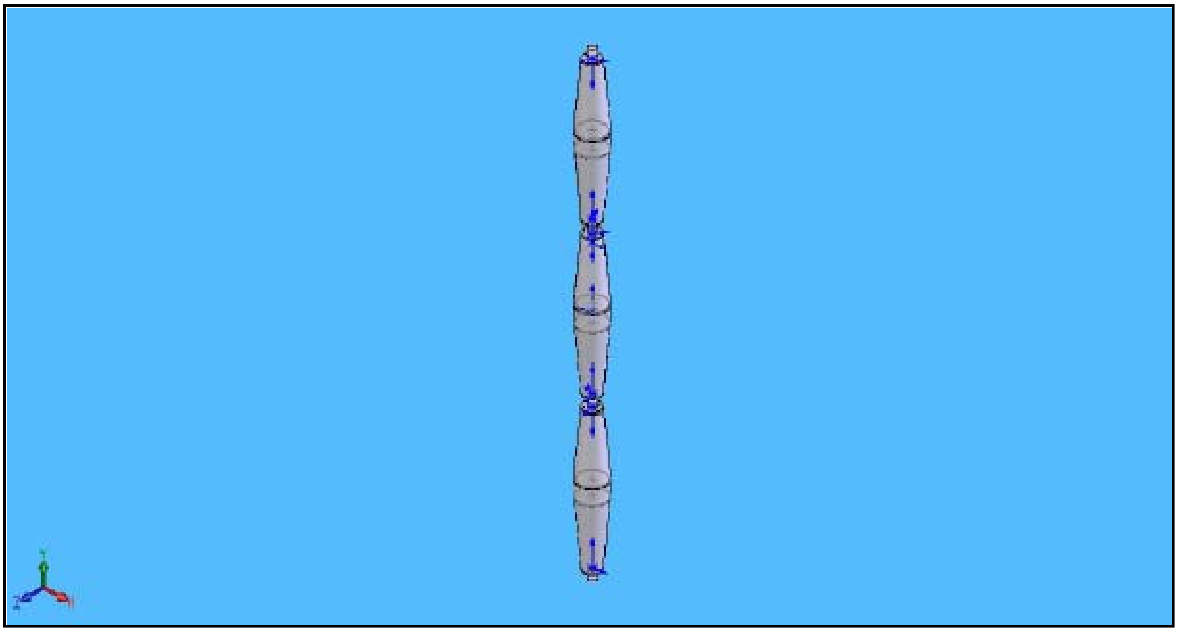


Figure A-26: Tapered FLUTe packer design, using 3 packers in unison

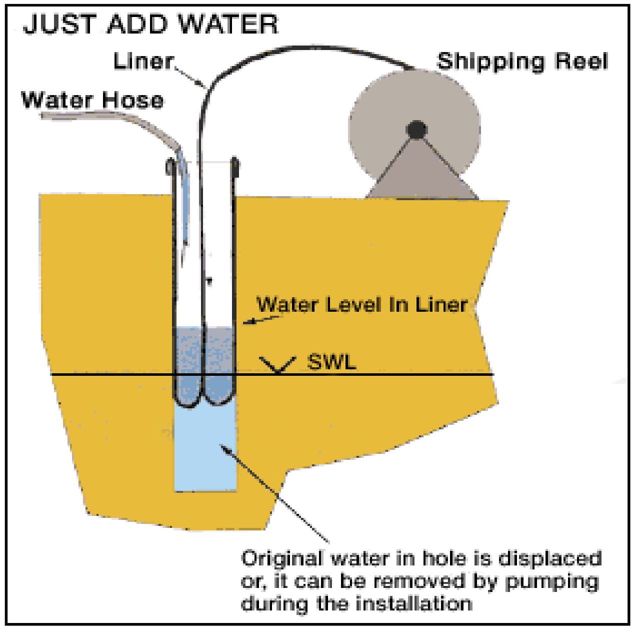


Figure A-27: Installation of FLUTe liner by adding water. (Keller 2008)

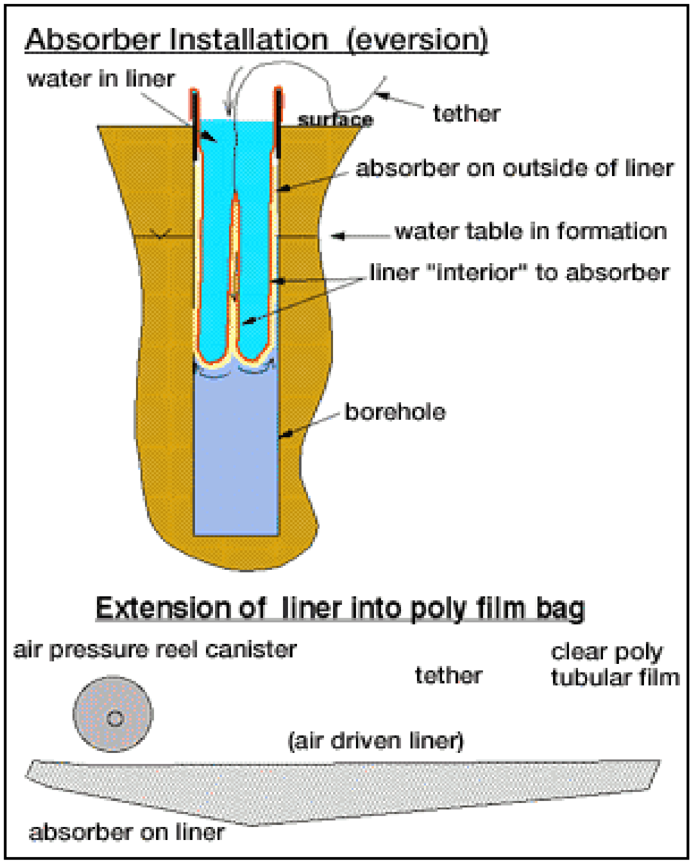


Figure A-28: FLUTe liner with sorbent material on outside (Keller 2008)

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